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WHITE SPRUCE DYNAMICS IN THE FOREST-TUNDRA ECOTONE, THE SOUTHWEST YUKON TERRITORY

A thesis submitted to
The School of Graduate Studies and Research
In partial fulfillment of the requirements
For the degree Master of Science

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PREFACE

Variations in the structure and physiognomy of treeline areas are indicative of changing physical and environmental factors, thus making treeline areas a useful tool for understanding tree response to past and present climate variations. Numerous studies throughout the Northern Hemisphere, focusing on the sensitivity of vegetation at higher altitudes and latitudes in response to climate change, have provided insight as to how vegetation responds to warmer and colder climates. Altitudinal treeline vegetation in the southwest Yukon, however, has yet to be studied. For this reason, the following study on white spruce (*Picea glauca* [Moech] Voss) dynamics in the forest-tundra ecotone in the southwest Yukon Territory in response to the 20th century climate warming has been undertaken.

This thesis is divided into four chapters. The first chapter is an introduction presenting a literature review of the research topic, research objectives and the hypothesis of this study. Chapter 2 describes field and laboratory methods in detail. Chapter 3 is presented in the form of an article, providing an abbreviated introduction and methodology, followed by the results and discussion portion of the study. Lastly, chapter 4 summarizes the thesis and provides concluding remarks.

Dendrochronological techniques were used to study white spruce (*Picea glauca* [Moech] Voss) dynamics in the altitudinal forest-tundra ecotone in the southwest Yukon Territory. At two sampling sites, all *Picea glauca* individuals within 9 delineated quadrats in the forest-tundra and forest were sampled to estimate dates of establishment and growth variations using tree-ring chronologies. Regeneration in the forest-tundra ecotone was low from the late 1800s to the mid-1900s, however has increased since the 1920s. Recent peak periods of establishment parallel increased radial growth trends, which may have resulted from the long-term warming trend of the 20th century. Seedling proximity to pre-established individuals in the forest-tundra ecotone suggests regeneration from a local seed source. Growth in height of pre-established krummholz individuals accelerated around the 1950s. Tree establishment in the forest-tundra and forest appear to be influenced by summer temperatures of the current growing season, and a high degree of similarity in tree growth at different sites in the southwest Yukon suggests a regional response to a large-climate signal. An increase in krummholz height and improved seedling establishment in the forest-tundra ecotone could result in a shift from krummholz to symmetrical trees and/or from patch forest to continuous forest.

Des techniques dendrochronologiques ont été employées pour étudier la dynamique de l'épinette blanche (*Picea glauca* [Moech] Voss) dans l'écotone altitudinale de la toundra forestière dans le sud-ouest du Yukon. À deux sites, toutes les épinettes blanches dans 9 quadrats situés dans la toundra forestière et la forêt ont été échantillonnées pour determiner les dates d'établissement et de croissance en utilisant des séries chronologiques basées sur les anneaux de croissance annuels. La régénération dans l'écotone de toundra forestière était basse du 19^{e} au milieu du 20^{e} siècle. Elle a toutefois augmenté depuis les années 1920. Les périodes récentes d'établissement reflètent les tendances de croissance résultant du réchauffement à long terme du 20ème siècle. La présence de jeunes épinettes à côté de vieux arbres dans l'écotone de la toundra forestière suggère une régénération des semences locales. La croissance de la taille de vieux krummholz a accéléré autour des années 1950. L'établissement et la croissance d'arbre de la toundra forestière semblent être influencés par les températures de la saison de croissance. Un degré élevé de similitude dans la croissance d'arbre à différents emplacements dans le sud-ouest du Yukon suggère une réponse régionale à un signal climatique de grande échelle. Une augmentation de la taille des krummholz et l'établissement de jeunes épinettes dans l'écotone de toundra forestière a pu avoir comme conséquence le passage de krummholz à des arbres symétriques et/ou de la forêt discontinue à la forêt continue.

So many people to thank, in so little space.

Firstly, I would like to thank Dr. M. Vetter, from the Department of Botany at the University of Regina, for so kindly sharing her knowledge of the Yukon flora with me, and for delegating numerous hours to the botanical section of this thesis. Thanks Mary, for being the kind and generous person that you are.

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Over the last 150 years, the Arctic has substantially warmed by approximately 1.5°C (Bradley and Jones, 1983; Overpeck *et al.*, 1997). Increasing concentrations of greenhouse gases in the atmosphere have resulted in unusually warm conditions since the 1920s, and further warming is expected to be more pronounced in higher latitudes (Bradley and Jones, 1983). These climatic changes have significant impacts on arctic ecosystems, hence it is important to understand tree response in subarctic regions with respect to past and present climatic variations (Payette *et al.*, 1985).

Trees at latitudinal and altitudinal treeline grow at the limits of their ecological tolerance and are therefore extremely sensitive to climate change (Fritts, 1976). In addition to temperature, treeline trees are constrained by a variety of physical and environmental factors including topography, snowcover, soil moisture and wind. Individual trees respond to these factors by adopting different growth forms and/or methods of reproduction (i.e. vegetative versus sexual). Many authors have reported a response to the 20th century warming expressed through minor treeline displacements and/or increased tree population densities in the forest-tundra ecotone, which is the transition zone between the continuous forest and the tundra (Hansell *et al.*, 1971; Kullman, 1986a; Lavoie and Payette, 1994; Lescop-Sinclair and Payette, 1995; Kullman and Engelmark, 1997). Therefore, to predict future vegetation response to climate warming, it is necessary to understand how and why trees at their northern limit have responded in the past.

1.1 HOLOCENE TREELINE DISPLACEMENTS IN CANADA

Studies focusing on treeline distributions throughout the Holocene have detected shifts ranging from 50 to 100 km over periods of hundreds to thousands of years (Ritchie and Hare, 1971; Spear, 1983; Lamb, 1985; Luckman and Kearney, 1986; Moser and MacDonald, 1990; Lavoie and Payette, 1996). In northwestern Canada, treeline was further north during the early Holocene between 9000 to 5000 yr B.P. (Ritchie and Hare, 1971; Moser and MacDonald, 1990). In central Canada, an increase in black spruce (*Picea mariana* [Mill.] B.S.P.) pollen abundance suggests the establishment of a forest-tundra ecotone at approximately 5000 yr B.P., and a reversion to tundra around 3500 yr B.P. (Moser and MacDonald, 1990). In the southwest Yukon, spruce immigrated into the White River Valley around 8000 ^{14}C yr B.P. and grew above the present treeline until approximately 3600 to 3000 ^{14}C yr B.P. (Denton and Karlén, 1977). Evidence of subsequent fluctuations in treeline positions is lacking. Spruce reached its present-day limit in northern Québec much later, approximately 5000 to 4500 yr B.P. as a result of a later deglaciation in this region (Payette and Morneau, 1993). Ritchie and Hare (1971) have concluded that the controlling factor of the northward displacement of treeline in central and northwestern Canada is climate. Therefore, by understanding treeline fluctuations during the Holocene, inferences can be made about recent tree responses to climate change.

The previous studies used paleoecological evidence, such as pollen records, wood fragments or macrofossils, to infer the postglacial history of treeline in response to climate change. Both palynological evidence and the presence of subfossils above the current treeline indicate a forest beyond the present forest limit (Denton and Karlén, 1977; Payette and Gagnon, 1979; Black and Bliss, 1980; Karlén, 1983; Spear, 1983; Payette *et al.*, 1989). For instance, in the Mackenzie Delta region, Spear (1983) found a spruce stump 50 km north of the present treeline. This suggests that more favorable growing conditions similar to those currently in the boreal forest were present when the tree was growing.

1.2 RECENT TREELINE ADVANCES IN THE NORTHERN HEMISPHERE

Recent studies have detected minor treeline advances since the end of the Little Ice Age [ca. 1580-1880] (Grove, 1988). Nevertheless, treeline advances since the end of the 19th century have not reached the same extent as had been reached 9000 to 5000 yr B.P. Studies focusing on recent treeline dynamics use dendrochronological techniques rather than paleoecological evidence from lake sediments. Tree-rings provide a temperature-sensitive record of changing conditions, therefore can be used to investigate the response of tree growth to climate change (Fritts, 1976).

The warming trend of the last 100 years has resulted in northern latitudinal and altitudinal treeline expansions in Canada (Hansell *et al.*, 1971; Payette and Filion, 1985; Szeicz and MacDonald, 1995a), the United States (Garfinkel and Brubaker, 1980; Suarez et *al.*, 1999), Sweden (Kullman, 1986b; Kullman and Engelmark, 1997) and Russia (Gorchakovsky and Shiyatov, 1978). Altitudinal forest-tundra ecotones appear to be expanding as a result of the 20th century warming, however only minimal changes in the position of latitudinal treelines have been detected. Most reports suggest that minor altitudinal treeline displacements are a result of increased stand density in the forest-tundra ecotone caused by seedling establishment and changes in stem morphology of pre-established trees individuals. On the eastern coast of Hudson Bay, Payette and Filion (1985) showed that *Picea glauca* stand densities rapidly increased via sexual reproduction throughout the last 100 years without any evidence of latitudinal treeline displacements.

1.3 STRUCTURAL CHANGES AT TREELINE

Temperature has been considered as the primary factor controlling latitudinal treeline positions. Tranquillini (1979) states that the latitudinal treeline coincides with the 10°C July-isotherm, however this is simply a correlation. A better interpretation is the relation of latitudinal treeline with the mean summer position of the Arctic front (Bryson, 1966). On the other hand, altitudinal treeline is controlled by temperature and precipitation, in addition to other factors. The depth and distribution of snowpacks are affected by wind, local topography and tree islands themselves, which protect tree individuals from snow and particle abrasion above snow level. Deeper snowpacks in the forest-tundra ecotone reduce the amount of stem degradation, however its persistence throughout the growing season may limit tree establishment (Billings, 1969).

While regeneration at treeline is extremely sensitive to climate change, varying growth forms can also provide important information on the response of treeline to climate change. Studies in recent decades have focused on changes in krummholz growth forms (stunted, deformed woody stems) at treeline since the end of the Little Ice Age (Bégin, 1991; Lavoie and Payette, 1992; Payette and Delwaide, 1994; Payette *et al.*, 1994; Payette *et al.*, 1996; Pereg and Payette, 1998). The complexity of a krummholz growth form depends on its exposure to prevailing winds. Trees protected from snow and particle abrasion develop as normal trees, whereas exposed individuals are damaged by wind effects in the winter and adopt a stunted growth form. The phenotypic plasticity (capability of adapting to climate change by altering its growth form) of *Picea* spp. enables the individual trees to adapt to harsh winter conditions and increases their survival and longevity (Payette *et al.*, 1994). Once the supranival stems (vertical stems above snow level) die, a procedure referred to as adaptive reiteration occurs. This procedure maintains leaf area and enables the individual to continue photosynthesis by compensating for the loss of vertical stems above the snow level. Continuous particle abrasion results in the formation of numerous reiterate branches, eventually forming a group of stems below the snow cover. These stems are weighed down by the snow and covered by organic matter, which initiates root development. The stems can then become independent of the parent tree. By compensating for the loss of photosynthetic tissue above snow level, the tree conserves a positive carbon balance while maintaining its architectural integrity (Bégin, 1991). At treeline, *Picea mariana* often layers and adopts non-arborescent growth forms. Layering also occurs in *Picea glauca* individuals, however less commonly in comparison to *Picea mariana* (Payette, 1983). *Picea glauca* krummholz have been reported in treeline areas in the northern Yukon and the Northwest Territories (Elliot, 1979; Szeicz and MacDonald, 1995a).

Trees exposed to harsh winter conditions at treeline adapt by reproducing through layering. However, since the end of the Little Ice Age, winters have been milder and snowier, consequently providing favorable conditions encouraging supranival stem growth. For instance, in northern Québec, Payette and Delwaide (1994) detected an increase in supranival stem growth since the 1930s. Stem analysis indicated slow lateral growth (layering) during the 19th century, and a relatively rapid increase in vertical growth since the 1930s. Additional studies in Sweden (Kullman, 1986b, 1990), the United States (Earle, 1993, Hessl, 1996) and Canada (Lavoie and Payette, 1992; Pereg and Payette, 1998) have recorded similar increases of supranival stem growth since the end of the 19th century.

1.4 RESEARCH OBJECTIVES

To explain the objectives of this study, the ecological limits at treeline regions need to be clarified. Treeline is used in a general sense for the altitudinal or northern limit of the boreal forest, however for this study a more precise description is necessary. The forest-tundra ecotone, which is the transition between the forest and the tundra, has several ecological limits above, within and below it (Payette, 1983). The following ecological limits have been described in Payette (1983) and will be used in this study.

1. *Limit of continuous forest* refers to the limit of a closed or open canopy forest.
2. *Forest limit* is the northern limit of forest stands, generally located in the northernmost parts of the forest-tundra.
3. *Treeline* is the northern limit of trees, where symmetrical tree individuals reaching heights of 5 m or more are present.

4. *Limit of tree species* refers to the northernmost limit of a specific tree species, whether tree form or shrub form.

It should be noted that this classification is based on a latitudinal and not an altitudinal gradient, however it corresponds well to the altitudinal treeline sites in this study. The spatial distance between the tundra and the forest ranges from several hundred kilometers in northern Québec to several hundred meters at altitudinal treelines, such as those in the southwest Yukon (Payette, 1983).

The three objectives of this study are:

1. to determine if the 20th century climate warming has resulted in an increase in *Picea glauca* seedling establishment and/or changes of tree growth form in the forest-tundra ecotone at Bear Creek,
2. to examine the response of tree growth to the 20th century warming and to determine which climatic factors are the most limiting to tree growth, and
3. to compare site chronologies from the southwest Yukon and northwestern British Columbia in order to examine similarities among growth trends throughout the region.

1.5 HYPOTHESIS

Two studies in northern Québec have detected *Picea mariana* responses to the recent climate warming at the lichen-spruce forest limit (Payette *et al.*, 1985; Lavoie and Payette, 1994). Both studies reported a *Picea mariana* reaction through phenotypic adaptation resulting in a shift from krummholz individuals to symmetrical trees. This northward advance of the forest limit resulted from increased vertical stem growth and increased regeneration in the forest-tundra. A shift from forest-tundra to open forest was also noted at treeline near Churchill, Manitoba (Scott *et al.*, 1987a). Scott *et al.* (1987a) suggest that an increase in *Picea glauca* seedling establishment during the 1920 to 1950 temperature maximum resulted in a conversion of the forest-tundra to open forest. Based on these previous findings, the following hypothesis will be tested in this study:

THE FOREST-TUNDRA ECOTONE IN THE SOUTHWEST YUKON TERRITORY IS RESPONDING TO THE 20TH CENTURY CLIMATE WARMING THROUGH AN INCREASE IN REGENERATION AND CHANGES IN TREE GROWTH FORMS.

1.6 IMPORTANCE OF STUDY

This study, focusing on *Picea glauca* dynamics in the forest-tundra ecotone, was conducted in the southwest Yukon Territory because of the abundance of ideal altitudinal treeline locations, with relatively small human influence in close proximity to dense old-growth spruce forests. Few dendrochronological studies have been performed in the southwest Yukon and none have studied alpine tree growth and regeneration in relation to climate change. Previous studies undertaken in this region have focused on fire history (Francis, 1996) and chronology development from various high and low elevation sites (Allen, 1982; Watson *et al.*, 2000). Extensive changes in vegetation could alter the ecological composition of the southwest Yukon, and since this area is one of the driest portions of North America's boreal forest it may provide analogues for other areas in the future.

1.7 SITE SELECTION

Potential treeline sites were identified by the analysis of topography maps, air photos and discussions with Dr. P. Johnson. A recent spruce bark beetle (Dendroctonus rufipennis [Kirby]) outbreak in the Shakwak Trench reduced the number of potential treeline study sites due to the abundance of beetle-killed trees across the entire landscape. Site selection was further based on accessibility and availability of krummholz individuals. The forest-tundra at Bear Creek, the southwest Yukon site, was extremely accessible, located approximately a kilometer from the highest point of the Alaska Highway (982 m a.s.l.). An abundance of krummholz individuals scattered throughout a relatively broad forest-tundra made for an ideal treeline site. The northwestern British Columbia site consists of several stands of symmetrical trees within the forest and forest-tundra, running parallel to the Haines Road. *Picea glauca*, an ideal species for dendrochronological research, is the dominant species at both sites. Because the purpose of this study was to analyze the dynamics of the forest-tundra ecotone, and not to develop long tree-ring chronologies for climate reconstructions, site selection was not based on tree age.

1.8 STUDY SITES

Dendrochronological studies were conducted at two treeline sites, Bear Creek and Tatshenshini, which are approximately 150 km apart (Figure 1, Table 1). The northern study site, Bear Creek, located in the southwest Yukon Territory, was sampled in more detail and is the primary area of this research. The second site, Tatshenshini, in northwestern British Columbia was studied for comparison.

Bear Creek lies on a gentle northeast-facing slope of the St. Elias Mountains (60°51'N, 137°49'W) adjacent to the Shakwak Trench. Located approximately 10 km west of Haines Junction, Bear Creek is close to the Haines Junction weather station at 596 m a.s.l. The mean annual temperature is –2.7°C, the mean summer (June-August) temperature is 11.3°C, and the mean winter (December-February) temperature is –18.4°C. This region is subject to cold Arctic and mild Pacific air masses resulting in a rapid change from season to season (Wahl *et al.*, 1987). The study site is located in the rain shadow of the St. Elias Mountains, and is therefore arid with a total annual precipitation of approximately 300 mm. Nearly 50 percent of the precipitation falls as snow. The previous values were based on the 1961-1990 normals. Mean seasonal temperature and total seasonal precipitation data from three stations in the southwest Yukon show similar curves, suggesting that there is a large-scale coherence in the climate of the region (Figure 2,3).

The Bear Creek site was divided into four zones: tundra, krummholz, patch forest and continuous forest (Figure 4). The tundra zone is comprised of herbaceous plants and shrubs such as willows (*Salix* spp.) and dwarf birch (*Betula glandulosa* [Michx]), which grow up to 0.8 m high. The krummholz zone is characterized by thick *Salix* spp. and *Betula glandulosa* stands reaching heights of 2 m, but typically less than 1m. Isolated scattered *Picea glauca* krummholz rise 2-3 m above this cover (Figure 5). Under the shrub layer is a diverse understory (Appendix A), a nearly continuous layer of feathermoss, and a thick organic mat (Appendix B). The patch forest consists of patches of symmetrical trees surrounded by a nearly continuous shrub layer. In the continuous forest, which is relatively open, the trees form a continuous canopy of symmetrical trees. *Picea glauca* is the dominant species at this site and forms the local altitudinal treeline at a mean altitude of 1120 m a.s.l.. The spruce limit is located at 1240 m a.s.l. The forest-tundra ecotone at this site is diffuse, unlike others in the Shakwak Trench, which tend to be more abrupt. *Picea mariana* is not present at Bear Creek. The site is located on well-drained sandy soil (Appendix B) and has clearly not been influenced by anthropogenic disturbances. The absence of charred stumps or charcoal in the soil suggests that this particular treeline site has not been recently burned.

The northwestern British Columbia study site is located in the Tatshenshini region along the Haines Road near the Yukon/British Columbia provincial border (59°52'N, 136°41'W - 59°56'N, 136°48'W), in the foothills of the Boundary Ranges (Coast Mountains) (Figure 6). Annual total precipitation maps suggest an increase in total annual precipitation along the Shakwak Trench towards British Columbia, where the Tatshenshini site falls within the 600 mm isohyet (Wahl *et al.*, 1987). This site is flat to moderately inclined, extremely moist and the organic content in the soil is high (Appendix B). The transition from forest to tundra runs parallel to the road making the entire zone accessible. The mean altitude of the treeline is 920 m a.s.l. and the dominant species is again *Picea glauca*, reaching a height of 10 m. This study area was divided into three zones: tundra, forest-tundra and forest. The tundra zone, which is relatively moist, consists of low-lying shrubs, including *Salix* spp. and *Betula glandulosa*, herbaceous plants and mosses (Appendix A). The forest-tundra consists of patches of symmetrical *Picea glauca* trees surrounded by a continuous shrub layer reaching heights of 2 m. The quadrats laid out in the forest-tundra ecotone are located on the periphery of a moist area. The forest zone is comprised of erect *Picea glauca* trees surrounded by a discontinuous shrub layer. Numerous plants present at the Tatshenshini site are absent at the Bear Creek site (Appendix A) suggesting a response to a transition from a dry continental climate to a wet maritime climate.

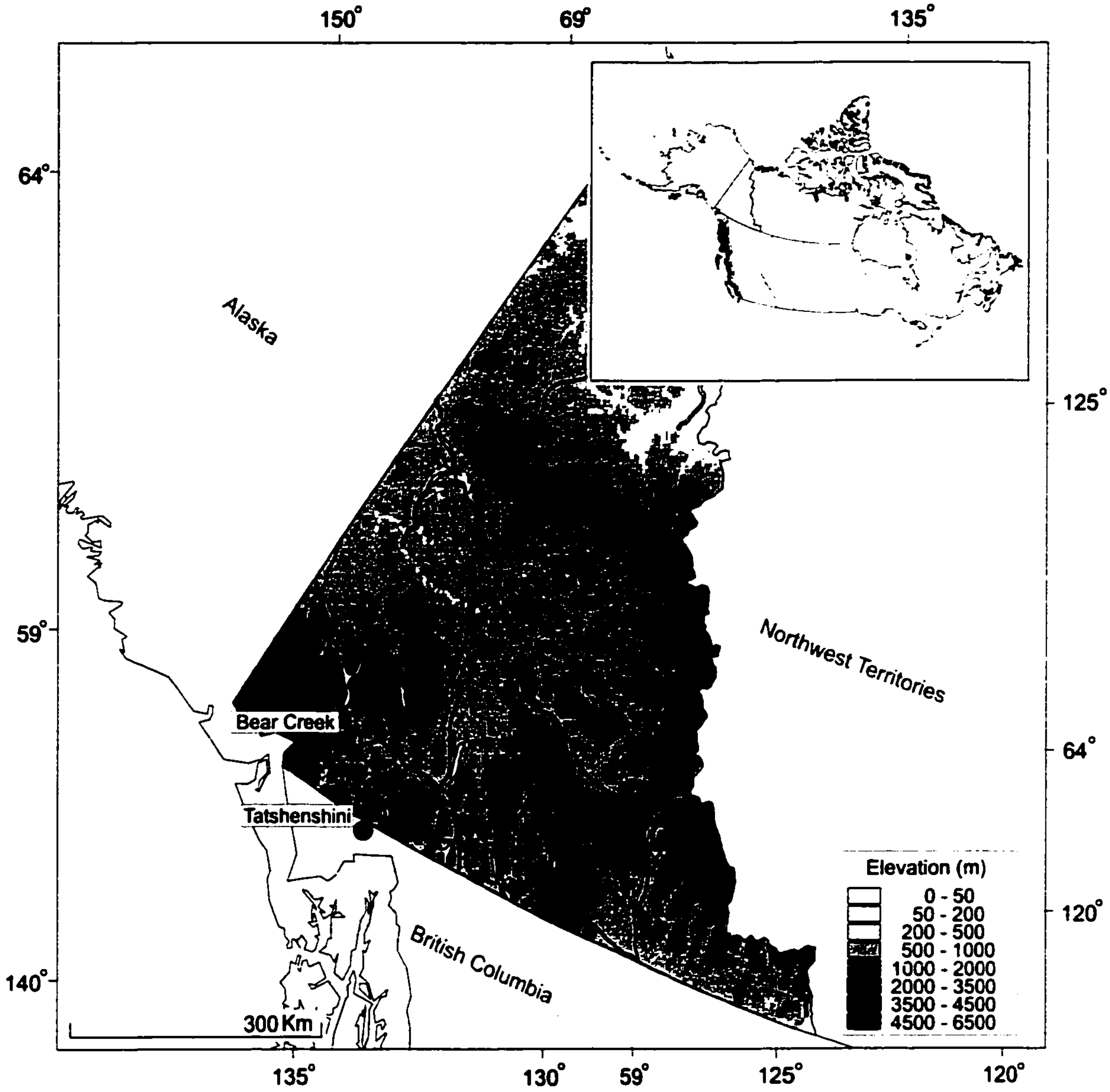

Figure 1 Location map of the Bear Creek and Tatshenshini sites in the southwest Yukon and northwestern British Columbia.

Table 1 Location and site description of the Bear Creek and Tatshenshini sites.

Study site	Quadrat	Quadrat code	Latitude (N)	Longitude (W)	Altitude (m a.s.l.)	Aspect	Slope (°)	No. of spruce* sampled
Bear Creek	Tundra	BeT	60° 51	137° 50	1250	N-E	2	—
	Forest-tundra							
	Quadrat 1	BFT	60 51	137 49	1166	N-E	1	8
	Quadrat 2	BFT2	60 51	137 48	1177	N-E	1	5
	Quadrat 3	BFT3	60 51	137 50	1174	N-E	3	6
	Quadrat 4	B2FT	60 51	137 50	1163	N-E	14	6
	Quadrat 5	B2FT2	60 51	137 50	1075	N-E	6	11
	Forest	BeF	60 51	137 49	1074	N-E	0	28
Tatshenshini	Tundra	TATT	59 52	136 41	928	N	0	—
	Forest-tundra							
	Quadrat 1	TATFT	59 54	136 46	938	N	2	20
	Quadrat 2	TATFT2	59 54	136 46	941	N	1	22
	Forest	TATF	59 56	136 48	918	N	0	43

* Krummholz were sampled in the Bear Creek forest-tundra ecotone

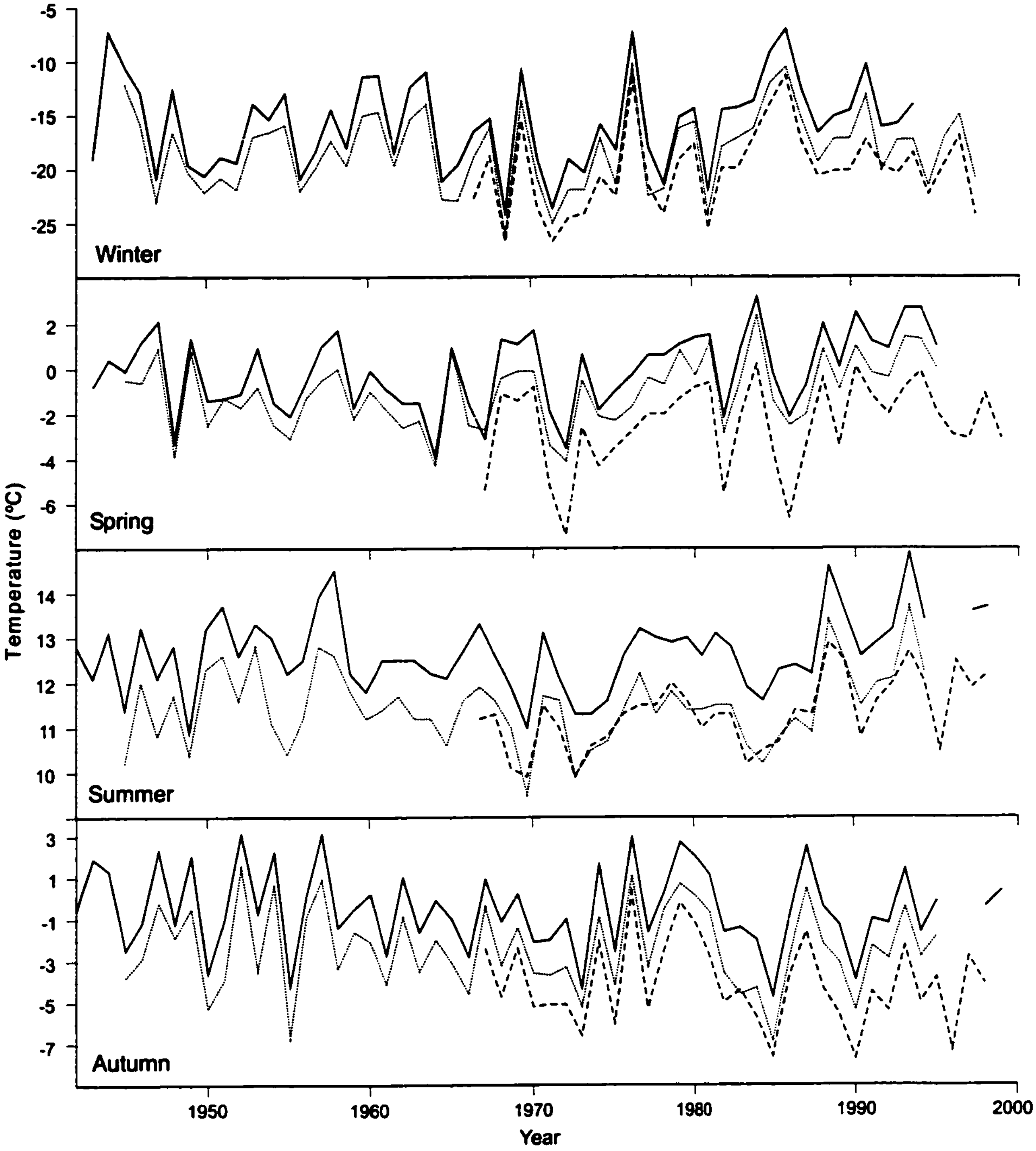

Figure 2 Mean seasonal temperatures from three weather stations in the southwest Yukon Territory. The solid line represents Whitehorse; the dashed line Burwash Landing; and the dotted line Haines Junction. Distance between the three stations is approximately 300 km. Source: Historical Canadian Climate Database, Meteorological Service of Canada.

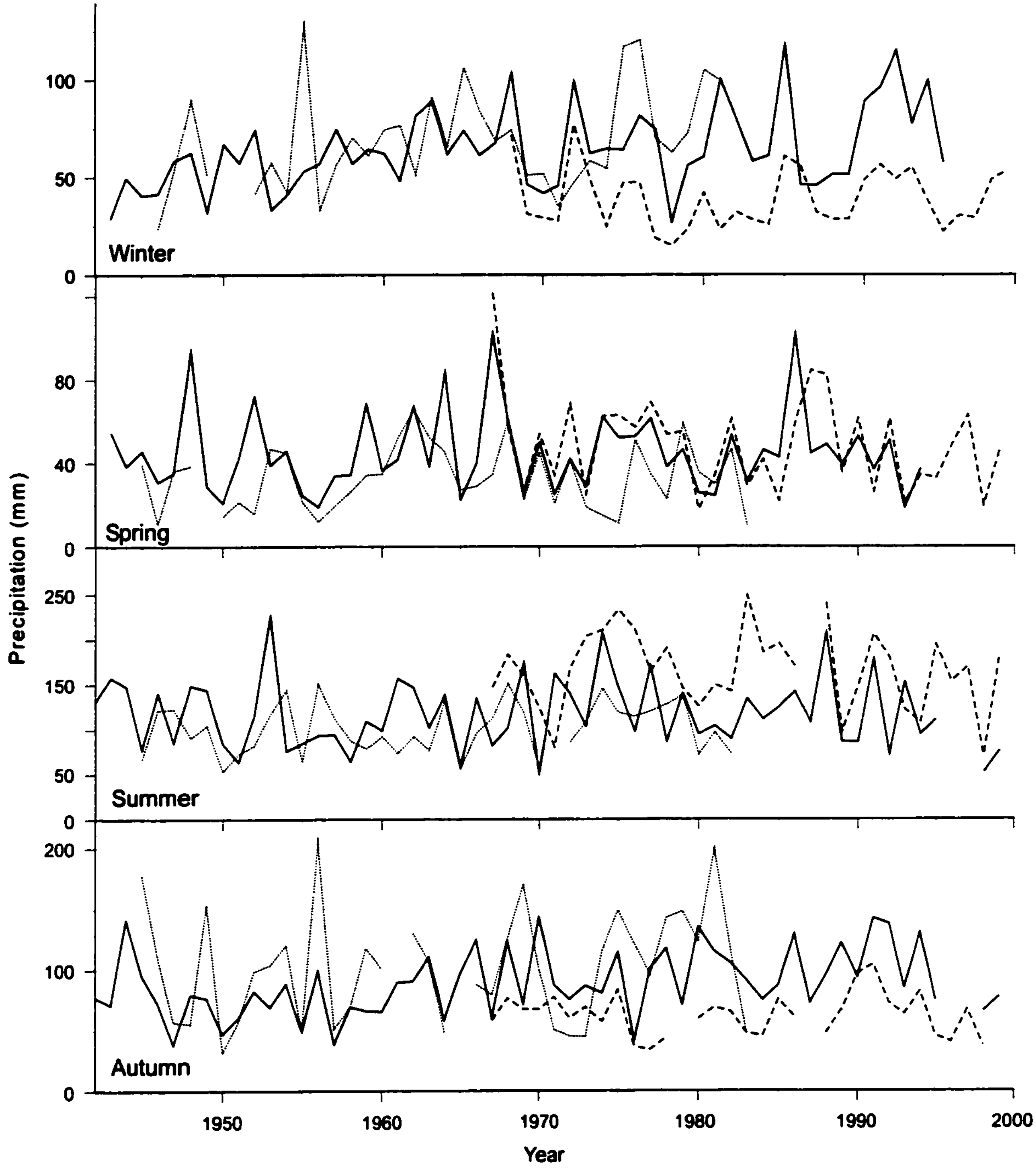

Figure 3 Total seasonal precipitation from three weather stations in the southwest Yukon Territory. The solid line represents Whitehorse; the dashed line Burwash Landing, and the dotted line Haines Junction. Distance between the three stations is approximately 300 km. Source: Canadian Historical Climate Data, Meteorological Data Service.

