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Evidence of Recent Treeline Dynamics in Southwest Yukon from Aerial Photographs

RYAN K. DANBY[1,2] and DAVID S. HIK[1]

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ABSTRACT. Small-scale vertical aerial photographs taken in 1947 and 1948 covering 200 km^2 of the Kluane Ranges, southwest Yukon, were compared with corresponding photographs taken in 1989 for the purpose of characterizing changes in the distribution and abundance of white spruce (*Picea glauca* (Moench) Voss) at the alpine treeline. Digital photogrammetry, including orthorectification and on-screen interpretation, was supplemented by stereoscopic inspection of the original prints. Qualitative assessment of change across nine image pairs was accompanied by quantitative analysis of changes in spruce density and elevation using 1 hectare plots and 100 m wide elevational belt transects, respectively, superimposed on the orthorectified images. Significant changes were observed over the 41 years, but the degree of change varied throughout the study area. The most common changes were an increase in canopy size of individual trees and an increase in stand density resulting from the establishment of new individuals. Several instances of treeline advance were also observed. An absence of major natural disturbances or widespread land use change indicates that treeline change is attributable to climate. Results from concurrent dendroecological studies indicate that these dynamics represent only part of the total extent of change to occur during the 20th century.

Key words: climate change, forest-tundra, ecotones, timberline, repeat photography, air photos, landscape change, Yukon, *Picea glauca*

RÉSUMÉ. Des photographies aériennes verticales à petite échelle prises en 1947 et 1948 sur une aire de 200 km^2 de la chaîne de montagnes Kluane, dans le sud-ouest du Yukon, ont été comparées à des photos correspondantes prises en 1989 dans le but de caractériser les changements en matière de répartition et d'abondance de l'épinette blanche (*Picea glauca* (Moench) Voss) à la hauteur de la limite alpine des arbres. La photogrammétrie numérique, dont les techniques de redressement différentiel et d'interprétation à l'écran, a été supplémentée par l'inspection stéréoscopique des épreuves photographiques originales. L'évaluation qualitative du changement par rapport à neuf paires d'images s'est accompagnée de l'analyse quantitative des changements en matière de densité des épinettes et d'élévation à l'aide de parcelles de 1 hectare et de transects d'élévation en bandes de 100 m de large, respectivement, superposés sur les images ayant fait l'objet du redressement différentiel. D'importants changements ont été observés au cours de la période de 41 ans, mais le degré de changement variait d'un endroit à l'autre visé par l'étude. Les changements les plus courants consistaient en l'augmentation de la taille du couvert des arbres individuels ainsi qu'en l'augmentation de la densité de peuplement découlant de l'établissement de nouveaux individus. Plusieurs occurrences d'avancement de la limite des arbres ont également été observées. L'absence de perturbations naturelles majeures ou d'importants changements sur le plan de l'utilisation des terres laisse croire que le changement de la limite des arbres est attribuable au climat. Les résultats découlant d'études dendroécologiques concurrentes indiquent que ces dynamiques ne représentent qu'une partie de l'ampleur totale du changement s'étant produit au cours du XX^e siècle.

Mots clés : changement climatique, toundra forestière, écotones, limite des arbres, photographie répétée, photos aériennes, changement de paysage, Yukon, *Picea glauca*

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INTRODUCTION

The boundary between forest and tundra zones, hereafter referred to as the treeline, is expected to change in structure and position with continued climate warming (Grace et al., 2002). A host of studies have documented recent changes in the growth, density, or distribution of high-altitude and high-latitude forests in response to 20th century warming using dendroecological techniques (e.g., Lescop-Sinclair and Payette, 1995; Szeicz and MacDonald, 1995; Lloyd and Fastie, 2003). Ground-level repeat photography has also been used to document these changes. By its very nature this research has mostly been carried out at fine scales, examining change at individual locations or even the growth of individual trees (e.g., Kullman, 1987, 2005; Vale, 1987; Rochefort and Peterson, 1996; Luckman and Kavanagh, 2000; Munroe, 2003; but see Butler and Dechano, 2001, for a broader perspective). Fewer published studies have used vertical aerial photography to examine treeline change across larger areas (Scott et al., 1987; Klasner and Fagre, 2002), largely because the more recent advent of aerial photography precludes observation of changes prior to the

[1] Department of Biological Sciences, University of Alberta, Edmonton, Alberta T6G 2E9, Canada
[2] Corresponding author: rdanby@ualberta.ca

mid-1900s. In addition, the small scale of early aerial photography in remote areas can preclude detection of all but extensive changes in forest density or distribution (Rhemtulla et al., 2002).

In this study we used sequential vertical aerial photography to examine the pattern and extent of treeline change in the northern section of the Kluane Ranges, southwest Yukon. This region has experienced a significant increase in mean annual temperature of approximately 0.5˚C per decade since 1965 (Zhang et al., 2000; Ogden, 2006) and therefore provides a useful locale for examining treeline response to climate change. Moreover, results from an extensive dendroecological investigation in the area (Danby and Hik, 2007a) indicate a period of rapid change in spruce distribution and density from 1920 to 1950, coinciding with a period of above-average temperatures. Given this time frame, as well as the degree of change inferred, we hypothesized that these changes should be partly visible when comparing the earliest aerial photographs of the region (1947 and 1948) with those most recently acquired at a similar scale (1989). Specific objectives of this investigation included: (i) characterizing the extent and pattern of change in spruce density and distribution evident from the photographs, (ii) determining the extent to which the dendroecological data are representative of the entire landscape, and (iii) refining a technique for quantifying treeline change that could be applied to other regions where only small-scale historical aerial photography is available. The study was a component of a larger investigation of treeline dynamics that examined the pattern and process of change at multiple spatial, temporal, and biological scales (Danby, 2003, 2007).

