GROWTH AND DIEBACK OF ASPEN FORESTS IN THE GRANDE PRAIRIE AREA IN RELATION TO CLIMATE AND INSECTS

E.H. (Ted) Hogg[1], James P. Brandt[1], and Bob Kochtubajda[2]

Final Report to Weyerhaeuser Canada Ltd.

Grande Prairie Operations

31 October 1998

[1] Canadian Forest Service, Northern Forestry Centre, 5320-122 Street, Edmonton AB T6H 3S5

[2] Atmospheric Environment Branch, Room 200, 4999-98 Avenue, Edmonton AB T6B 2X3

Please address all inquiries concerning this report to:

E.H. (Ted) Hogg

phone (403)-435-7225
fax (403)-435-7359
e-mail: thogg@nrcan.gc.ca

EXECUTIVE SUMMARY

Observations of aspen dieback, dating back to the period 1990-92, have been reported from the Grande Prairie area of northwestern Alberta. Aspen dieback was reported initially by Henry J. Pirker (Peace Country Agricultural Protection Association, PCAPA), and subsequent aerial surveys by Cerezke and Gates (Canadian Forest Service, CFS) in August 1992 showed patches of aspen dieback in the valleys of the Smoky and Wapiti rivers near Grande Prairie. The issue of aspen dieback in the region was later raised as part of a statement of concern by the PCAPA to the Clean Air Strategic Alliance of Alberta (CASA).

As a separate initiative, the present study was conducted to examine how past climatic events and forest insects or pathogens may have contributed to the dieback of aspen in the Grande Prairie area. The objectives were 1) to determine the severity and extent of aspen dieback; 2) to conduct tree-ring analysis as a means of documenting the onset of reduced stem growth and crown dieback in declining aspen stands; 3) to examine the combined impacts of insect defoliation and climate variation on aspen growth and dieback; and 4) to conduct detailed forest health assessments to identify the likely importance of secondary infestations as factors contributing to the observed dieback.

The study area covered about 27000 km^2 surrounding Grande Prairie, including patches of aspen forest on predominantly agricultural land (white zone) and continuous aspen forest in the adjacent areas of provincial crown land (green zone) in the Forest Management Agreement areas of Weyerhaeuser Canada and Canadian Forest Products.

Aerial reconnaissance in June 1997 revealed little evidence of extensive, severe forest dieback. Severe aspen dieback was restricted mainly to small areas of aspen trees in flooded areas and on agricultural land, including heavily grazed areas, trees along fence lines and along stand edges or openings. In these areas, aspen would be exposed to a variety of stresses including soil compaction and damage by wind and sunscald.

Light dieback of aspen crowns was common throughout the white zone and was also encountered occasionally in the green zone. Those aspen stands showing significant crown dieback and/or evidence of damage by insects and fungal pathogens were considered to be "declining" for the purpose of this study, while unaffected aspen stands were considered to be "healthy".

Field sampling was conducted on a total of 18 pure aspen stands with ages ranging from 41 to 89 years. The sites included five healthy and declining stands in the white zone, and four healthy and declining stands in the green zone. Declining stands had a higher average percentage of dead aspen (33%) compared to healthy stands (17%), and about one-third of the live stems showed light (10-40%) dieback of crowns. However, only a small percentage of live stems showed severe (>40%) crown dieback, even in the declining stands (average of 9%). In general, the level of dieback was found to be considerably less than that observed in a previous study of aspen decline in western Saskatchewan.

Forest health assessments indicated that all nine of the declining stands sampled were affected by two or more of the following insects and diseases: poplar borer, root rot, conks, hypoxylon canker and leaf and twig blight. In contrast, few insects or diseases were encountered in healthy stands.

Tree-ring analysis was conducted on disks collected from ten trees per site (total of 180 aspen) at each of three heights (1.3, 5 and 10 m) in July 1997. The presence of white-coloured tree rings in the disks was used to indicate the years when stands were defoliated by forest tent caterpillar (FTC). The results using this method showed good agreement with the known history of FTC defoliation in the study area, based on the annual record of insect surveys by the Canadian Forest Service. Based on both methods, defoliation of aspen stands occurred during two major periods: 1958-64 and 1979-90. In both the green and white zone sites, aspen showed reduced stem growth during these periods, especially during years with severe defoliation.