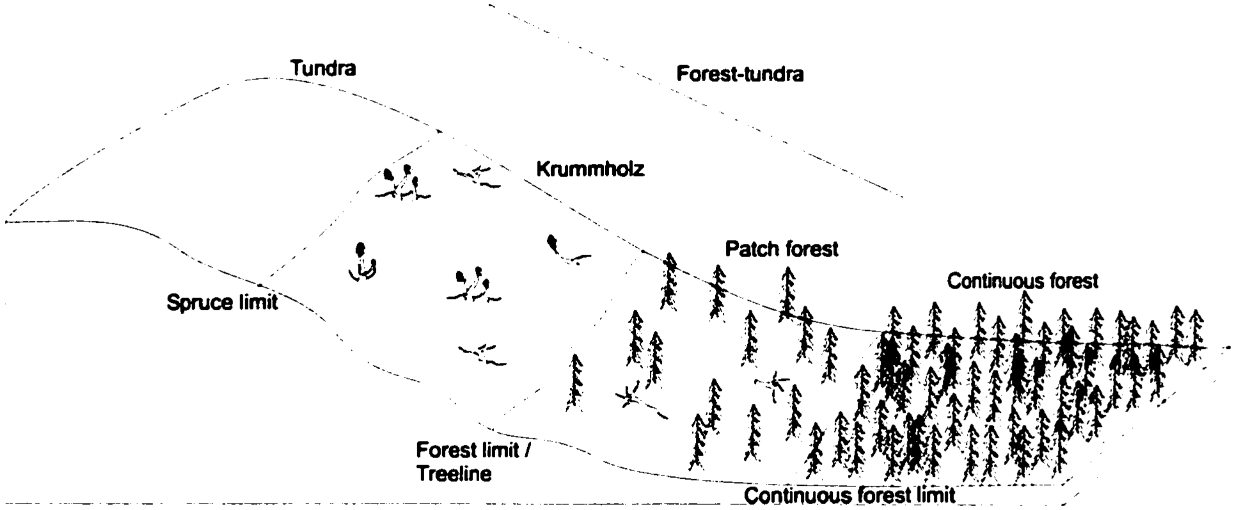

Figure 4 Schematic representation of the vegetation zones and ecological limits at Bear Creek, southwest Yukon Territory. The spruce limit refers to the uppermost limit of spruce irrespective of size and growth form. The forest limit is the altitudinal limit of forest stands. Treeline is the upper limit of trees, in this case, the same as the forest limit. The limit of continuous forest refers to the limit of closed or open canopy forest.

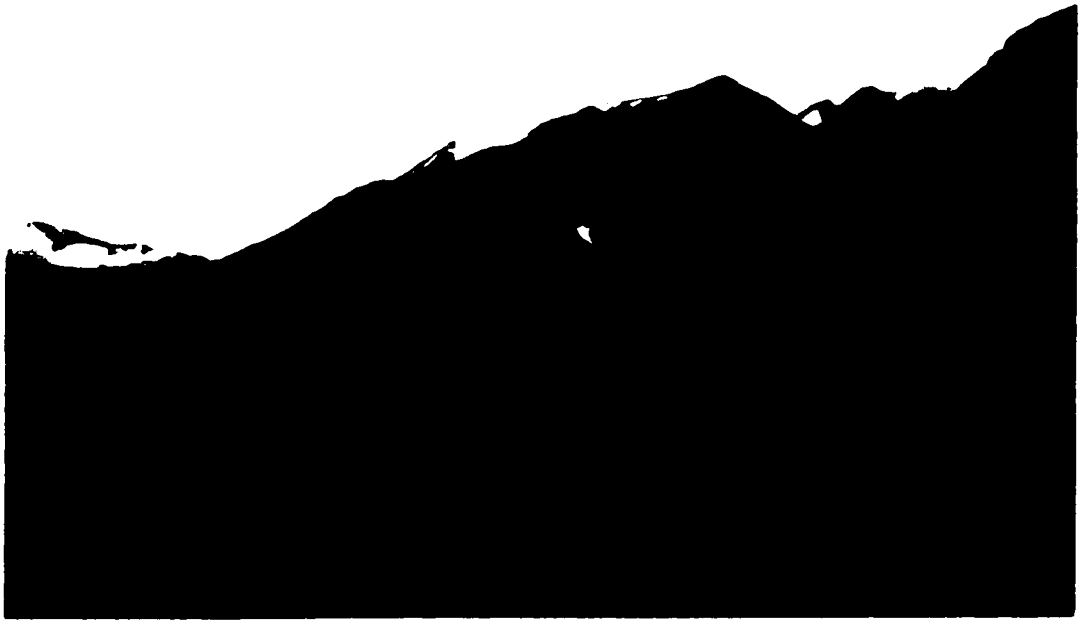

Figure 5 The forest-tundra ecotone (krummholz zone) at the Bear Creek site (1135 m - 1240 m a.s.l.). The vegetation cover consists of *Salix* spp., *Betula glandulosa* and scattered *Picea glauca* krummholz individuals.

Figure 6 Tatshenshini forest-tundra site (990 m a.s.l.). The transition from forest to tundra runs parallel to the Haines Road. The ground cover is composed of dense shrub species (i.e. *Salix* and *Betula glandulosa*) and scattered *Picea glauca* tree individuals.

FIELD METHODS

2.1 SAMPLING DESIGN

Dendrochronological studies were conducted at two treeline sites, Bear Creek and Tatshenshini, to obtain the data needed to assess alpine vegetation dynamics in the southwest Yukon Territory. Fieldwork was undertaken in the summer of 2001, with the bulk of the sampling concentrated in the Bear Creek forest-tundra ecotone. A total of 11 quadrats were delineated at both sites (Figure 7, 8).

The quadrats laid out in the forest were located in an open canopy stand where competition among trees is at a minimum. Quadrats ranged in size from 200 to 900 m^2 depending on stand density. All *Picea glauca* individuals in the quadrat were sampled. To determine the age of all tree individuals with a circumference greater than 20 cm in each quadrat, two cores were extracted to allow for the interpretation of variance among and within trees (Fritts, 1976). Each core was taken at right-angles to each other at the base using a Swedish increment borer until the pith was reached (Stockes and Smiley, 1968). All remaining trees in the quadrat, including seedlings (<2 m), were sawn off at the base to determine the age.

Dendrochronological studies of stunted *Picea glauca* individuals in the Bear Creek forest-tundra required a different sampling design. Due to the complex morphology of these individuals, each krummholz in the quadrat was dissected in three phases. First, supranival stems were sawn off at what was interpreted to be snow level, to determine the timing of release of the stems above snow level. The snow level corresponds to the snow-air interface, where a skirt consisting of dense stems covered with healthy foliage lies below the snowcover. Cross-sections were then collected at the multi-stem level (where reiterate stems branch off from the base stem) to determine lateral stem development and layering frequencies. Finally cross-sections were collected as close to the base as possible. This provided an approximate age of establishment of the individual. The asymmetric growth of the stems collected at the base and the multi-stem level generated high concentrations of reaction wood as well as numerous locally absent rings. By collecting cross-sections instead of cores, dating and measurement errors resulting from these discrepancies were minimized.

The height and growth form of all sampled krummholz were noted. Sketches of all sampled *Picea glauca* individuals in the forest-tundra at Bear Creek are presented in Figures 9. Terminology used in this study is based on five general spruce growth forms described by Lavoie and Payette (1992). They are:

1. *Mat growth form* which rarely exceeds 0.3 m in height, all of which remains below the snow cover in winter;
2. *Infranival cushion* is a shrub growth form with erect shoots no taller than 2 m;
3. *Supranival skirted growth form* refers to a spruce with supranival stems exposed to snow abrasion, and a skirt consisting of dense stems covered with healthy foliage below the snow level in winter;

4. *Whorled growth form* are erect spruce with numerous reiterated shoots developing at the snow-air interface around the main stem; and
5. *Tree form* are symmetrical spruce with the absence of significant morphological damage due to snow abrasion.

At Bear Creek four line transects from the tundra to the forest (~0.8 km each) were walked by three to four people, while observing spruce distributions. The general characteristic of the forest-tundra ecotone at Bear Creek was determined by recording the altitude of all seedlings, krummholz, subfossils and snags, and trees encountered along the transects. Seedlings were considered to be single-stemmed individuals below 2 m in height with no connection (through roots or branches) to other individuals. Spruce with two or more stems were defined as krummholz regardless of height. Subfossils refer to dead spruce remains, and trees were defined as symmetrical individuals reaching heights above 2 m tall. The altitude of each individual was noted using a GPS (Global Positioning System) and all seedlings were sawn off at the base and dated to determine periods of regeneration in the forest-tundra ecotone. At both sites, evidence of *Picea glauca* regeneration and mortality (i.e. subfossils) throughout the tundra were also noted to assess past and present species limit positions.

Elevation, aspect, slope and evidence of fire, such as charcoal in the soil and/or charred stumps, were noted for each quadrat. Vegetation cover was studied in three randomly placed 1 m^2 quadrats located within each delineated quadrat. Plant voucher specimens were collected, pressed, identified and stored in the LPC (Laboratory for

Paleoclimatology and Climatology) herbarium. A soil pit was also dug in each quadrat to determine the soil composition.

LABORATORY METHODS

2.2 SAMPLE PREPARATION AND DATING TECHNIQUES

Once air dry, the cores were glued into slotted wooden mounts and wound tightly with string. The cores were then sanded with increasingly finer grain sandpaper (120, 220, 300, 600, 1500 grit) to permit identification of annual ring boundaries. Once sanded, the annual rings were counted using a stereomicroscope at 40x magnification, following the techniques outlined in Stokes and Smiley (1968). Ensuring that the proper date is assigned to each annual ring is the most important principle in dendrochronology. This procedure, known as cross-dating, was first performed by using the skeleton plot method, where groups of cores are compared to one another by matching patterns and assigning a date to each annual ring (Stokes and Smiley, 1968). Once the signature years (years of extremely narrow or wide growth present in a majority of the dated samples) had been defined, the skeleton plot method was no longer necessary. Further samples were visually cross-dated using the signature years, and all cross-dating was verified using the computer program COFECHA (Grissino-Mayer *et al.*, 1992). When dating stressed trees (i.e. krummholz), numerous complications such as false and locally absent rings can arise. False rings, which can easily be mistaken as a true growth ring were scarce, however numerous locally absent rings were present in the krummholz samples. Locally absent rings develop during a year of extreme climate, when radial growth is at a minimum (Fritts, 1976). In this study, locally absent rings resulted from reaction wood, which occurs on the lower side of leaning stems. Reaction wood is common in krummholz individuals because of the continuous mechanical pressure from wind and snow (Tranquillini, 1979).

2.3 AGE-STRUCTURE ANALYSIS

Once the cores were successfully cross-dated, age-structure histograms were generated from the data. Analysis of the histogram can show if the population is expanding or decreasing. A 10-year age class interval was used to account for the differences between the true age of the stem and the age at sampling height (Payette *et al.* 1985). Samples that could not be cross-dated and those with pith rot were not included in the age structures.

2.4 CHRONOLOGY DEVELOPMENT

A tree-ring chronology is a filtered time series of ring-widths from a number of trees sampled from a specific site. The ring-widths from the cross-dated cores were measured to the nearest 0.001 mm using an ACU-RITE glass scale linear encoder connected to a digital measuring device Quick-Check (QC-1000). All measurements were recorded and stored in a desktop computer. The last ring measured was the year 2000 because 2001 was incomplete. For samples containing high concentrations of reaction wood, ring-width measurements were taken along a radius excluding reaction wood. Samples where the direction of the reaction wood changed throughout the cross-section were rejected from the chronology, however used in the age structures.

In order to adequately select a group of ring-width series to be included in the tree-ring chronology, a principal components analysis (PCA) was performed. The PCA determined which trees are highly correlated and therefore contain the large-scale climate signal. The PCA also showed that the trees sampled in different quadrats within the forest-tundra ecotone at both sites had sufficient variance in common to be grouped and included in a single chronology. Once a group of cross-dated samples had been selected using the PCA, a tree-ring chronology was developed. The program ARSTAN (Cook, 1985; Grissino-Mayer *et al.*, 1992) was used to produce chronologies from the selected tree-ring measurement series. The ARSTAN program produces tree-ring chronologies by standardizing the series to remove endogenous noise. The PCA and the methods of standardization used in the ARSTAN program will be elaborated in the following sections.

2.4.1 PRINCIPAL COMPONENTS ANALYSIS

Before developing a tree-ring chronology, a principal components analysis (PCA) was used to determine the similarity in growth variation among trees within a quadrat. A detailed description of one of the analyzes (the Tatshenshini forest) is provided in Appendix C. A similar analysis was performed on the Tatshenshini forest-tundra and the Bear Creek forest and forest-tundra. The PCA provides component loadings for ring-width series and component scores for years. In all four analyzes, the first principal component was highly loaded on a majority of the series. The second component was also highly loaded on most or several series, and presumably contained a portion of the climate signal that was not captured in the first component. Higher order components were typically loaded on only one or two series, suggesting that they record local non-climatic growth factors. Ring-width series that were not highly loaded on the first two components were removed from the standard tree-ring chronology (Enright, 1984).

The information extracted from a PCA has been used as an alternative to develop tree-ring chronologies. Jacoby and Cook (1981) and Enright (1984) found that the results obtained from the PCA are similar to those obtained using standard tree-ring methods described by Fritts (1976). In this study, the principal component scores obtained from the PCA were used to evaluate similarities in ring-width variance within a site and to guide the chronology development.

2.4.2 STANDARDIZATION

In order to obtain a tree-ring chronology, individual ring-width series were standardized so that growth trends and other non-climatic factors (growth suppression and/or release periods) are removed while maintaining the long-term climate trend. Standardization was used on series to transform ring-width series into dimensionless tree-ring indices with an arbitrary mean of 1.00. These indices are computed by dividing each measured ring-width by the transformed ring-width value after standardization. The ring-width indices are then averaged to produce a chronology (Cook *et al.*, 1992).

In this study, five methods of detrending were needed to remove growth effects: linear regression and negative exponential detrending, a horizontal trend line, a linear regression of negative slope, and a cubic smoothing spline. The linear regression detrending method fits a least squares regression line through the data. The negative exponential curve is designed to remove the decreasing growth response, where large rings develop early in the life of the tree and thinner rings as the tree ages. A horizontal line simply removes the series mean, and therefore does not remove any growth trends. The cubic smoothing spline fits a series of cubic polynomial curves to successive sections of the data. This method of detrending is flexible and can be adjusted to properly fit each ring-width series (Cook and Peters, 1981; Grissino-Mayer *et al.*, 1992). This method is needed if there are medium-frequency changes in the ring-width series, such as periods of reaction wood and/or release due to competition. Spline stiffness was selected by subjectively fitting splines of 5, 10, 25 and 50 years with a 50 percent frequency-response until most non-climatic trends were eliminated. The 50 percent frequency-response cutoff is where 50 percent of the amplitude of a signal is removed. All standardization was performed using the program ARSTAN.

For the Bear Creek forest-tundra chronology, a 25-year cubic smoothing spline was needed for the three longest series to remove the growth effects resulting from high concentrations of reaction wood. Most sections with large amounts of reaction wood were not used, however some were retained in order to obtain a longer record. This low-pass digital filter was used on these older series because it provided the most appropriate natural fit and eliminated medium-frequency growth trends obviously due to reaction wood, while maintaining a strong climatic signal. The remaining series were standardized with a linear regression, a negative exponential curve or a horizontal line. The ring-width series obtained from the *Picea glauca* trees in the Bear Creek forest, Tatshenshini forest and Tatshenshini forest-tundra quadrats were fitted with a negative exponential curve, a linear regression line of negative slope or, if they were not needed, a horizontal line (Table 2). A plot of the raw ring-widths and results obtained from the PCA illustrate the nature of the ring-width curves, and thus were useful in ascertaining the appropriate curve for growth trend removal. The plotted raw ring-widths and the PCA results are presented in Appendix C and D.

Following standardization, the program ARSTAN computes three chronology versions: the 'RESID' (residual), the 'STNDRD' (standard) and the 'ARSTAN' (arstan). Only the 'STNDRD' and 'ARSTAN' versions will be discussed further. The 'STNDRD' version of the chronology is developed by computing means for each year as the biweight robust mean (computed mean which reduces the variance and bias caused by outliers) and does not incorporate any autoregressive modeling, unlike the 'ARSTAN' version of the chronology, which is computed from autoregressive modeling of detrended series (Grissino-Mayer *et al.*, 1992). The percentage of variance due to autoregression and the error variance was reduced in the chronology by autoregressive modeling (Table 3). For this reason, the 'ARSTAN' version of the chronology was selected for all four chronologies and used for further analysis.

Once the chronologies have been developed, the synchronicity of tree growth throughout the region can be tested. Correlations between the four chronologies developed in this study (BeFT, BeF, TATFT, TATF) as well as three chronologies obtained from the ITRDB (International Tree-Ring Data Bank) were computed. The correlation coefficients obtained will determine whether the forest-tundra and forest growth patterns are similar, and whether the region is responding to a large-scale climate signal.

2.5 CLIMATE-TREE GROWTH RELATIONSHIP

A correlation analysis between tree-ring chronologies and climate data was performed to determine the relationship between tree growth and climate. The two *Picea glauca* forest and forest-tundra tree-ring chronologies from Bear Creek were related to temperature and precipitation records to illustrate potential climate effects on tree growth in the area. The analysis was restricted to a common period where both climate records and ring-widths were available. Mean monthly temperature and total monthly precipitation for the current and the previous growing season were used in the analysis. The climate data (temperature: 1945-1995; precipitation: 1945-1982) used comes from the Haines Junction weather station located at 596 m a.s.l. available from the Meteorological Service of Canada. The precipitation data series was truncated because of excessive missing values. The Tatshenshini chronologies were not used in this analysis because of the lack of climate records in close proximity to the site.

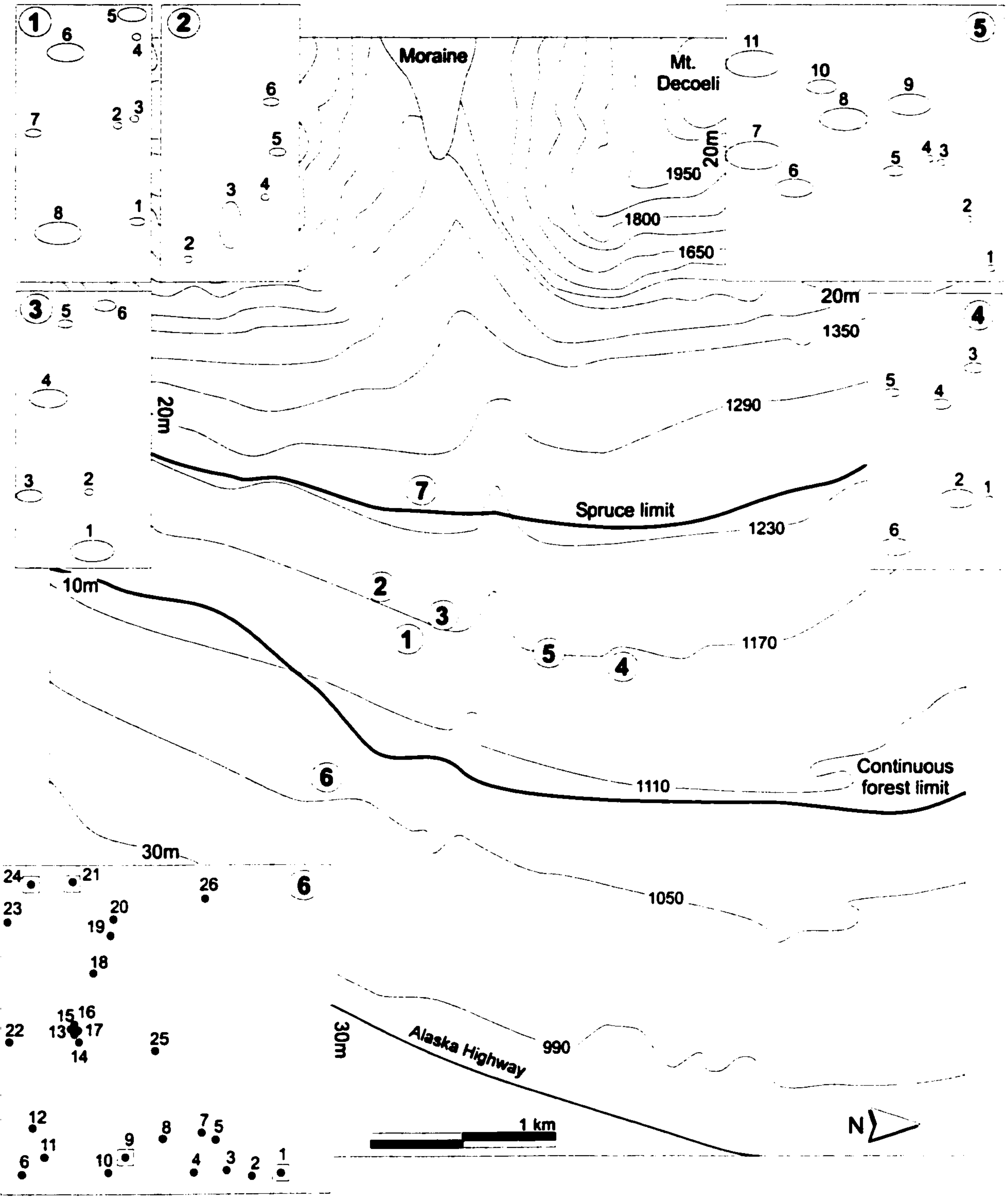

Figure 7 Location of the seven quadrats at Bear Creek (60°50'N, 137°49'W), southwest Yukon Territory. Quadrats 1,2,3,4,5 are located in the forest-tundra, quadrat 6 is located in the forest, and quadrat 7 in the tundra. The distribution of *Picea glauca* individuals sampled in each quadrat are presented in the inset quadrats, with the location corresponding to the circled numbers on the map. The squares around the dots in the forest quadrat represent beetle-killed trees. Contour intervals are in meters.

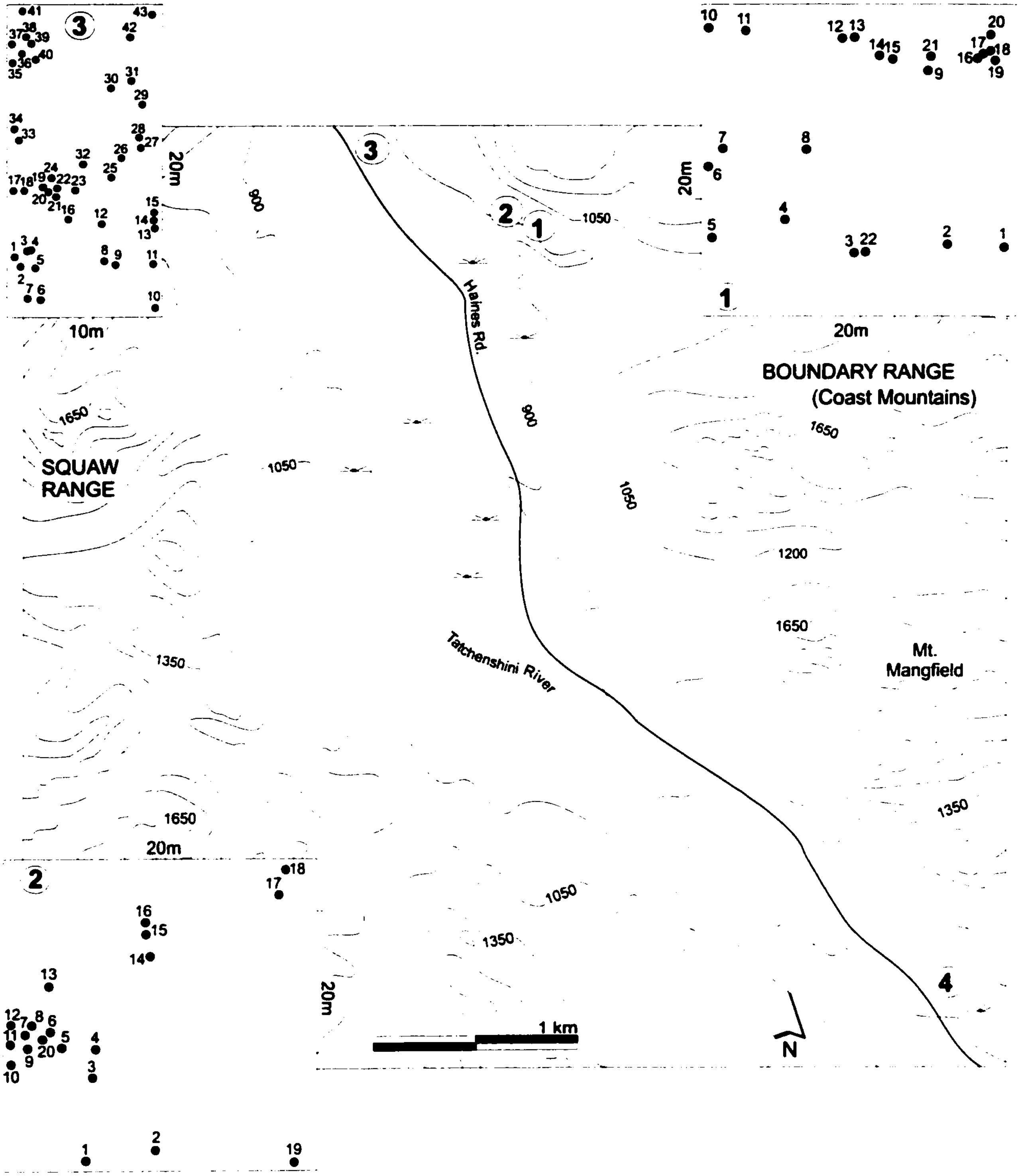

Figure 8 Location of the four quadrats at the Tatshenshini site (59°52'N, 136°41'W - 59°56'N, 136°48'W), northwestern British Columbia. Quadrat 1 and 2 are located in the forest-tundra, quadrat 3 is located in the forest, and quadrat 4 in the tundra. The distribution of *Picea glauca* individuals sampled in each quadrat are presented in the inset quadrats, with the location corresponding to the circled numbers on the map. Contour intervals are in meters.

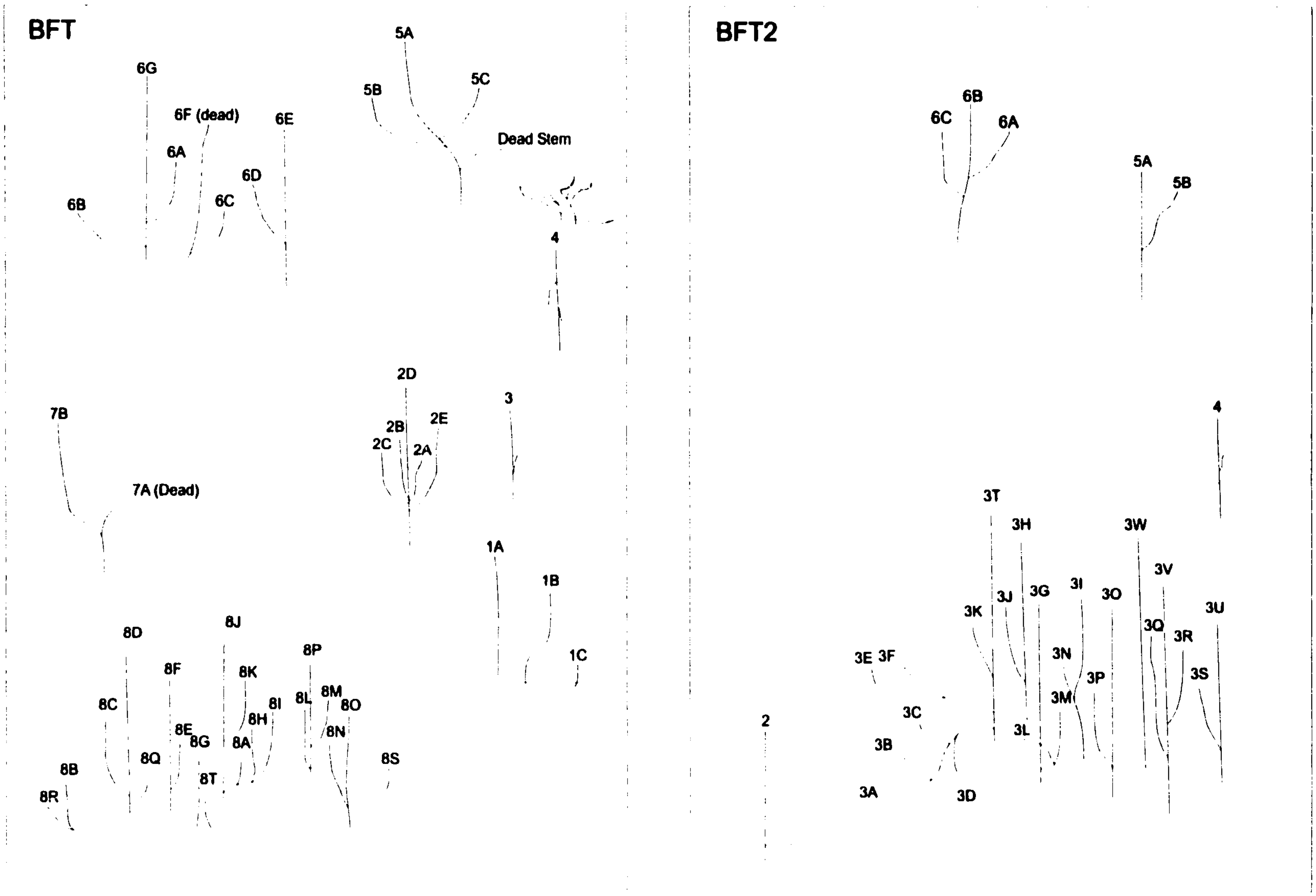

Figure 9a *Picea glauca* krummholz structure and distribution within quadrats 1and 2 located in the forest-tundra ecotone at Bear Creek, southwest Yukon Territory.

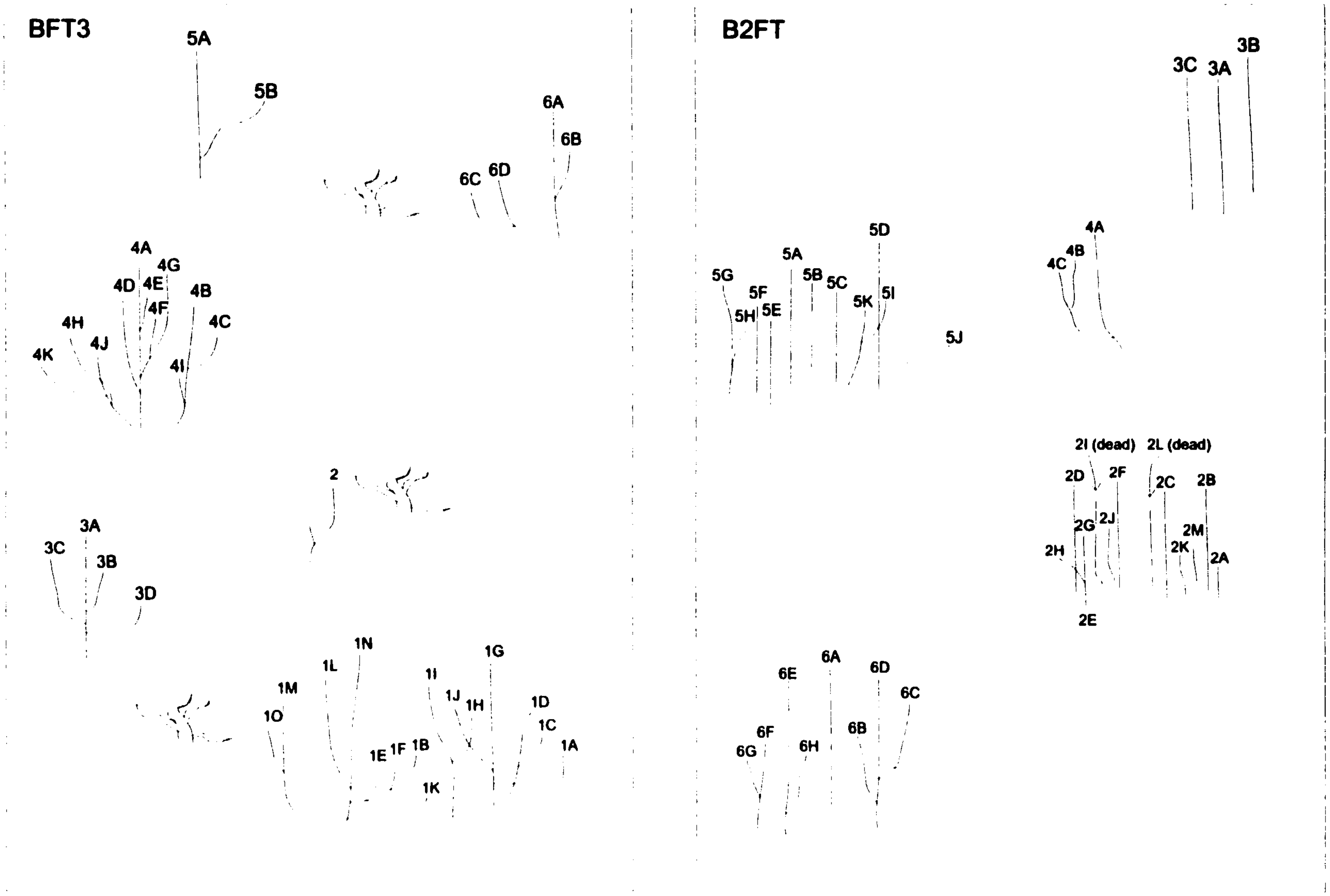

Figure 9b *Picea glauca* krummholz structure and distribution within quadrats 3 and 4 located in the forest-tundra ecotone at Bear Creek, southwest Yukon Territory.