Given the variety of terms in use (see review in Hustich, 1979), it is important to clarify our terminology. We refer to the general transition from forest to tundra as the forest-tundra ecotone. The term "treeline" is used with specific reference to the boundary coinciding with the upper altitudinal limit of individuals typical of a tree growth form, which we define as individuals having one dominant stem, being generally taller than wide, and tall enough that crown growth is governed by prevailing atmospheric conditions (generally > 2 m).

MATERIALS AND METHODS

Study Area

The area examined is bounded by the Duke and Donjek rivers in the northern section of the Kluane Ranges of the St. Elias Mountains (Fig. 1). White spruce, *Picea glauca* (Moench) Voss, is the only conifer of note in the region, forming closed-canopy stands in valley bottoms. Density thins with increasing altitude, and an open canopy prevails at the lower end of the ecotone (the forest zone). At 1300 m, the spruce canopy is discontinuous, and the crowns of individuals generally do not overlap (the woodland zone).

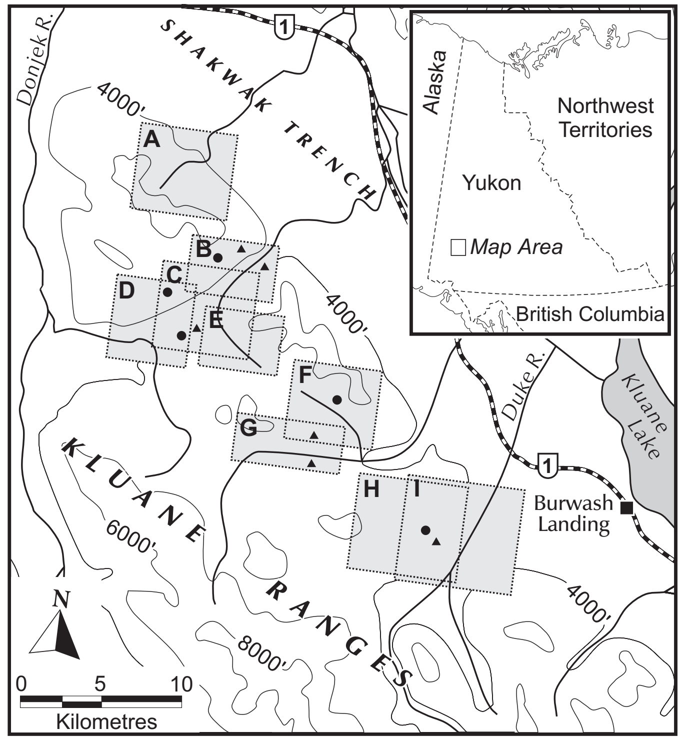

FIG. 1. The southwest Yukon study area. Boxes demark the areas that were examined from each of the nine photo pairs. Letter at upper left of each box corresponds to photo details provided in Table 1. Solid circles indicate the locations of aerial photographs shown in Figures 3, 4, and 5, and triangles indicate locations of dendrochronological sampling reported in Danby and Hik (2007a). Contour interval is 2000 feet (610 m).

Only occasional spruce are found above 1400 m and these are typically short, stunted (krummholz) growth forms. Aspect has an important influence on ecotone structure and community composition. The treeline is typically 50 to 150 m higher on drier south-facing slopes than on the cooler and more mesic north-facing slopes (Fig. 2). Natural disturbances such as fires and avalanches are rare at the treeline in this area, meaning that changes observed through photographic comparison are more likely to be a response to climatic change than to other external influences.

Orthorectification

The earliest aerial photographs available for the area (1947 and 1948, ca. 1:40 000), as well as the most recent of comparable scale (1989, ca. 1:57 500) were identified from the Yukon Energy, Mines and Resources air photo database (Whitehorse, Yukon), and prints were acquired from the National Air Photo Library of Canada (Table 1). We selected nine areas for detailed examination on the basis of image illumination and clarity (Fig. 1). Digital orthorectification is a process that removes the scale, camera tilt, and topographic relief distortions present in aerial photographs and matches the images to a map projection, and was undertaken so that the older and newer images could be accurately compared (see Lillesand and Kiefer, 2000).

TABLE 1. Characteristics of aerial photographs from each study area. Images from 1989 were initially used to generate an orthomosaic georeference control from which GCPs for rectification of 1947–48 photos were obtained (see text for details).

Map ID (Fig. 1)	Name	Area (km^2)	Date	Photo Number[1]	RMSE (m)[2]
A	Swede Johnson Creek	31.4	1947/07/25	A11014-418	27.16
			1989/08/10	A27518-141	35.58
B	Nickel Creek	18.7	1947/07/25	A11002-386	19.77
			1989/08/10	A27518-82	19.44
C	Quill Ponds	31.8	1948/06/09	A11383-215	15.62
			1989/08/10	A27518-82	22.24
D	Maple Creek	25.1	1948/06/09	A11383-217	21.41
			1989/08/10	A27518-83	18.12
E	Quill Creek	17.8	1948/06/09	A11383-216	20.05
			1989/08/10	A27518-82	18.98
F	Tatamagouche Creek	26.4	1947/07/25	A11002-418	17.20
			1989/08/10	A27518-74	15.83
G	Burwash Creek	19.4	1947/07/25	A11002-415	18.62
			1989/08/10	A27518-74	17.24
H	Burwash Uplands	39.4	1947/08/01	A11015-83	19.46
			1989/08/10	A27518-2	19.32
I	Squirrel Creek	46.7	1947/08/01	A11015-84	22.72
			1989/08/10	A27518-1	21.57

[1] Photo scales: 1947–48 = 1:40 000 (Focal length = 152.40 mm, Flying altitude = 20 000'); 1989 = 1:57 600 (Focal length = 152.86 mm, Flying altitude = 28 800').