In general, stands showed excellent growth during the 1970s and periods with reduced growth over the period since 1979. Declining stands in the green zone have shown weaker growth since 1966, when stands may have been impacted by a spring frost event. In the white zone, declining stands have shown reduced growth since 1981, which was an unusually dry year. However, the growth of most stands has shown significant recovery of stem growth since the early 1990s.

A dynamic regression model was used to examine the relative importance of insect defoliation and climatic factors in controlling the year-to-year variation of stem growth over the period 1950-96. Model results indicated that stem growth was most strongly affected by defoliation, while moisture and warmth during the growing season had a significant but smaller impact on the variation in growth. The results suggested that aspen growth was relatively more sensitive to moisture and less sensitive to growing season temperatures in the white zone, which is climatically warmer and drier because of its lower elevation.

Sections of dead and live branches were also collected from the crowns of trees showing dieback at the declining sites, for the purpose of dating when dieback occurred. Based on a limited sample, it appeared that most of the recent dieback occurred over the period 1990-95. Previous surveys in the study area indicated that significant dieback and stem mortality had already occurred by the summer of 1992.

A detailed analysis of the climate record was conducted to examine the possible role of extreme climatic events as a contributor to the observed forest dieback. Climate records from Grande Prairie and Beaverlodge indicated that summer drought was not a direct cause of the dieback, because no major droughts have occurred since 1988, and summers were generally wetter than average during the period 1981-96. However, during this same period, winters were significantly warmer with less snow cover when compared to the long-term record.

During four consecutive years (1990-93), snow cover was much below normal during the late winter period. This may have caused damage to aspen roots through soil drying and by increasing the likelihood of freeze-thaw events in the rooting zone. The winter of 1991-92 was particularly unusual: following periods of extreme cold in October, conditions were exceptionally mild with several brief cold periods. March 1992 was the warmest in history with negligible snow cover and early soil thaw, resulting in flowering of aspen by the end of the month. However, this was followed by another period of severe frost (-16°C) in April, which would have likely caused damage to aspen through damage to buds and roots, coupled with cavitation of xylem in the stems.

The results of this study indicate that several factors have contributed to the observed pattern of past growth and dieback of aspen in the Grande Prairie area. Past forest tent caterpillar defoliation caused periods of reduced growth and predisposed some stands to secondary infestations by wood-boring insects and fungal pathogens. Drought in 1981 also weakened the aspen at some sites, especially in the climatically-drier white zone. However, the results also indicate that dry, mild winters followed by severe spring frost in the early 1990s, especially 1991-92, would have caused additional stress and may have triggered the observed dieback in some stands. Since 1993, it appears that the moist climatic conditions and absence of major defoliation events have allowed significant recovery of most aspen stands throughout the study area, except for those most severely affected by insects and diseases.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES

INTRODUCTION

Trembling aspen (*Populus tremuloides* Michx.) is the most important deciduous tree species in the boreal forest of western Canada, both ecologically and commercially (Peterson and Peterson 1992). Trembling aspen is also common in the aspen parkland, a climatically drier vegetation zone in the Canadian prairie provinces that represents a transition between the boreal forest and the prairie grasslands to the south (Bird 1961; Hogg and Hurdle 1995).

Observations of aspen dieback, dating back to the period 1990-92, have been reported from the Grande Prairie area of NW Alberta. Aspen dieback was reported initially by Henry J. Pirker (Peace Country Agricultural Protection Association, PCAPA), and subsequent aerial surveys by Cerezke and Gates (Canadian Forest Service, CFS) in August 1992 showed patches of aspen dieback in the valleys of the Smoky and Wapiti rivers near Grande Prairie. The issue of aspen dieback in the region was later raised as part of a statement of concern by the PCAPA to the Clean Air Strategic Alliance (CASA).

As a separate initiative, the present study was conducted to examine how past climatic events and forest insects or pathogens may have contributed to the dieback of aspen in the Grande Prairie area. In a previous study (Hogg and Schwarz, submitted), it was found that aspen decline at the southern edge of the boreal forest near St. Walburg, Saskatchewan was initiated following defoliation of aspen by forest tent caterpillar (*Malacosoma disstria* Hbn.) in several successive years during the period 1979-1990. Major infestations of this insect have also been reported during this period in the Grande Prairie area, based on the records of the CFS Forest Insect and Disease Survey (Brandt 1995; see Appendix 1). Earlier studies have shown that repeated defoliation by forest tent caterpillar leads to reduced growth (Hildahl and Reeks 1960) and crown dieback (Batzer et al. 1954) of aspen stands. Insect defoliation may also increase the susceptibility of stands to infestation by wood-boring insects and fungal pathogens, leading to further dieback and eventual forest decline (Churchill et al. 1964; Hildahl and Campbell 1975; Houston 1992). Thus we postulated that insect defoliation has been a significant predisposing factor to the observed decline and dieback of aspen near Grande Prairie.