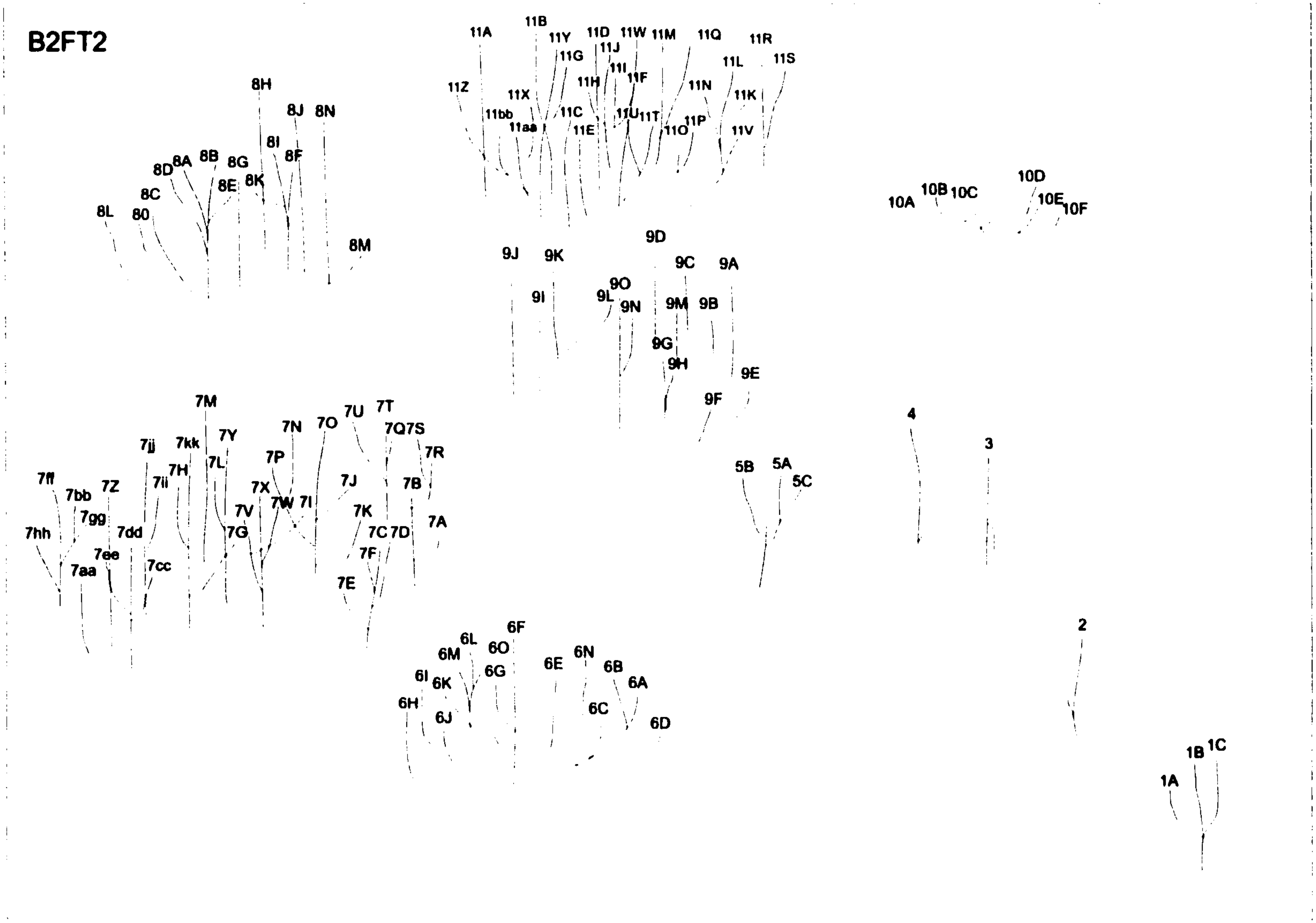

Figure 9c *Picea glauca* krummholz structure and distribution within quadrat 5 located in the forest-tundra ecotone at Bear Creek, southwest Yukon Territory.

Table 2 Detrending methods applied to each individual ring-width series included in the four chronologies.

	Dentrending methods					
Sampling site	Linear regression	Horizontal line	Neg. exponential	Linear regression of neg. slope	25-yr smoothing spline	Total no. of series
BeF		34		7		41
BeFT	24	8	5		3	40
TATF		28	1	8		37
TATFT		30	4	7		41

Table 3 Chronology statistics for the Arstan and Standard versions of the chronology obtained from the program ARSTAN.

	Variance due to autoregression (%)		Error variance	
Chronology code	Standard	Arstan	Standard	Arstan
BeF	74.0	63.5	0.01	0.01
BeFT	44.2	39.4	0.01	0.01
TATF	77.0	73.2	0.01	0.01
TATFT	72.2	59.9	0.27	0.24

CHAPTER 3

WHITE SPRUCE DYNAMICS IN THE FOREST-TUNDRA ECOTONE, SOUTHWEST YUKON TERRITORY

3.1 ABSTRACT

Dendrochronological techniques were used to study white spruce (*Picea glauca* [Moech] Voss) dynamics in the altitudinal forest-tundra ecotone in the southwest Yukon Territory. At two sampling sites, all *Picea glauca* individuals within 9 delineated quadrats in the forest-tundra and forest were sampled to estimate dates of establishment and growth patterns using tree-ring chronologies. Regeneration in the forest-tundra ecotone was low from the late 1800s to the mid-1900s, however has increased since the 1920s. Recent peak periods of establishment parallel increased radial growth trends, which may have resulted from the long-term warming trend of the 20th century. Seedling proximity to pre-established individuals in the forest-tundra ecotone suggests regeneration from a local seed source. Vertical growth above snow level accelerated around the 1950s. Tree growth in the forest-tundra and forest appears to be influenced by summer temperatures of the current growing season. A high degree of similarity in tree growth at different sites in the southwest Yukon suggests a regional response to a large-climate variability. An increase in krummholz height and improved seedling establishment in the forest-tundra ecotone could result in a shift from krummholz to symmetrical trees and/or from patch forest to forest.

3.2 INTRODUCTION

Over the last 150 years, the Arctic has substantially warmed by approximately 1.5°C (Bradley and Jones, 1983; Overpeck *et al.*, 1997). Increasing concentrations of greenhouse gases in the atmosphere have resulted in unusually warm conditions after the 1920s, and further warming is expected to be more pronounced at higher latitudes (Bradley and Jones, 1983). These climatic changes have significant impacts on arctic ecosystems, hence it is important to understand tree response in subarctic regions with respect to past and present climate variations (Payette *et al.*, 1985).

Trees at the latitudinal and altitudinal treeline grow at the limits of their ecological tolerance, and are therefore extremely sensitive to climate change (Fritts, 1976). Treeline responses to the 20th century warming are expressed through minor treeline displacements and/or increased tree population densities at treeline sites in Canada (Hansell *et al.*, 1971; Payette and Filion, 1985; Szeicz and MacDonald, 1995a), the United States (Garfinkel and Brubaker, 1980; Suarez *et al.*, 1999), Sweden (Kullman, 1986) and Russia (Gorchakovsky and Shiyatov, 1978).

Latitudinal treeline coincides with the mean summer position of the Arctic front (Bryson, 1966). On the other hand, altitudinal treeline is controlled by temperature and precipitation, in addition to other factors. Local variations in snow depth and duration, as well as wind also shape the physiognomy of treeline areas (Tranquillini, 1979). The depth and snowpacks is affected by wind, local topography and tree islands themselves, which protect tree individuals from snow and particle abrasion above snow level. Deeper snowpacks in the forest-tundra ecotone reduce the amount of stem degradation, however its persistence throughout the growing season may limit tree establishment (Billings, 1969).

While regeneration at treeline is extremely sensitive to climate change, varying growth forms can also provide important information on the response of treeline to climate. For example, Bégin (1991), Lavoie and Payette (1992), Payette and Delwaide (1994), Payette *et al.* (1994), Payette *et al.* (1996), and Pereg and Payette (1998) have documented changes in krummholz growth forms at treeline since the end of the Little Ice Age [ca. 1580-1880]. The phenotypic plasticity of *Picea* spp. enables the tree individual to adapt to harsh winter conditions and increases its survival and longevity (Payette *et al.*, 1994). Since the end of the Little Ice Age, winters have been milder and snowier, consequently providing favorable conditions encouraging supranival stem growth. For instance, in northern Québec, Payette and Delwaide (1994) detected an increase in vertical growth since the 1930s. Stem analysis indicated slow horizontal growth (layering) during the 19th century, and a relatively rapid increase in vertical growth since the 1930s. Additional studies in Sweden (Kullman, 1986, 1990), the United States (Earle, 1993, Hessl, 1996) and Canada (Lavoie and Payette, 1992; Pereg and Payette, 1998) have recorded similar findings of supranival stem growth since the end of the 19th century.

The purpose of this study is to determine if the 20th century climate warming resulted in an increase in *Picea glauca* seedling establishment and/or changes in growth form at treeline areas in the southwest Yukon Territory. This was accomplished by conducting a dendrochronological study at two treeline sites by analyzing age structures, growth forms and by developing tree-ring chronologies from *Picea glauca* krummholz and tree individuals. The chronologies developed in this study will be compared with other chronologies from the southwest Yukon. This region is particularly important, as it is a relatively dry area of the boreal forest, and may provide analogues for other areas experiencing climate warming.

3.3 STUDY AREA

Dendrochronological studies were conducted at two treeline sites approximately 150 km apart (Figure 1, Table 1). The northern study site, Bear Creek, located in the southwest Yukon Territory was sampled in more detail. The second site, Tatshenshini, in northwestern British Columbia was studied for comparison.

Bear Creek lies on a gentle northeast-facing slope of the St. Elias Mountains (60°51'N, 137°49'W) adjacent to the Shakwak Trench. Located approximately 10 km west of Haines Junction, Bear Creek is close to the Haines Junction weather station at 596 m a.s.l. The mean annual temperature is –2.7°C, the mean summer (June-August) temperature is 11.3°C, and the mean winter (December-February) temperature is –18.4°C. This region is subject to cold Arctic and mild Pacific air masses resulting in a rapid change from season to season (Wahl *et al.*, 1987). The study site is located in the rain shadow of the St. Elias Mountains, and is therefore arid with a total annual precipitation of approximately 300 mm. About 50 percent of the precipitation falls as snow. Bear Creek was divided into four zones: tundra, krummholz, patch forest and continuous forest (Figure 4). The tundra zone is comprised of herbaceous plants and low-lying shrubs such as willows (*Salix* spp.) and dwarf birch (*Betula glandulosa* [Michx]). The forest-tundra ecotone, which includes the krummholz zone in the uppermost part and the patch forest in the lowermost part, is comprised of herbaceous plants, *Salix* spp. and *Betula glandulosa* with isolated *Picea glauca* krummholz in the krummholz zone and scattered symmetrical trees in the patch forest. In the continuous forest, the trees form a continuous but relatively open canopy of symmetrical trees. *Picea glauca* is the dominant species at this site and forms the local altitudinal treeline at a mean altitude of 1120 m a.s.l. Black spruce (*Picea mariana* [Mill.] B.S.P.) is not present at Bear Creek. The forest-tundra has not been influenced by anthropogenic disturbances and the absence of charred stumps and charcoal in the soil suggests that this particular treeline site has not been recently burned.

The northwestern British Columbia study site is located in the Tatshenshini region along the Haines Road near the Yukon/British Columbia provincial border (59°52'N, 136°41'W - 59°56'N, 136°48'W). The site is flat to moderately inclined and the soil is extremely moist. The dominant species is again *Picea glauca* and forms the mean altitudinal treeline at 920 m a.s.l. The forest-tundra ecotone consists of low-lying shrubs, such as *Salix* spp. and *Betula glandulosa*, herbaceous plants and mosses.

3.4 METHODOLOGY

3.4.1 SAMPLING DESIGN

Dendrochronological studies were conducted at two treeline sites, Bear Creek and Tatshenshini, to obtain the data needed to assess alpine vegetation dynamics in the southwest Yukon Territory. A total of 11 quadrats were delineated in the tundra, forest-tundra and forest at both sites. The quadrats ranged in size from 200 m^2 to 900 m^2 depending on tree density. The forest quadrats were placed in a typical open canopy stand where competition among trees is apparently minimal. To determine the age of all *Picea glauca* individuals with a circumference greater than 20 cm in each quadrat, two cores were extracted to allow for the interpretation of variance among and within trees (Fritts, 1976). Each core was taken at right-angles to the other at the base using a Swedish increment borer until the pith was reached (Stokes and Smiley, 1968). Extracting two cores per tree allows for the interpretation of variance among and within trees (Fritts, 1976). All remaining *Picea glauca* individuals in the quadrat, including seedlings (<2 m), were sawn off at the base to determine the age.

Dendrochronological studies of stunted *Picea glauca* individuals in the Bear Creek forest-tundra required a different sampling design. Due to the complex morphology of these individuals, each krummholz was dissected in three phases. First, supranival stems were sawn off at the apparent snow level to determine the timing of release of the stems above snow level. Cross-sections were then collected at the multi-stem level to determine lateral stem development frequencies. Finally, cross-sections were cut as close to the base as possible. This provided an approximate age of establishment of the individual. The asymmetric growth of the stems collected at the base and the multi-stem level generated high concentrations of reaction wood as well as numerous locally absent rings. By collecting cross-sections instead of cores, dating and measurement errors resulting from these discrepancies were minimized. The height and growth form of all sampled krummholz was noted.

Characteristics of the forest-tundra ecotone at Bear Creek were determined by recording the altitude of all seedlings, krummholz, subfossils and snags, and trees encountered along four line transects from the tundra to the forest. Three to four people walked along these transects and noted all spruce encountered in a 10 m swath. The altitude of each individual was noted using a GPS (Global Positioning System) and all seedlings were cut off at the base and dated.

At both sites, vegetation cover was studied in three randomly placed 1 m^2 quadrats located within each delineated quadrat in the forest, forest-tundra and tundra. Evidence of fire such as charcoal in the soil and/or charred stumps was noted. Evidence of regeneration and mortality (subfossils) in the tundra were also noted to assess past and present species limit positions.

3.4.2 CHRONOLOGY DEVELOPMENT

Cores and cross-sections were mounted, sanded and cross-dated following the techniques outlined in Stokes and Smiley (1968). The ring-widths were measured to the nearest 0.001 mm using a stereomicroscope at 40x magnification and an ACU-RITE glass scale linear encoder connected to a digital measuring device Quick-Check (QC-1000). Cross-dating was verified using the computer program COFECHA (Grissino-Mayer *et al.*, 1992). For samples containing high concentrations of reaction wood, ring-width measurements were taken along a radius excluding reaction wood. Samples where the direction of the reaction wood changed throughout the cross-section were rejected from the chronology, however used for computing age-structure histograms.

Before developing a tree-ring chronology, a principal components analysis (PCA) was used to determine which trees are highly correlated and therefore contain the large-scale climate signal. The selected ring-width series from both sites were then used to develop tree-ring chronologies. Standardization was used on the series to transform ring-width series into dimensionless tree-ring indices with an arbitrary mean of 1.00. These indices were computed by dividing each measured ring-width by the transformed ring-width value after standardization. The ring-width indices were then averaged to produce a chronology (Cook *et al.*, 1992). Ring-width series were standardized by fitting one of five detrending methods: a linear regression, a negative exponential curve, a horizontal trend line, a linear regression of negative slope, or a 25-year cubic smoothing spline using the program ARSTAN (Cook, 1985; Grissino-Mayer *et al.*, 1992). The choice of detrending methods, which removes growth related factors, was determined by inspection of chronology output statistics and graphs of the raw ring-width data.

3.4.3 AGE-STRUCTURE ANALYSIS

Once the cores were successfully cross-dated, age-structure histograms were generated from the data. A 10-year age class interval was used to account for the differences between the true age of the stem and the age at sampling height (Payette *et al.*, 1985). Samples that could not be cross-dated and those with pith rot were not included in the age structures.

3.4.4 CLIMATE-TREE GROWTH RELATIONSHIP

The correlations between tree-ring chronologies and climate data were computed to determine the relationship between tree growth and climate. The two *Picea glauca* forest and forest-tundra tree-ring chronologies from Bear Creek were correlated with temperature and precipitation records to illustrate potential climate effects on tree growth in the area. Mean monthly temperature and total monthly precipitation for the current growth year and the previous year were used in the analysis. The climate data (temperature: 1945-1995; precipitation: 1945-1982) used comes from the Haines Junction weather station and is available from the Meteorological Service of Canada. The precipitation data series was truncated because of excessive missing values. The Tatshenshini chronologies were not used in this analysis because of the lack of climate records in close proximity to the site.

3.5 RESULTS

3.5.1 CHARACTERISTICS OF THE FOREST-TUNDRA ECOTONE

At Bear Creek, the spruce limit is located at 1255 m, the krummholz zone spreads from 1125 m to 1255 m in the forest-tundra ecotone, the mean altitudinal treeline (forest limit) is at 1120 m, and the limit of continuous forest is located at 1105 m (Figure 12). The ecological zonation in this region is comparable to that described by Payette (1983), with minor differences related to the location of the forest limit and treeline. At Bear Creek, the forest limit and the altitudinal treeline are the same, and both limits are located slightly beyond the continuous forest limit where patches of symmetrical trees (>5 m) are present. A dense band of tall *Salix* spp. and a small number of spruce tree indidividuals explains the lack of regeneration between 1120 m and 1140 m. Seedlings tend to establish in favorable microenvironments provided by krummholz patches and in shrub openings in the patch forest. Seedlings and subfossils were observed throughout the forest-tundra ecotone, however were absent in the tundra. The ground cover throughout the tundra and forest-tundra includes bog bilberry and mountain cranberry (*Vaccinium* spp.), mountain heather (*Phyllodoce* spp.), *Salix* spp., *Betula glandulosa*, mosses and many herbaceous plants (Appendix A).

3.5.2 *PICEA GLAUCA* GROWTH FORMS

Picea glauca individuals in the Bear Creek forest-tundra have undergone numerous morphological changes during the 20th century. Particle abrasion above the snow level has shaped exposed tree individuals within the forest-tundra ecotone (Figure 10). Canopy height (*Salix* and *Betula glandulosa* shrubs) and the spatial distribution of *Picea glauca* individuals influence tree exposure, and therefore shape and alter tree growth forms. As a result, mat, infranival cushion (Figure 11), supranival skirted, and whorled growth forms (Lavoie and Payette, 1992) are all present throughout the forest-tundra ecotone at Bear Creek. The mat and infranival cushion growth forms are located where exposure is at a maximum. The supranival skirted and whorled growth forms were most often observed in depressions where *Salix* stands reached heights of 2 m and where higher densities of spruce were located. Krummholz growth forms are also affected by elevation. Krummholz height at lower elevations ranged from 2 m to 6m and those closest to the tundra ranged from 0.5 m to 1 m. Height, however, is not necessarily positively correlated with age. For example, two krummholz individuals sampled outside of the delineated quadrats, reaching heights of approximately 0.5 m to 1 m, had established in 1819 and 1875.

The forest-tundra, at the Tatshenshini site, is also dominated by dense *Salix* and *Betula glandulosa* stands. Similar to the Bear Creek forest-tundra, seedlings, snags and fallen logs were noted in the Tatshenshini forest-tundra, however not in the tundra. The mean altitudinal treeline at this location is at 920 m a.s.l. There was no evidence of fire at either sampling site.

3.5.3 AGE-STRUCTURE ANALYSIS OF *PICEA GLAUCA* IN THE FOREST-TUNDRA ECOTONE

The ages of all trees sampled in the quadrats in the forest and forest-tundra at the Bear Creek and Tatshenshini sites were aggregated into 10-year age classes. The Bear Creek forest-tundra age-structure histogram (Figure 13) suggests an extended period of lateral stem growth and reproduction by layering throughout the last 250 years during which sexual reproduction was at a minimum. Diminished layering and lateral stem growth since the 1940s was compensated by an increase in supranival stem growth. Vertical stem growth above the snow level began in the 1950s, and reached a maximum in the 1970s. Due to the difficulty of reaching the base of most krummholz individuals, few tree establishment dates are available, and only the single-stemmed krummholz bases could be dated. These individuals began to establish in the 1920s along with an increase in lateral and supranival stem growth around 1910. Individual krummholz age-structure histograms grouped by quadrat show the growth patterns of each *Picea glauca* individual sampled in the forest-tundra ecotone (Figures 14 a,b,c,d,e). Most krummholz show irregular but continuous layering and lateral stem growth, and a more recent peak in vertical stem growth. Successful seedling establishment from 1970-1980 appears to parallel increased vertical stem growth in the last few decades (Figure 13). Seedlings tend to establish in openings with fewer *Salix* populations and in close proximity to pre-established tree individuals. *Picea glauca* krummholz in the forest-tundra ecotone at Bear Creek have been producing cones, however appear to have no seeds.

The Bear Creek forest age structure shows improved regeneration in the 20th century (Figure 13). Of course, the reliability of the curve decreases back through time, as individuals may have established and died during the last few centuries. The earliest date of establishment recorded was in 1810 from a tree in the forest, which had been killed by a spruce bark beetle (Dendroctonus rufipennis [Kirby]) attack in the early 1990s. The 1980-1990s peak in seedling establishment suggests a positive response to the recent climatic warming trend.

Both age-structure histograms for *Picea glauca* at the Tatshenshini forest and forest-tundra quadrats demonstrate similar age structures (Figure 15). The oldest date of establishment in the forest was 1850 and the forest-tundra 1880. The forest-tundra histogram shows a similar increase in successful establishment from the 1900s to the 1920s and a second peak in the 1980s. Regeneration in the forest has been continuous in the last 150 years with a significant peak in the 1920s. The peak in successful regeneration in the forest appears to lag the forest-tundra by a decade. The trees at this site are producing cones, and the establishment throughout the last 100 years attests to the viability of seeds. Seedling establishment in the forest-tundra ecotone has increased since the 1970s.

3.5.4 TREE-RING CHRONOLOGIES

A total of 64 and 85 *Picea glauca* trees were sampled at the Bear Creek and Tatshenshini study sites. Approximately 90 percent of the samples were successfully cross-dated and 54 trees from each site were used to develop four chronologies. Trees included in the chronology were successfully cross-dated and had a minimum concentration of reaction wood. The standard deviation, first-order autocorrelation, mean correlation between trees, and variance in the first eigenvalue are higher in the forest chronologies (Table 4). The first principal component for the forest sites accounted for approximately 40 percent of the variance, indicating a strong common growth variation among the trees. The BeFT chronology has the lowest mean ring-width (0.55 mm), standard deviation (0.20), first-order autocorrelation (0.64), mean correlation between trees (0.135), and variance in the first eigenvalue (21%). This suggests that the sampled *Picea glauca* krummholz have a weaker common signal, perhaps due to reaction wood. There is no significant difference between the chronology statistics from Bear Creek and Tatshenshini.

The four tree-ring chronologies developed from the Bear Creek and Tatshenshini sites show comparable growth trends suggesting that a similar climate is affecting tree growth at both sites (Figure 16). Periods of diminished radial growth in the 1930s and 1970s, and a peak from 1943 to 1953 are depicted in the chronologies. However, the 1940s peak is most pronounced in the Tatshenshini forest chronology and the reduction in growth in the 1930s is less noticeable in the Bear Creek forest-tundra chronology. It must be noted that all chronologies are more reliable in more recent decades because of the diminishing number of samples through time. The Bear Creek forest-tundra chronology shows a weaker climate signal perhaps due to the stressed nature of the *Picea glauca* krummholz individuals and/or the abundance of reaction wood in the samples, resulting in reduced ring-width variability. Bégin (1991) found that a climate signal in krummholz growth is less pronounced, because the effect of climate on low-frequency variations in the ring-width series appears biased due to variations in the trees morphological structure.

Results from the principal components analysis used to evaluate the similarity among trees from each chronology are presented in Appendix C. The first principal component accounted for up to 42 percent of the total variance (BeF), and the second component accounted for up to 24 percent (TATFT). The loadings and scores from this analysis are presented in Appendix C. A high common variance and similarity in the time series of the scores suggest that the trees are responding to a similar climate signal.

Correlations between the four chronologies developed in this study and three obtained from the ITRDB from the southwest Yukon range from 0.02 to 0.81 (Table 5). Significant correlations exist between the forest and forest-tundra chronologies at the Bear Creek and Tatshenshini sites, however this correlation is higher at the Tatshenshini site (r = 0.81). Significant correlations exist between the forest and forest-tundra chronologies at both the Bear Creek and Tatshenshini sites. Chronologies from nearby locations, however, are not necessarily highly correlated. For instance, the Kathleen Lake chronology is poorly correlated with both Tatshenshini chronologies (r = 0.10, r = 0.03), however it is well-correlated with three chronologies located further north (Haines Junction, Bear Creek forest-tundra and Christmas Creek). Diminished correlations can be the result of local site conditions or local disturbances, for example a spruce bark beetle outbreak. The significance of correlations may also depend on altitude and location, where temperature or other climatic factors can be limiting.

3.5.5 CLIMATE –TREE GROWTH RESPONSE

Overall, temperature appears to influence tree growth at Bear Creek more than precipitation (Figure 17), although this may be due to the lower variance of the temperature data. The correlation coefficients from the forest-tundra and forest show similar trends regardless of altitudinal position. Tree growth in the forest-tundra and forest at Bear Creek are most highly correlated with the current spring and summer temperature conditions. There is also a negative relationship between previous summer temperatures and tree growth. March precipitation of the current year and September precipitation of the current and previous year are significantly correlated with tree growth, and there is a slight correlation with winter conditions as well. The correlation coefficients for the current growing season show a weak correlation between precipitation and tree growth. Significant positive correlations, however, do exist with the previous winter, suggesting the importance of snow on tree growth.

3.6 DISCUSSION

Dendrochronological investigations at Bear Creek show minimal *Picea glauca* regeneration and continuous layering and stem development during the 19th century. The development of the lateral stems is significant, as these can cause reproduction through the development of new individuals by layering. Since the 1920s, there has been increased regeneration throughout the forest-tundra ecotone. High seedling densities tend to occur in krummholz patches and openings in the *Salix* cover. Peak periods of recruitment and increases in krummholz height appear to be associated with the recent warming trend registered by the four tree-ring chronologies developed in this study. The growth patterns among the chronologies developed in this study and those obtained from the International Tree-Ring Data Bank (ITRDB) are similar, suggesting a large-scale climate influence on tree growth across the entire region.

The presence of spruce krummholz individuals throughout the forest-tundra at Bear Creek suggests that temperature, along with other environmental conditions, limit tree growth at higher altitudes. To test whether *Picea glauca* regeneration is climate-driven, periods of increased regeneration should be compared with climate records. However, since there are no long climate records available in the southwest Yukon, tree-ring chronologies may be used as proxies for meteorological data. The BeFT age-class histogram (Figure 13) shows continuous lateral stem growth and reproduction through layering in recent centuries. The absence of successful regeneration in the forest-tundra ecotone during the late 1800s to the mid-1900s corresponds to a period of decreased tree growth and/or perhaps to the lack of dated krummholz bases, which had established at this time. The apparent gap in regeneration may also be due to subsequent tree mortality. However, the absence of extensive snags and subfossils on the ground would tend to argue against significant mortality in the recent past. During this cool period of limited sexual reproduction, spruce trees were able to maintain their population by lateral stem development and layering. These findings are consistent with other studies, reporting diminished regeneration during the Little Ice Age (Payette *et al.*, 1985; Szeicz and MacDonald, 1995a). Further tree responses to climate variations such as the Little Ice Age have been recorded in Holocene glacial and treeline fluctuations throughout the southwest Yukon Territory (Denton and Karlén, 1997).

Increased global mean temperatures since the beginning of the 20th century have provided favorable conditions leading to an increase in *Picea glauca* regeneration in the forest-tundra in northern Québec (Payette and Filion, 1985) and in northwestern Canada (Szeicz and MacDonald, 1995a). The age structures from the forest and the forest-tundra at Bear Creek (Figure 13) show similar evidence of an increase in regeneration that corresponds with the unusually warm conditions between 1920 and 1940. The subsequent cooling that lasted until the 1970s (Bradley and Jones, 1983; Findlay *et al.*, 1994) resulted in a decrease in seedling establishment, however warming conditions until the present have lead to an increase in regeneration. Scott *et al.* (1987a) and Payette and Filion (1985) documented a similar positive regeneration response during the 1920s, and seedling establishment since the 1970s also occurred at other treeline sites in Alaska (Suarez *et al.*, 1999). In northwestern Canada, Szeicz and MacDonald (1995a) observed an increase in regeneration since the 1970s in the Northwest Territories, however seedling establishment decreased in the last 40 years in the northern Yukon. This may be due to local physical and environmental factors.

Most climate-tree growth analyzes in northern Canada suggest that summer temperature is the main climatic control on tree growth (Jacoby *et al.*, 1988; Szeicz and MacDonald, 1995b). At Bear Creek, the correlation coefficients between climate and tree growth indicate generally higher correlations between temperature and tree growth than with precipitation. The low precipitation correlation coefficients may be due to the short duration (37 years) of the precipitation data, and site-to-site variability of precipitation in alpine regions. Thus, it is possible that precipitation is more important than the correlations might indicate. At Bear Creek, tree growth is highly correlated with spring and summer temperatures of the current growth year (Figure 17). There is also a negative relationship between tree growth and summer temperatures of the previous year. These findings are consistent with other studies in northwestern Canada and Alaska (Garfinkel and Brubaker, 1980; Szeicz and MacDonald, 1994, 1995b), which detected a strong relationship between tree growth and current summer temperatures, and a negative relationship with previous summer temperatures.

Significant relationships between tree growth and precipitation are present during certain months (September and May), however correlations do not follow a seasonal trend (Figure 17). It should be noted that the reliability of correlation coefficient interpretations is reduced because of the inability to separate correlations among the different months from those with the ring-widths. For instance, if July temperatures are highly correlated with January temperatures, both months will be correlated with tree growth although only one of the months may be truly impacting tree growth.

A long-term increase in radial growth is seen in the forest and forest-tundra chronologies from Bear Creek (Figure 16). Other tree-ring chronologies developed in northwestern Canada show similar trends. For instance, most chronologies described in Watson *et al.* (2000) from the southwest Yukon and northern British Columbia, and those obtained from the ITRDB (i.e. Haines Junction, Kathleen Lake, and Christmas Creek) in this region show similar growth trends associated with the 1900s to the 1940s warming, the cooling until the 1970s and the warming to the 1990s (Findlay *et al.*, 1994). This large-scale signal must be associated with climate, as chronologies in differing local microenvironments across a large-scale area show a similar signal. In the northern Yukon, *Picea glauca* tree-ring chronologies developed by Szeicz and MacDonald (1995b) do not show increased tree growth in recent decades, and may therefore be responding to a different regional climate.

