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Image modelling of forest changes associated with acid mine drainage

N.A. Walsworth, D.J. King*

Department of Geography, Carleton University, 1125 Colonel By Drive, Ottawa, Ont., Canada K1S 5B6

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Abstract

A planar cellular transition model was investigated as a predictive methodology for modeling tree canopy dynamics along a chemical contamination gradient adjacent to an acid mine. Stochastic raster transitions were developed as a function of both proximity to the tailings and local stem density neighborhood configuration. Model inputs consisted of scanned and registered archival photographs that were segmented into three forest classes using two different apex delineation techniques, one incorporating double-aspect calculations and the other using a high-pass filter. The results for each were integrated over selected sample windows. The accuracy of the two techniques was compared using a synthetic data set. The double-aspect technique was better able to identify and delineate tree crowns in synthetic data with significant noise and shadow representative of typical forest conditions. However, the window integration results were more visually interpretable when classes were derived from the high-pass technique. Application of these techniques to the archival photography and subsequent temporal analysis using the Mann–Krendall statistic revealed significant forest degradation over a 40-year period nearer the tailings and within areas of mixed canopy types. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Tree density mapping; Geographic raster modeling; Mixed forest canopy; Acid mine drainage; Automata; Archival air photography; Landscape change

1. Introduction

The Kam-Kotia Mine site is an abandoned zinc and copper deposit located North–West of Timmins, Ontario. During operations, the milled waste rock slurry was pumped into a tailings settling area. An acid mine drainage problem has resulted from the reaction of surface water with the sulphide mineralogy within the tailings forming sulfuric acid which, with surface and ground water flow, leaches heavy metals and transports them into the surrounding forested area. Mussakowski and Chan (1993) compiled a sequence of archival aerial photographs showing the catastrophic spread of the tailings and associated forest death within the tailings zone. They proposed a drainage model as a means for understanding this change. Rates of spread have slowed since the closure of the mine in the early 1970s; changes are now characterized by more subtle landscape differences. Besides moderate to high levels of heavy metals in the forest soils adjacent to the tailings, windblown deposition of contaminants and tree blow-down have contributed to the observed forest stress near the tailings. In analysis of

* Corresponding author. Tel.: +1-613-520-2600 ext. 8439; fax: +1-613-520-4301.

E-mail address: doug_king@carleton.ca (D.J. King)

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the forest downstream from a large section of unimpounded tailings, Lévesque and King (1998), using semivariogram analysis on 0.5 and 1 m resolution airborne digital camera imagery, found significant correlations between the contamination gradient and canopy measures such as crown size, tree height and canopy closure. Seed and King (1997) have found significant relations of leaf area index (LAI) and basal area with the proportion of shadow in airborne imagery. Recent field measures at the site have shown lower LAI, stem density and greater accumulations of blow-down near the tailings (Olthof, pers. comm., Oct. 1997).

Long-term landscape modeling suffers from limited availability of calibrated digital data. In contrast, aerial photography offers a greater temporal record, but due to film tonal variability, often requires manual interpretation and later digitization which may be tedious for large data sets. This study is an illustration of an integrated technique for undertaking temporal archival photographic modeling of forest canopy changes, and represents a first attempt to integrate natural segmentation routines utilizing first-order density techniques and a cell space model for temporally tabulating changes.

Traditionally, in manual photographic interpretation, single trees or stem clumps are distinguishable by interstitial darker tones and bright apexes forming the image primitives and, in turn, characterizing canopy textures through their density differences (Hay and Niemann, 1994). This represents a 'natural' segmentation of space based upon ground objects. Temporal comparison of such images results in interpretable change since segmented images are based upon real objects for which spatial theory may be directly applied (Flamm and Turner, 1994). Canopy structural change is the result of death, growth and competition for resources such as light and soil nutrients (Peterson and Squiers, 1995a, 1995b), the implication being, that existing canopy spatial configurations determine future individual vitality. This temporal transformation of space in which an outcome is dependent upon previous spatial associations, is referred to as a geographic model (Tobler, 1979).

1.1. Segmentation

Recognition of the tree image primitives requires some form of segmentation technique. Haralick and Shapiro (1985) outlined several image segmentation techniques in a summary article which, although not directly applied to tree delineation, shows how methods are commonly a hybridization of techniques. Aerial photography represents trees as irregular conical or domal shapes commonly having irregular edges and diffuse tones. A gradient guided technique was proposed for high resolution digital imagery by Gougeon (1997), in which shadows were traced and topology created. Contrast measures such as high-pass filters have been applied to define edges of homogeneous areas. The theoretical basis of this technique is to mask high contrast areas from which histograms can be generated containing equal pixel proportions of background and foreground which then serve to enhance cluster separability (Weszka et al., 1974). Depending upon scale, Laplacian filters can be applied directly to segment tree apexes or stems. An alternative segmentation algorithm is to apply differing measurement intervals iteratively so that a generated segment maximizes its coincidence with a border defined by an edge operator (Milgram, 1979). This latter technique provides a means to threshold preliminary textural technique results, such as results from a high-pass filter, to approximate a broad thematic division within the landscape. In this paper, a new tree apex segmentation technique, based on a double-aspect measurement of a grey tone surface is introduced and compared to high-pass modeling of forest change.

1.2. Temporal modelling

Hagerstrand (1967) coined the term 'neighborhood effect' while studying diffusion in order to explain the ordered transfer/dispersal of information between adjacent nodes. This definition of geographic locality is a defining feature of cellular space models. In raster systems, this is termed a cell neighborhood. The consideration of spatial neighborhood conceptually maintains continuity of structure in the form of edge and contiguity (Phipps, 1989). This characteristic is a necessity for modeling phenomena such as disease spread, forest blow-down and competitive growth (Bitterlich et al., 1993). For a full description of automata refer to Wolfram (1984) or Toffoli and Margolus (1987).