[2] Average Root Mean Square Error = 20.6 m.

The first step in the process was to scan the photographs at 1000 dpi, using an Epson 1560 large-format flatbed scanner, and save them in tagged interchange file format (TIFF). The images were then matched to the UTM (Zone 7) projection using the rigorous ortho-rectification models in PCI Orthoengine (PCI Inc., Richmond Hill, Ontario). As elevation input, we used 30 m resolution digital elevation models (DEMs) generated by the Yukon Territorial Government (YTG). We experimented with three different resampling algorithms (nearest neighbour, bilinear, and cubic convolution) at three different resolutions (0.5, 1.0, and 2.0 m) and chose bilinear resampling with 1.0 m pixel spacing. This product maintained the ability to identify the individual spruce observable in the original images while optimizing file size and processing time.

The photographs from 1989 were orthorectified first to create a georeference control. Camera-specific calibration information, including lens length, distortion, and spacing of fiducial coordinates, was used to parameterize the model. All 1989 photos were taken on the same flight path, and we incorporated 90 tie-points to connect overlapping portions. Coordinates for 28 ground control points (GCPs) were obtained in the field with a Garmin 12XL handheld GPS receiver (Garmin International Inc., Olathe, Kansas). An additional 39 GCP coordinates were obtained from features identified from the Natural Resources Canada 1:50 000 National Topographic Database (NTDB, 2nd edition) vector map coverages. The overall root mean square (RMS) registration error for these images was 15.7 m (x-axis) and 11.1 m (y-axis).

The 1947–48 images were individually registered to these orthoimages. However, camera calibration data was not available for these early photographs. Lens distortion was assumed to be zero and fiducial measurements were

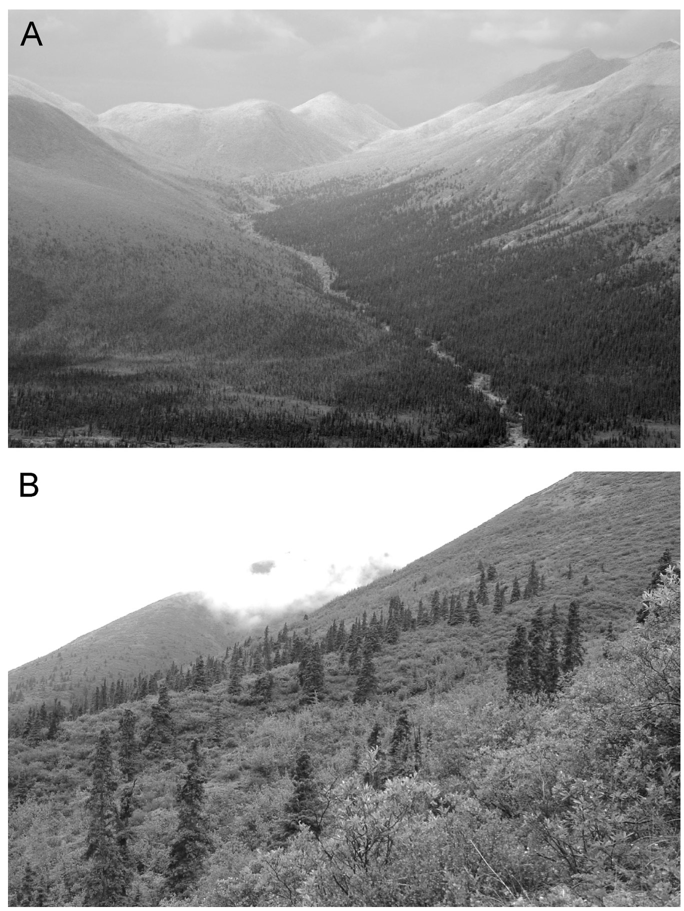

FIG. 2. Forest-tundra environments in the northern Kluane Ranges, Yukon. (A) Landscape-scale ground-level photograph looking north illustrates the differences between southwest (right of creek) and northeast (left of creek) aspects. (B) Ground-level perspective on a southwest-facing slope showing the woodland subzone, where coniferous canopy cover is discontinuous and the crowns of individual trees generally do not overlap. The treeline typically coincides with the upper limit of this zone.

obtained by manual measurements of the photographic prints. As a result, RMS error was inflated for each of these early orthoimages relative to the 1989 images. To help remedy this situation, we re-rectified the 1989 images individually, using the same set of GCPs used to process the 1947–48 images. Although this increased RMS error (Table 1), image-to-image comparison indicated that by registering the 1989 photos to the 1947–48 photos, we were able to reduce the relative positional error (i.e., improve alignment) between the two photos in each pair.

Analysis

Automated classification of panchromatic aerial photography for the purpose of vegetation change detection has been applied successfully to large-scale photography (i.e., ≤ 1:20000) (Carmel and Kadmon, 1998; Kadmon and Harari-Kremer, 1999), but it becomes increasingly problematic at smaller scales. For example, pixel-based image classification schemes based only on gray values may fail because of reduced variation in brightness between vegetation types, particularly in older photographs (Fensham et al., 2002). Shadows are also problematic for automated pixel-based classification of panchromatic images (Hutchinson et al., 2000). Experience is growing with object-based classification (Laliberte et al., 2004), but poor contrast in the 1947–48 photographs limited its possible application to the 1989 images, and scale remained an issue. For these reasons, we opted for user-based interpretation of the digital images rather than automated classification.