Contrary to what one may expect, annual growth and regeneration trends in the forest-tundra and the forest at Bear Creek depict similar patterns. This is puzzling, since the presence of an open krummholz-dominated forest-tundra implies a different climate from that of a continuous forest. Perhaps the altitudinal range considered in this study was not wide enough to detect significant differences. Although the short-term variability may be coherent, the general climate is cooler at higher altitudes and this must be affecting the form and density of *Picea glauca* individuals across the landscape. Thus, the mean climate determines the overall structure of these ecosystems, and the reproductive success depends on higher-frequency variability. These results are consistent with other studies on Norway spruce (*Picea abies* [L.] Karst.) in central Finland (Mäkinen *et al.*, 2000). The high degree of similarity in tree growth at the different sites in the southwest Yukon and northern British Columbia suggests a response to a large-scale climate signal (Table 5). For example, the two furthest chronologies (TATFT and CC) are significantly correlated (0.51), demonstrating a large-scale coherence in growth over this diverse region.

Temperature is a key controlling factor on tree growth and regeneration at treeline sites, however other ecological factors affected by temperature can also be important determinants for successful seedling establishment. A deep and stable snow cover (Hessl, 1996; Kullman, 1986) and soil moisture (Weisberg and Baker, 1995) have been associated with increased seedling establishment at numerous treeline sites. In Rocky Mountain National Park, Hessl (1996) detected a strong relationship between seedling establishment and a deep snow cover. High snow depths enhance soil moisture in the subsequent growing season, therefore allowing establishment to occur. On the other hand, deeper snow may lead to a shorter growing season, which could inhibit establishment. Insufficient precipitation data has made it impossible to determine exactly which of these factors has contributed to an increase in seedling establishment in the Bear Creek forest-tundra ecotone.

Additional factors which may have affected regeneration in the forest-tundra ecotone at Bear Creek include *Picea glauca* productivity and vegetation cover. Recent increases in regeneration throughout the forest-tundra ecotone at this site suggest that *Picea glauca* individuals have been productive, with energy available for reproduction as well as growth. Seedlings are frequently found in proximity to pre-established tree individuals suggesting that establishment has been initiated by nearby cone-bearing krummholz individuals (Figure 12). It is highly improbable that long-distance seed dispersal stimulated regeneration in the forest-tundra ecotone because of the elevation gradient at the Bear Creek site. In northern Québec, Payette and Filion (1985) concluded that regeneration occurred in remote areas in the forest-tundra ecotone by long-distance seed dispersal. The presence of local seed sources is probably more important in the southwest Yukon, as upslope transport of seeds against the prevailing winds appears improbable.

Vegetation cover such as *Salix* and krummholz individuals provide a protected and favorable environment for seedlings, hence the increased seedling density in these microenvironments. Microenvironments produced in krummholz patches and *Salix* openings accumulate deep snowpacks, which insulate seedling roots and increase soil moisture early in the growing season (Billings, 1969). *Salix* stands are often considered beneficial for seedling establishment, however they may also inhibit spruce reproduction by providing competition. Similar reports of increased seedling density have been documented in Rocky Mountain National Park (Weisberg and Baker, 1995). Scott *et al.* (1987b) suggest that moss cover, a dominant understory at Bear Creek, is a favorable seedbed for *Picea glauca* seedlings in open forests. Mosses moderate the ground temperature, therefore increasing the lower root zone temperature early in the growing season. The latter, however, does not necessarily apply to the forest-tundra or tundra where moss development is generally patchy (Scott *et al.*, 1987b).

Structural changes in tree growth form can also be useful indicators of short-term climate variability, and the recent increase in supranival growth is indicative of a warming trend. Inferences of increased krummholz height in the forest-tundra during the 20th century are consistent with other studies throughout the Northern Hemisphere, however in these studies, peak growth periods occurred earlier during the 1930s (Kullman, 1986; Payette and Delwaide, 1994; Hessl, 1996). A decrease in vegetative reproduction and lateral stem growth since the 1920s and an increase in vertical stem growth above the snow level is demonstrated in Figure 13. The shift from lateral stem development to supranival growth suggests milder and snowier winter conditions with a reduction in winter snow abrasion (Bégin, 1991; Lavoie and Payette, 1994; Hessl, 1996).

An increase in krummholz height has occurred in the forest-tundra ecotone at Bear Creek and a continued warming trend could lead to a transition from krummholz individuals to symmetrical trees, similar to the shift detected throughout the northern Québec forest-tundra ecotone (Payette *et al.*, 1985; Lavoie and Payette, 1994). The northward shift of the forest limit, which refers to the northern limit of forest stands, resulted from an increase in krummholz height and regeneration in the forest-tundra ecotone. Increases in regeneration in the patch forest detected in this study may also lead to a shift towards continuous forest. Changes in *Picea glauca* growth form and regeneration frequencies appear to have been affected by more favorable temperatures in recent decades.

Vegetation in the forest-tundra ecotone at Bear Creek is responding to the 20th century warming through structural changes and increased regeneration. However the position of the local altitudinal spruce limit does not appear to have considerably changed in the last 150 years. The latter inference is based on the absence of subfossils and seedlings in the tundra. Short-term milder periods are required for changes in tree growth and seedling establishment, while long-term changes are necessary for variations in the position of the species limit. If the current warming trend continues, seedlings may establish in the tundra, however seed dispersal would need to occur. An experimental test of tree establishment in the Alaskan arctic tundra by Hobbie and Chapin III (1998) suggests that *Picea glauca* is more likely than other species to invade the tundra because its seeds had the highest germination rates. In addition, *Picea glauca* seedlings had positive growth and high survivorship in the tundra, particularly with increased temperatures.

3.6.1 *PICEA GLAUCA* DYNAMICS IN THE FOREST-TUNDRA AT THE TATSHENSHINI SITE

Increased seedling establishment in the forest-tundra ecotone at the Tatshenshini site demonstrates a response of *Picea glauca* stands to the climate warming of the 20th century. Similar regeneration and growth trends to the Bear Creek site suggest that both treeline sites are responding to a similar regional climate signal. A small sample size has made it difficult to generate many tangible conclusions about changes in the treeline position, however evidence suggests that regeneration in the forest-tundra in this region has responded to climate change. Regeneration in the forest-tundra ecotone at this site may be of a greater magnitude then at Bear Creek because of the presence of symmetrical trees, which tend to be more productive than stunted individuals (Tranquillini, 1979). Further dendrochronological research is needed in northwestern British Columbia to further determine vegetation responses to a long-term climate warming.

3.7 ACKNOWLEDGEMENTS

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Figure 10 A krummholz individual located in the forest-tundra ecotone at Bear Creek. The highest supranival stem reaches a height of ~ 2.5 m. Note the stem defoliation due to particle and snow abrasion.

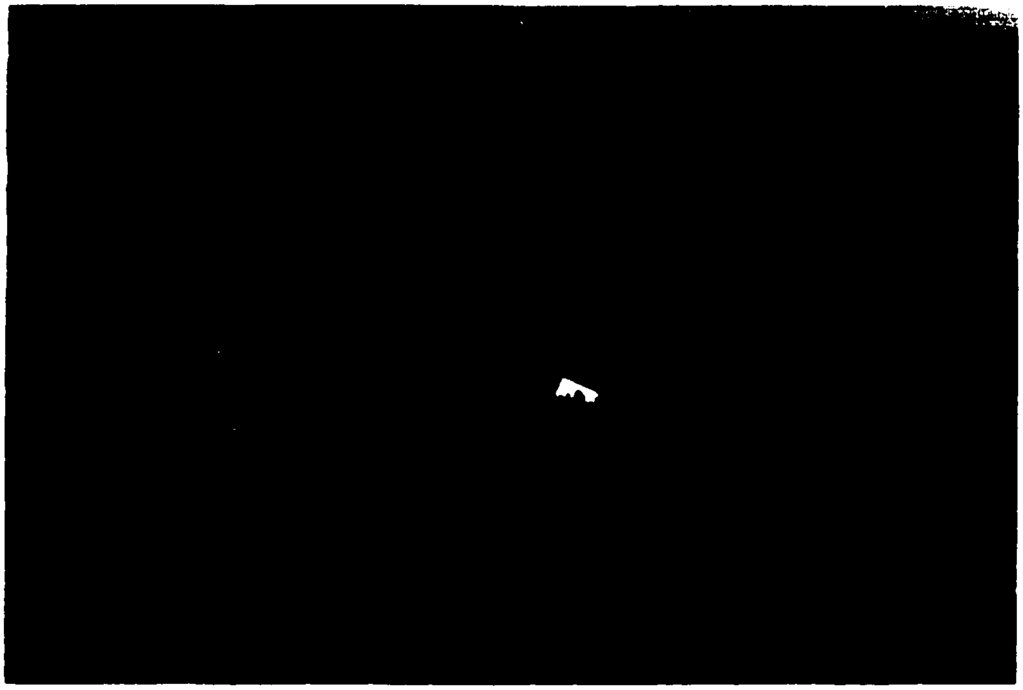


Figure 11 Infranival cushion growth form located in the forest-tundra (Bear Creek) at 1221 m a.s.l. The *Picea glauca* individual is 1 m high.

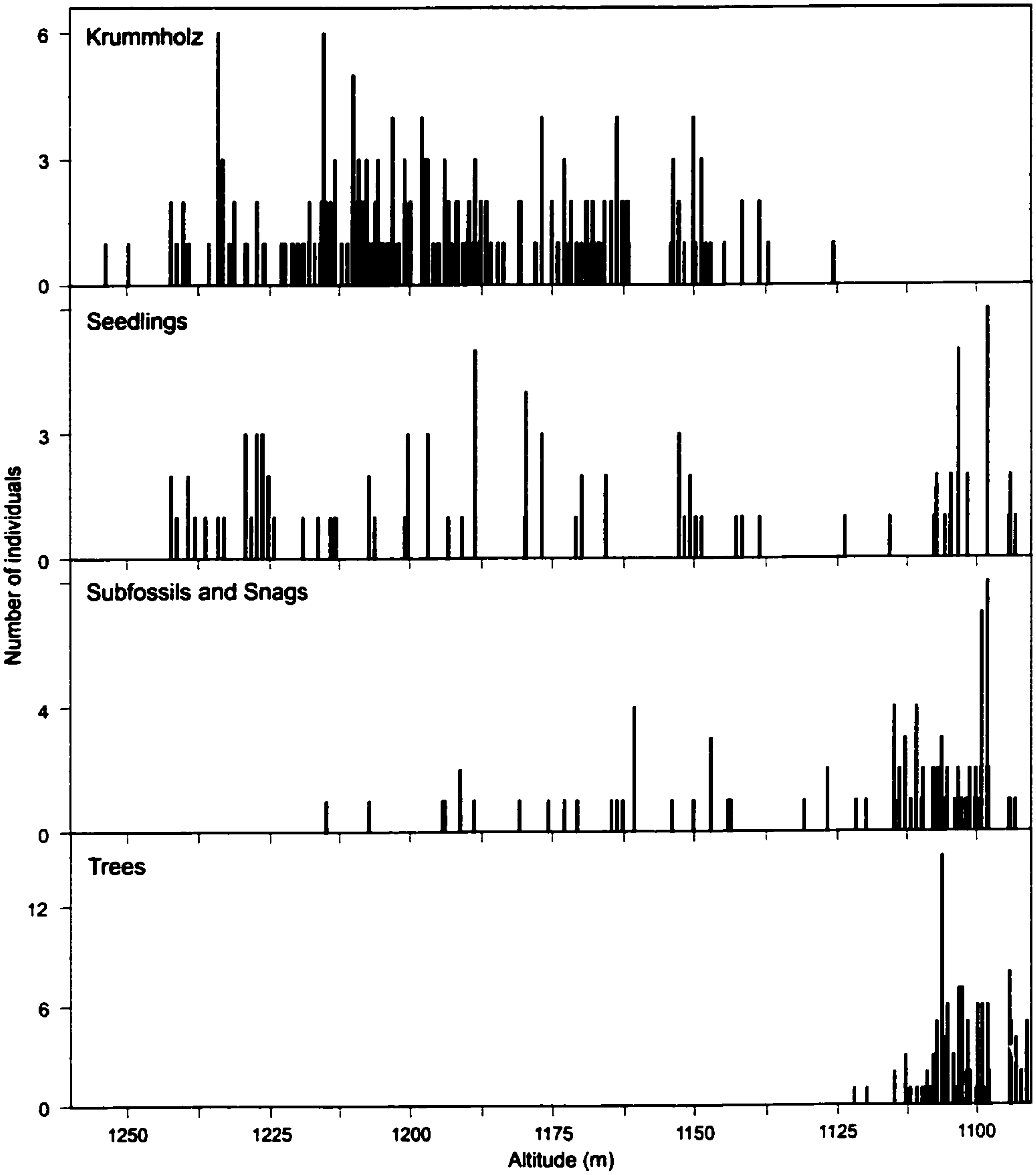
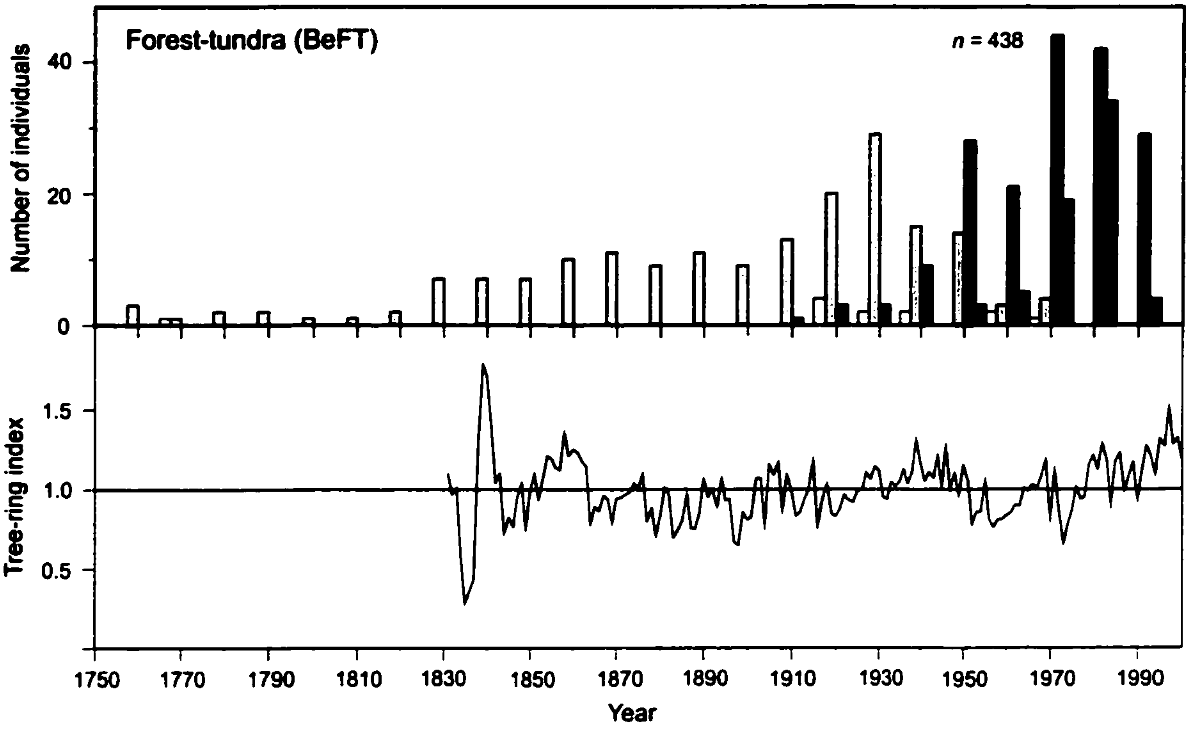


Figure12 Krummholz, seedling, subfossil and snag, and tree distribution across the forest-tundra ecotone at Bear Creek. The altitude of each *Picea glauca* individual was noted using a GPS (Global Positioning System).



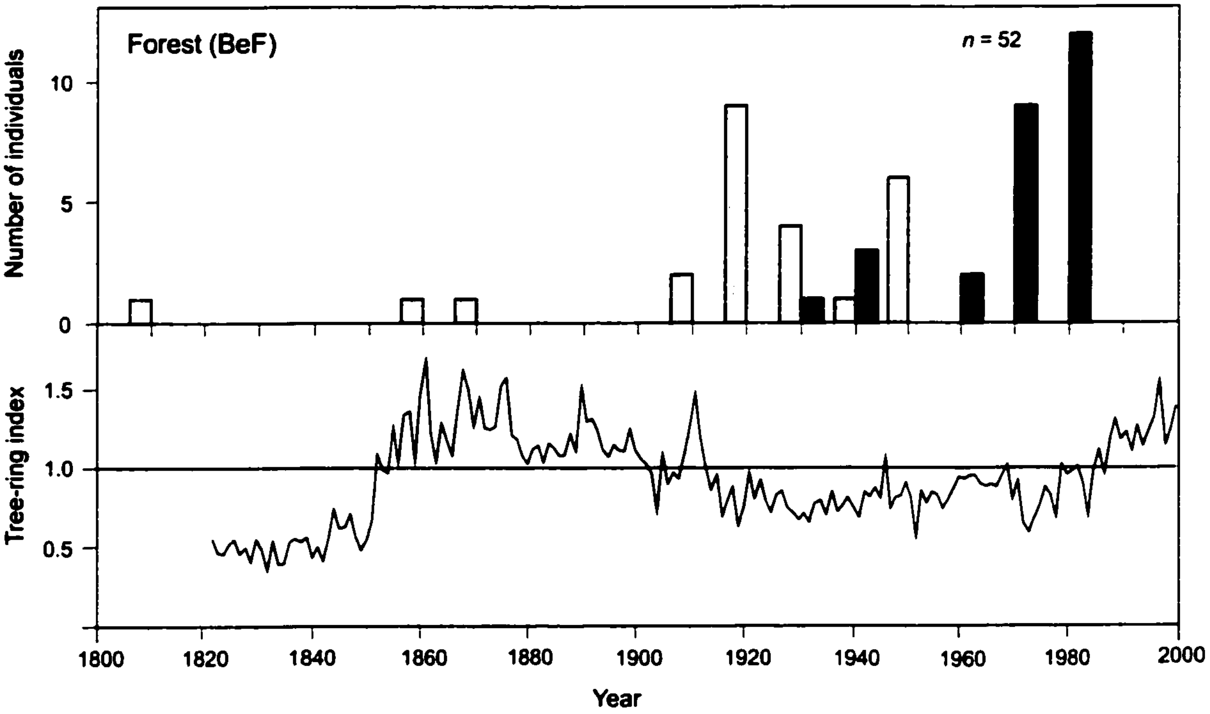


Figure 13 *Picea glauca* age-structure histograms (10-year classes) and tree-ring chronologies for Bear Creek. White bars indicate base stems; light grey bars indicate samples collected at the multi-stem level; dark grey bars indicate seedlings; and black bars indicate supranival stems.

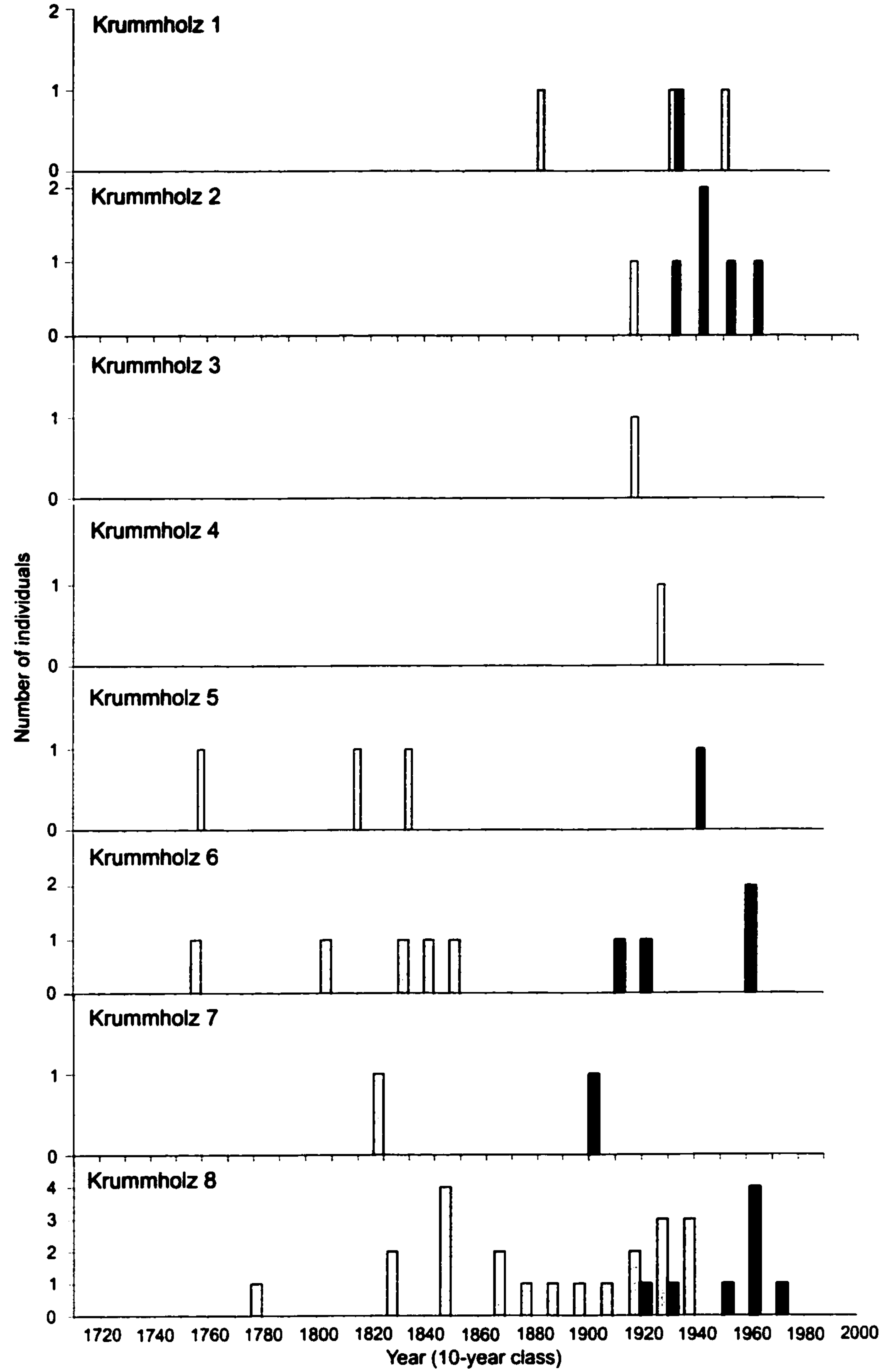


Figure 14a Krummholz age structures (10-year classes) for individuals in quadrat 1 in the forest-tundra ecotone at Bear Creek. White bars indicate base stems; light grey bars indicate samples at the multi-stem level; and the dark grey bars indicate supranival stems.

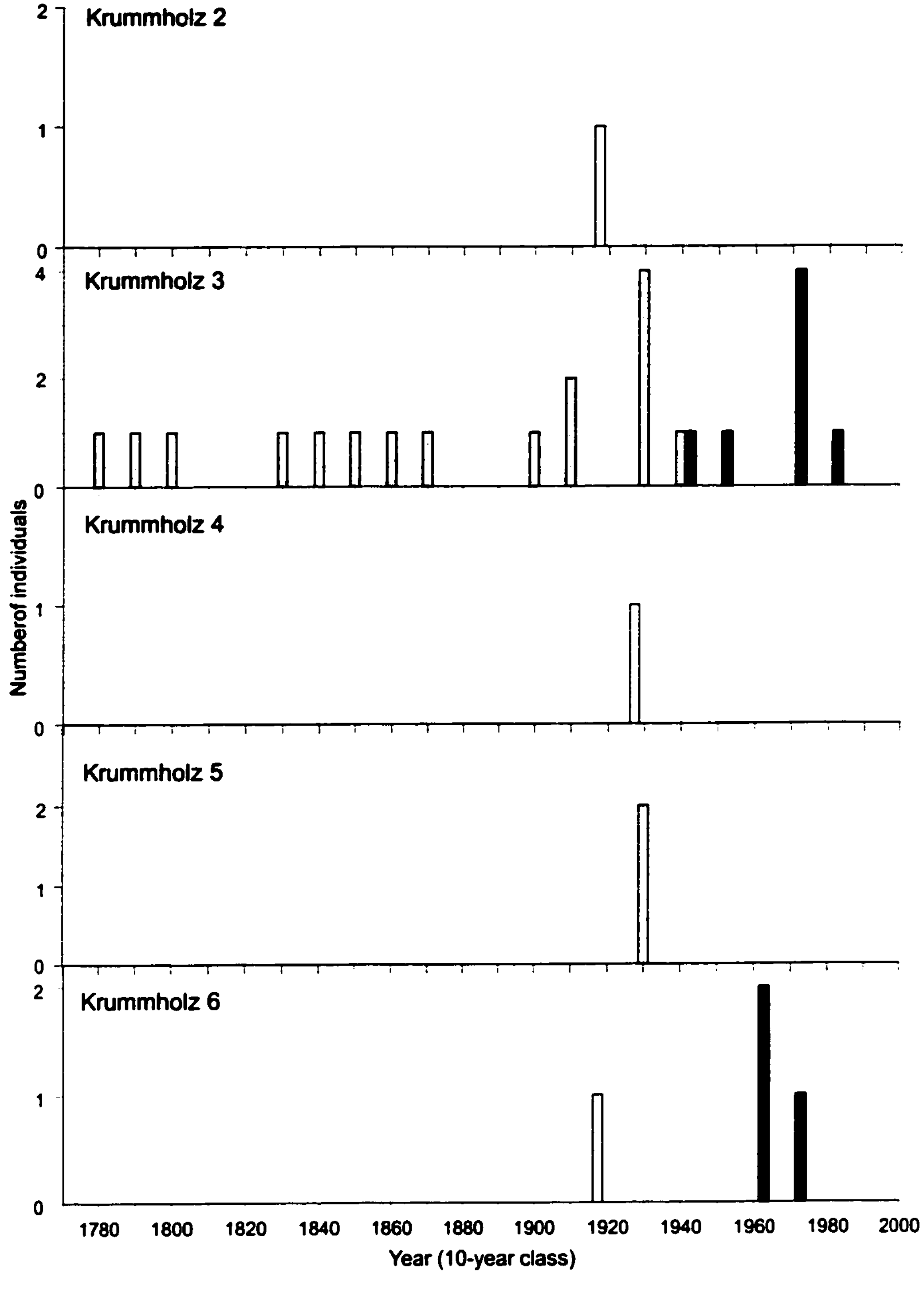


Figure 14b Krummholz age structures (10-year classes) for individuals in quadrat 2 in the forest-tundra ecotone at Bear Creek. White bars indicate base stems; light grey bars indicate samples at the multi-stem level; and dark grey bars indicate supranival stems.

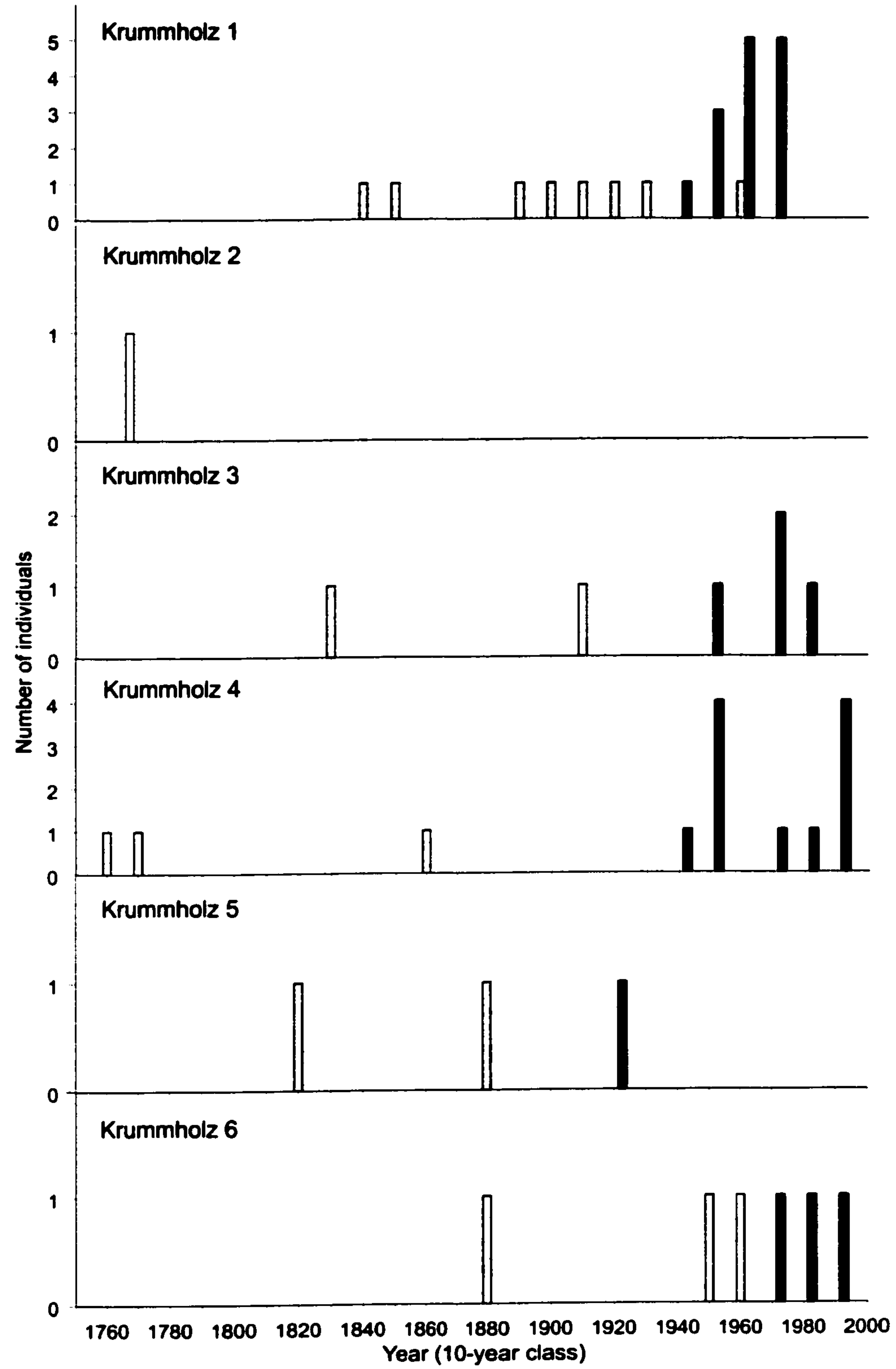


Figure 14c Krummholz age structures (10-year classes) for individuals in quadrat 3 in the forest-tundra ecotone at Bear Creek. White bars indicate base stems; light grey bars indicate samples at the multi-stem level; and dark grey bars indicate supranival stems.

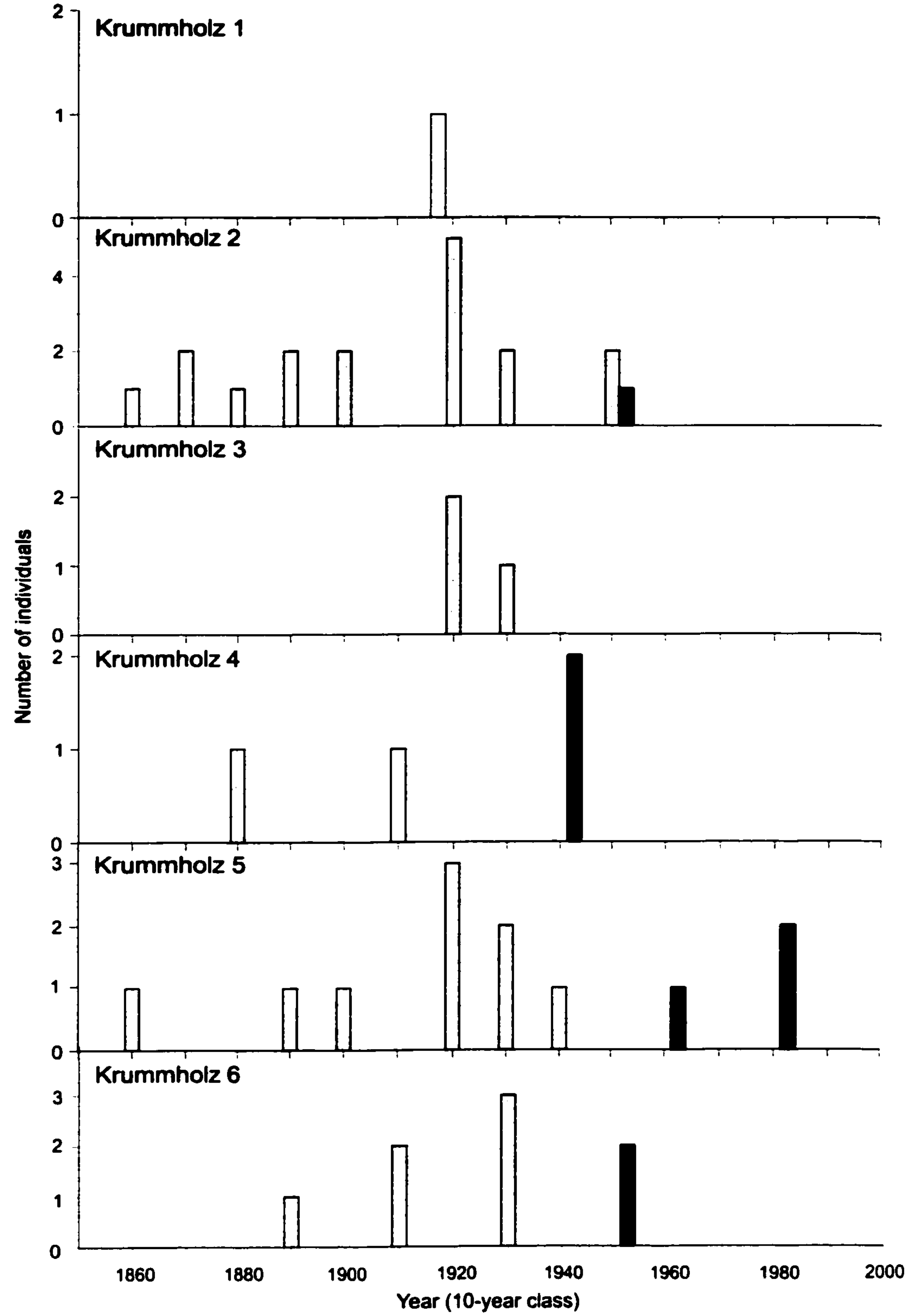


Figure 14d Krummholz age structures (10-year classes) for individuals in quadrat 4 in the forest-tundra ecotone at Bear Creek. White bars indicate base stems; light grey bars indicate samples at the multi-stem level; and dark grey bars indicate supranival stems..