Sato and Iwasa (1993) used automata to simulate wave regeneration of forest rings within subalpine areas as a neighbor function of tree height and wind exposure. 'Backward automata' focus upon projection through comparison of states between individual time steps in order to derive a transformation and then iterate the model for relatively few generations rather than thousands. Zhou and Liebhold (1995) derived a model for gypsy moth outbreaks using the stochastic backward method showing that defoliation was highly correlated between successive years, the consideration of neighbors improving the prediction of the model over that of straight cell-to-cell comparisons. In implementation, 'backward automata' are similar to Markovian methods in which individual classes or signatures are transitionally modeled with the aid of a square probability matrix (Harbaugh and Bonham-Carter, 1970;

Hall et al., 1991). The automata transition matrix tabulates probabilities of change within the central cell as a function of the cell and its neighborhood. Within noisy data, transitions will show alternating behavior. To negate such transition effects, 'memory' is incorporated into modeling mechanisms to maintain temporal continuity past single iterative steps. For the purposes of this study, in which we are attempting to derive a trend for a photographic sequence, the Mann–Krendall statistic is utilized to establish the significance of changes (Gilbert, 1987).

2. Objectives

The principal objectives of this research were:

- Determine if tree density mapping, as derived from aerial photography, combined with cellular automata modeling, can be used to extrapolate forest canopy changes in an area that is believed to be affected by localized stress from an acid mine.
- Demonstrate and compare delineation techniques for deriving tree apexes from aerial photography.
- Demonstrate how the consideration of context may help to infer spatial processes.
- Show how the integration of the Mann–Krendall statistic can assist in obtaining temporal trends in noisy data sets.

3. Methodology

3.1. Study site

The site under consideration is part of a study to develop quantitative forest and tree health monitoring methods using airborne digital camera imagery (King, 1995; Lévesque and King, 1998). The study area is composed of mature trembling aspen (*Populus tremuloides*) and Jack pine (*Pinus banksiana*) with white spruce (*Picea glauca*), black spruce (*Picea mariana*) and balsam fir (*Abies balsamifera*) in the understory. The area, shown in Fig. 1, is located adjacent to approximately 130 ha of unimpounded open mine tailings at the Kam-Kotia Mine, Timmins, Ontario. It is subjected to a negative gradient of soil metal concentrations with distance from the tailings. Along the Western margin of the study area is a spruce bog, from which spruce forest forms a convex easterly arc penetrating into the aspen dominated areas along the northern image edge and, to a lesser degree, centrally within the study area, forming an indentation of open canopy coniferous amongst the aspen. Degradation at the site is characterized by thinning canopy, particularly closer to the tailings. Some areas also exhibit a high degree of fallen trees, presumably a result of winds that develop over the open tailings surface. Dead tree counts in the forest indicate greater wind effects within 200 m of the tailings than beyond. The net effect of chemical and mechanical stress is an observed increase in canopy openness and reduced stem density near the tailings.

3.2. Image data

Three 1:15,840 Forest Resource Inventory and one 1:20,000 Ontario Basic Mapping Program (OBM) diapositive images were scanned using a digital camera and then registered, resulting in a pixel spacing of approximately 0.47 m. The aerial photographs were acquired during the summers of 1946, 1961, 1979 and 1991, although the lighter aspen crowns found within the 1946 photograph probably indicate Fall acquisition. Images were selected to represent time periods of significant change, as well as the two end points — i.e. the initial premine and recent conditions. In this medium scale imagery many individual trees could be visually identified and matched. The time interval of the analysis represents a forest maturing sequence. Overstory aspen ages in the area currently average 79 years ($s = 12$). The images show differing qualities and representation of the terrain. Variations include differing contrasts, illuminations, shadows and resolutions, and consequently, for the temporal trend modeling of this research, a 360 by 180 m subarea was selected which displayed relatively few photographic differences.

3.3. Tree stem temporal modeling

An image sampling methodology was designed to detect tree apexes and delineate openings within the aspen canopy. Openings were characterized by smaller mixed understory vegetation of lower tone and increased shadow. For temporal modeling, a backward cellular automata was employed rather than a diffusion model, since it made fewer assumptions of transitional process. Canopy transition statistics were accumulated as a function of neighborhood and proximity to the tailings. To alleviate the extraneous transitions, only significant trends were recorded, removing alternating changes which were thought to be more representative of image noise and inconsistent photographic quality.

The modeling methodology consisted of five stages:

1. Development of an automated tree-apex-detection methodology, results of which, through stem packing counts, could be used to characterize canopy types. Two primary techniques were implemented and compared: a standard high-pass filter and a