Change at the treeline from 1947–48 to 1989 was first assessed through a qualitative comparison of images. This was accomplished through the flicker and swipe visualization techniques within PCI Focus (PCI Inc., Richmond Hill, Ontario). These techniques allow the analyst to view two georeferenced images simultaneously or in rapid succession, and thereby allow for identification of the type and extent of change across a landscape.

After this qualitative assessment, we quantified stem density and maximum spruce elevation at random locations to provide a more rigorous analysis of change. Using ArcGIS (ESRI, Redlands, California), we generated random points along a linear representation of the treeline derived from YTG Forest Resource Inventory maps. Points were separated by a minimum 200 m and confined to areas where the image was clear enough to distinguish individual trees. In total, 104 points were generated. A one-hectare "virtual plot" was overlaid on the orthophotos immediately upslope of each random point. The position of several plots was adjusted slightly to minimize differences between images. Individual spruce were identified and marked within each plot. For each pairing of plots, we examined the 1989 plot first and then identified corresponding individuals in the 1947–48 plot. The original photographic stereo pairs were used to aid image interpretation. We then tallied the individuals in each plot and used this number to estimate spruce density in each year.

Change in the elevation of spruce was analyzed by extending a 100 m wide belt-transect directly upslope from 100 of the random sample points. The three uppermost spruce in each belt on the 1947–48 and 1989 images were identified and marked. The original photographic stereo-pairs were again used to aid interpretation of the digital orthophotos. The elevation of each data point was obtained from the DEM, resampled to 5 m resolution using a cubic convolution. The positions of spruce identified in the 1947–48 images were located and marked in the 1989 images, and elevations were determined from these adjusted positions. This prevented any errors that would be introduced by the differences in image registration. The three elevations from each time step were then averaged to yield a single value for each belt transect. Our decision to measure maximum spruce elevation rather than treeline elevation was based on the fact that the delineation of the treeline would be subject to discrepancies between time steps (Armand, 1992).

A one-way, repeated-measures analysis of variance (RMANOVA) was used to analyze the density and maximum elevation data. This analysis accounts for correlation between dates, thereby avoiding violation of the assumption of independence (Von Ende, 2001). Net solar radiation was used as the between-subjects factor. This is an important variable controlling soil temperature and vegetation composition in mountainous regions of the Subarctic (Dingman and Koutz, 1974) and plays an important role in treeline structure and position in the study area (Danby and Hik, 2007b). Using the 30 m DEM, we modeled net radiation across the study area for the summer solstice with the terrain analysis module of SAGA GIS (Göttingen University, Germany). Two solar radiation levels were used for the ANOVA model: low for areas receiving less than 7.0 kWh m^{-2} of solar radiation, and high for those receiving 7.0 kWh m^{-2} or more. Although the threshold used is arbitrary, areas of high solar radiation corresponded to slopes with more southerly aspects while low-radiation areas corresponded to more northerly aspects.

RESULTS

Initial inspection of the photographic prints with the naked eye suggested little change from 1947–48 to 1989. However, magnification of the prints under a stereoscope and subsequent on-screen comparison of the digital orthophotos at 100% resolution revealed that change was widespread throughout the study area. The degree of change varied significantly, ranging from areas where no change was evident to areas where rapid, large-scale landscape transformation had occurred.

An increase in the overall canopy cover of individual spruce was the most common type of change observed (Fig. 3A). Canopy closure increased in most areas of woodland and forest, even in areas where there was little or no evidence of new individuals. An increase in stand density resulting from the recruitment of new individuals was the next most common change evident between the photo pairs (Fig. 3B). Although it was evident at a number of sites, advance in the