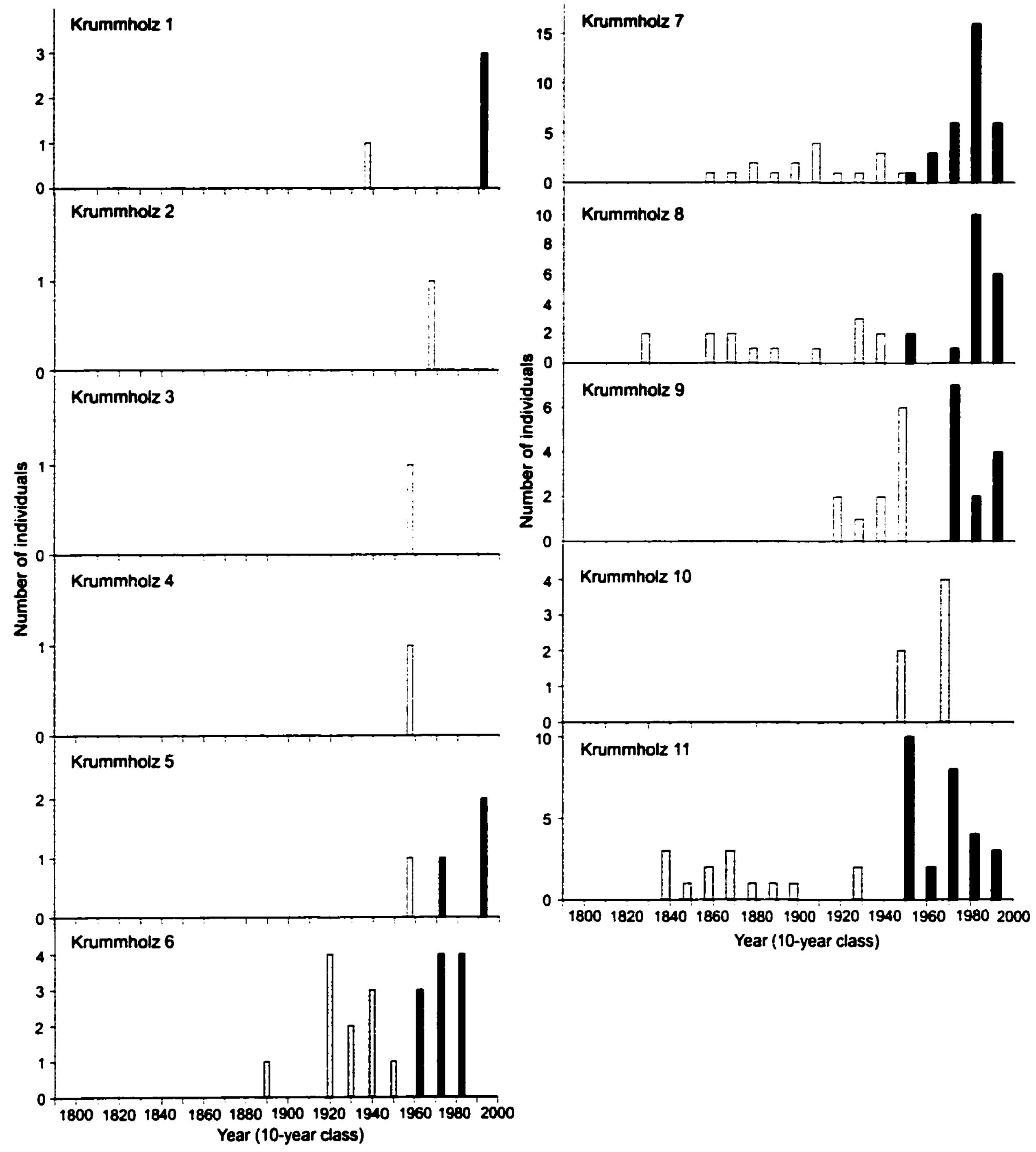


Figure 14e Krummholz age structures (10-year classes) for individuals in quadrat 5 in the forest-tundra ecotone at Bear Creek. White bars indicate base stems; light grey bars indicate samples at the multi-stem level; and dark grey bars indicate supranival stems.

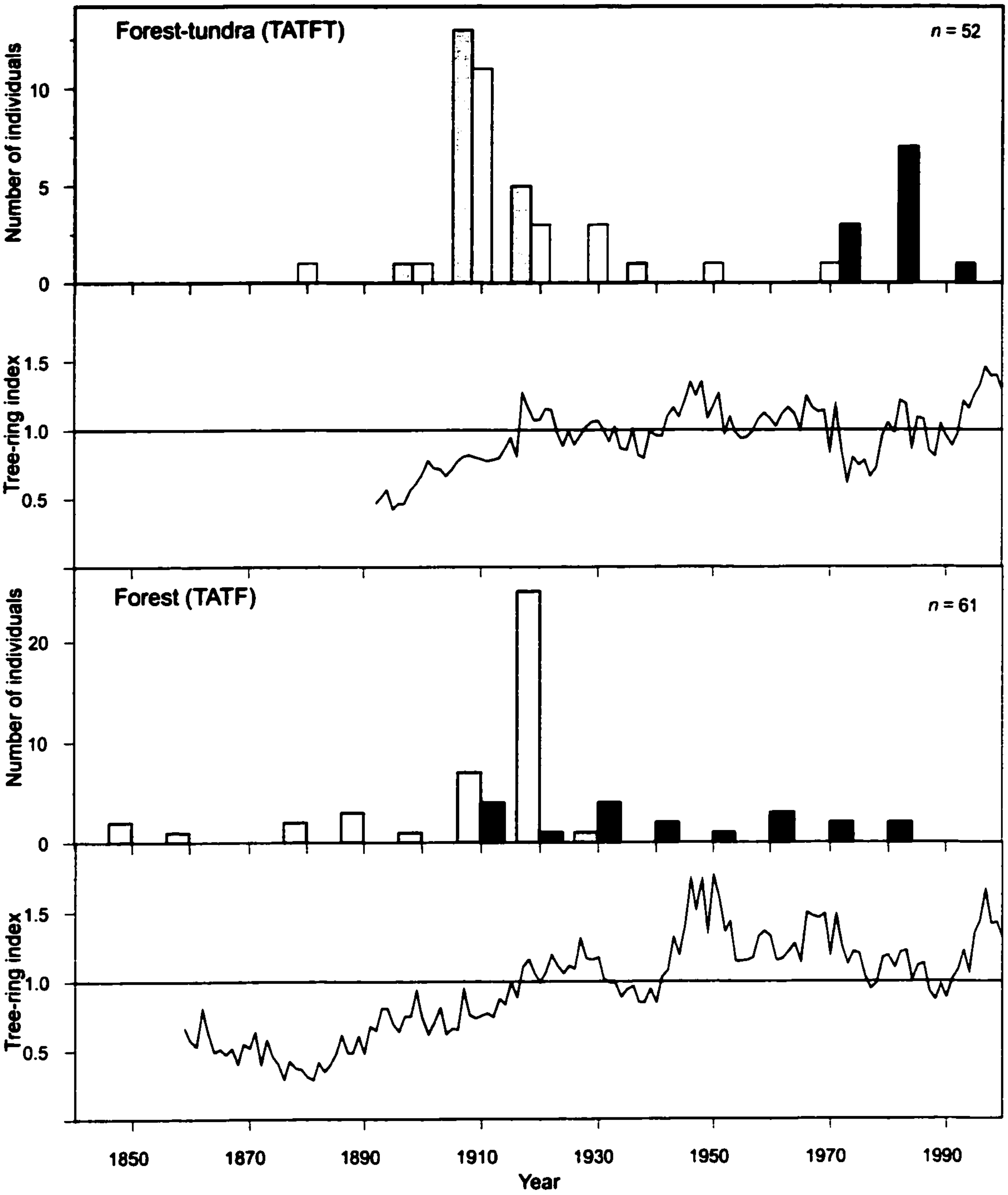


Figure 15 *Picea glauca* age-structure histograms (10-year classes) and tree-ring chronologies for the Tatshenshini site. Light grey bars indicate the date of establishment of trees at TATF and TATFT; white bars indicate trees sampled at TATFT2; and dark grey bars indicate seedlings.

Table 4 Summary statistics for four *Picea glauca* Arstan chronologies developed in the southwest Yukon Territory and northwestern British Columbia

								Common interval	
Chronology code	Period	No. of trees	No. of radii	Mean ring width (mm)	Mean sensititvity	SD	First-order autocorrelation	Mean correlation between trees	Variance in the first eigenvalue (%)
BeF	1822-2000	26	41	2.51	0.13	0.29	0.84	0.31	40.87
BeFT	1830-2000	28*	40	0.55	0.13	0.20	0.64	0.14	21.01
TATF	1859-2000	25	37	1.65	0.12	0.35	0.91	0.37	43.15
TATFT	1891-2000	29	41	3.41	0.10	0.22	0.80	0.28	33.59

[*] This value represents the number of sections collected from 36 krummholz in the forest-tundra at Bear Creek

The mean sensitivity measures the ring width difference between a ring and the adjacent ring;

The standard deviation measures the variance within the ring-width series;

First-order autocorrelation is a correlation between the ring widths of a particular year with the ring widths of the previous or following year.

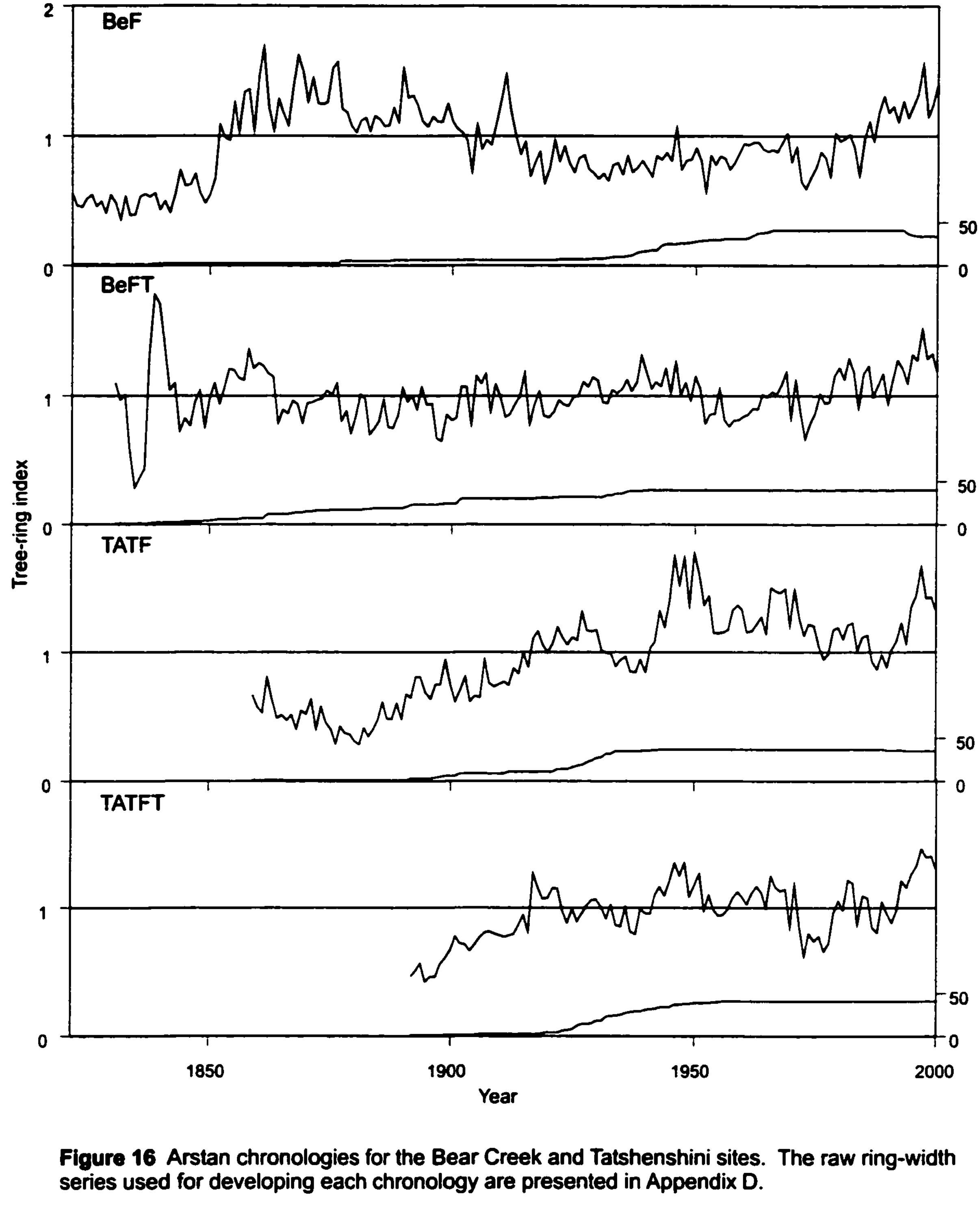


Figure 16 Arstan chronologies for the Bear Creek and Tatshenshini sites. The raw ring-width series used for developing each chronology are presented in Appendix D.

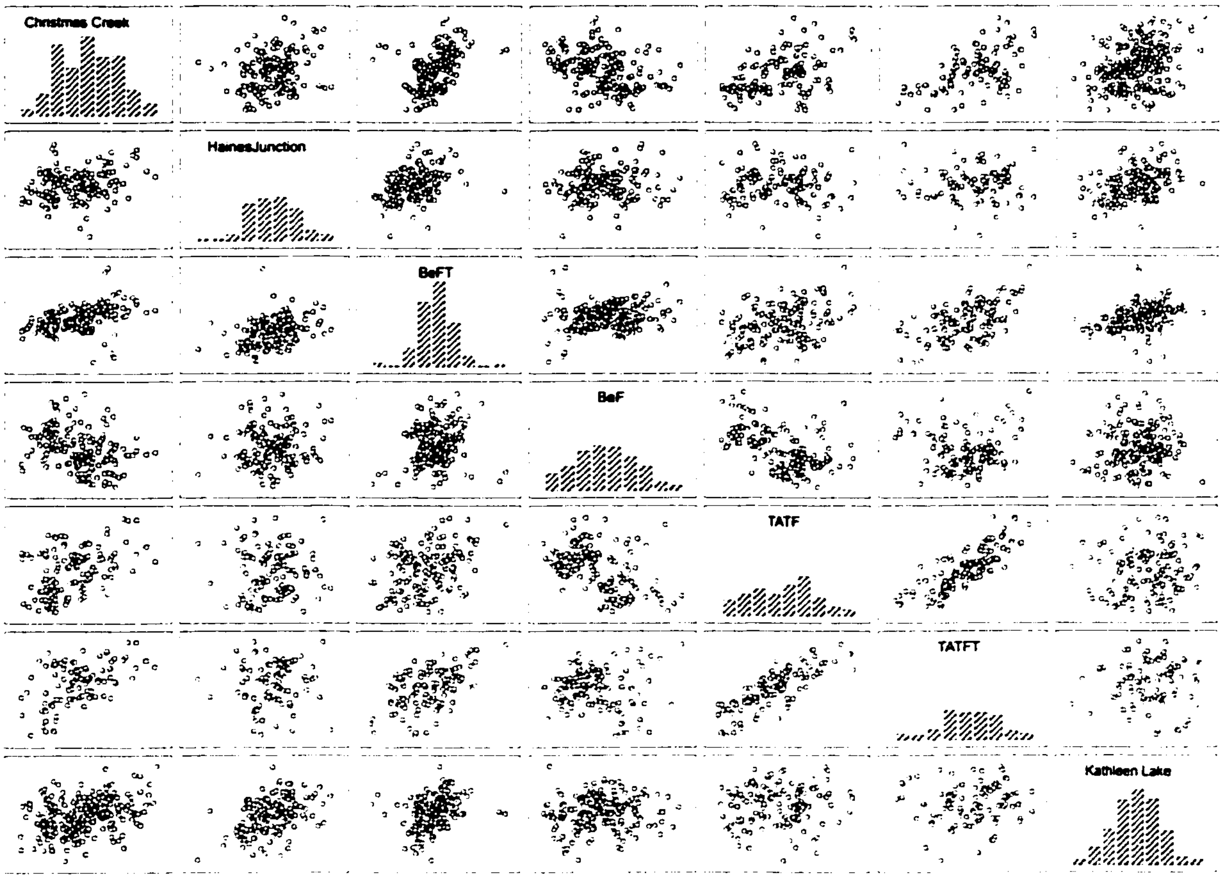


Table 5 Correlation matrix of five chronologies in the southwest Yukon Territory and 2 in northwestern British Columbia

Chronology	CC	HJ	BeFT	BeF	TATF	TATFT	KL
CC		0.26*	0.40*	-0.36*	0.43*	0.51*	0.32*
HJ	0.26*		0.37*	0.06	0.02	0.02	0.43*
BeFT	0.40*	0.37*		0.16*	0.36*	0.51*	0.34*
BeF	-0.36*	0.06	0.16*		-0.47*	-0.01	0.11
TATF	0.43*	0.02	0.36*	-0.47*		0.81*	0.10
TATFT	0.51*	0.02	0.51*	-0.01	0.81*		0.03
KL	0.32*	0.43*	0.34*	0.11	0.10	0.03	

* Significant at $p < 0.05$

HJ: Haines Junction (CAN; 60N,137W; Parker,M.L.; White spruce); CC: Christmas Creek (CAN; 60N,137W; Kaiser,K.; Black spruce);

KL: Kathleen Lake (CAN; 60N,137W; Schweingruber,F.H.; Black spruce)

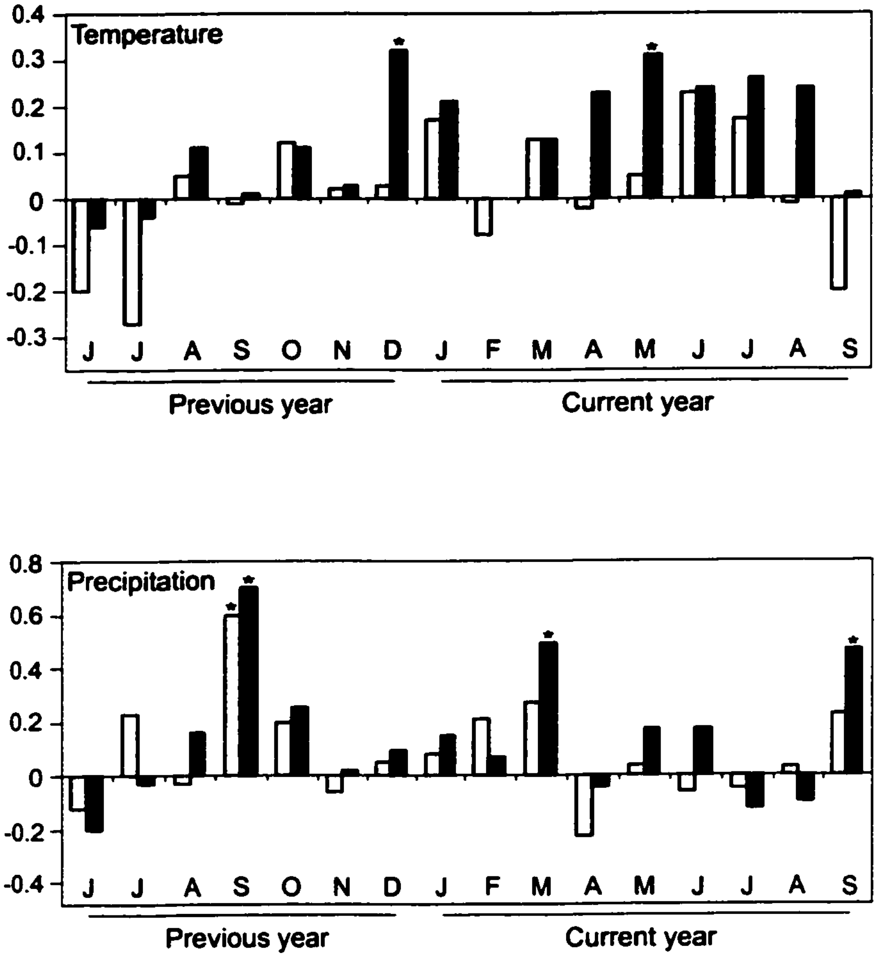


Figure 17 Climate-tree growth correlation coefficients. Bear Creek forest and forest-tundra tree-ring chronologies, mean monthly temperature and total monthly precipitation from Haines Junction were used in the analysis. Light grey bars indicate correlation coefficients for the forest-tundra; dark grey bars indicate correlation coefficients for the forest.
Note * significant at $p < 0.05$

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4.1 SUMMARY AND CONCLUSIONS

This study of *Picea glauca* dynamics in the forest-tundra ecotone in the southwest Yukon Territory investigated regeneration, morphological changes and growth patterns of *Picea glauca* individuals at Bear Creek. Additional research was conducted at a northwestern British Columbia treeline site (Tatshenshini) for comparison. Dendrochronological studies based on age-class distributions and tree-ring chronologies offer the possibility to determine alpine vegetation response to climate change. Findings obtained from this research provide information about the response of sensitive high altitude trees to climate variations.

Tree-ring chronologies were used to test whether *Picea glauca* regeneration was climate-driven because long climate records are not available for the southwest Yukon. A lack of regeneration during the late 1800s to the mid-1900s corresponds with unfavorable growing conditions during the ending phases of the Little Ice Age. To maintain their population during this extensive cooling period, *Picea glauca* individuals developed lateral stems and reproduced through layering. A significant increase in regeneration during the 20th century infers warmer, more favorable growing conditions. Improved regeneration occurred during the warming of the early 1900s to the 1940s and has subsequently reached a peak since the warming trend initiated in the 1970s. Successful seedling establishment is concentrated in patches with lower *Salix* densities and near krummholz patches, which provide protection from the harsh winter conditions. The abundance of seedlings in the forest-tundra ecotone suggests productivity and establishment by seeds from nearby cone-bearing krummholz. Structural changes in tree growth form have occurred by means of an increase in supranival stem growth. The latter structural change, occurring since the 1950s, infers milder and snowier winter conditions in the forest-tundra ecotone at Bear Creek.

A long-term trend in radial growth, apparently associated with the 20th century warming, is represented in all four chronologies developed in this study. Regeneration and radial growth at the Bear Creek and Tatshenshini sites show similar trends suggesting a vegetation response to a large-scale climate signal. Tree growth at the Bear Creek site is highly correlated with summer temperatures of the current growing season.

In conclusion, the results of this study support the proposed hypothesis that an increase in seedling establishment and morphological changes of pre-established trees in the forest-tundra ecotone at Bear Creek resulted from the 20th century climate warming. Despite the responses in the forest-tundra ecotone to climate change, shifts in the position of the local altitudinal spruce limit are insignificant. However, a continued warming trend could lead to a shift from krummholz individuals to symmetrical trees at Bear Creek and/or from patch forest to continuous forest at both treeline sites.

Despite the fact that this area is one of the driest areas of North America's boreal forest, vegetation response at the Bear Creek site is similar to the British Columbia site as well as other sites throughout Canada. For example, the Tatshenshini site receives on average an additional 300 mm of precipitation than Bear Creek, therefore precipitation is not a primary growth limiting factor at these treeline sites.

4.2 FUTURE RESEARCH

This study investigated two treeline sites in the southwest Yukon and northwestern British Columbia. Whether regeneration in the forest-tundra ecotone is representative of the entire region still remains unanswered. Empirical evidence suggests a response of treeline vegetation to the 20th century warming, however to more effectively detect treeline displacements, it is necessary to sample all *Picea glauca* individuals along an elevation gradient. For instance, sampling all spruce along numerous transects perpendicular to the slope would provide information on age-class distributions from the forest to the tundra. A more extensive search of the tundra for seedlings and subfossils would also provide insight concerning past and present treeline displacements.

This study has opened doors to further treeline studies in the southwest Yukon Territory. An architectural study of *Picea glauca* growth forms at treeline similar to Bégin (1991) would provide pertinent information about *Picea glauca* growth forms in northwest Canada. Moreover, if the climate continues to warm throughout the 21st century, a follow up study would be extremely interesting to determine if krummholz in the forest-tundra ecotone are indeed shifting towards symmetrical trees and/or if infilling of the patch forest is occurring due to seedling establishment.

As always, this study has raised more questions then it has answered. The abundance of altitudinal treeline sites in this region of the southwest Yukon Territory provide infinite opportunities for further treeline research.

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VEGETATION COVER AT THE BEAR CREEK AND TATSHENSHINI SITES

Plant vouchers were collected in the field, pressed, identified and stored in the LPC (Laboratory for Paleoclimatology and Climatology) herbarium. All plant species were identified using Cody (1996). The vegetation cover tables presented in this Appendix represent the understory at the Bear Creek and Tatshenshini treeline sites.

Table A-1 Vegetation cover at Bear Creek, southwest Yukon Territory
(+, present; 1, 1-10%; 2, 11-20%; 3, 21-30%; 4, 31-40%; 5, 41-50%; etc.)

	Tundra			Forest-Tundra															Forest		
				Plot1			Plot2			Plot3			Plot4			Plot5					
Species	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Betula glandulosa	4	5	5	+	+	9	2	1	7	4	1	1	7	4	5	2		1			
Arctostaphylos rubra								2													
Vaccinium uliginosum				4		2	4	1	3	1	4	1	1			1	4	5			
Vaccinium vitis-idaea		2	2							1	1	1	+			1		1			
Phyllodoce empetriformis				1				6	2		1		4	9	4		1	6			
Dryas crenulata																+					
Pedicularis labradorica										2		+									
Pedicularis oederi										+	1					1	1	1			
Salix sp.*			3	1		2		7		1	6	7		5	1	1	+	7	1	7	1
Oxytropis scammiana				1																	
Woodsia ilvensis							1														
Cassiope tetragona								5													
Lupinus arcticus																			2	5	1
Arnica cordifolia																			1	+	
Achillea millefolium																			1		1
Juniperus communis																			+		
Castilleja unalaschcensis																				1	1
Aconitum dephinifolium																				1	
Mertensia paniculata																				+	
Gentianella propinqua																					+
Galium boreale																					+
Senecio lugens																					+
Delphinium glaucum																					1
Solidago multiradiata																			1	1	
Hedysarum boreale																+	1				
moss **	7	6	8	10	10	9	6	1	6	9	9	10	1		5	9	10	9	4	3	1
herbaceous ***	3	3	2		3	1				3	6	7			1	1	1	5	3	7	2
lichen ****		+		1		1	2	1	1	1	1	1	1		2	4	2				

**Salix* species include: *Salix glauca*, *Salix bebbiana*, *Salix arctica*
**moss species include: *Aulacomnium palustre*
***herbaceous species include: *Festica altaica*, *Carex consimilis*
****lichen species include: *Cetraria*

Other species present in the tundra: *Saxifraga tricuspidata*, *Dryas crenulata*, *Potentilla fruticosa*, *Petasites frigidus*, *Valeriana capitata*, *Eriophorum brachyantherum*, *Pedicularis oederi*, *Ledum groenlandicum*, *Saussurea angustifolia*
Other species present in the krummholz zone: *Equisetum scirpoides*, *Cassiope tetragona*, *Saxifraga tricuspidata*, *Petasites frigidus*, *Valeriana capitata*, *Ledum groenlandicum*

Table A-2 Vegetation cover at the Tatshenshini site, northwestern British Columbia (+, present; 1, 1-10%; 2, 11-20%; 3, 21-30%; 4, 31-40%; 5,41-50%; etc.)

	Tundra			Forest-Tundra						Forest		
				Plot 1			Plot2					
Species	1	2	3	1	2	3	1	2	3	1	2	3
Achillea millefolium				1	1	+					+	
Rubus arcticus	1	+	+		1					1	1	1
Sanguisorba canadensis	3		+	2		1			1	2	1	1
Arctostaphylos alpina		2									1	
Solidago multiradiata			+	1		1				1		1
Cornus canadensis					+	1	1	1	1	1	3	1
Campanula aurita								1	+	+		+
Pedicularis labradorica										+		
Epilobium angustifolium										1		
Potentilla fruticosa		1										1
Platanthera hyperborea				+								+
Senecio lugens	2			+			+	+	1			+
Senecio tundricola												+
Aster alpinus			1	1	4	+	1		1	+		
Parnassia fimbriata				+		+	1		1			
Castilleja hyperborea									1			
Valeriana sitchensis				3		+	3		1			
Pyrola asarifolia								+				
Juniperus communis										6		
Ledum groenlandicum										1	1	
Equisetum pratense	+		+	1	5	6	1	1	1	1	1	5
Vaccinium uliginosum		1	1							+		
Thalictrum alpinum			1							1		
Polygonum viviparum		+										
Phyllodoce sp.	3	7	1					1		8	2	
Andromeda polifolia		1										
Betula gladulosa	1	+	1	1			1	8	4		1	1
Salix sp.	1		1	7	5		1		1	6	1	1
Pedicularis labradorica	+											
Galium boreale					1	+	1					
Arnica diversifolia						+						
Viola sp.					1	1	1					
Gentianella propinqua					1							
Veratrum viride							1	1	1			
Viola langsdorfii							1		1			
Vaccinium caespitosum			3				2					
Gymnocarpium dryopteris							7	5	9			
Parnassia kotzebuei							1					
Geranium erianthum							1	1	1			
Actaea rubra				1			2	2				
Luzula parviflora	2											
Geocaulon lividum	1											
Equisetum palustre	+											
moss	10	10	10	2	1	9	2		8	3	9	9
herbaceous*	7	9	8	1	1		1	1	6	2	1	1

*herbaceous species include: *Eriophorum angustifolium*, *Calamagrostis canadensis*, *Carex aquatilis*

Other species present in the tundra: *Achillea millefolium*, *Campanula aurita*, *Ledum groenlandicum*, *Andromeda polifolia*, *Pedicularis oederi*, *Delphinium glaucum*, *Trifolium hybridum*, *Aconitum delphinifolium*, *Polemonium* sp.
Other species present in the forest-tundra: *Campanula aurita*, *Potentilla fructicosa*, *Castilleja unalaschcensis*, *Aconitum delphinifolium*

SOIL ANALYSIS

The results presented in the following tables show weight-loss-on-ignition (LOI) and grain-size at the Bear Creek and Tatshenshini sites. Soil samples were collected from each delineated quadrat in the tundra, forest-tundra and forest at both treeline sites. The soil samples were divided into layers (O layer, etc.) depending on the soil structure.

In the laboratory, soil samples were analyzed for weight-loss-on-ignition (LOI), which measures the approximate percentage of organic matter in the soil; and grain-size, which measures particle size. For the LOI, the samples were dried overnight at 95°C in a drying oven, then volumes of sediment were weighted (weight ranged from 8 to16 g) along with the crucibles in which each sample was contained in. The weighted samples were then ignited in a muffle furnace for three hours at 500 °C to remove the organic content from the soil. The final step was to weigh the samples after ignition and determine the percentage of organic matter in the soil at each layer. Grain-size analysis was performed using the wet sieving method. This method is more often used to separate fines from coarse materials. The soil particles were divided into three categories: fines (<0.063 mm), sands (>0.063 mm - <2 mm), and gravels (>2 mm). The samples retained in each sieve were then dried and weighted. Grain size analysis was performed on the A layer and not the O layer, because of high organic content. It was not possible to perform a grain-size analysis for the Tatshenshini site because of the high organic content in both the O and A layer. Both techniques were based on the standard methods outlined in Gale and Hoare (1991).