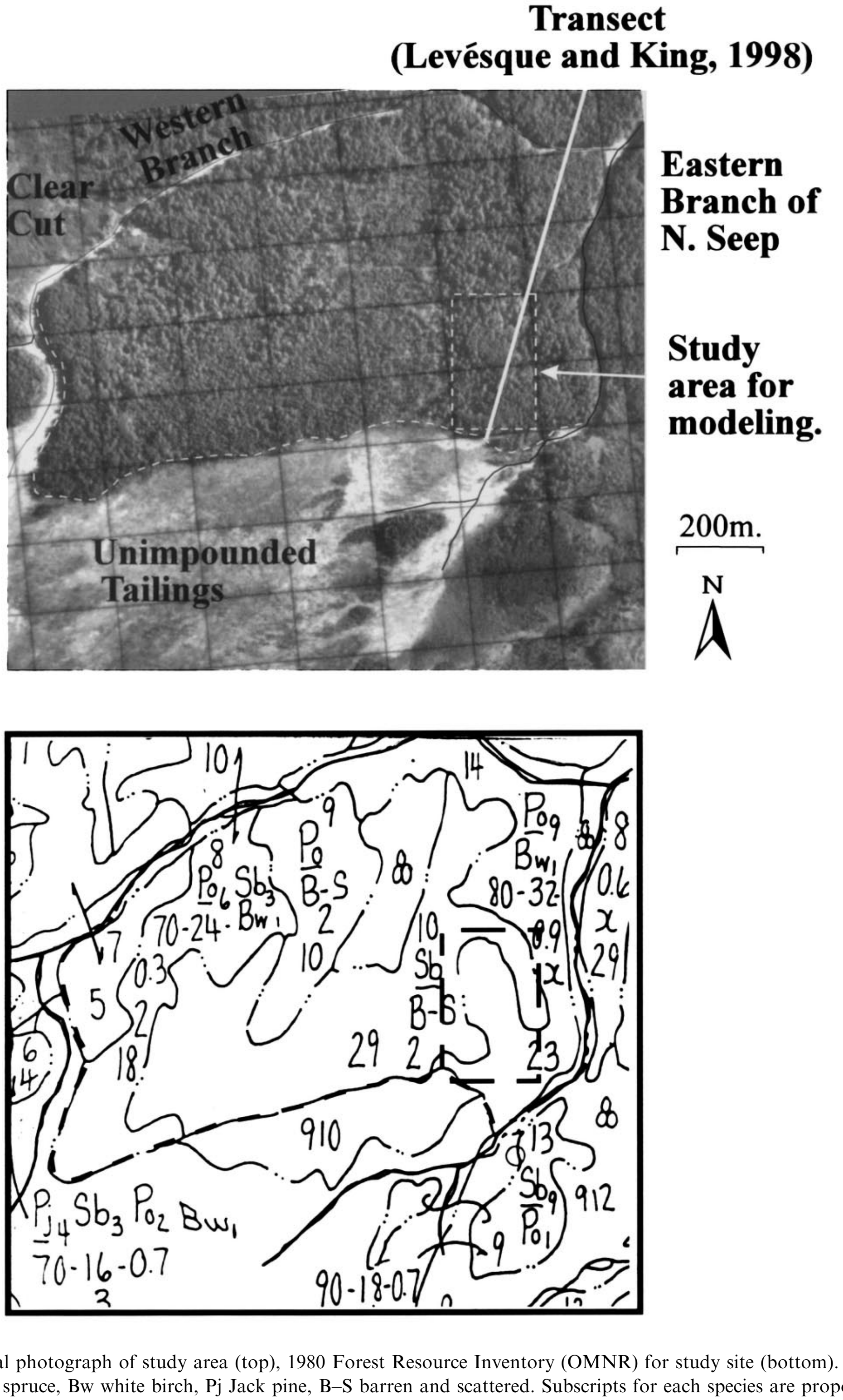


Fig. 1. 1991 aerial photograph of study area (top), 1980 Forest Resource Inventory (OMNR) for study site (bottom). Po represents poplar, Sb black spruce, Bw white birch, Pj Jack pine, B–S barren and scattered. Subscripts for each species are proportions out of 10.

double-aspect technique. Both take advantage of brighter tones being coincident with the center of the tree crown.

The high-pass 3×3 filter (weighted by $+8$ in the center cell and -1 in the outer cells) was applied to accentuate areas of high frequency data within a roving window, darker areas being negative and brighter areas positive, each with greater magnitude as the differences between the central cell and its surroundings varied. High-pass pixel values were classified according to their representation of tree morphology, which varied due to photographic quality differences.

To overcome the susceptibility of high-pass filtering to noise and the need to specify a window size, a second delineation technique was applied. The double-aspect tree delineation technique identified tree centers by determining the intersection of ridge lines calculated by a double application of gray tone surface aspects for each of the four directional pairs (two using the pixel orthogonal direction approximately N–S, E–W, and two diagonally approximately, NW–SE, NE–SW). To compensate for crowns with multiple apexes, subsequent merging was undertaken. Details of this technique are outlined in Fig. 2 and further described in Walsworth and King (1997). Derived apexes were assigned a brightness value within a 10-class range derived from the original image values, in order to gauge peak prominence.

The two methods were first tested for accuracy against a synthetic dataset in which differing noise levels were applied. The synthetic dataset was created through a random point generation program of two densities (1/25 pixels and 1/150 pixels) and spatially defined by an underlying class image. The underlying image was created by applying a modal 3×3 filter to a two-class random image a number of

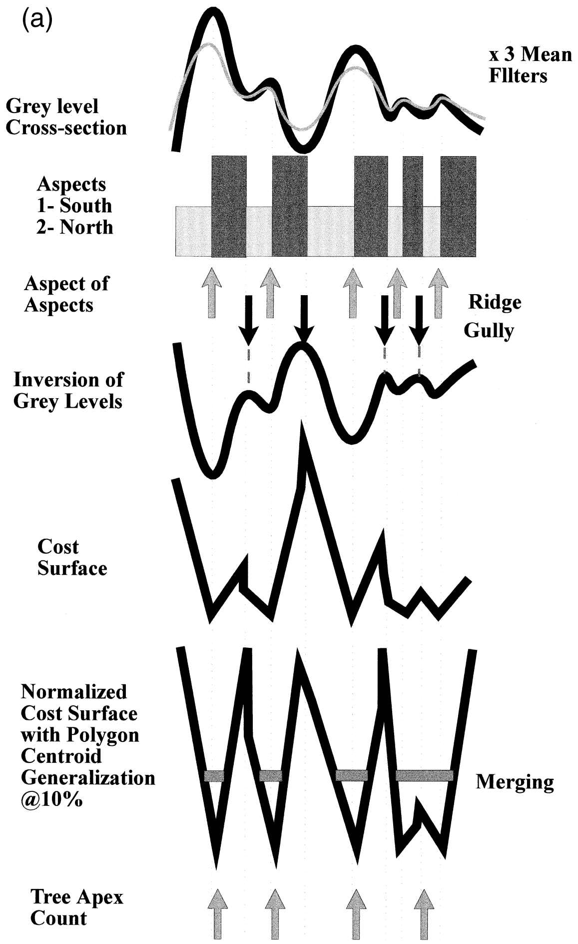


Fig. 2. (a) Double aspect technique showing sequence for derivation of tree apexes; (b) Double aspect technique applied to aerial photography.