It is also important to consider the potential role of climatic factors and extreme weather events as contributors to forest dieback and decline. We postulated that moisture (drought) could be a significant factor, because lowlands in the Grande Prairie - Peace River area are climatically drier than the adjacent uplands (Hogg 1994). This area includes northern outliers of the aspen parkland zone, where summer drought leads to reduced productivity and periodic dieback of aspen stands (Zoltai et al. 1991; Hogg and Hurdle 1995). However, it is also important to consider the possible impact of extreme weather events including hail (Riley 1953) or winter thawing followed by severe spring frost (Cayford et al. 1959; Auclair et al. 1990; Braathe 1995).

The objectives of the present study were:

1) to determine the severity and extent of aspen dieback in the Grande Prairie area;

2) to conduct tree-ring analysis (dendrochronology) as a means of documenting the onset of reduced stem growth and crown dieback in declining aspen stands;

3) to apply the results of tree-ring analysis to examine the combined impacts of insect defoliation and climate variation on aspen growth and dieback; and

4) to conduct detailed forest health assessments to identify the potential contribution of secondary agents such as wood-boring insects and fungal pathogens as factors contributing to the observed dieback.

METHODS

Study area description

The study area covered about 27000 km^2 surrounding Grande Prairie, Alberta (Figure 1). The boundaries of the study area were latitude 56°00' N on the north, longitude 117°15' W on the east, latitude 54°40' N on the south, and the Alberta – British Columbia border on the west. Sites occurring in the contiguous boreal forest were located on provincial crown lands within the Forest Management Agreement areas of Weyerhaeuser Canada Ltd. and Canadian Forest Products. These areas within Alberta are part of what is commonly referred to as the "green zone". The remaining study sites occurred in more or less fragmented aspen forests within the "white zone", a general area of agricultural development on private land, but which also includes provincial parks and other small areas of provincial crown land (e.g. along rivers).

The study area is located within the Boreal Forest region of Rowe (1972), which includes the Lower Foothills (B.19a) and Mixedwood (B.18a) sections, as well as small areas classified as Aspen Grove (B.17), commonly referred to as aspen parkland. Pure aspen stands, and stands with aspen and balsam poplar (*Populus balsamifera* L.) are common, especially at the lower elevations. Aspen is also important component of mixedwood stands that include white spruce (*Picea glauca* [Moench] Voss) and other conifers. Common understorey plants found in association with aspen are prickly rose (*Rosa acicularis*), low-bush cranberry (*Viburnum edule*), saskatoon (*Amelanchier alnifolia*), Canada buffalo-berry (*Shepherdia canadensis*), and *green alder* (*Alnus crispa*) (Beckingham and Archibald 1996, Beckingham et al. 1996).

Climate of the Grande Prairie area

The climate of the area is continental, characterized by short, warm summers and long, cold winters (Phillips 1990). At Grande Prairie (elevation 669 m), the mean annual temperature is 1.2°C and mean monthly temperatures range from -17.7°C in January to 15.9°C in July (Environment Canada 1983). Average monthly precipitation is greatest during the summer months of June, July and August (60 to 70 mm) but is much less during the remaining months (19 to 37 mm).

Climate stations within 160 km of Grande Prairie are shown in Figure 2, and the locations and elevations are given in Table 1 for stations established before 1960. Weather data are collected year round at five sites, while most of the stations are fire lookouts that measure temperature and precipitation from May to September only. The climate record from these stations shows that areas at higher elevation (up to about 1500 m) have considerably cooler and moister climates than those at lower elevations in the white zone surrounding Grande Prairie (Figure 3).

Reconnaissance and site selection

Initial site selection in June 1997 was based on an aerial reconnaissance of the study area followed by additional reconnoitering on the ground. Sites were selected along two levels of stratification: level of decline (i.e., healthy or declining) and zonation (i.e., green or white). Initially, a total of 27 sites were selected, but 9 were rejected on the basis of the criteria for suitability (see below). Of the suitable sites, five healthy and declining stands were located in the white zone, and four healthy and declining stands were situated in the green zone. The location of these 18 sites is given in Figure 1 and Table 2.