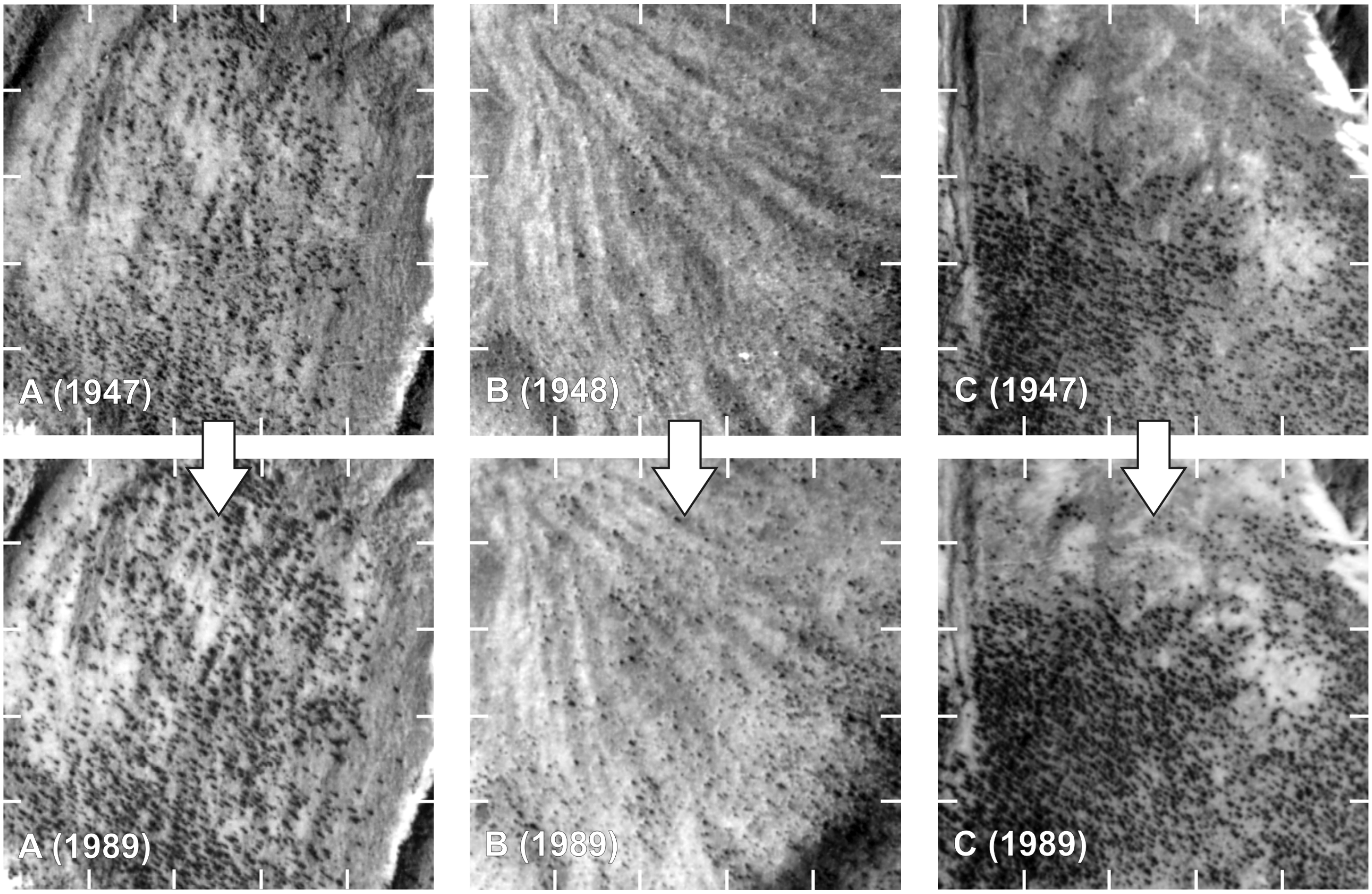

FIG. 3. Air-photo subsets from three locations (1947–48 on top, 1989 on bottom) illustrating the types of change observed at the treeline. (A) Increase in the size of individual spruce canopies, but negligible change with respect to density or elevation of trees. (B) Increase in the density of spruce, but no advance of the treeline. (C) Advance in spruce distribution indicated by the establishment of new individuals upslope of the 1947–48 treeline, combined with an increase in canopy size and spruce density in areas below the treeline. All areas shown are 500 × 500 m. Individual spruce or clumps of spruce are identifiable as distinct dark spots. The slope rises from lower right to upper left in each photo.

elevation of the treeline (Fig. 3C), as well as recruitment of scattered new individuals above the treeline, was limited in comparison with changes in canopy cover and density.

Overall, the most extensive change was observed on the Burwash Uplands. Large portions of its southern and eastern slopes underwent a transformation from shrub tundra, with only scattered individuals above the treeline, to woodland vegetation. At lower elevations, it was apparent from the photographs that areas of woodland vegetation in 1947–48 had become open-canopy forest by 1989 (Fig. 4). Significant change was also observed at the heads of several creek valleys throughout the study area where spruce advance along the creek drainage was observed (Fig. 5).

The quantitative analyses of plot and transect-based spruce counts support these observations. The density of spruce increased significantly over the 40-year period ($F_{1,102} = 65.056$, $p < 0.001$), from a mean of 21.3 ha^{-1} in 1947–48 to 30.3 ha^{-1} in 1989 (Table 2). The mean upper elevation of spruce also increased significantly ($F_{1,98} = 23.745$, $p < 0.001$), from 1396 m in 1947–48 to 1406 m in 1989. In 1989, the average maximum spruce elevation on slopes with high solar radiation was 1432 m (± 90), versus 1336 m (± 78) on slopes with low solar radiation. The absence of any significant within-subject interactions indicates that the amount of change did not vary between the two levels (high and low) of solar insolation (Table 2).

Despite the statistically significant changes, the net differences in density and elevation (i.e., 1989 minus 1947–48 values) were not normally distributed (Fig. 6). Nearly two-thirds of all sites experienced no change in uppermost spruce elevation (n = 61). Where change was observed, its extent varied greatly. The distribution of differences in density was less, though still positively, skewed. As visual inspection of the photographs indicated, the sites with the largest increases in density were located on the Burwash Uplands. The eight plots located in this area experienced an average 840% increase in spruce density from 1947–48 to 1989. Spatial clustering of change was not evident in any other part of the study area.

DISCUSSION

Treeline Dynamics

MacDonald et al. (1998) identified three possible responses of the treeline to a warming climate: (1) increased