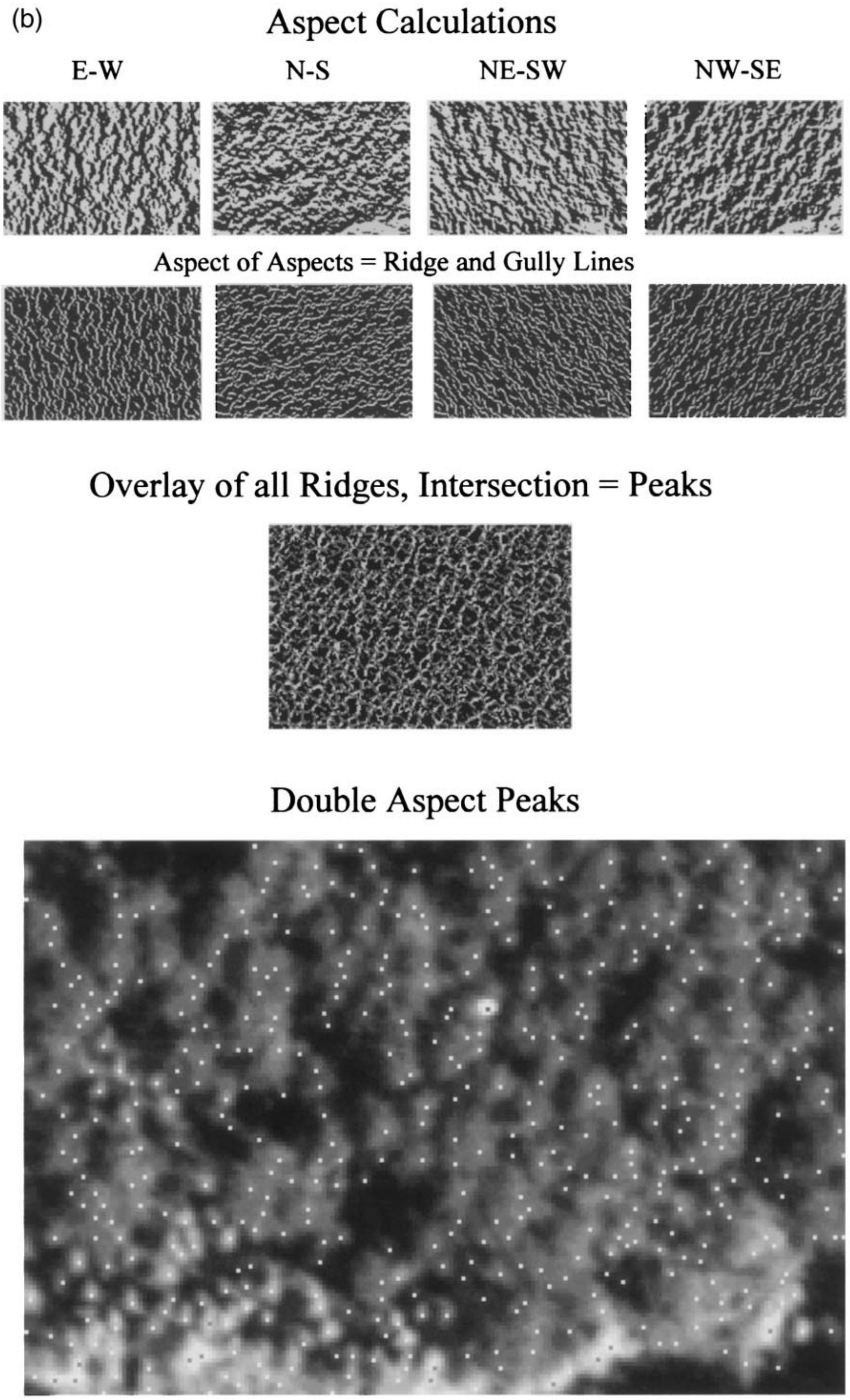
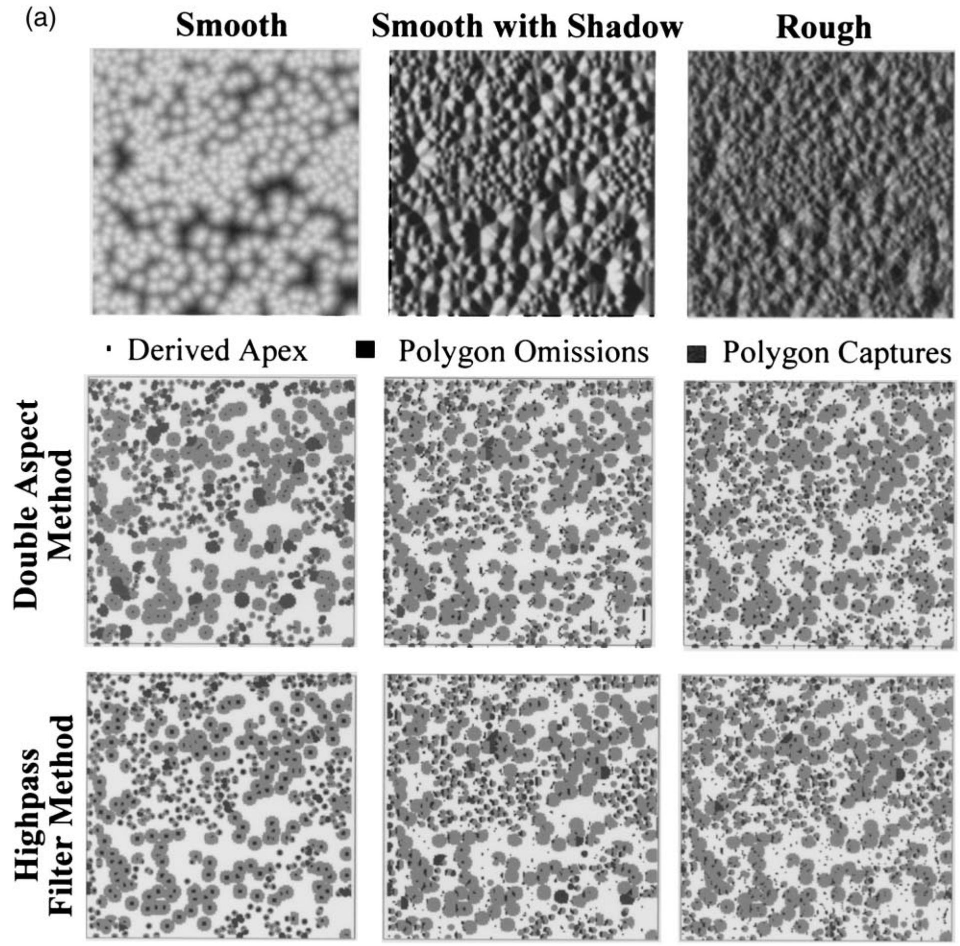


Fig 2 (*continued*)