The criteria for site suitability were that stands should be composed of pure aspen about 50-70 years old, within areas of relatively undisturbed forest with a minimum size (where possible) of 20-40 ha. Heavily grazed sites, sites affected by flooding, and stands located along the edges of roads, seismic lines or crops (that may have been sprayed with herbicides targetting broad-leaved plants) were avoided. Permission to sample was obtained at all sites. Healthy stands were defined as those with an average crown dieback of less than 10%, while our initial criterion for "declining" stands was that the aspen should have an average crown dieback greater than 40%. However, it was necessary to modify the definition of "declining" during site selection, after it became apparent that average crown dieback of aspen in the study area was rarely as high as 40% within the study area.

Field measurements and sampling

Field sampling was conducted in July 1997. At each site a circular plot 20 m in diameter was established at a representative location within the stand. Each aspen tree ≥5cm diameter at breast height within the plot was assessed or measured for percent crown dieback in 10% classes, incidence of five of the most prevalent insects and diseases, and diameter at breast height. The diameter of all dead trees was also measured. Near the plot center the dominant understory vegetation was identified and its percent cover recorded to the nearest 25%. The depth of the LFH layer was measured and a sample of the mineral soil to a depth of 30 cm was collected.

Ten trees representing the range of tree conditions (living and dead, as required) in the stand were then selected and felled. Total height, height to the base of the living crown, and height to the top of the living crown was measured for each felled tree. Disks 3-4 cm thick were then collected from the felled trees from stump height (30 cm from the ground), breast height (1.3 m), 5 m, and 10 m. Sections of dead and live branches were also collected from the crowns of trees showing dieback at the declining sites, for the purpose of dating when dieback occurred. All disks and samples were carefully labeled.

In the laboratory, disks were oven-dried at 50° C and then polished in succession using 50, 80, 120, 220, 320, and 600 grit sand paper. Disks were dated and tree rings were measured along two radii using an ocular micrometer mounted on a Zeiss® compound dissecting microscope at 20× magnification. Ring width data were entered directly into a spreadsheet program on a portable computer. Tree rings that were abnormally pale in colour ("white rings"), indicating years when insect defoliation occurred (Hogg and Schwarz, submitted) were also noted. Soil samples were air-dried at 20-25° C and 20-60% relative humidity and then analyzed for particle size and electrical conductivity according to the procedures of Kalra and Maynard (1991).

Tree ring analysis

Ring width measurements (in mm) were used to estimate annual values of stem area increment (in cm^2) at the three heights (1.3, 5 and 10 m) where disks had been collected from each tree, as follows: First, the annual tree ring measurements were expressed as a cumulative distance (mm) from the center of the tree. Area increment for a given year was then calculated as:

$$3.14 * (r_y^2 - r_{y-1}^2),$$

where r_y and r_{y-1} are the radii (cumulative distance to center in cm) at the end of that year (y) and the previous year (y-1) respectively. Mean area increment for each year was then calculated based on the average for the ten aspen at each site.

Climate data and analysis

Temperature and precipitation data from the two longest observing stations (Beaverlodge and Grande Prairie) in the region were used to identify trends in recent climate that may have contributed to the observed aspen dieback. Several analyses were conducted, including a comparison of mean monthly temperature and precipitation at these stations for the period 1990-1996 with the long-term climate normals for 1951-1981.

Annual changes in moisture were examined using a Climate Moisture Index (CMI) developed by Hogg (1997). The CMI was based on the quantity P minus PET, where P is the annual precipitation and PET is the annual potential evapotranspiration (i.e., expected loss of water vapor loss from the landscape under well-watered conditions) using a simplified form of the Penman-Monteith equation. In general, negative values of the CMI denote dry conditions typical of the aspen parkland, whereas positive values indicate levels of moisture that are normally associated with boreal forest (Hogg 1994; Hogg 1997). PET was calculated from the estimated vapor pressure deficit, which was in turn estimated from the average daily maximum and minimum temperature for each month.

Precipitation that falls late during a calendar year (e.g. October-December) cannot have an effect on tree growth during that year. Thus both annual precipitation and the CMI were calculated based on a "tree water year" beginning on 1 September of the previous year and ending on 31 August of the current year.

Data sources on insect defoliation events

Data on past insect defoliation events were obtained from the records of the Forest Health Network, Canadian Forest Service. Sketch-maps of forest tent caterpillar defoliation were used to determine the defoliation history within the study area. The historical records were also compared with the years when white rings denoting defoliation (Hogg and Schwarz, submitted) were formed in the aspen collected at each site.