Table B-1 Grain-size analysis at Bear Creek.

Quadrat	% fines	% sand	% gravel
BeFT	n/a	n/a	n/a
BFT	21	36	44
BFT2	25	55	21
BFT3	48	28	24
B2FT	43	56	1
B2FT2	48	43	9
BeF	33	67	0
Mean	36.3	47.3	16.4

Note Grain-size analysis was not peformed at the Tatshenshini site due to the high organic content of the soil.

Table B-2 Weight-loss-on-ignition for the Bear Creek and Tatshenshini sites

Quadrat	Organic layer	A layer
BeFT	76.07	50.11
BFT	45.48	7.41
BFT2	65.65	6.51
BFT3	46.81	8.83
B2FT	54.65	12.00
B2FT2	43.27	8.41
BeF	51.51	11.02
TATT	85.93	81.71
TATFT	84.04	n/a
TATFT2	81.43	79.88
TATF	79.07	73.25

TATSHENSHINI FOREST PRINCIPAL COMPONENTS ANALYSIS (PCA) DESCRIPTION

The results from the PCA for the Bear Creek and Tatshenshini forest-tundra and forest are presented in figures C-1 to C-4. Only the PCA for the Tatshenshini forest will be further discussed (Figure C-1). The first step in interpreting the results obtained from a PCA is to study the eigenvalues, which represent the variance explained by each component. For instance, factor 1 accounts for 39 percent of the variance, factor 2 for 20 percent, factor 3 for 7 percent and so forth (Table C-1). The factors are extracted consecutively, with higher-order factors accounting for progressively less and less of the variance. These eigenvalues are then used to determine the number of components to retain for further analysis.

The principal component loadings are the correlations between the component factors and the variables (ring-width series). A scatterplot (Figure C-1) illustrates the first two component loadings obtained from the Tatshenshini forest PCA. All series except for series 39, are negatively loaded on factor 1, which means that most trees are responding similarly, indicating a common trend between each other. Ring-width series are positively or negatively loaded on factor 2. This represents a long-term trend (see scatterplot), superimposed on factor 1, which can be positive or negative.

The communality table (Table C-2) presents the amount of variance of each variable explained by the component factors. Very low communalities for the first and second components may indicate that the series is not highly correlated with the other series and therefore is not responding to the large-scale climate signal. For example, only 12 percent of the variance in series 11 is explained by factors 1 and 2. It is only with 6 factors that a majority of the variance of this series is explained (80 percent). For this reason, series 11 is treated as an outlier and removed from the chronology. This specific tree must be responding to endogenous disturbance trends resulting in a ring-width series that differs substantially from other series. All outliers, loaded on the third or higher order factors, were removed from the chronology.

The component scores illustrate the trends captured by the components. Factor 1 shows a period of negatively loaded components in the 1940s preceded by a slight increase until the late 1980s. Since the series are computed by multiplying the loadings and score coefficients, this produces a series with a positive anomaly in the 1940s as is observed in most of the ring-width series (Figure C-1). Therefore the first PCA in all cores resembles the chronology, providing evidence that the chronology is truly recording the long-scale climate signal. Factor 2 shows an increasing trend from the 1930s to the late 1980s. This trend is superimposed on the first component. Trees highly loaded on this component, either positively or negatively, would differ in the importance of the long-term decrease in ring-widths since the 1950s. Scores of the factors 3 to 6 show short period variations in ring-width. These explain only small amounts of the variance for most series. If one particular tree is highly loaded on one of these components, and not on the first two, (i.e. 11), this may be due to periods of suppression or release that dominate the growth curve of this particular tree.

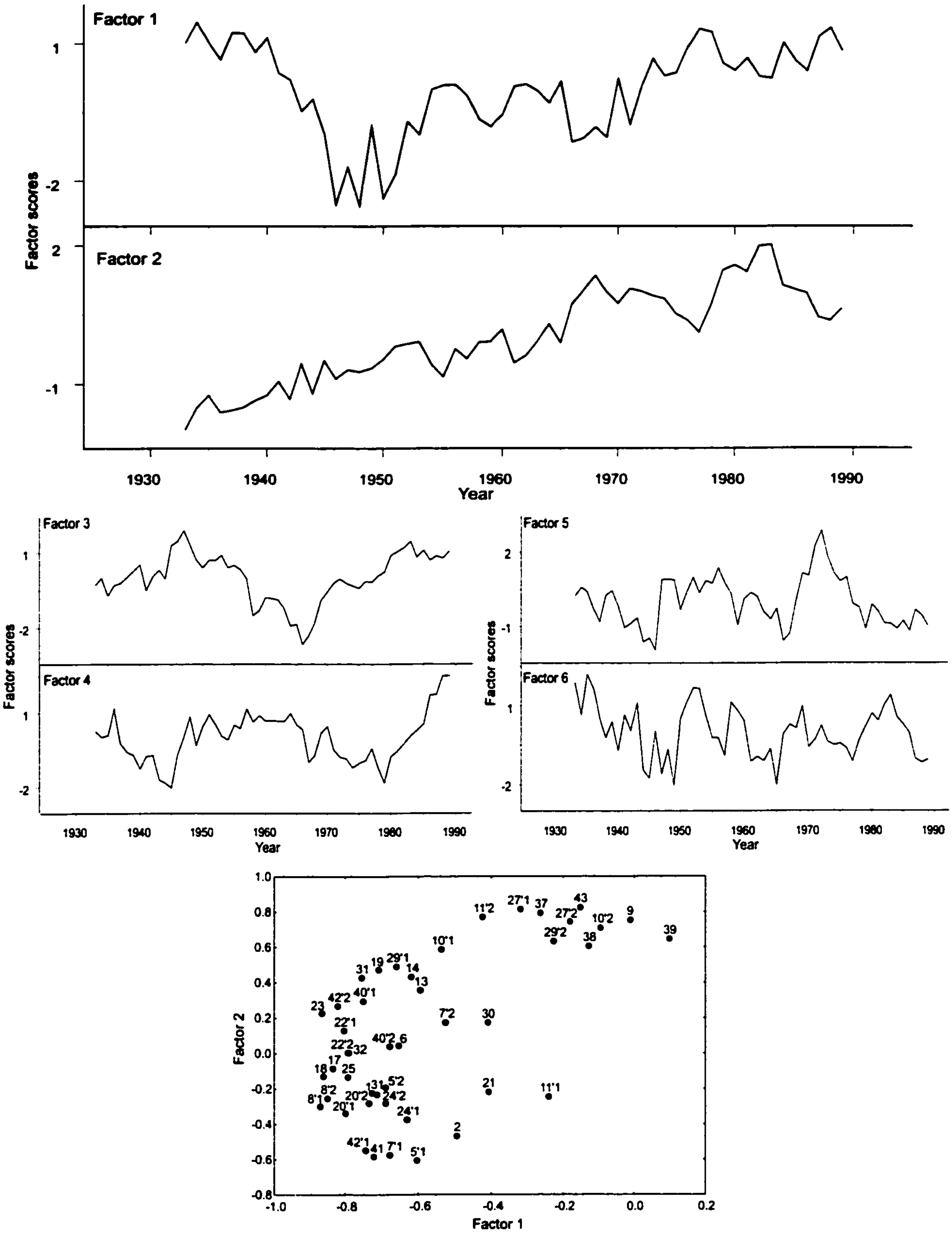


Figure C-1 Component scores and loadings for the Tatshenshini forest.

Table C-1 Eigenvalues obtained from the PCA for the Tatshenshini forest tree-rings

Factor	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	17.73	39.41	17.73	39.41
2	9.41	20.91	27.15	60.32
3	3.38	7.52	30.53	67.84
4	2.35	5.21	32.88	73.06
5	1.86	4.12	34.73	77.18
6	1.56	3.47	36.29	80.65
7	1.11	2.46	37.40	83.11

Table C-2 Communalities for the Tatshenshini forest

Series	From 1 Factor	From 2 Factors	From 3 Factors	From 4 Factors	From 5 Factors	From 6 Factors	From 7 Factors	Multiple R-Square
TATF10_1	0.29	0.64	0.71	0.73	0.87	0.87	0.89	0.98
TATF10_2	0.01	0.52	0.74	0.85	0.87	0.88	0.88	0.97
TATF1_1	0.53	0.57	0.58	0.60	0.63	0.63	0.68	0.92
TATF11	0.06	0.12	0.12	0.14	0.38	0.80	0.81	0.89
TATF1_2	0.18	0.78	0.78	0.78	0.81	0.81	0.82	0.97
TATF13	0.36	0.48	0.59	0.72	0.79	0.86	0.86	0.94
TATF14	0.38	0.57	0.57	0.63	0.65	0.65	0.65	0.96
TATF17	0.69	0.70	0.76	0.77	0.81	0.81	0.82	0.98
TATF18	0.74	0.76	0.76	0.76	0.79	0.85	0.85	0.96
TATF19	0.50	0.73	0.73	0.78	0.78	0.80	0.81	0.96
TATF43	0.02	0.71	0.75	0.77	0.77	0.79	0.87	0.98
TATF5_1	0.37	0.73	0.73	0.90	0.90	0.90	0.90	0.99
TATF5_2	0.47	0.51	0.60	0.77	0.81	0.85	0.85	0.98
TATF6	0.43	0.43	0.47	0.52	0.54	0.60	0.89	0.97
TATF7_1	0.46	0.79	0.81	0.82	0.82	0.83	0.84	0.98
TATF7_2	0.28	0.31	0.33	0.34	0.56	0.64	0.69	0.93
TATF8_1	0.76	0.85	0.87	0.88	0.90	0.91	0.92	0.99
TATF8_2	0.72	0.79	0.84	0.89	0.91	0.92	0.93	0.99
TATF9	0.00	0.57	0.76	0.80	0.87	0.88	0.90	0.97
TATF2	0.25	0.46	0.83	0.83	0.88	0.89	0.90	0.98
TATF20_1	0.64	0.75	0.84	0.87	0.87	0.87	0.92	0.98
TATF20_2	0.54	0.62	0.62	0.66	0.76	0.76	0.76	0.91
TATF21	0.17	0.21	0.26	0.36	0.67	0.77	0.78	0.90
TATF22_1	0.65	0.66	0.78	0.88	0.90	0.90	0.91	0.99
TATF22_2	0.63	0.63	0.79	0.85	0.89	0.89	0.89	0.99
TATF23	0.75	0.80	0.80	0.82	0.83	0.86	0.86	0.98
TATF24_1	0.40	0.54	0.62	0.64	0.70	0.75	0.81	0.94
TATF24_2	0.47	0.55	0.71	0.71	0.73	0.77	0.81	0.97
TATF25	0.63	0.65	0.77	0.77	0.80	0.80	0.81	0.98
TATF27_1	0.10	0.77	0.82	0.84	0.84	0.86	0.87	0.99
TATF27_2	0.03	0.59	0.59	0.69	0.69	0.72	0.72	0.92
TATF29_1	0.44	0.68	0.68	0.83	0.83	0.84	0.84	0.98
TATF29_2	0.05	0.46	0.51	0.60	0.62	0.72	0.90	0.97
TATF3_1	0.51	0.56	0.85	0.88	0.89	0.90	0.90	0.97
TATF3_2	0.63	0.63	0.74	0.74	0.75	0.75	0.75	0.96
TATF30	0.17	0.20	0.54	0.54	0.56	0.56	0.60	0.92
TATF31	0.57	0.75	0.81	0.84	0.85	0.85	0.86	0.97
TATF37	0.07	0.70	0.82	0.85	0.85	0.86	0.88	0.97
TATF38	0.02	0.39	0.39	0.70	0.80	0.82	0.82	0.95
TATF39	0.01	0.43	0.55	0.73	0.75	0.75	0.77	0.96
TATF40_1	0.56	0.65	0.66	0.72	0.77	0.77	0.78	0.96
TATF40_2	0.46	0.46	0.49	0.52	0.53	0.76	0.76	0.96
TATF4_1	0.52	0.86	0.90	0.90	0.90	0.91	0.91	1.00
TATF4_2	0.55	0.85	0.89	0.89	0.89	0.89	0.90	1.00
TATF42_2	0.68	0.75	0.76	0.76	0.76	0.80	0.83	0.96

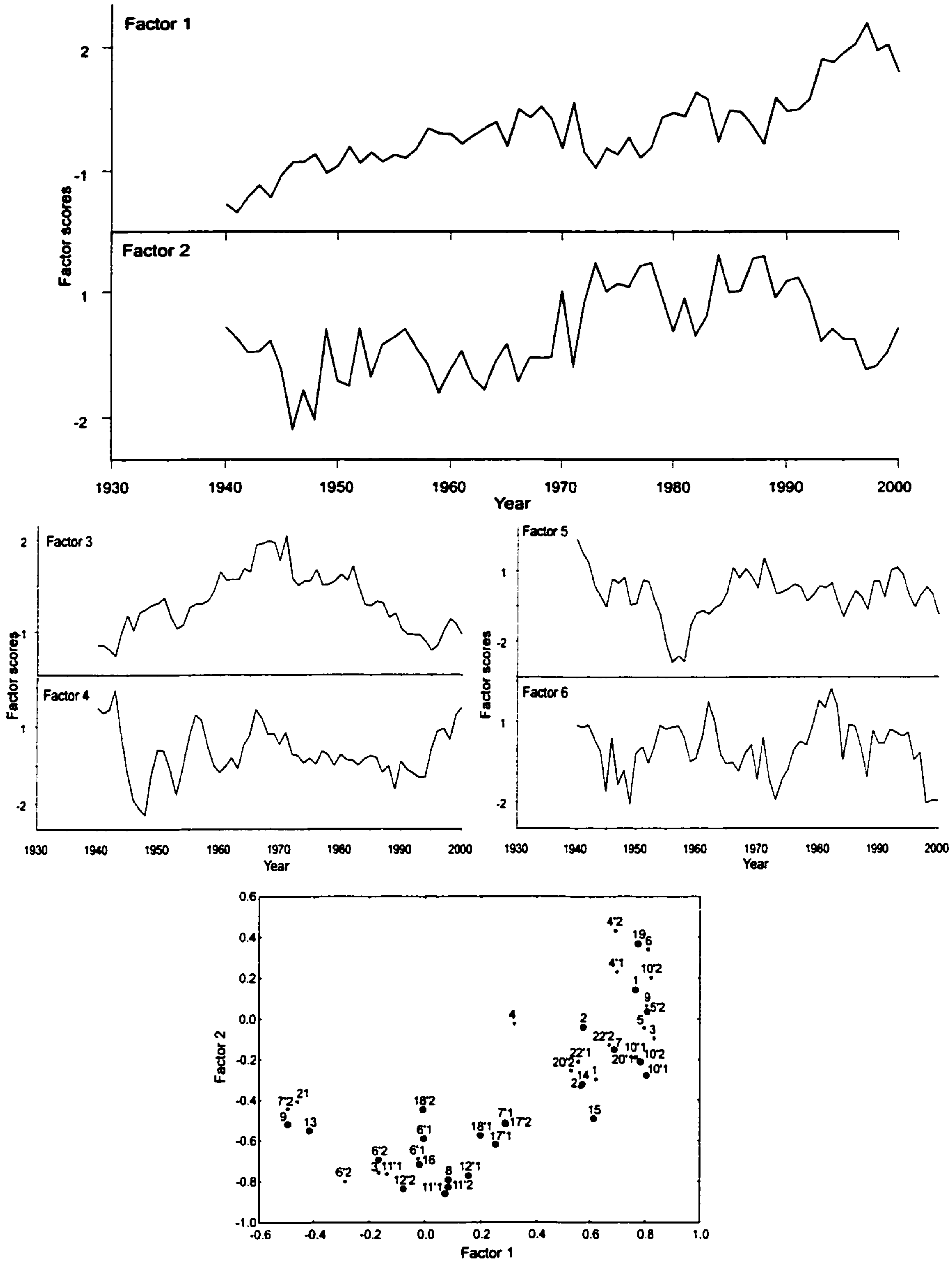


Figure C-2 Component scores and loadings for the Tatshenshini forest-tundra. The grey points in the scatterplot represent trees from TATFT and the black points are from TATFT2.

Table C-3 Eigenvalues obtained from the PCA for the Tatshenshini forest-tundra

Factor	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	13.23	29.39	13.23	29.39
2	10.73	23.85	23.96	53.24
3	4.80	10.67	28.76	63.92
4	2.89	6.42	31.65	70.34
5	2.07	4.60	33.72	74.94
6	1.97	4.38	35.69	79.31
7	1.43	3.19	37.13	82.50
8	1.17	2.60	38.29	85.10
9	1.06	2.36	39.35	87.45

Table C-4 Communalities for the Tatshenshini forest-tundra

Series	From 1 Factor	From 2 Factors	From 3 Factors	From 4 Factors	From 5 Factors	From 6 Factors	From 7 Factors	From 8 Factors	From 9 Factors	Multiple R-Square
TATFT10_1	0.59	0.63	0.83	0.83	0.86	0.89	0.92	0.94	0.94	1.00
TATFT10_2	0.67	0.72	0.74	0.78	0.82	0.86	0.87	0.87	0.88	0.97
TATFT11_1	0.02	0.60	0.73	0.76	0.80	0.84	0.85	0.85	0.86	0.95
TATFT1_1	0.39	0.47	0.55	0.56	0.60	0.87	0.90	0.90	0.92	0.99
TATFT1_2	0.32	0.43	0.53	0.54	0.57	0.84	0.90	0.91	0.93	0.99
TATFT13	0.03	0.60	0.63	0.63	0.67	0.69	0.70	0.74	0.81	0.94
TATFT14_1	0.49	0.54	0.66	0.70	0.72	0.74	0.77	0.77	0.85	0.99
TATFT14_2	0.48	0.67	0.72	0.75	0.79	0.80	0.84	0.84	0.86	0.98
TATFT15	0.63	0.63	0.88	0.90	0.90	0.91	0.91	0.92	0.94	0.99
TATFT16_1	0.00	0.47	0.59	0.59	0.60	0.62	0.64	0.68	0.72	0.96
TATFT16_2	0.09	0.72	0.75	0.77	0.79	0.79	0.81	0.91	0.93	0.98
TATFT17_1	0.08	0.34	0.35	0.75	0.93	0.94	0.94	0.96	0.96	1.00
TATFT17_2	0.25	0.44	0.44	0.47	0.52	0.52	0.66	0.67	0.71	0.87
TATFT19	0.64	0.65	0.67	0.68	0.76	0.79	0.80	0.81	0.81	0.95
TATFT20_1	0.58	0.62	0.82	0.83	0.85	0.89	0.92	0.93	0.94	1.00
TATFT20_2	0.28	0.34	0.59	0.62	0.76	0.77	0.77	0.86	0.87	0.97
TATFT21	0.21	0.38	0.43	0.66	0.66	0.74	0.83	0.88	0.90	0.97
TATFT22_1	0.31	0.35	0.38	0.78	0.83	0.83	0.85	0.86	0.91	0.98
TATFT22_2	0.44	0.46	0.46	0.77	0.83	0.83	0.90	0.91	0.95	0.99
TATFT31	0.69	0.70	0.71	0.77	0.77	0.80	0.80	0.80	0.91	0.98
TATFT4	0.10	0.10	0.61	0.61	0.69	0.77	0.80	0.84	0.88	0.94
TATFT6	0.66	0.77	0.78	0.80	0.82	0.82	0.86	0.86	0.93	0.97
TATFT2_10_1	0.65	0.72	0.74	0.75	0.76	0.76	0.76	0.84	0.84	0.96
TATFT2_10_2	0.61	0.65	0.70	0.72	0.73	0.75	0.78	0.83	0.83	0.96
TATFT2_11	0.00	0.74	0.77	0.77	0.90	0.91	0.91	0.91	0.92	0.99
TATFT2_112	0.01	0.69	0.73	0.75	0.89	0.90	0.90	0.90	0.92	0.99
TATFT2_1	0.58	0.61	0.61	0.61	0.62	0.66	0.74	0.75	0.75	0.88
TATFT2_121	0.02	0.61	0.70	0.71	0.75	0.76	0.78	0.80	0.84	0.98
TATFT2_122	0.01	0.70	0.70	0.74	0.78	0.78	0.84	0.87	0.88	0.99
TATFT2_13	0.17	0.48	0.52	0.54	0.65	0.75	0.82	0.83	0.86	0.98
TATFT2_14	0.33	0.43	0.43	0.52	0.55	0.56	0.62	0.69	0.73	0.87
TATFT2_15	0.37	0.61	0.63	0.63	0.63	0.66	0.66	0.75	0.76	0.96
TATFT2_16	0.00	0.51	0.71	0.74	0.85	0.88	0.88	0.88	0.90	0.98
TATFT2_17_1	0.06	0.44	0.46	0.76	0.85	0.87	0.90	0.92	0.93	0.98
TATFT2_17_2	0.08	0.35	0.36	0.75	0.93	0.94	0.95	0.96	0.97	1.00
TATFT2_18_1	0.04	0.37	0.58	0.66	0.66	0.75	0.77	0.89	0.91	0.97
TATFT2_18_2	0.00	0.20	0.24	0.24	0.24	0.71	0.92	0.92	0.93	0.96
TATFT2_19	0.60	0.74	0.88	0.89	0.89	0.91	0.91	0.91	0.92	0.99
TATFT2_21	0.33	0.33	0.77	0.77	0.80	0.80	0.81	0.82	0.86	0.95
TATFT2_5_2	0.65	0.65	0.75	0.75	0.79	0.79	0.81	0.83	0.85	0.98
TATFT2_6_1	0.00	0.35	0.90	0.90	0.91	0.91	0.91	0.92	0.93	0.99
TATFT2_6_2	0.03	0.51	0.92	0.92	0.93	0.93	0.93	0.93	0.93	0.99
TATFT2_7	0.47	0.50	0.57	0.58	0.68	0.72	0.76	0.82	0.86	0.94
TATFT2_8	0.01	0.63	0.63	0.64	0.64	0.66	0.70	0.78	0.82	0.95
TATFT2_9	0.25	0.51	0.60	0.74	0.75	0.78	0.83	0.83	0.83	0.97

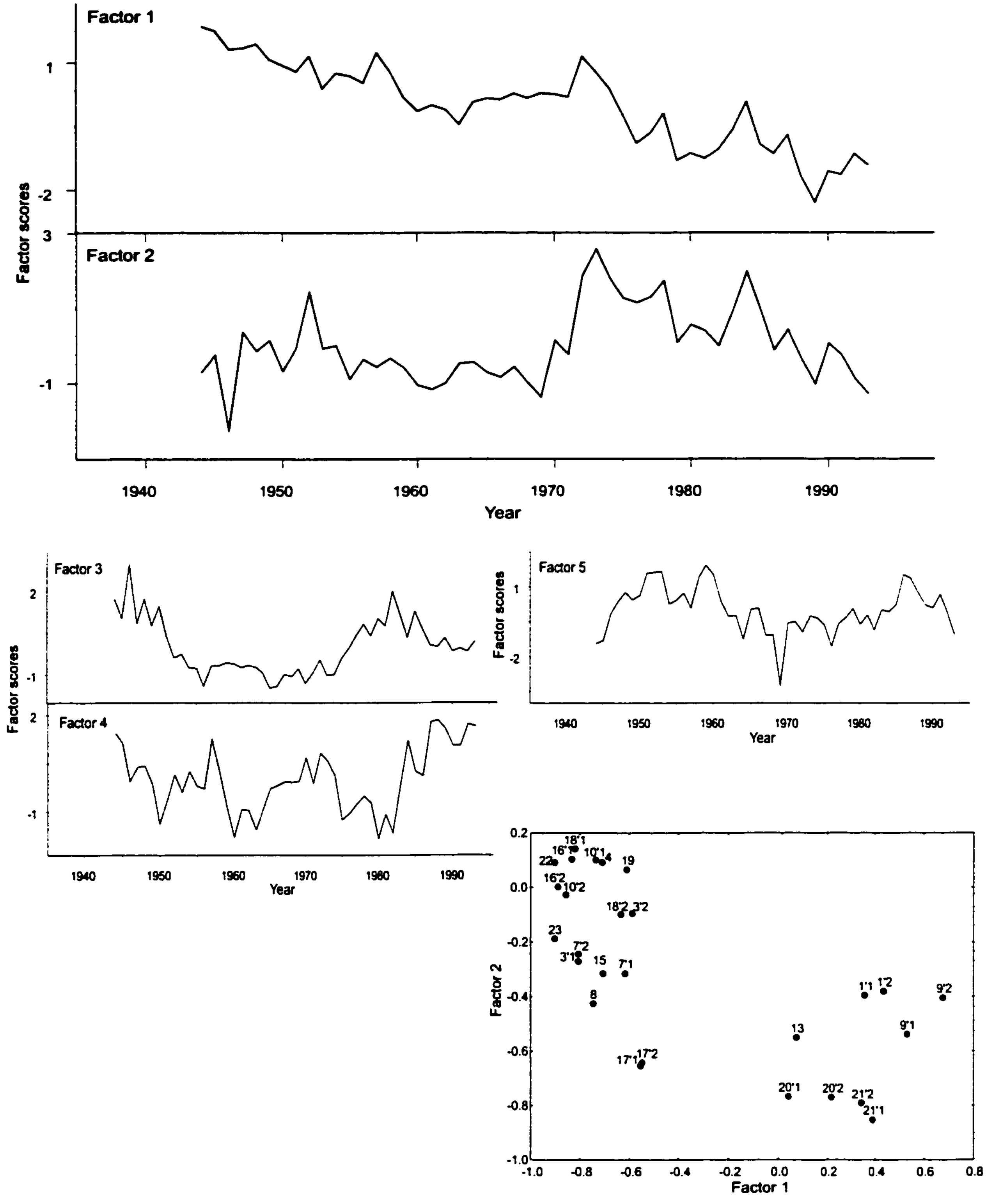


Figure C-3 Component scores and loadings for the Bear Creek forest.

Table C-5 Eigenvalues obtained from the PCA for the Bear Creek forest

Factor	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	11.44	42.37	11.44	42.37
2	5.04	18.66	16.48	61.03
3	2.93	10.84	19.41	71.87
4	1.81	6.69	21.21	78.56
5	1.18	4.38	22.39	82.94

Table C-6 Communalities for the Bear Creek forest

Series	From 1 Factor	From 2 Factors	From 3 Factors	From 4 Factors	From 5 Factors	Multiple R-Square
BeF1_1	0.13	0.28	0.85	0.85	0.87	0.96
BeF1_2	0.19	0.33	0.86	0.87	0.87	0.97
BeF9_1	0.28	0.57	0.70	0.76	0.86	0.93
BeF9_2	0.46	0.62	0.67	0.81	0.86	0.94
BeF21_1	0.15	0.87	0.88	0.92	0.92	0.95
BeF21_2	0.12	0.74	0.75	0.83	0.84	0.94
BeF16_1	0.70	0.71	0.75	0.77	0.91	0.96
BeF16_2	0.79	0.79	0.83	0.83	0.91	0.94
BeF17_1	0.31	0.74	0.77	0.88	0.88	0.99
BeF17_2	0.30	0.71	0.75	0.84	0.84	0.98
BeF20_1	0.00	0.59	0.61	0.69	0.74	0.87
BeF20_2	0.05	0.64	0.64	0.71	0.77	0.80
BeF4	0.51	0.52	0.56	0.59	0.59	0.92
BeF10_1	0.54	0.56	0.82	0.82	0.82	0.96
BeF10_2	0.73	0.74	0.84	0.88	0.88	0.95
BeF13	0.01	0.31	0.70	0.86	0.87	0.92
BeF15	0.50	0.60	0.74	0.76	0.90	0.92
BeF18_1	0.67	0.69	0.69	0.74	0.82	0.88
BeF18_2	0.40	0.41	0.42	0.50	0.77	0.79
BeF19	0.37	0.38	0.65	0.67	0.72	0.79
BeF22	0.82	0.83	0.92	0.95	0.95	0.98
BeF23	0.82	0.85	0.87	0.87	0.88	0.98
BeF3_1	0.65	0.72	0.72	0.88	0.88	0.91
BeF3_2	0.35	0.36	0.44	0.60	0.60	0.83
BeF7_1	0.38	0.48	0.49	0.72	0.77	0.90
BeF7_2	0.65	0.71	0.72	0.84	0.86	0.94
BeF8	0.56	0.74	0.76	0.79	0.83	0.89

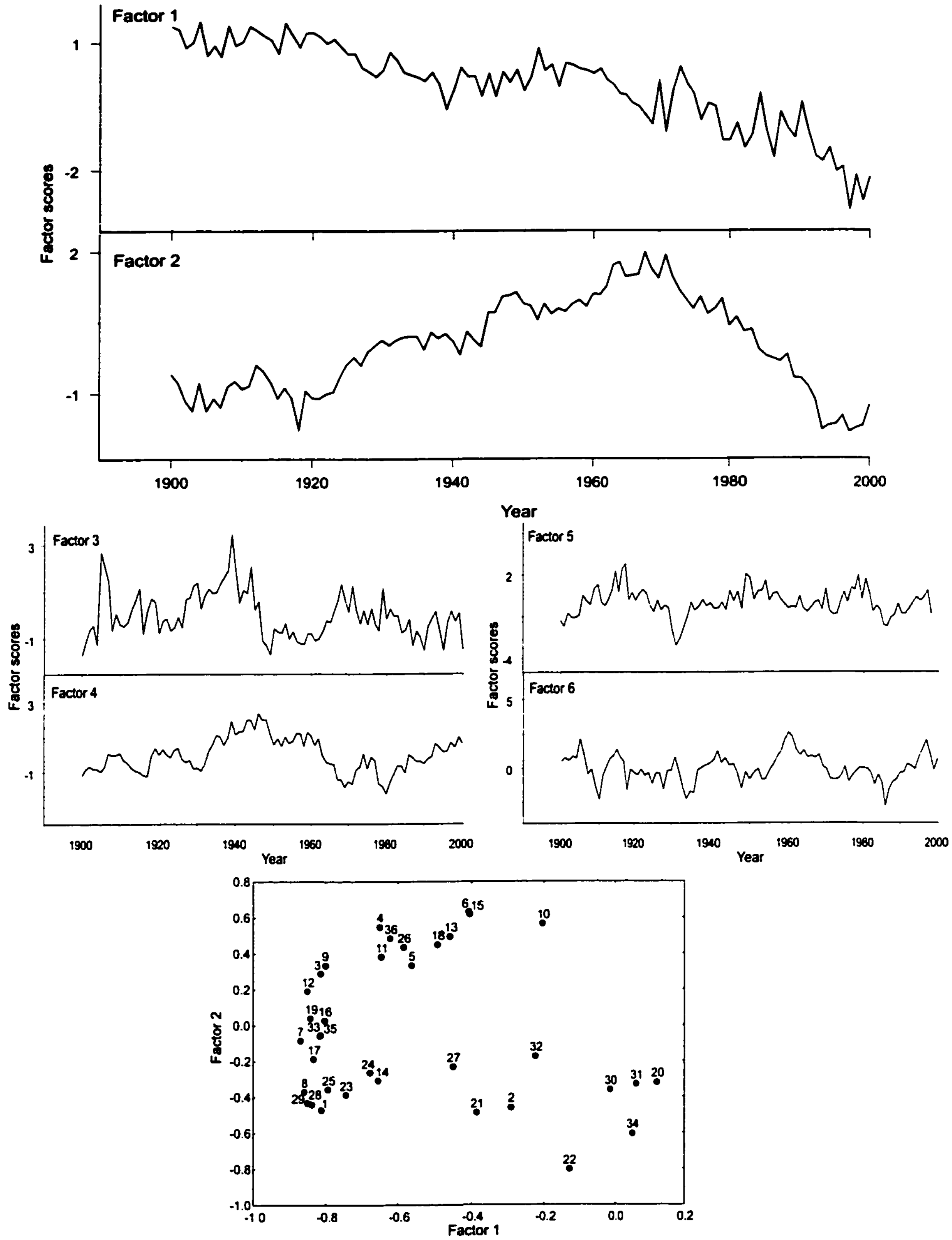


Figure C-4 Component scores and loadings for the Bear Creek forest-tundra.