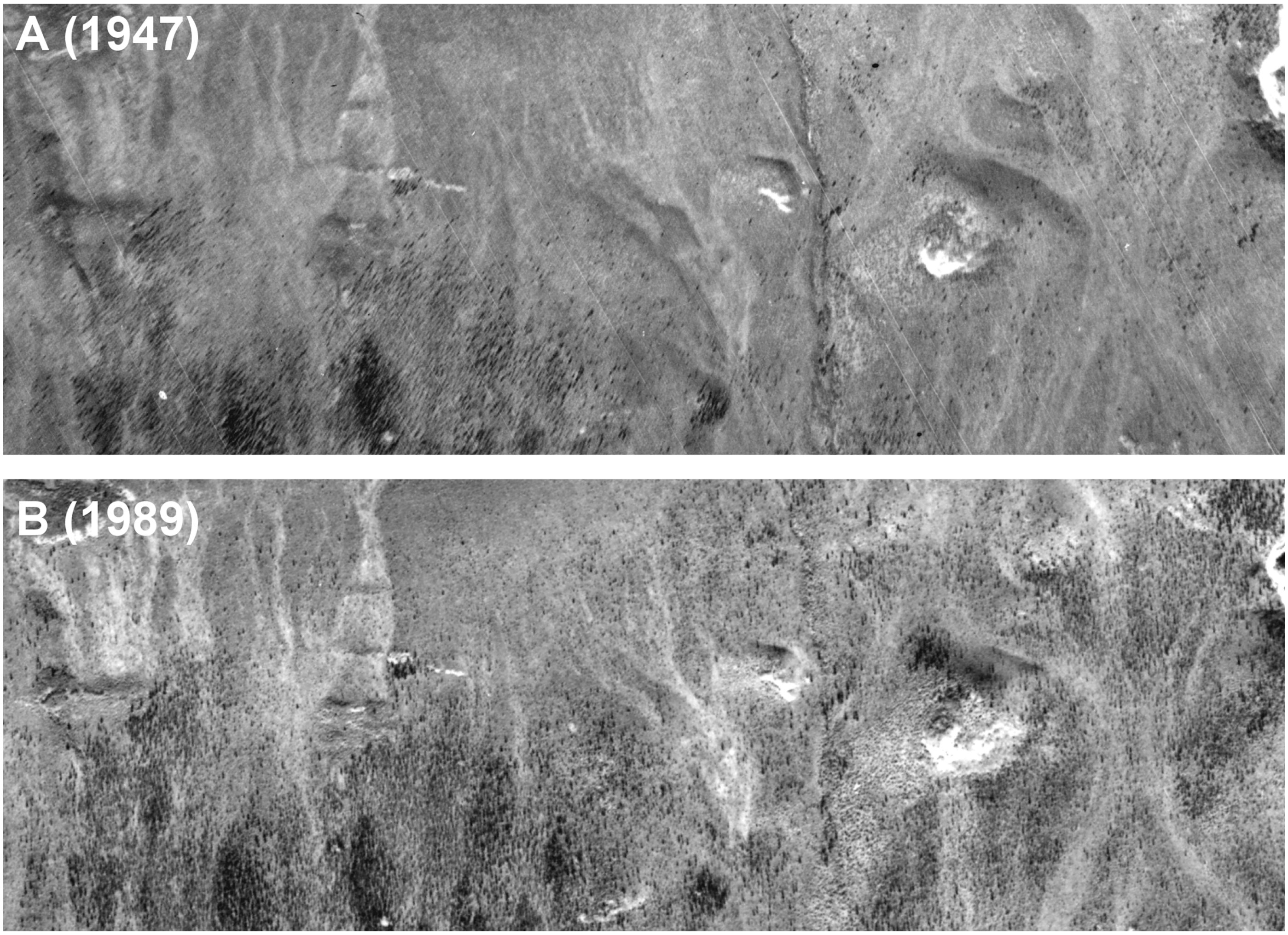

FIG. 4. Treeline change on the Burwash Uplands, southwest Yukon. Individual spruce or clumps of spruce are identifiable as distinct dark spots against the lighter background of shrub tundra. Each photo represents a land area 2500 m wide. Slope rises from the bottom to top of each image.

growth of individual trees, (2) increased population density of trees at the treeline, and (3) expansion of the distribution of trees (i.e., invasion into tundra). Our results indicate that each of these responses occurred in southwest Yukon during the last half of the 20th century, with increased growth being most frequent, increased density less frequent, and expansion into tundra least frequent. Additionally, the extent and type of change evident from the photographic pairs varied across the landscape.

The larger canopies of individual spruce relocated in the 1989 photographs indicated net growth since 1947–48. The growth of spruce was not unexpected, but a noticeable increase in the overall size of treeline individuals was not a certain outcome. Slow growth rates combine with mechanical damage at high elevations and latitudes to limit increases in the size of tree canopies, especially in isolated individuals above the treeline (Holtmeier, 2003). So, while this result would be expected for individuals at lower elevations, the change observed in the size of individuals at the treeline (and, especially, above it) is noteworthy. Significant net growth of individuals has been observed in several ground-level repeat photography studies and appears to have been the most consistent type of change evident at treelines worldwide during the 20th century (e.g., Vale, 1987; Kullman, 1987). Indeed, growth at the latitudinal treeline in parts of northern Quebec has been so significant and widespread that the treeline has advanced because of a shift from stunted individuals (i.e., krummholz) to upright growth forms (i.e., trees), rather than through establishment of new individuals (Lescop-Sinclair and Payette, 1995).

The growth of pre-existing individuals likely contributed to the significant increase in spruce density observed. Given the small scale of the photographs, it is probable that many spruce were not identifiable in the 1947–48 photographs but by 1989 had grown to a size that could be detected. Rather than a result of widespread change in growth form from krummholz to tree, this increase is more likely the result of small individuals maturing into trees in the interim. The 1947–48 photos were taken at the end of the rapid period of establishment identified in our dendroecological studies, and our height and diameter measurements from these individuals suggest that it would have taken them two to three decades to attain a size that could be detected in the photographs. This estimate is