Dynamic regression modelling

A dynamic regression approach using Forecast Pro software (Business Forecast Systems, Inc.) was used to examine the combined influences of climatic factors and insect defoliation events on aspen stem growth for the period from 1950-1996. The dependent variable describing stem growth was based on annual values of mean area increment from the tree-ring analysis of disks at 1.3 m height. The independent variable describing insect defoliation intensity each year was determined based on the proportion of trees having white rings for each year. The following climatic factors were also tested as independent variables: annual precipitation and the CMI (based on several methods of determining "tree water year", annual growing degree days, and a frost index. Growing degree days were calculated as the annual cumulative sum of mean daily temperatures above 5°C. The Frost Index was calculated as the sum of squares of daily deviations of minimum temperature from 0°C following leafout, which was assumed to occur when the number of growing degree days had reached 120 (Hogg, submitted). Regression analyses were tested using both untransformed and log-transformed values of the dependent variable describing aspen growth, and autocorrelation effects were addressed by testing the inclusion of variables from the previous 1-2 years. The best fitting regression equation was obtained after removing independent variables with coefficients that were not statistically significant at the 5% level.

The sensitivity of aspen growth to each significant factor was assessed using a Sensitivity Index. This index was calculated by multiplying the regression coefficient for each factor by the standard deviation of that factor for the period of interest (1950-1996).

Role of extreme weather events

We also examined the potential impact of several types of extreme weather events that are either difficult to quantify for the purposes of regression modelling, or which are not captured in the monthly or annual temperature and precipitation records. These included hail, snow depth, and episodes of late-winter thawing followed by severe, early spring frost.

The Northern Alberta Environmental Services Centre (NAESC), formerly known as the Alberta Weather Centre (AWC) of Environment Canada has operated a summer severe weather program to detect and forecast severe thunderstorms for central and Northern Alberta since 1982. Severe summer weather includes tornadoes, strong winds, hail, lightning and heavy rain (Joe et al. 1995). A thunderstorm is classified as severe if hail 20 mm in diameter or larger is produced. Records of severe hail for the Grande Prairie forecast region were obtained from the annual internal reports of AWC (1982-1994, unpublished) and NAESC (1995-97, unpublished).

RESULTS AND DISCUSSION

Reconnaissance and stand characteristics

Aerial reconnaissance of the study area revealed little evidence of extensive, severe forest dieback. Severe aspen dieback was restricted mainly to small areas of aspen trees in flooded areas and on agricultural land, including heavily grazed areas, trees along fence lines and along stand edges or openings. In these areas, aspen would be exposed to a variety of stresses including soil compaction, and damage due to wind and sunscald (Kozlowki et al. 1991; Peterson and Peterson 1992). Small patches of forest showing dieback of balsam poplar (*Populus balsamifera* L.) were also visible from the air, and it appeared that balsam poplar dieback was generally more prevalent than aspen dieback.

During site selection on the ground, light crown dieback of aspen stands was found to be common in the white zone, but was encountered only occasionally in the green zone. In both zones, suitable sites were designated as "declining" on the basis of having a) greater than normal crown dieback; b) a larger proportion of dead trees and c) significant evidence of damage by insects, pathogens and other factors.

General stand characteristics of the 18 sites are summarized in Table 3. Tree height was variable among the stands (11-23 m), and averaged slightly greater in the green zone (17 m) compared to the white zone (14 m). Average tree diameter at breast height (DBH) was also slightly greater at the sites in the green zone (19-22 m) than in the white zone (14-16 m). Based on tree-ring analysis of disks at stump height, the stands sampled in the green zone were generally older (51-89 years) than in the white zone (41-70 years). However, in each zone, declining and healthy stands were of similar age and height.

Soil texture was variable, ranging from clay to sandy loam with no clear difference between healthy and declining sites (Table 3). Average soil conductivity was 0.30 mS/cm with a maximum value of 0.66 mS/cm. These values are well below the minimum level (ca. 2 mS/cm) considered to be damaging to tree growth (Y. Kalra, Canadian Forest Service, pers. comm.).