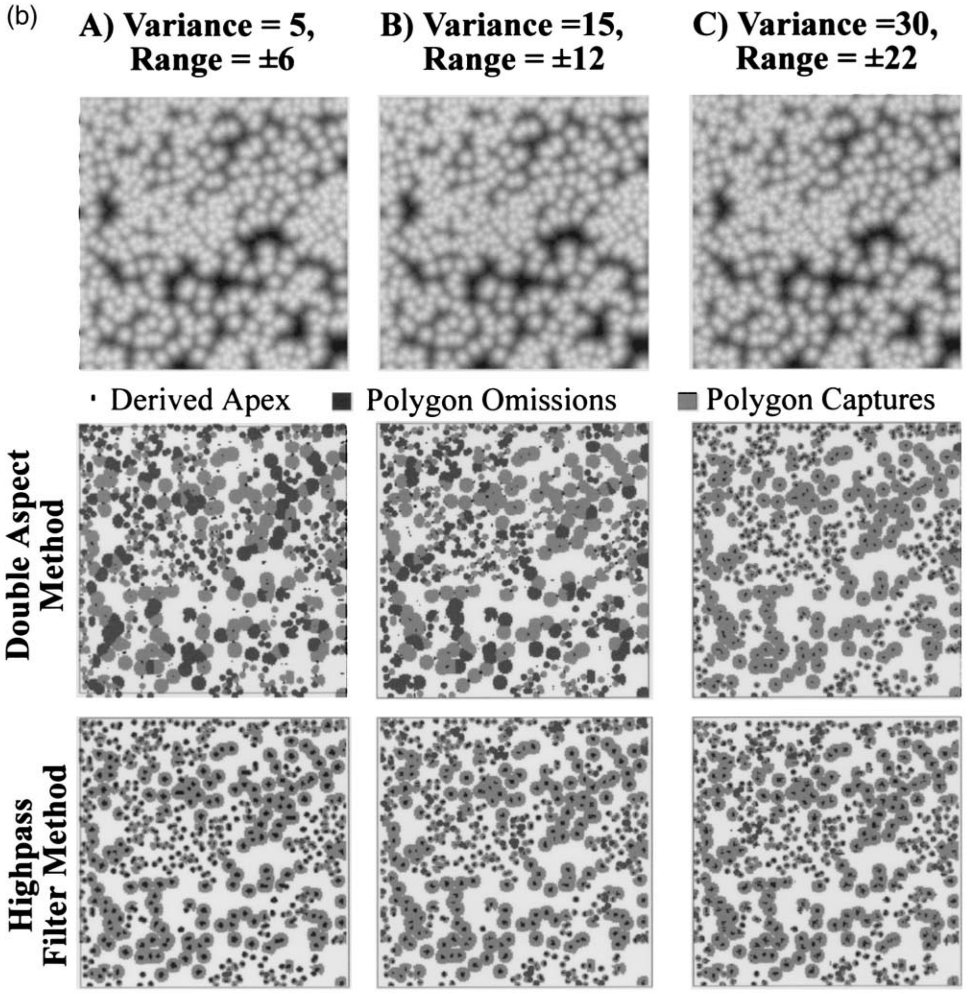
times to aggregate class space (Zeigler, 1976). Conical crowns were created through outward dilation from the generated pixel centers, followed by inversion and conversion, to occupy a grey-tone range between 50 and 200. The effects of shadow were modeled through application of a hill-shading algorithm. Additionally, texture was added to the shadow image model. This was accomplished by replacing the smooth dilation away from the points with an uneven but constantly decreasing dilation formed using a cost surface over a random image, followed by shadowing.



	Smooth		Shadow		Rough+Shadow	
Total# of Poly = 562	D.A	H.P.	D.A.	H.P.	D.A.	H.P.
Captured Polygons	377	484	492	508	522	517
% Captured	68%	84%	88%	90%	92%	92%
# of Local Maxima	403	495	635	682	932	1058
Mult.& Misses*	7%	2%	29%	34%	79%	104%

* (# of Local Maxima-Captured) / Captured

Fig. 3. (a) Effects of shadow upon tree apex delineation. Points within lighter polygons are correctly identified tree peaks and are evaluated by Tree Peaks ID statistic. Dark grey polygons are errors of omission. Points outside polygons are errors of commission. Multiple and Misses statistic combines these errors and includes multiple apexes found for single tree crowns; (b) Variation of high-pass and double-aspect delineation with noise and shadow.



	A		B		C	
Total# of Poly = 562	D.A	H.P.	D.A.	H.P.	D.A.	H.P.
Captured Poly	281	541	302	467	536	499
% Captured	50%	96%	54%	83%	95%	88%
# of Local Maxima	226	478	263	461	476	604
Mult.& Misses*	-20%	-12%	-13%	-1%	-1%	21%

* (# of Local Maxima-Captured) / Captured

Fig 3 (*continued*)

2. After application of the two tree-delineation techniques to the archival photography, the double-aspect points and the positive representative high-pass pixel classes were integrated with a roving 8 m radius circular window, at a 4 m grid sample spacing. This spacing corresponded approximately to the minimum tree-stem spacing. Window count inputs for the double-aspect points were thresholded by crown brightness, whereas for the high-pass pixels only the positive pixels representative of aspen were utilized. Distributions of results were visually compared to Ontario Ministry of Natural Resources forest resources inventory (FRI) classes. The high-pass classes more closely matched the polygonal

FRI classes, and thus this technique was adopted for further work.

Tree canopy classes were created by applying count thresholds and creating an intermediate third class in order to approximate the general FRI divisions between mixed aspen forest and open spruce bog areas. The resulting three-class images represented the input to the automata model consisting of a 2550-point sample.

3. The significance of pixel transitions was then assessed using the Mann–Krendall statistic (Schlagel and Newton, 1996). The technique compared the four images or six forward combinations assigning each a 1, −1 or 0 value depending upon the class rank transition direction. Adding these transition images produced a maximum of five unidirection transitions possible for the three class images, with more negative or positive values being indicative of a more significant and consistent transition trend. A minimum sum of four was adopted as the trend cutoff producing a stated significance of 0.167 (Gilbert, 1987).
4. The trend statistics were then tallied as a function of distance from the tailings and plotted. The probabilities of single-step neighbor transitions from the significant trends >0.167 were also calculated using a 1-cell offset Rook-case neighborhood. This produced a table of 135 differing combinations (15 neighbor configurations $\times$ 3 differing central cells $\times$ 3 differing outcomes).
5. The percentage outcome of a pixel neighborhood could then be multiplied by the probability of a significant change at that distance to form a model of change. Due to the random nature of the implementation, the model was run a number of times and plotted to show changes in forest composition.