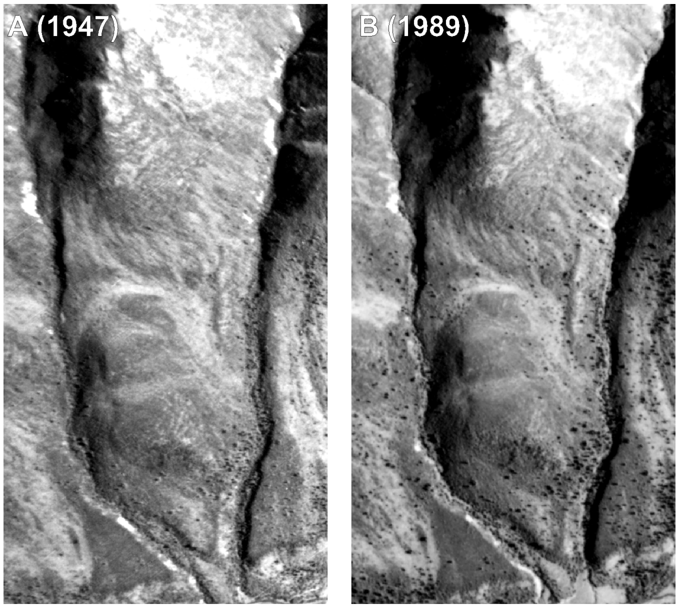

FIG. 5. Changes in spruce distribution along two tributaries of Tatamagouche Creek, southwest Yukon. Each photo represents a land area that measures 650 × 1250 m. Slope rises from the bottom to top of each image.

supported by the fact that density calculations from the aerial photographs were approximately half of that measured on the ground for south-facing slopes, and approximately one-tenth of those for north-facing slopes. In essence, only larger individuals were discernable in the photographs. This fact in turn explains the lack of significant effect of insolation on density in the ANOVA model, which contradicts the significant difference detected through ground-level measurements.

Though statistically significant, the changes in maximum spruce elevation were slight and considerably less prevalent than changes in density. Changes in treeline elevation may have been more substantial, but difficulties consistently delineating a boundary precluded use of a metric to test this. The effect of solar insolation on elevation was anticipated and concurs with observations from other Subarctic alpine regions (e.g., Dingman and Koutz, 1974; Viereck, 1979). The lack of interaction between insolation and elevation change is attributable to the relatively small differences we observed.

These results are in agreement with dendroecological data from southwest Yukon. From stem analysis of individuals in the southern portion of the Kluane Ranges, Ayotte (2002) concluded that spruce at and above the treeline have increased in overall size since the early 1950s, providing evidence of a growth release from stunted krummholz to tree forms. Our dendroecological results (Danby and Hik, 2007a) indicated a significant increase in density in the second quarter of the 20th century and a gradual infilling of the forest-tundra ecotone since that time. Finally, with respect to elevation, the dendroecological data indicate that treeline advance occurred mainly during the second quarter of the 20th century (i.e., in the 25 years that preceded the first set of photographs). Limited sampling (n = 20) of "outpost" trees and krummholz well above the treeline indicate that approximately three-quarters of these individuals were also established during this period.

Assessment of Methodology

Overall, the combination of manual interpretation with digital image transformation was successful. Manual interpretation allowed us to take advantage of characteristics such as texture, shape, and pattern when differentiating individual spruce from adjacent vegetation types and shadows. When using the original photographic prints, it also enabled us to exploit the vertical dimension by way of stereoscopic viewing. Image digitization allowed for continuous adjustment of contrast and brightness values. This was particularly important for the early photographs, which despite being at a larger scale, were of poorer clarity and contrast. Digitization also permitted the use of various filters, such as edge detection algorithms, to supplement on-screen interpretation of features. We were able to quantify change by using the virtual plot and transect overlays, but this would not have been possible without orthorectification to remove distortion and permit standardized measurements across the images.

Several difficulties encountered during the study require mention, however. They did not result in significant error, but are important caveats to consider, especially if the approach is to be applied elsewhere in similar environments. Small photographic scale was the root cause of most of these difficulties and proved problematic during image interpretation. For example, an inability to resolve small spruce in the photographs meant that the differences we observed are applicable only to individuals above a certain size. Our field data suggest that this was less problematic on south-facing slopes than on north-facing slopes, where spruce are much sparser and smaller in stature. In addition, in several instances a spruce was identified in the 1989 image, but its presence or absence in the earlier image was uncertain. In these instances, we erred on the side of caution, tagging the location as a spruce so as not to overestimate the degree of change. It is possible that this caution led to an underestimation of change, and our results should be considered in this light.

Errors in rectification were significant relative to the resolution of the rectified images. Known sources of error were (1) spatial inaccuracies in the GCPs obtained from the NTDB (up to 40 m difference on either axis between GPS and NTDB coordinates of the same feature), (2) the lack of camera and lens calibration information for the early photographs, and (3) inaccuracies in the DEM, which is mostly based on NTDB hypsography and therefore subject to the same error as the NTDB-derived GCPs. While the resulting positional error did not affect our results, it did present problems that required adjustments. This included slight shifting of plots and belt transects, relocating spruce from the 1947–48 images on the 1989

TABLE 2. Results of repeated measures ANOVA on two metrics of treeline change. S = Solar insolation; Y = Year (repeated). Bold text indicates statistical significance.

	Spruce Density				Maximum Spruce Elevation			
Between Subjects	df	MS	F	*p*	df	MS	F	*p*
S	1	42.8	0.150	0.699	1	351849.5	23.745	**< 0.001**
Error	102	285.08			98	14817.8		
Within Subjects[1]	F	Num df	Den df	*p*	F	Num df	Den df	*p*
Y	65.056	1	102	**< 0.001**	14.519	1	98	**< 0.001**
Y*S	2.316	1	102	0.131	0.925	1	98	0.339

[1] Values based on Wilks' lambda are reported.