Table C-7 Eigenvalues otained from the PCA for the Bear Creek forest-tundra

Factor	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	17.73	39.41	17.73	39.41
2	9.41	20.91	27.15	60.32
3	3.38	7.52	30.53	67.84
4	2.35	5.21	32.88	73.06
5	1.86	4.12	34.73	77.18
6	1.56	3.47	36.29	80.65
7	1.11	2.46	37.40	83.11

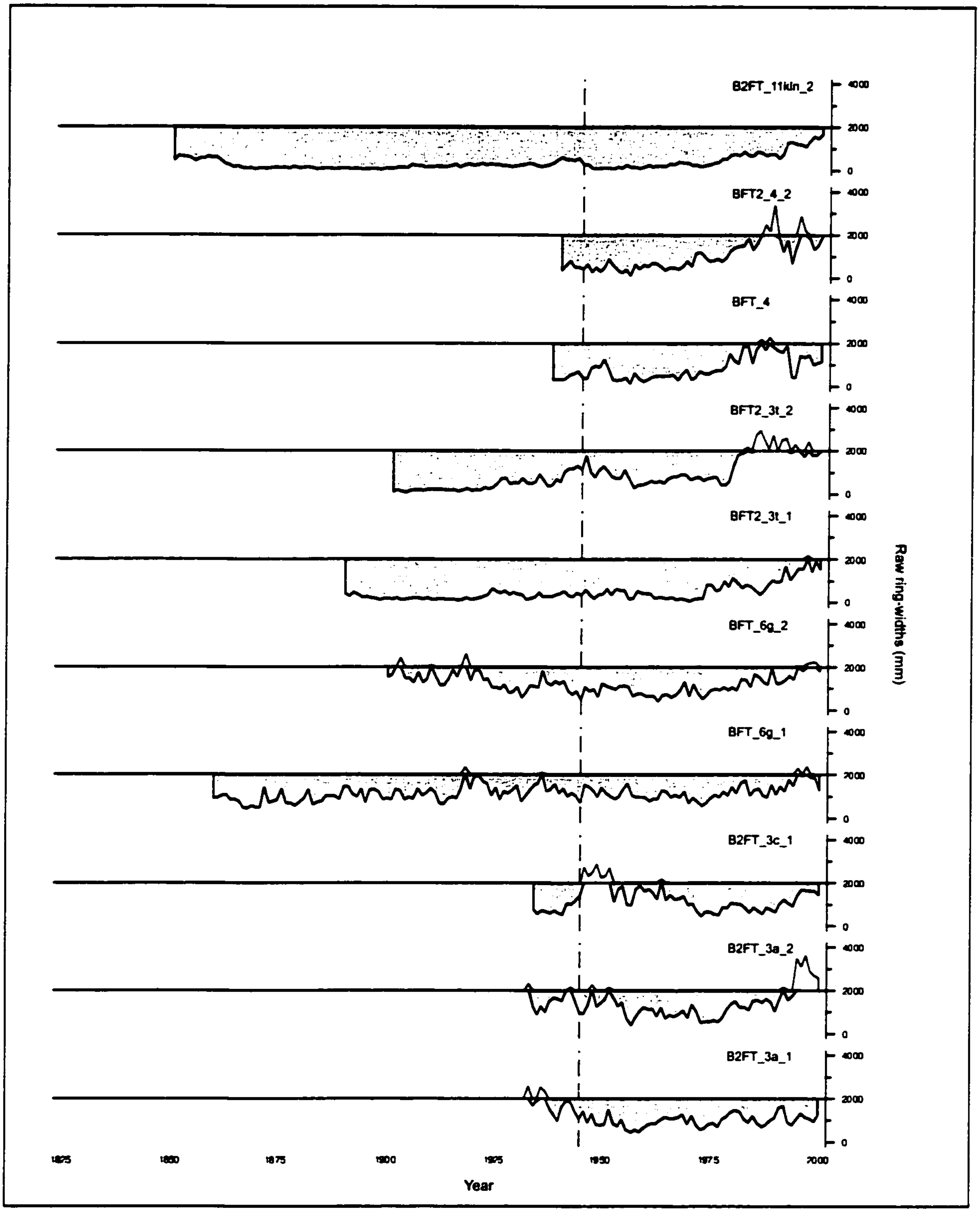
Table C-8 Communalities for the Bear Creek forest-tundra

Series	ID	From 1 Factor	From 2 Factors	From 3 Factors	From 4 Factors	From 5 Factors	From 6 Factors	From 7 Factors	Multiple R-Square
BFT.8d'1	1	0.66	0.88	0.91	0.92	0.92	0.92	0.92	0.95
BFT.8d'2	2	0.08	0.29	0.32	0.42	0.55	0.57	0.69	0.80
B2FT.5a'1	3	0.67	0.75	0.75	0.84	0.86	0.86	0.86	0.99
B2FT.5a'2	4	0.42	0.73	0.75	0.76	0.79	0.79	0.79	0.89
B2FT2.11b	5	0.32	0.43	0.55	0.60	0.61	0.61	0.62	0.76
B2FT2.11c	6	0.17	0.55	0.57	0.69	0.70	0.71	0.71	0.85
B2FT2.11e'1	7	0.76	0.77	0.79	0.81	0.84	0.84	0.84	0.91
B2FT2.11e'2	8	0.74	0.88	0.88	0.88	0.92	0.92	0.92	0.95
BFT.5a'2	9	0.64	0.76	0.76	0.83	0.87	0.87	0.87	0.99
BFT3.4khj	10	0.04	0.36	0.40	0.69	0.71	0.72	0.73	0.81
BFT3.6ab'1	11	0.42	0.57	0.57	0.68	0.73	0.74	0.77	0.82
BFT3.6ab'2	12	0.73	0.76	0.79	0.79	0.81	0.84	0.87	0.91
BFT.5b'1	13	0.21	0.46	0.46	0.75	0.75	0.76	0.76	0.82
B2FT2.11fjhig	14	0.43	0.52	0.53	0.54	0.72	0.77	0.82	0.87
B2FT2.11mq'2	15	0.17	0.57	0.76	0.76	0.76	0.77	0.78	0.88
B2FT2.11rs'1	16	0.65	0.65	0.71	0.73	0.74	0.76	0.76	0.82
B2FT2.11rs'2	17	0.70	0.73	0.76	0.76	0.78	0.80	0.81	0.88
B2FT2.7jjii'1	18	0.24	0.45	0.47	0.66	0.67	0.84	0.85	0.84
B2FT2.7jjii'2	19	0.71	0.71	0.74	0.74	0.75	0.84	0.85	0.92
BFT.6c	20	0.02	0.12	0.18	0.39	0.68	0.70	0.77	0.63
BFT.6g'1	21	0.15	0.38	0.39	0.44	0.52	0.55	0.59	0.81
BFT.6g'2	22	0.02	0.66	0.66	0.67	0.72	0.73	0.74	0.87
BFT.8c'1	23	0.55	0.70	0.75	0.79	0.82	0.82	0.86	0.91
BFT.8c'2	24	0.46	0.53	0.61	0.61	0.68	0.70	0.71	0.85
BFT2.3t'1	25	0.63	0.76	0.80	0.80	0.81	0.81	0.81	0.89
BFT.k5a'1	26	0.34	0.53	0.53	0.59	0.62	0.67	0.87	0.85
BFT.k5a'2	27	0.20	0.26	0.28	0.29	0.30	0.75	0.86	0.81
B2FT2.11kln'1	28	0.70	0.90	0.91	0.91	0.92	0.93	0.93	0.97
B2FT2.11kln'2	29	0.73	0.91	0.91	0.91	0.92	0.92	0.92	0.97
BFT3.1cd'1	30	0.00	0.13	0.77	0.81	0.83	0.91	0.95	0.98
BFT3.1cd'2	31	0.00	0.11	0.79	0.81	0.84	0.92	0.95	0.97
BFT3.1m'1	32	0.05	0.08	0.24	0.25	0.39	0.41	0.61	0.72
BFT3.1m'2	33	0.67	0.67	0.69	0.69	0.69	0.69	0.72	0.86
BFT.8hi'1	34	0.00	0.36	0.37	0.38	0.65	0.67	0.71	0.78
BFT.k5b'1	35	0.66	0.67	0.67	0.73	0.73	0.80	0.84	0.89
BFT.k5b'2	36	0.39	0.62	0.68	0.72	0.72	0.83	0.87	0.90

RAW RING-WIDTH MEASUREMENTS

The raw ring-width series included in the four chronologies developed in this study are presented. The raw ring-width series were plotted using a SAS program written by D. E. Atkinson. The program individually plots each ring-width series providing a visualization of the trends within the series. This visualization was useful when selecting the appropriate detrending method to remove all non-climatic noise and maintain the climate signal.

Bear Creek Forest-Tundra



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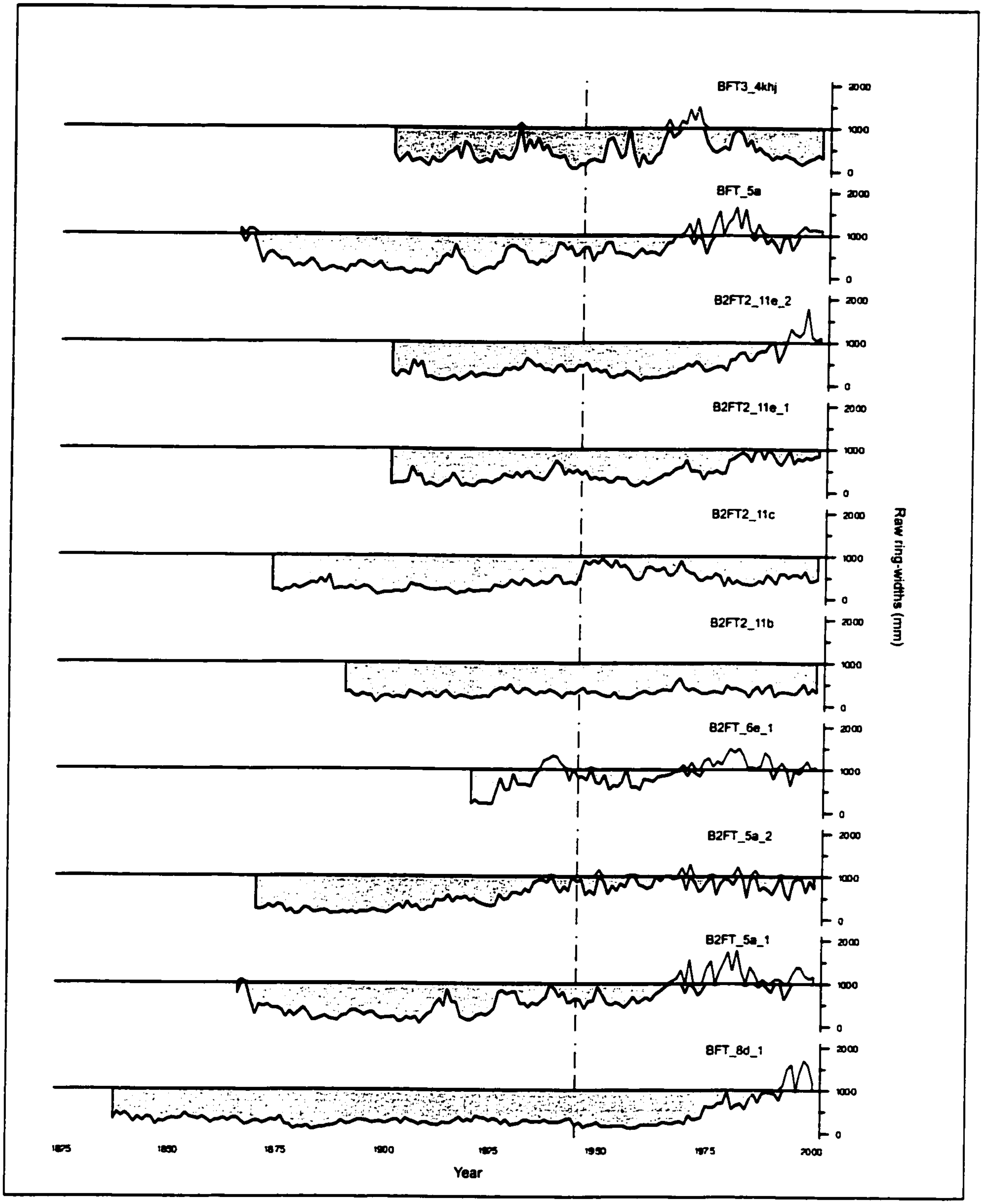

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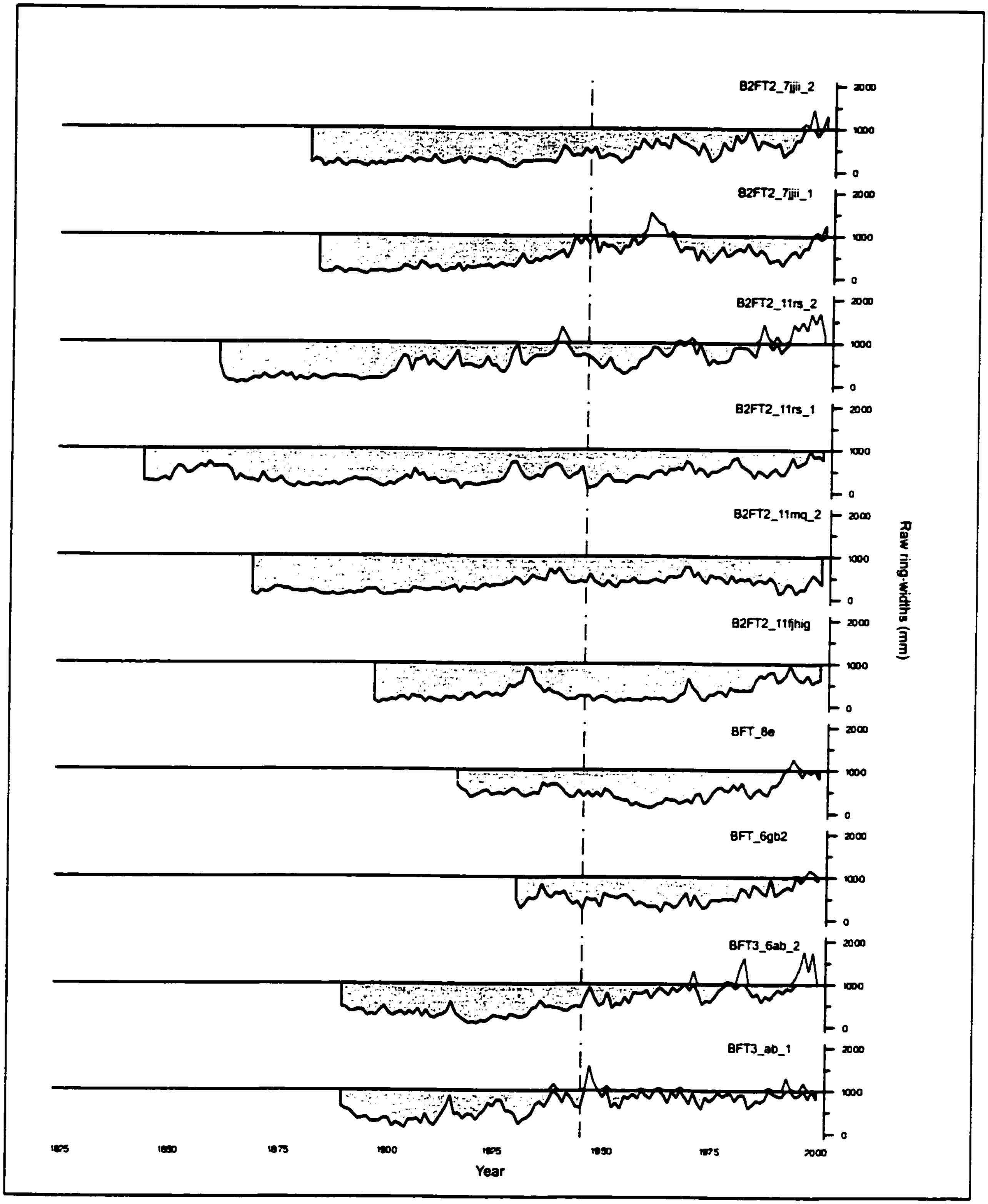

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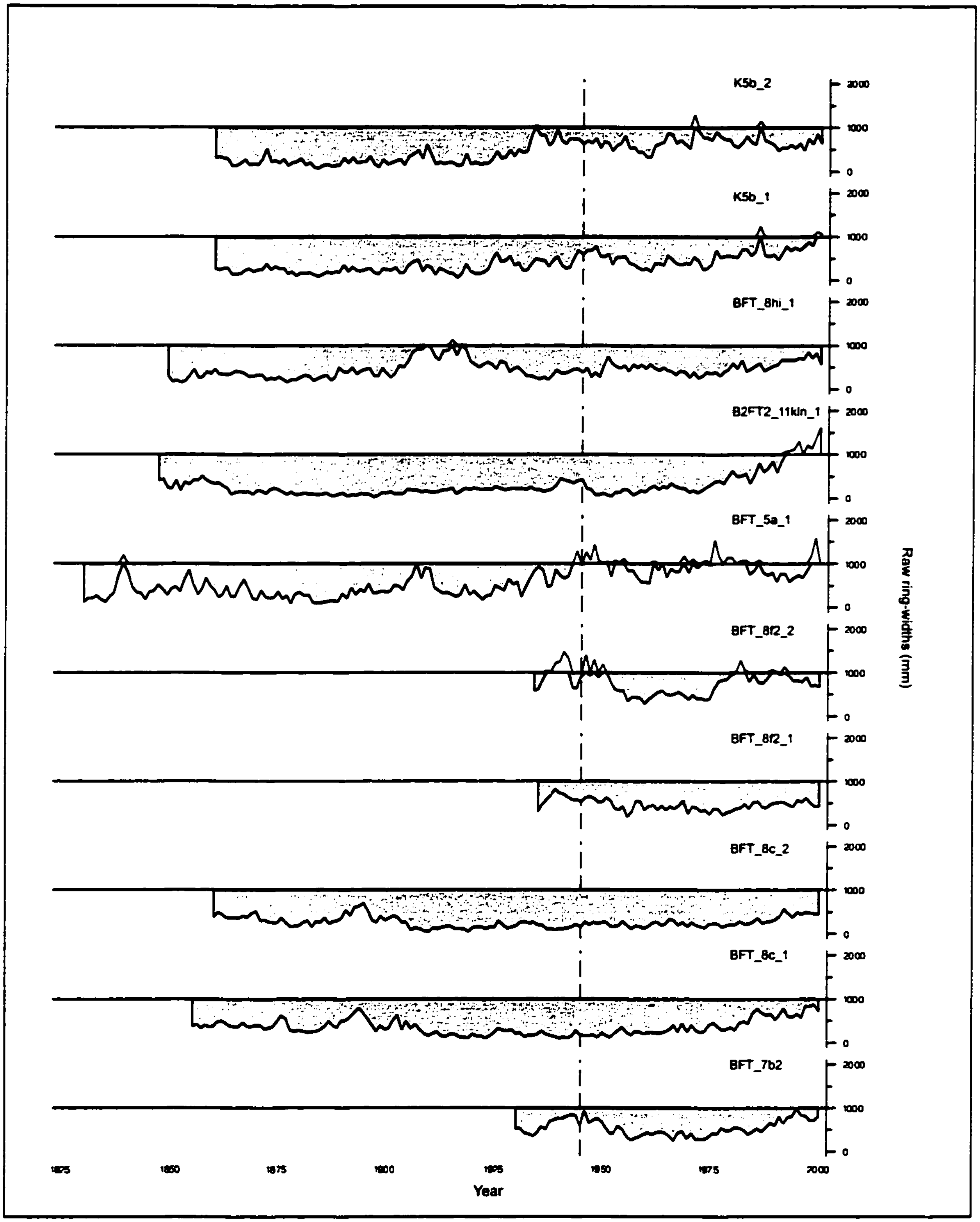

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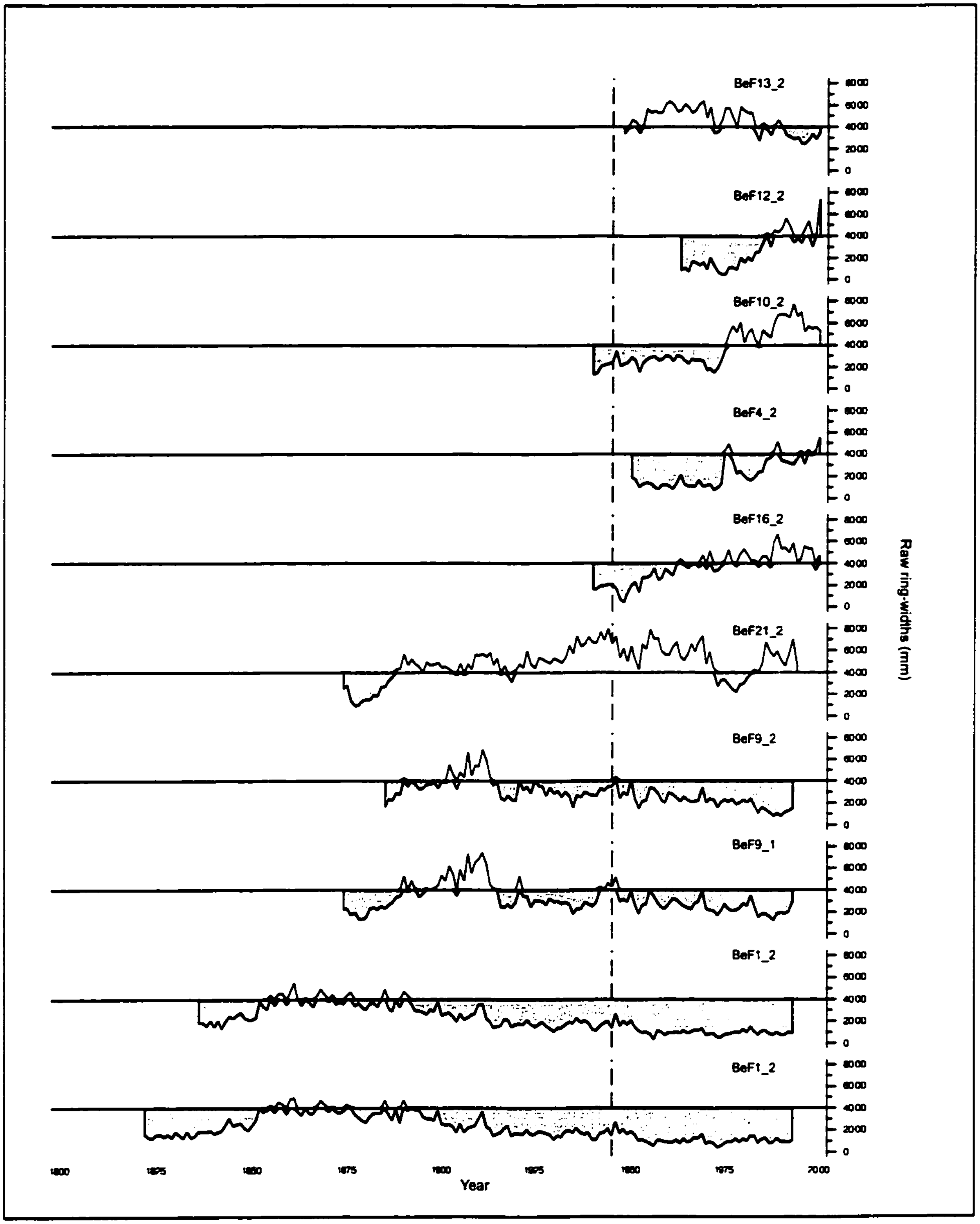

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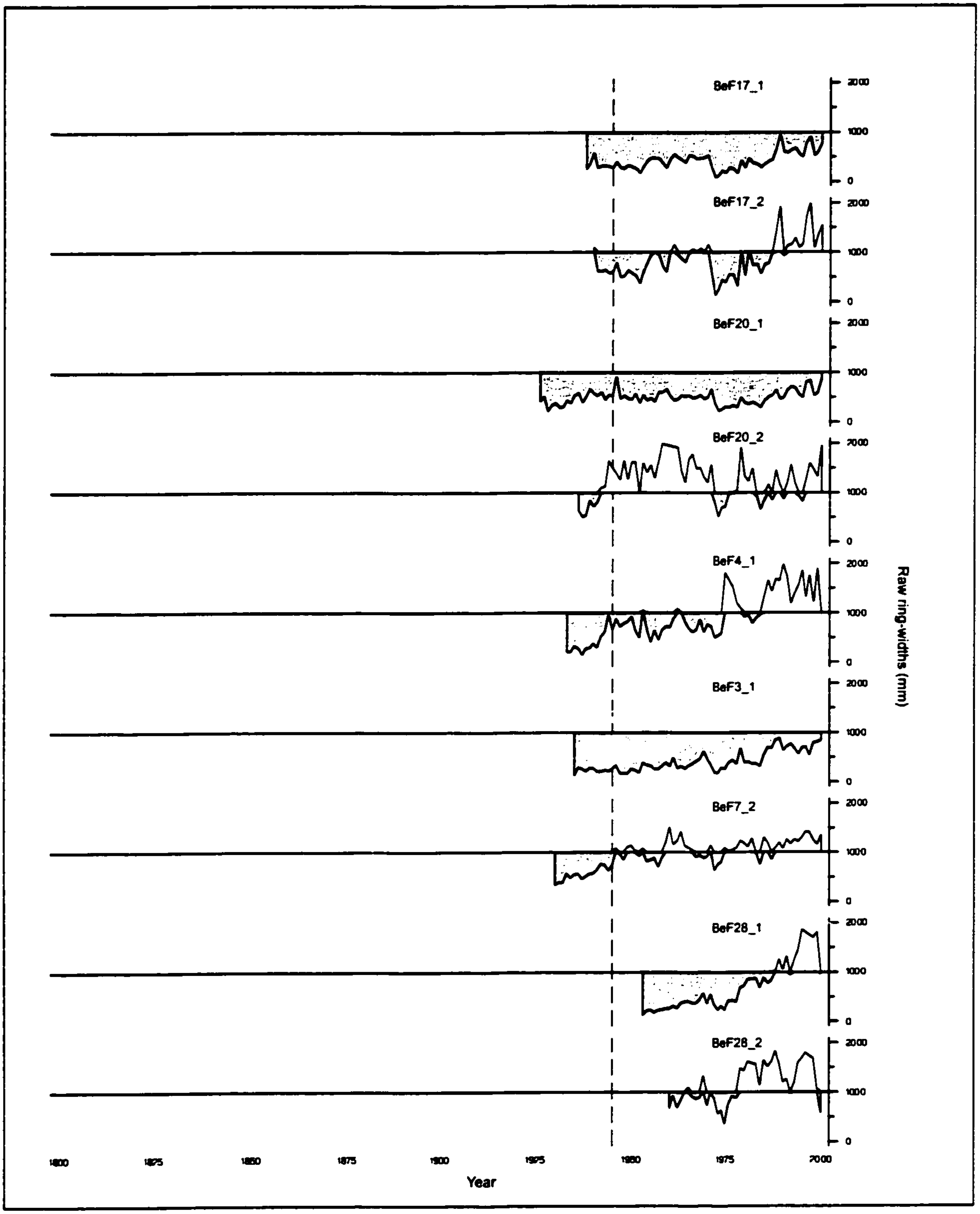

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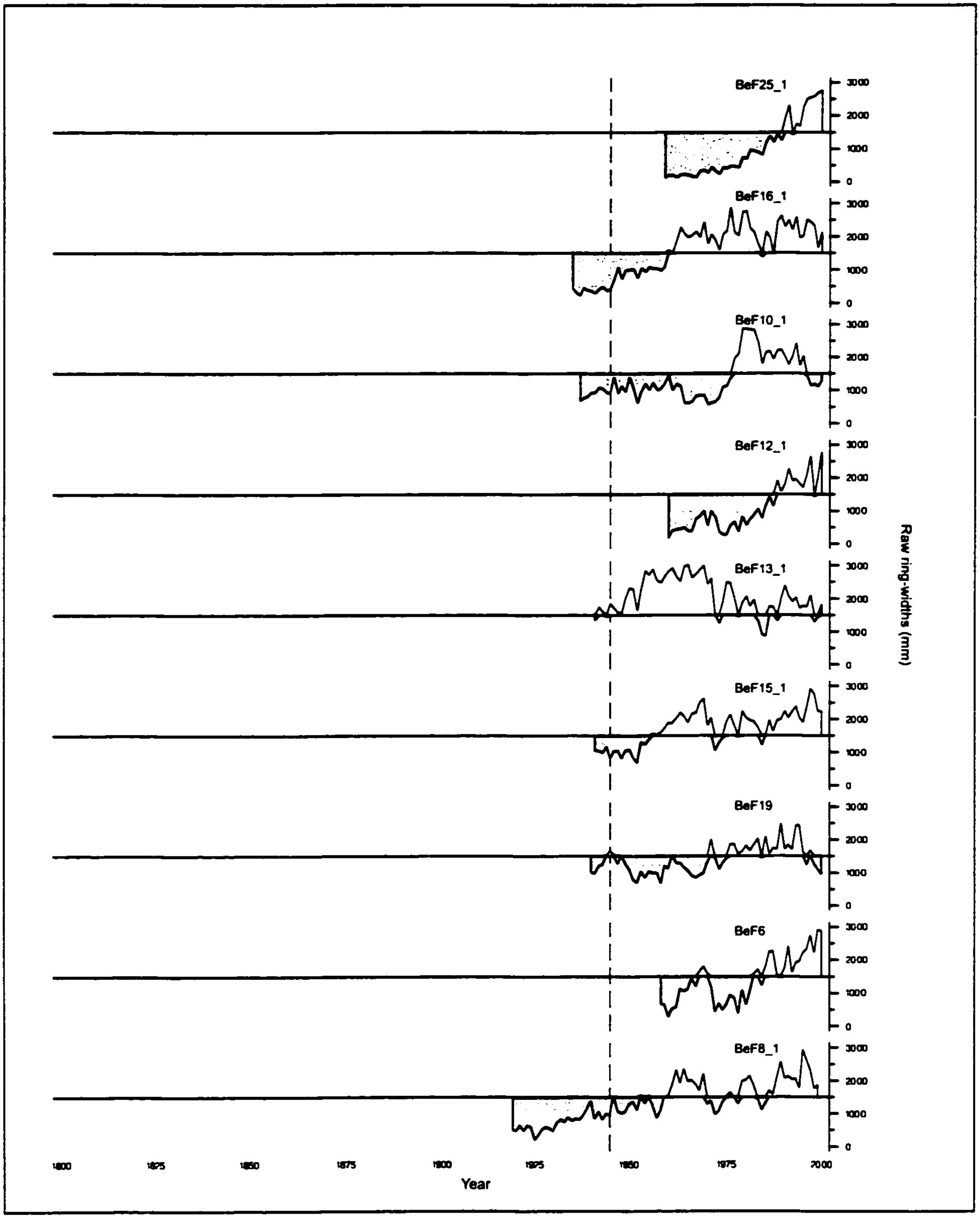

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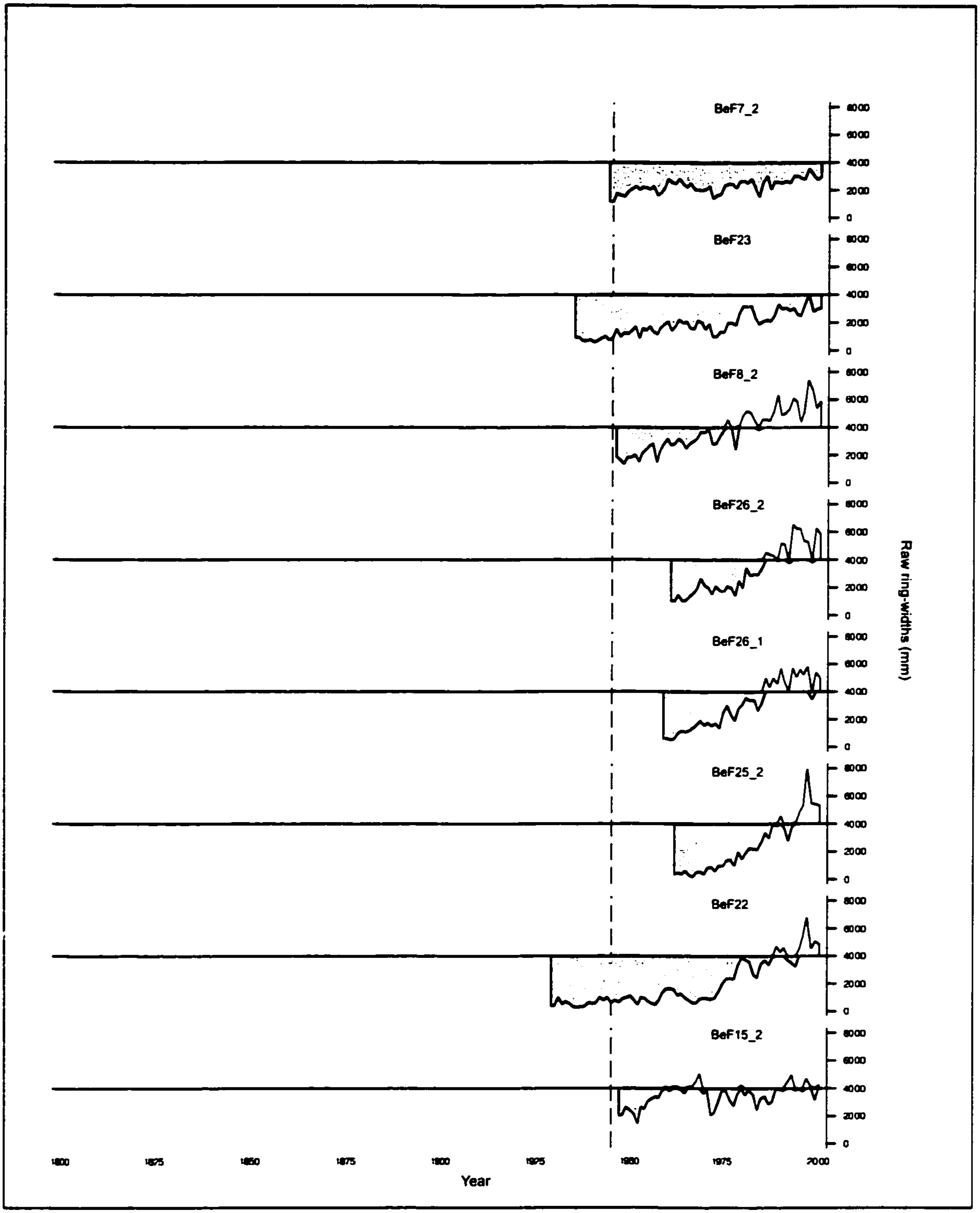