4. Results

4.1. Comparison of tree delineation techniques using synthetic images

Creation of initial synthetic images (termed 'smooth' in Fig. 3a) resulted in flat and broad image peaks, which, when densely packed had ill defined edges. Addition of texture resulted in mottled profiles with many smaller peaks whereas synthetic illumination enhanced these perturbations (labeled 'rough'). Fig. 3b shows the effects of noise upon the apex delineation with dark grey polygons indicative of tree-counting omissions. The high-pass filter methodology proved to be the most effective over the variance range of the synthetic images, while the double aspect methodology attained its best results with random noise values similar to that found within the photography. In all situations, addition of noise or high frequencies had the effect of broadening derived peaks as evidenced by larger points. Trends showed that the double aspect performance improved greatly when some variance was added to the imagery whereas the high-pass method proved susceptible to added variance. In comparison of errors due to detection of multiple apexes in a single crown or due to detection of an apex where one did not exist, the double-aspect technique proved to be moderately susceptible to the latter whereas the high-pass technique was not overly sensitive to either. In the shaded images, Fig. 3a, the maximum illumination center was typically displaced towards the illumination ray (left) and thus detected tree apexes were also shifted by both techniques. In the 'rough' textured images, both techniques suffered from false recognition of many small grey-tone perturbations.

These idealized image tests, when utilizing tree densities and noise ratios similar to scanned photography, produced accuracies between 80–90% although they were dependent upon the degree of shadow. Shadow effects are image dependent, having a positive effect on counts for highly textured clumped crowns, or a negative effect caused by shadows obscuring smaller interstitial trees.

4.2. Tree peak counts

Tree counts for the two apex delineation techniques applied to the four temporal images showed that more tree stems were delineated in the more recent photography as a result of its improved dynamic range. Masking only the negative high-pass classes and maintaining the positive range provided a measure of apical shape as compared to the double-aspect technique which only provided a point. Fig. 4 shows the output from the two techniques. The high-pass technique showed better delineation of tree types similar to those interpreted by the 1980 FRI maps, especially for the 1979 and 1961 photos which highlighted spruce to the East and a thin discontinuous strand of spruce crossing through the central portion of the image, up its eastern side and back along the upper edge. In the 1991 image, intermediate conifers similarly showed high to medium contrast as measured by the high-pass filter but unfortunately most were obscured within shadows. However, in the 1949 image conifers had lower contrast than aspen, the flatness in conifer tone probably being a result of poor film quality and image blur.

From these results it was evident that, although the double-aspect technique performed better under synthetic conditions of high variance, the high-pass filter was more consistent, less susceptible to detection of nonexisting crowns and better in delineation of standard FRI tree types. Consequently, the high-pass filter was adopted for the subsequent temporal modeling.

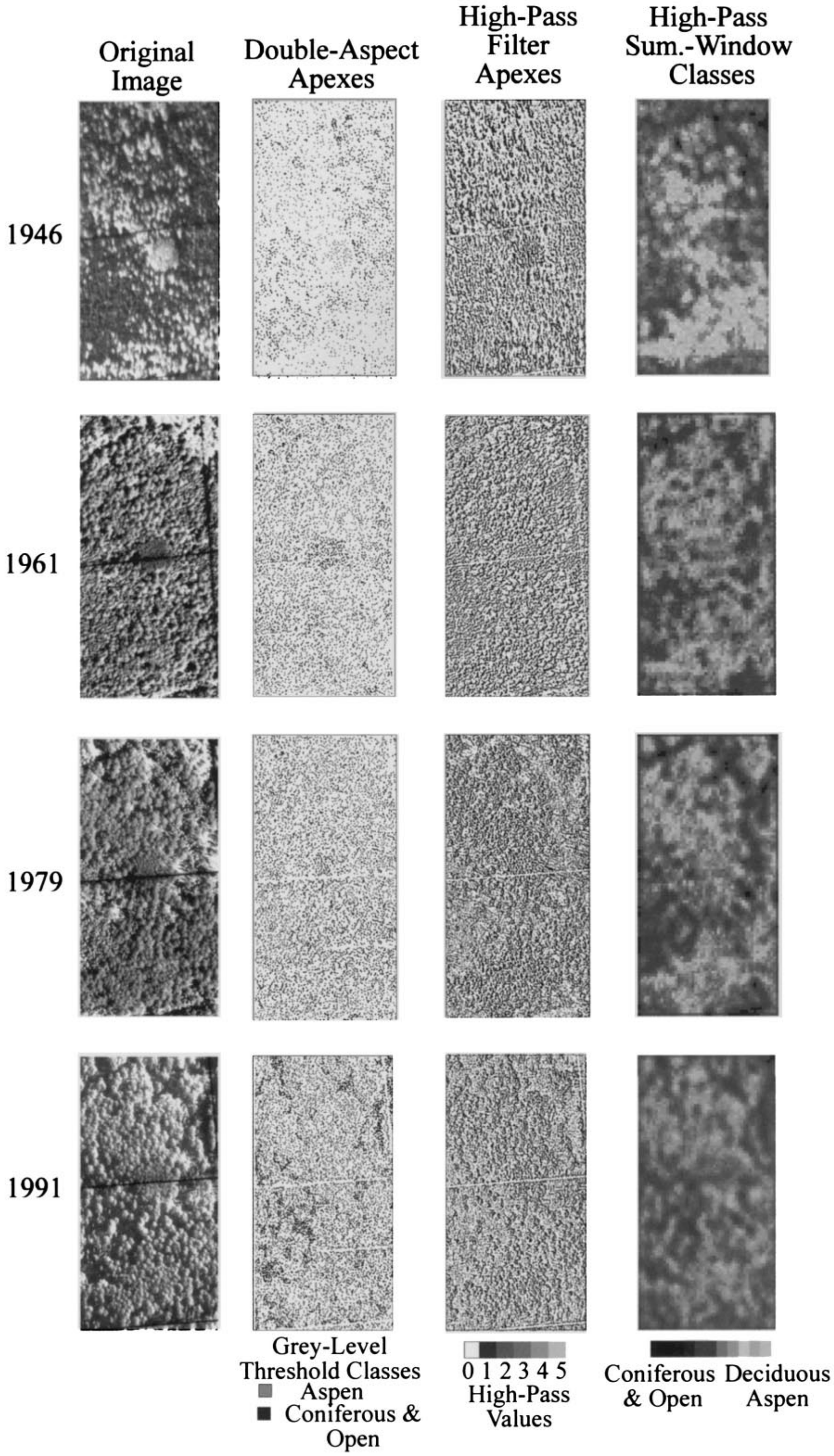


Fig. 4. Apex delineation results and high-pass filter classes for temporal aerial photography data set.