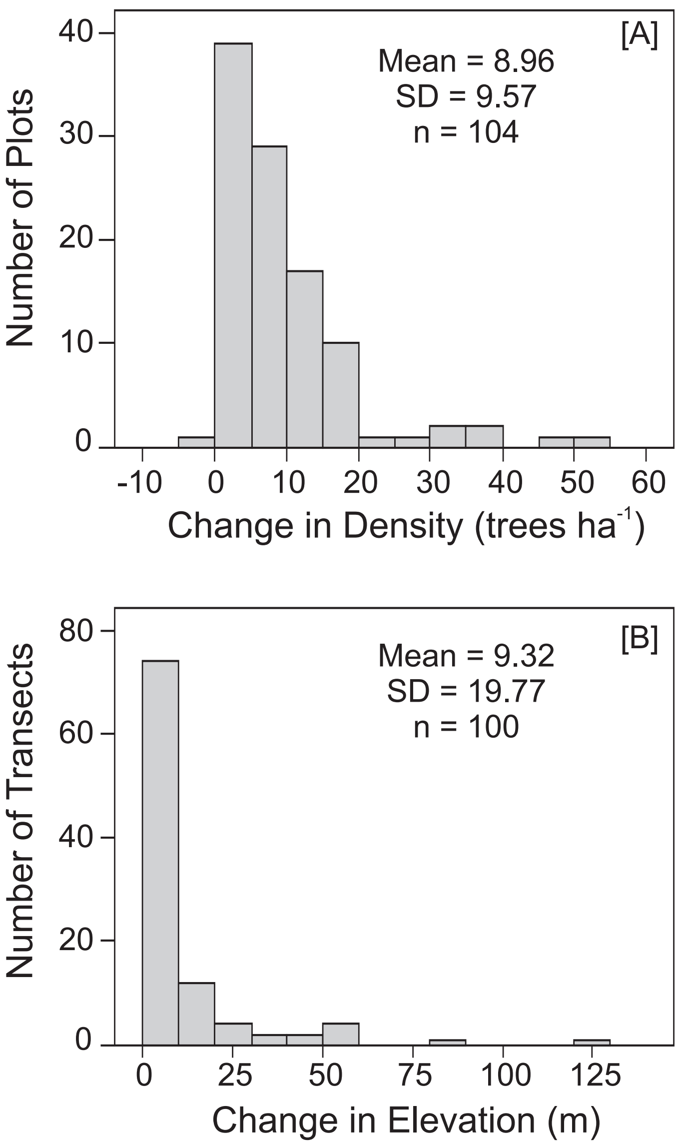

FIG. 6. Frequency distributions of the changes in (A) spruce density and (B) the uppermost spruce elevation. Changes in each plot (A) or belt transect (B) were calculated as the difference in the number of spruce identified in early (1947–48) and recent (1989) aerial photographs.

images for consistent elevation determination, and omitting peripheral areas on images where distortion and positional error were greatest.

One of the advantages of using sequential aerial photography over repeat ground-level photography is that the investigator is not limited to specific locations by the availability of existing photographs, since aerial coverage is generally widespread. In turn, it is possible to assess the extent to which the observed changes reflect the entire study area and not just a single location. Still, our experience indicates that it is important to nest fine-scale field investigations within the sequential photography investigation, especially when using small-scale photography. The field investigations facilitate an evaluation of the resolving power of the photographs, which is crucial for image interpretation. Equally important, they help to identify the mechanisms of change, a critical component of any such study.

Similarly, it is often difficult for non-experts to interpret scientific figures that quantify landscape change using spruce age histograms, lake sediment stratigraphies, or even change detection maps. Repeat and sequential photography are powerful tools for depicting landscape change, and the images provide a visual record that can be interpreted by anyone. These techniques need not be limited to qualitative assessments of change. As shown here, quantitative data, testable with inferential statistics, can be obtained from these images to provide the rigour and repeatability required of scientific investigations.

CONCLUSION

The potential ecological effects of climate change in Arctic and alpine regions have been the subject of extensive study. One of the most common predictions is that continued global temperature increases will cause the treeline to advance in elevation and latitude. Studies of past changes therefore have important value for forecasting the possible extent and pattern of treeline change. Our comparison of aerial photographs of southwest Yukon from 1947 and 1948 with those taken in 1989 indicates significant changes in the spruce forest–shrub tundra transition. In decreasing order of occurrence, these include (1) increased growth of individual spruce, (2) increased population density of spruce at the treeline, and (3) an upward expansion of spruce distribution.

Changes were not equitably distributed and tended to occur in a hierarchical fashion. Many areas exhibited increased growth of individual spruce without an increase in stand density or an advance in spruce distribution. An increase in both growth and density occurred in most other areas. Increases in the elevational distribution of spruce were observed in comparatively fewer areas, typically in combination with the other two types of change. The greatest changes were observed in the area of the Burwash Uplands in the southern portion of our study area, which experienced a transformation from sparsely treed shrubland to woodland and open-canopy forest. Other significant changes were observed along creek drainages.

Given the absence of major natural disturbances or widespread change in land use, we attribute these changes to climate. Dendrochronological evidence from the study area indicates that the most influential climatic period for the treeline was the 25 years immediately prior to the first photographs. Temperatures were consistently above the 100-year average (Luckman et al., 2002) and more than 40% of all treeline spruce date to this time (Danby and Hik, 2007a). Without earlier photographs, it is difficult to say what proportion of these spruce were actually visible in the 1947–48 photographs, and it is probable that the change we observed in the photographs represents only part of the total change during the 20th century.

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