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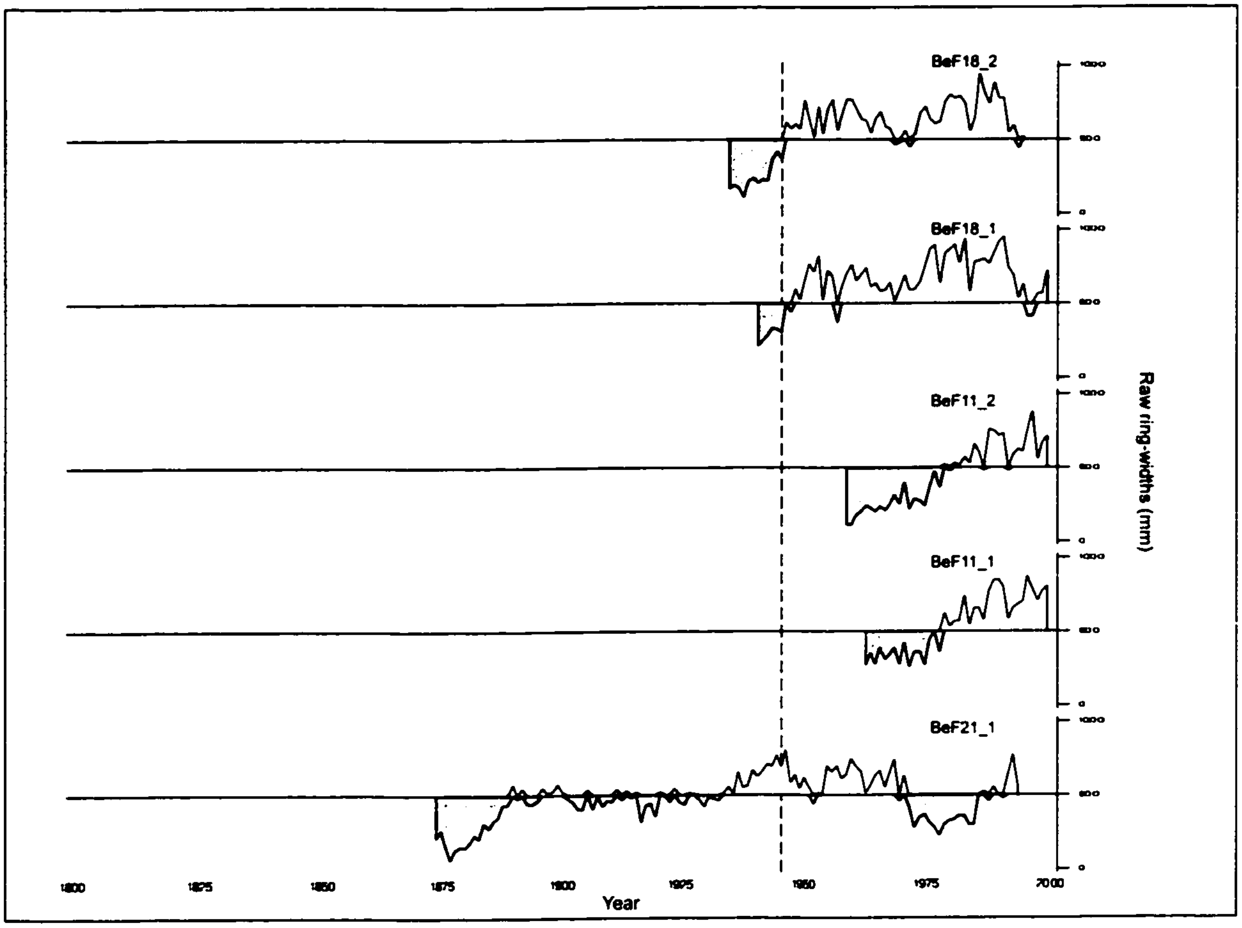

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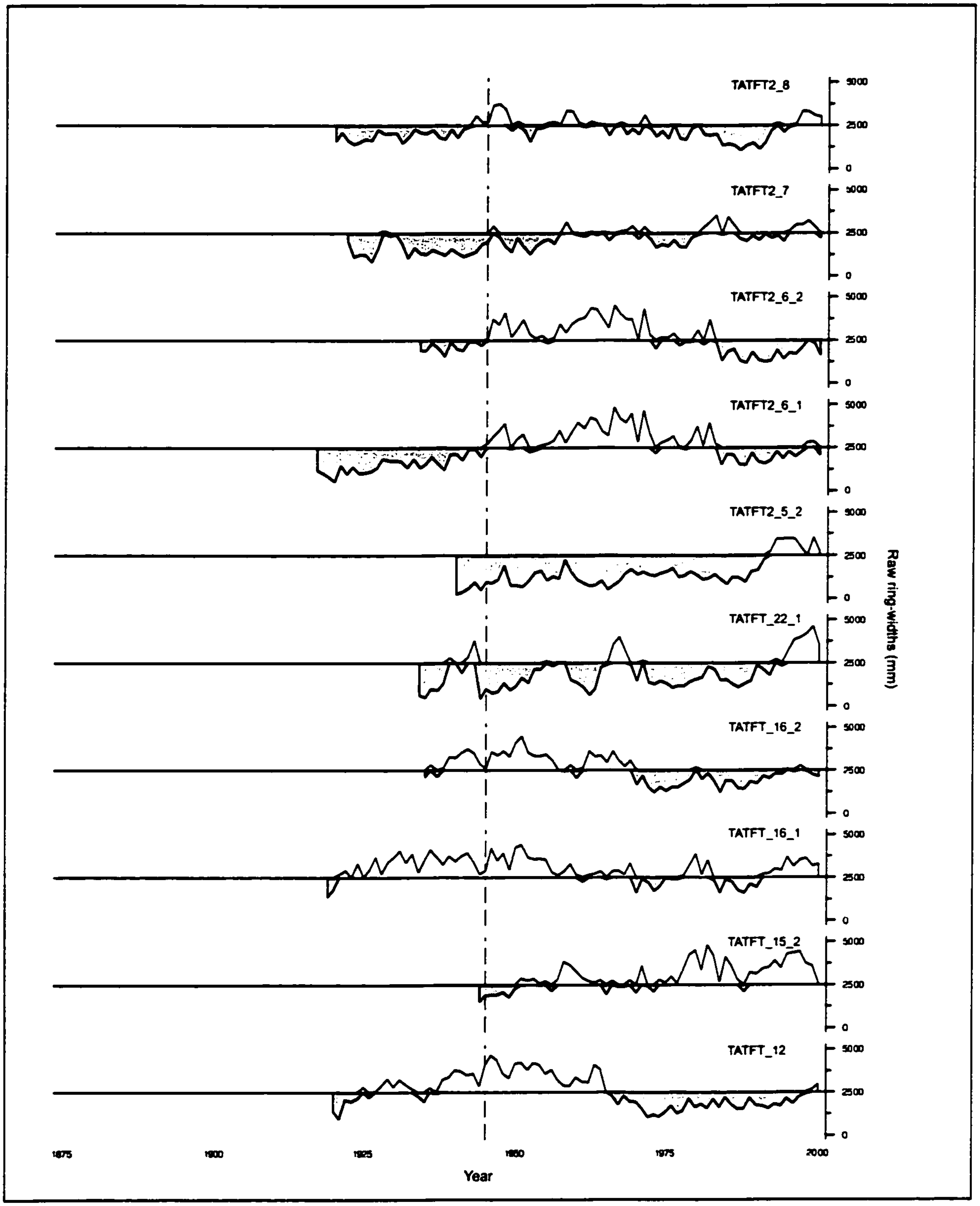

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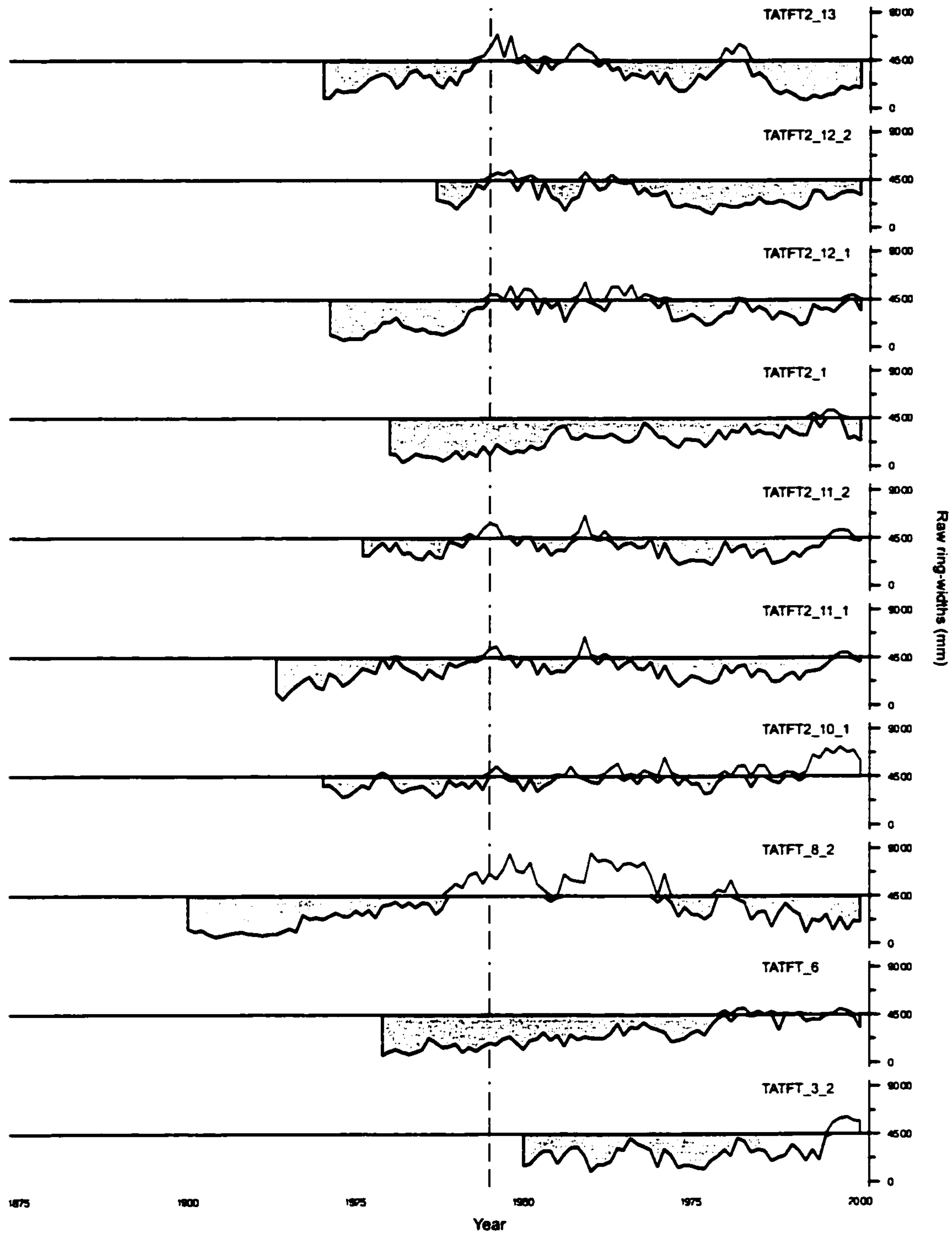

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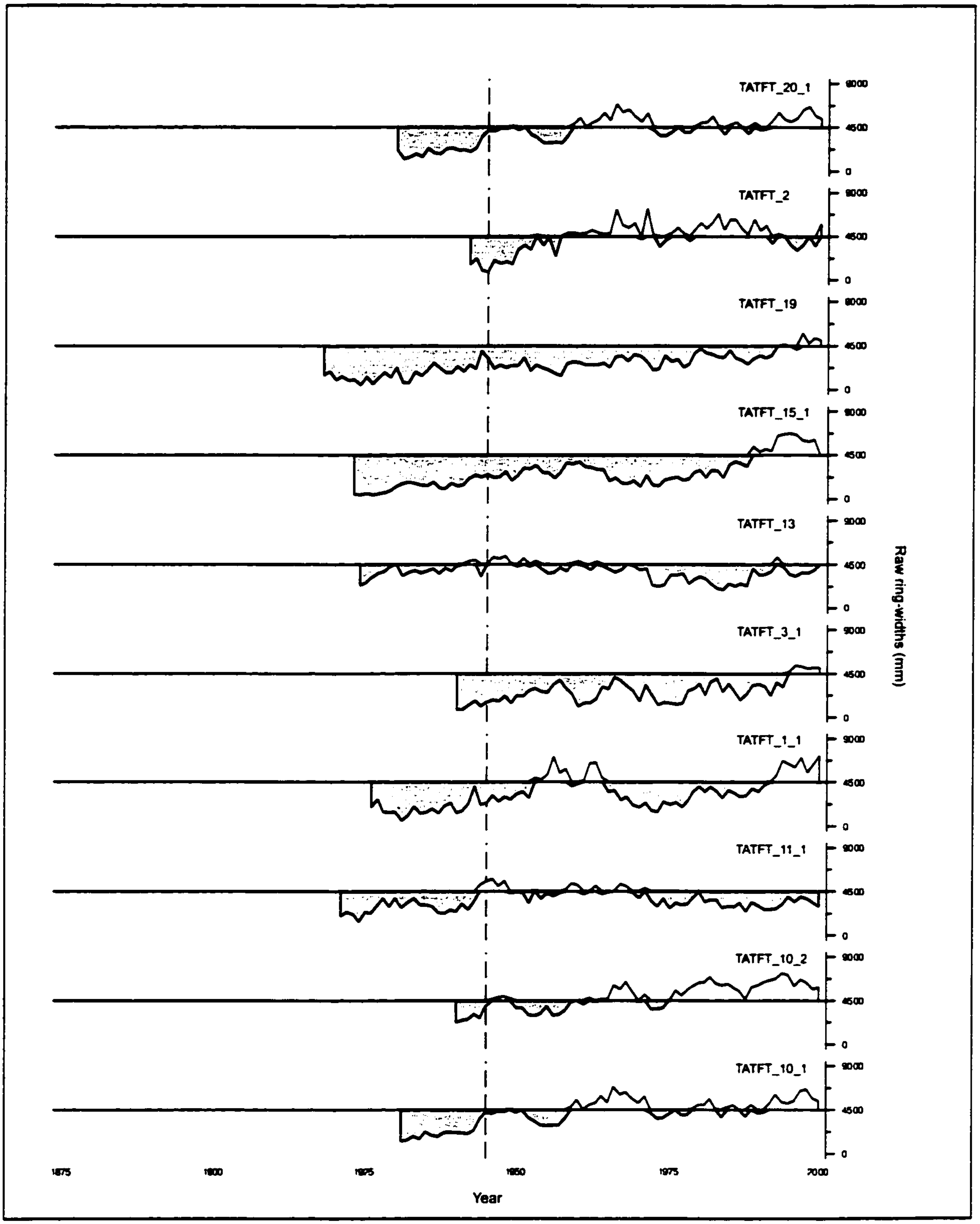

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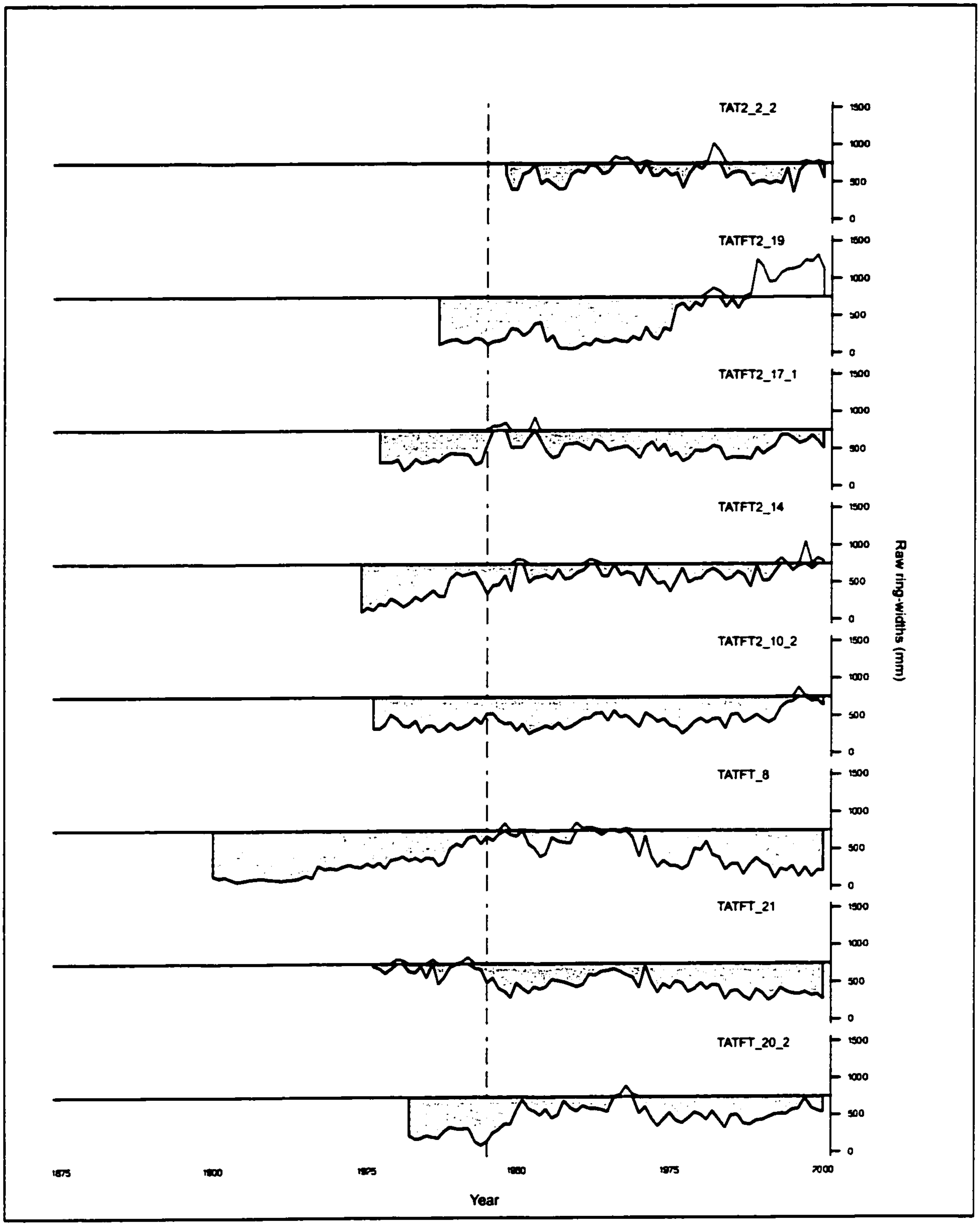

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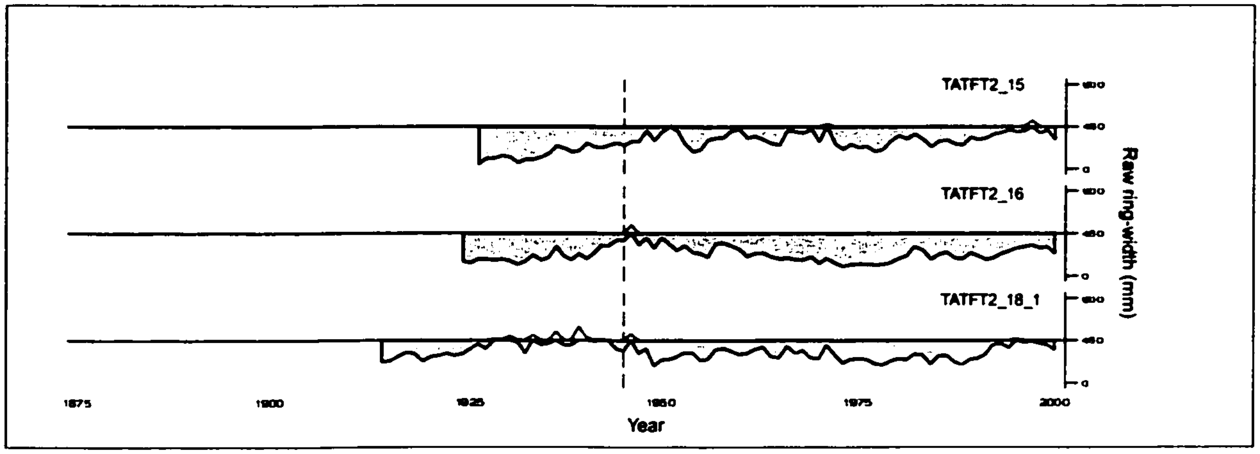

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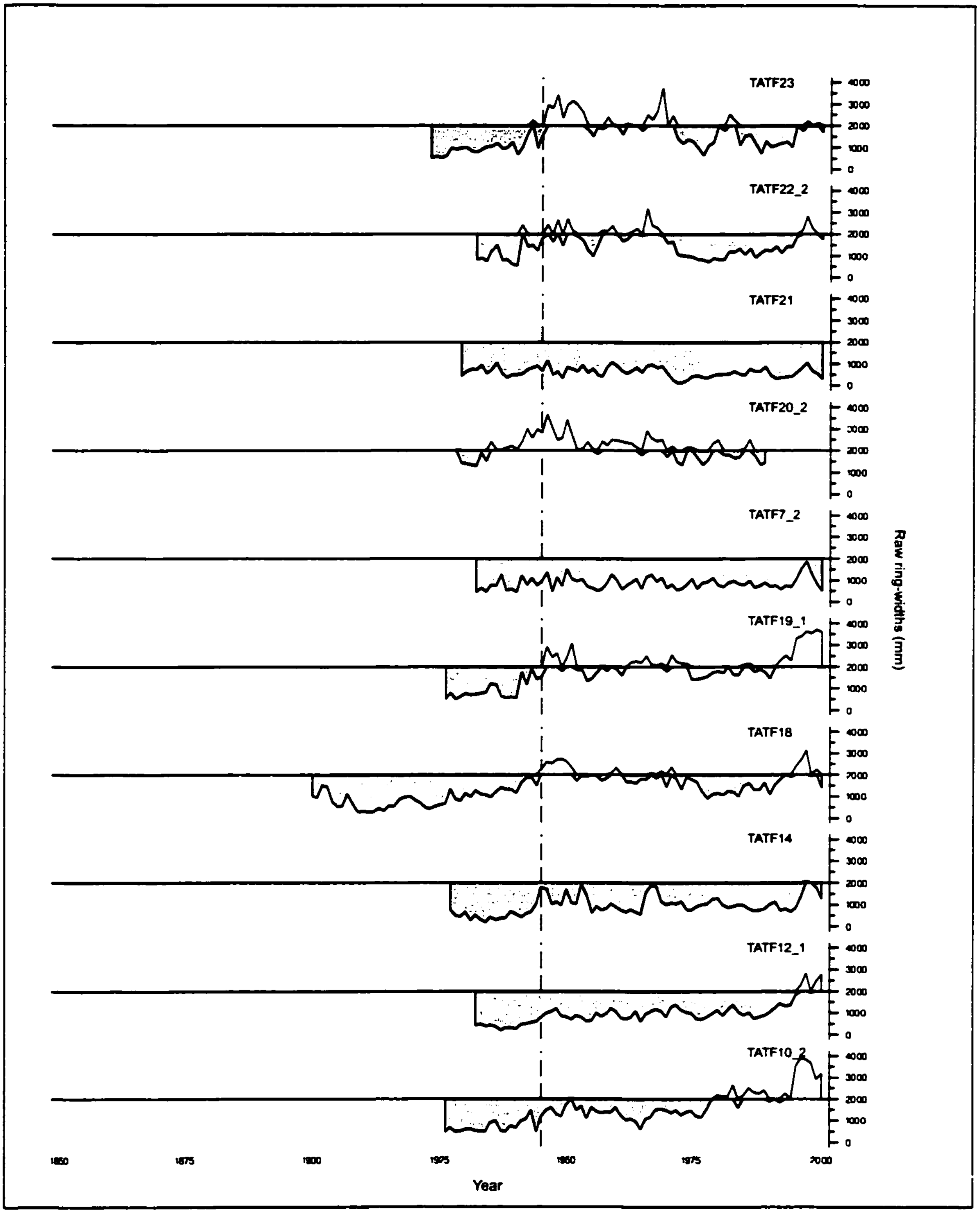

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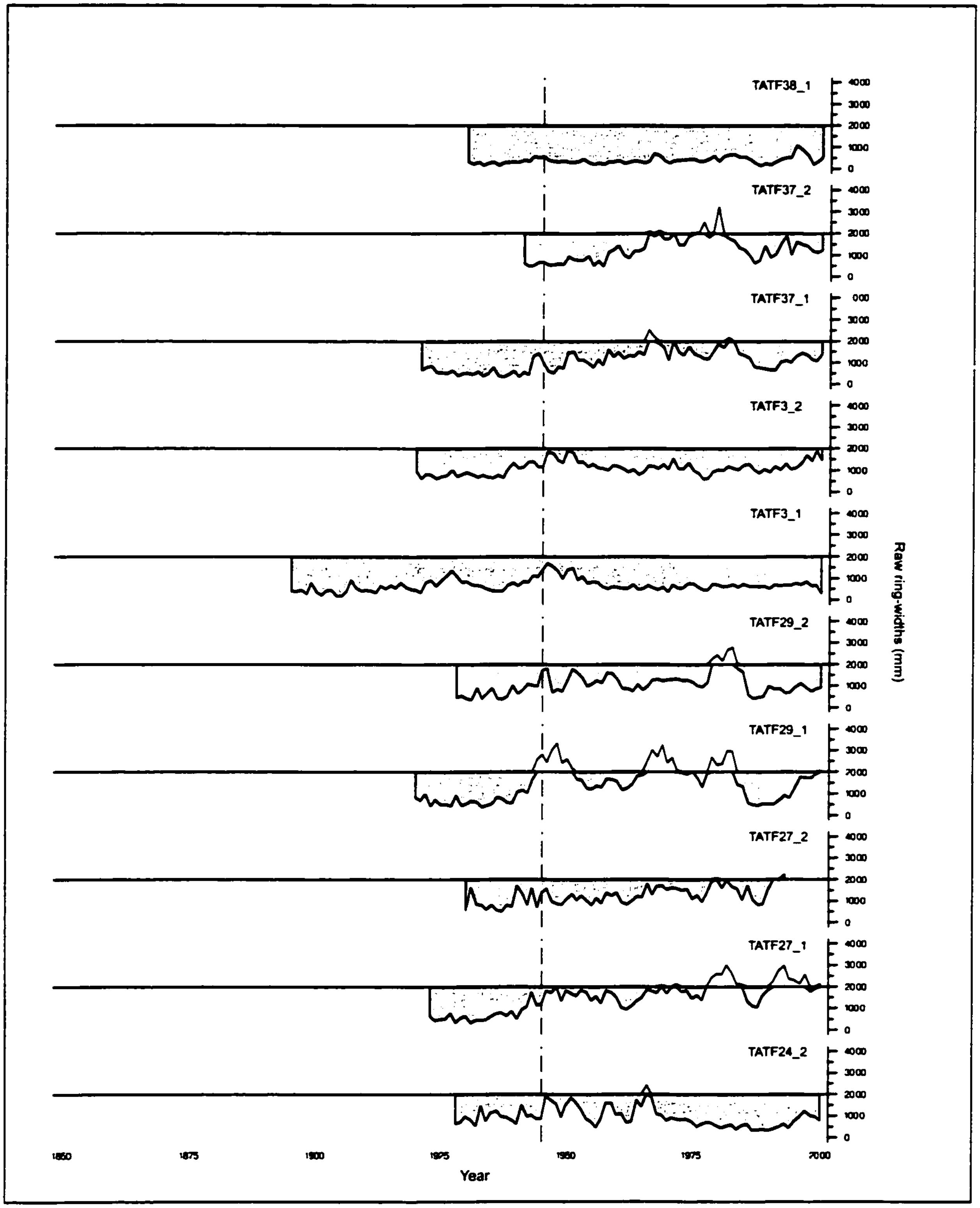

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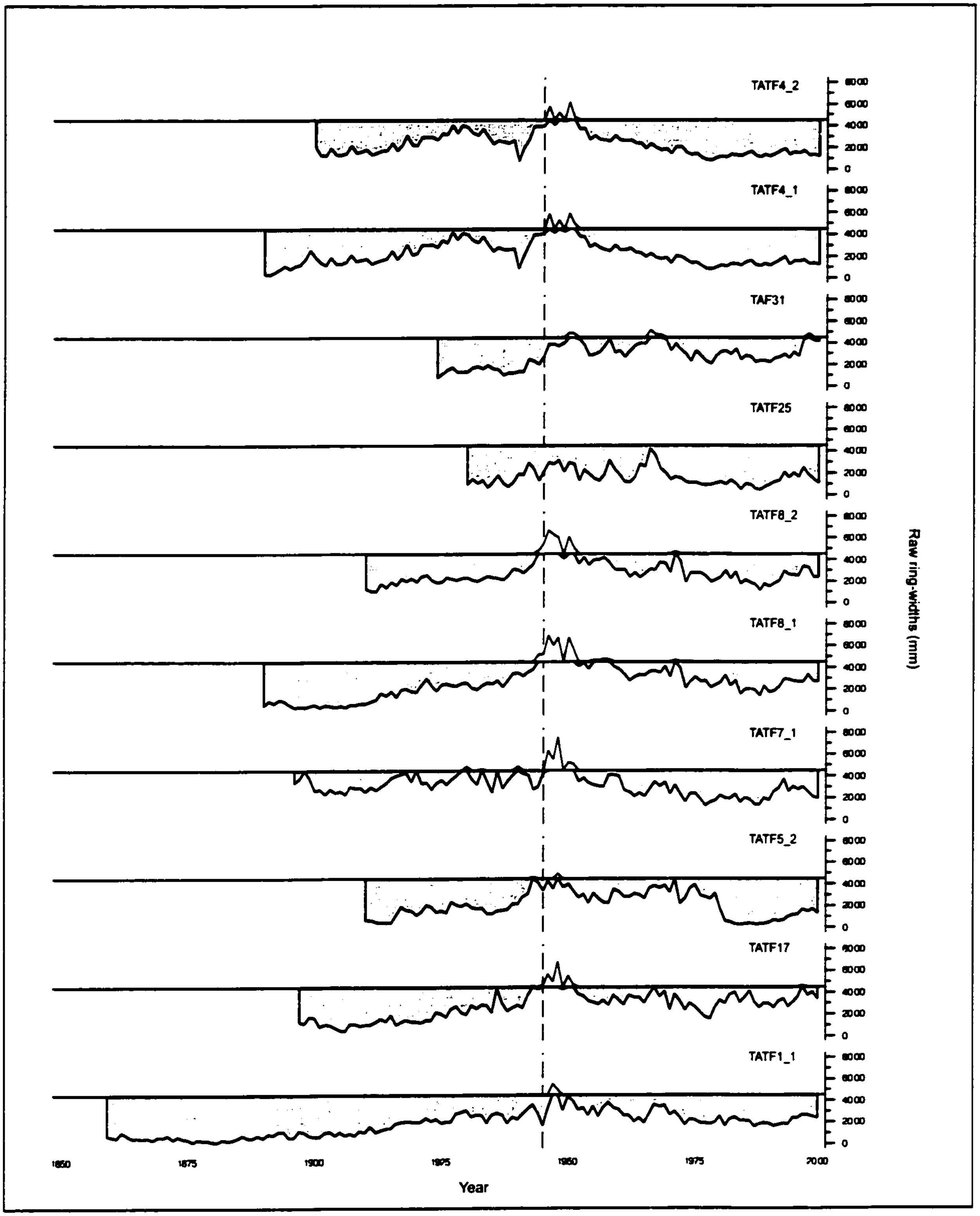

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