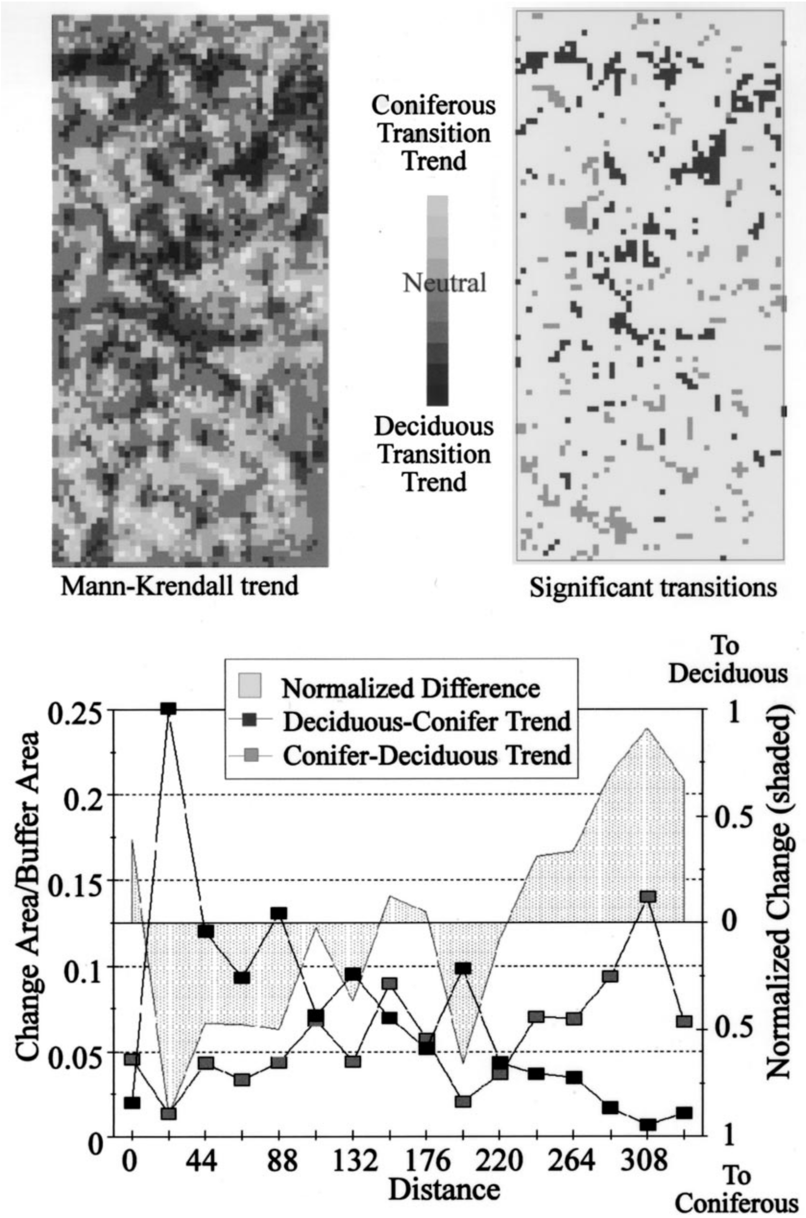


Fig. 5. Class transitions as function of proximity to tailings. Significant transition ~0.2 sigma.

4.3. Reconstruction of forest classes from stem counts

Roving window counting summed all the high-pass pixels representative of the deciduous cover classes. Conifer trees were not counted individually because they were present mostly in the lower canopy, occurring in gaps and spectrally mixing with shadows and other understory species. Based upon these count images, three canopy classes were defined: mature overstory aspen, coniferous/open canopy class, and an intermediate transitional class. The transitional class approximated the FRI class boundaries and compensated for differences in image contrast, see Fig. 4.

4.4. High-pass tree class trends

Mann–Krendall trends showed that increased numbers of openings had developed nearer the tailings during the 1946–1991 period and that there was a trend toward deciduous canopy closure farther from the tailings. Fig. 5 demonstrated this through averaging the Mann–Krendall results over interval distances away from the tailings. Plots in Fig. 5 display both the deciduous and open canopy/coniferous class trend lines. The normalized difference between the two curves indicated by the shaded area shows a decline in deciduous trees within approximately 150 m of the tailings edge, while the reverse is true farther from the tailings edge.

4.5. Neighbor transitions

Neighbor transition results have been expressed as class percentage stability, the ratio of the number of class transitions exhibiting no change to the total initial numbers in the class. These neighbor results were calculated for pixels showing a significant trend ($p = 0.167$) and as a function of similar and dissimilar numbers of Rook neighbors (Fig. 6). Resulting curves show that neighbor transitions favor landscape cover-class homogeneity. Landscape changes will consequently favor the local dominant class.

The two sets of curves in Fig. 6 are not complementary since the neutral class rounds out the totals.

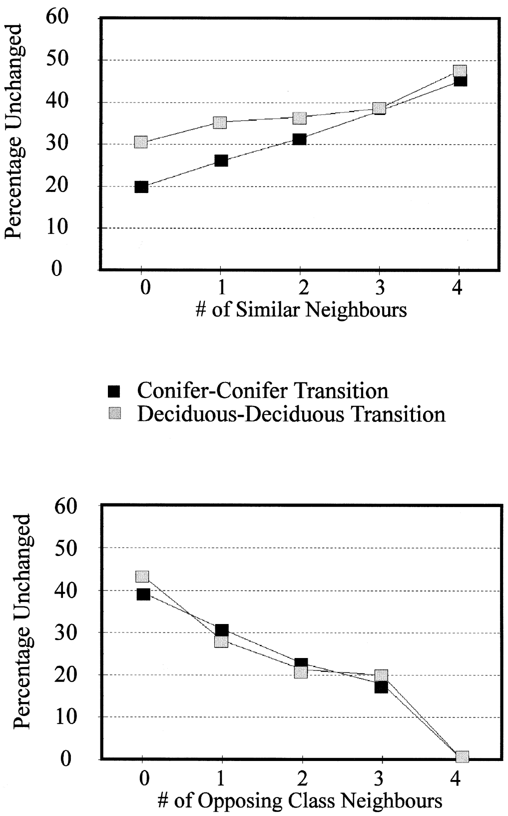


Fig. 6. Class transitions as function of rook case neighbor configuration.

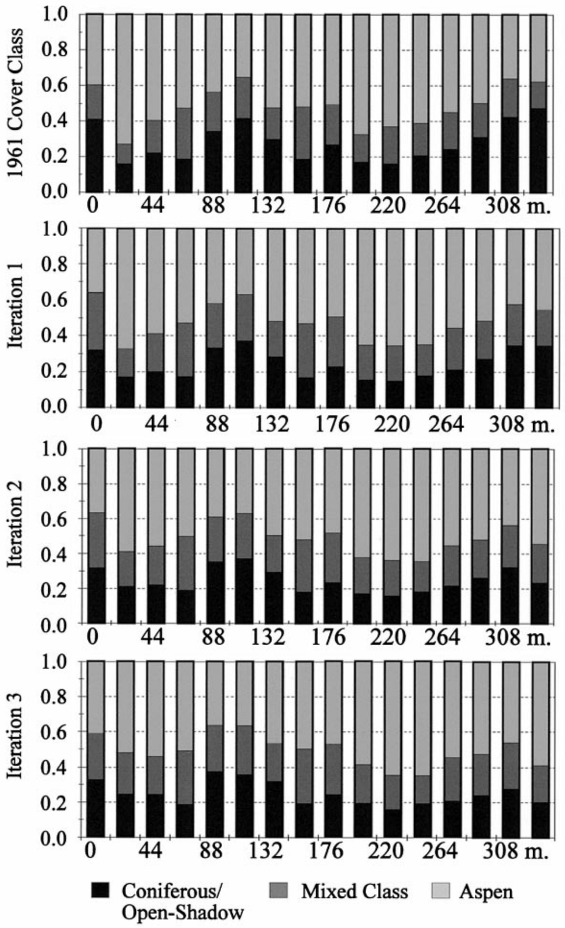


Fig. 7. Predicted class cover fractions as function of distance from tailings.

Aspens appear to have a greater ability to maintain homogeneity within configurations of similar neighbors (Fig. 6 top) whereas coincident paths within the 'dissimilar' curves do not show this.

4.6. Degradation model

The projection curves are shown in Fig. 7. They show the application of combining transitions based upon distance and neighborhood, using the 1961 density image as a base. Results show a predicted decrease in aspen close to the tailings and an increase further away. The model appears to smooth results spatially with each iteration as a result of overlapping window samples with distance boundaries and the removal of nonhomogeneous areas. Each model iteration favors changes that are consistent with underlying forest structure with propagation of change through edge relationships which favor the dominant neighborhood classes.

4.7. Results summary

- Comparison between the double-aspect and high-pass tree apex delineation techniques demonstrated differing capabilities. Overall, the high-pass technique was more consistent with existing inventory boundaries and was thus adopted in temporal modeling.
- The high-pass filter combined with a roving window counting technique has shown an ability to represent canopy cover classes.
- The transition probabilities for the 40-year temporal period favor spatial-class homogeneity within the landscape.
- Canopy degradation was recognized within approximately 150 m from the tailings front while areas farther away appear to be undergoing strong maturation.

5. Discussion

The double-aspect and the high-pass filter techniques both successfully delineated crown/stem apexes. The 3×3 high-pass filter technique showed better ability to delineate broad smooth crowns while the double-aspect techniques performance was superior at higher noise ratios. The intermediate step of calculating directional aspects however had the added benefit of enhancing understanding of image illumination which, as this study has indicated, seriously affects apex delineation capabilities. Further evaluation of these techniques should include different window sizes and image resolutions.

A window tree-stem counting technique was employed to delineate canopy types. Selected high-pass 'representative' classes showed better canopy delineation than gray-level thresholded double-aspect counts, indicating that stem density and inclusion of stem contrast, as opposed to solely utilizing tone, was an important source of information for delineation of canopy types. This window-sampling technique appears to have captured canopy characteristics with forest-class images derived from the high-pass technique being visually comparable to FRI interpretations. The tree apex and window sampling combination occupies a procedural position intermediate between aggregate texture techniques found within grey-level cooccurrence matrices (Haralick, 1973) and natural preattentive approaches such as the triangular primitive network technique proposed by Hay and Niemann (1994).

Automata transitional estimates indicate that canopy degradation is probably caused by a combination of the obvious environmental stress at the site and natural succession associated with the age structure of the trees under study. At a relatively early successional stage in boreal mixed-wood forests, aspen usually dominate, whereas spruce and balsam fir are frequently in the understory. In later successional stages, conifers may become dominant (Lieffers et al., 1996). At Kam-Kotia, aspen at the beginning of the photographic sequence (1946) were approximately 30 years old. Canopy expansion and closure is expected until ages are about 55 years (1972) after which relative stability would be expected until trees commence deterioration from old age ($>$80–90 years). Results in this study are consistent with the early and middle stages of canopy development. In this respect, results assume a steady-state change but clearly aging and natural die-back of aspens may contribute to the progressive opening of the canopy and replacement with conifers which was found in the area near the tailings.

Model behavior is likened to a consecutive application of a smoothing filter in which changes gradually decrease, the rates of change being dependent upon the predisposition of local, regional distributions and edge configurations. The difficulty of applying neighbor window techniques to individual trees is that tree growth is not necessarily in a tessellated configuration. The solution to this physical inconsistency was to create classes based upon stem density that could subsequently be modeled in the automata. A further limitation of this study was the photographic constraints of archival imagery. It was difficult to determine if the modeling results were correct given the tonal and resolution differences between the images. Tree delineation tests showed the effectiveness of both the double-aspect and high-pass technique, however, broadening of the data by inclusion of other photographic dates and observation of the temporal stability with differing combinations of data would help to further confirm these results. Two other possibilities may provide this confirmation, firstly, the utilization of calibrated digital imagery, or secondly, undertaking methods on a site of known change. At present both avenues are undergoing active research.

6. Conclusions

This study has demonstrated a methodological sequence for the modeling of temporal landscape changes utilizing archival photography. Temporal comparison was adversely affected by differing representations of canopy due to photographic deficiencies. A methodology mimicking human preattentive recognition was implemented to overcome these deficiencies by integrating a first-order density window technique of a high-pass filter image. Temporal trends were determined by the Mann–Krendall statistic, the assumption being that areas of consistent trend are more indicative of permanent change and will less likely be aberrant noise. Transitional trends showed that landscape-change processes favor homogenization of areas. An automata methodology was adopted as a suitable model of such behavior.

Acknowledgements

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