Forest health and crown dieback

Forest health assessments (Table 4) showed that all of the declining stands were damaged by two or more of the following insects and pathogens: poplar borer (*Saperda calcarata*) or the bronze poplar borer (*Agrilus liragus*), root rot (*Armillaria* spp.), false tinder conk (*Phellinus tremulae*), hypoxylon canker (*Hypoxylon mammatum*) and leaf and twig blight (*Venturia macularis*). Few insects and diseases were found at the healthy sites, with the exception of Site 21, where light defoliation by large aspen tortrix (*Choristoneura conflictana*) was noted. Other forms of damage were noted at both declining and healthy sites, including frost cracks, stem breakage and mechanical damage (e.g. caused by previous impact of falling trees).

In all of the declining stands, fewer than half (10-49%) of the total standing aspen stems were both living and undamaged, whereas in the healthy stands, more than half (54-84%) were in this category (Table 4). There was considerable variation among the sites in each class, but the average percentage of dead trees was about twice as great in the declining stands (33%) compared with the healthy stands (17%).

The overall average percentage of live trees showing severe (>40%) crown dieback was only 5.7% at the 18 sites, while the average percentage showing light (10-40%) crown dieback was 34% (Table 5). In general, declining stands showed considerably more dieback than healthy stands. The mean percentage dieback of living crowns ranged from 7-25% in the declining stands compared to 1-14% in the healthy stands.

Examination of tree rings in dead and live crowns suggested that most of the dieback occurred during the period 1990-95. However, reliable dates could be obtained from a total of only 15 dead crowns from eight of the declining sites, due to fungal decay and/or an insufficient number of tree rings for cross-dating of dead and live branches.

Insect defoliation history

During the tree-ring analysis, white (i.e., pale-coloured) rings were noted in the aspen disks at all sites. Annual percentage of aspen stems with white rings at each site is shown in Table 6; the incidence of white rings was very similar in the 5- and 10-m disks (data not shown). White rings were generally most abundant during two major periods: 1958-64 and 1979-1990, but the precise years of white ring formation varied considerably among sites.

The records of the forest insect and disease survey indicate that most of the aspen in the study area were defoliated at least once during the period 1988-92 (Appendix 1). An analysis of defoliation frequency and severity for the period 1937-97 shows that the areas most severely impacted by forest tent caterpillar were located in the white zone, especially in the areas to the south, east and northeast of Grande Prairie near the Wapiti and Smoky rivers (Appendix 2).

The overall abundance of white tree-rings since 1950 (mean of all 18 sites) showed a good correspondence to the annual percentage of the study area that was defoliated by forest tent caterpillar based on the past record of forest insect and disease surveys (Figure 4). This supports previous conclusions that white rings provide a good record of defoliation history at the tree- and stand-level (Hogg and Schwarz, submitted). Based on this conclusion, the average number of defoliation years per tree can be estimated by adding the annual proportion of white rings (Table 6) across the period of interest. Considering all sites as a whole, aspen were defoliated an average of 1.9 years since 1979 and an average of 3.3 years since 1958 (Table 7). Declining sites in the green zone tended to show the greatest number of years with defoliation, but the differences among site classes were not statistically significant.

Climate trends

The pattern of annual precipitation, the Climate Moisture Index (CMI) and growing degree days (GDD) was similar between the two primary climate stations in the study area (Grande Prairie and Beaverlodge) for the period 1950-1996 (Figure 5). Based on the CMI, major drought years occurred in 1967, 1981 and 1988, but conditions were moister than normal during the period 1993-1996.

Figure 6 shows a comparison of monthly mean maximum and minimum temperatures at Beaverlodge and Grande Prairie for the period 1981-1996 with the 1951-1980 climate normals. The more recent period shows a warming in both the monthly maximum and minimum temperatures at these stations, with a greater amount of warming (0.5 - 5 °C) during the winter and early spring months. The months of January and March showed the greatest increases of between 3 and 5°C warmer than normal. However, during the same period, October and November were between 0.5 and 1.5°C cooler than normal.

Total annual precipitation (Figure 7) during the 1981-1996 period were not significantly different from the 1951-80 normal. However, the monthly distribution of precipitation showed a 10% increase during the summer and early fall [May-September] season and a 22% decrease during the winter and early spring [December-March] season. June tended to be the wettest month at Grande Prairie, with precipitation averaging 16% above normal. At Beaverlodge the precipitation during July averaged 25% above normal. March tended to be the driest month, with precipitation averaging 30% below normal at Grande Prairie, and 38% below normal at Beaverlodge.

Tree ring analysis of aspen stem growth

Stem growth in the breast height (1.3-m) disks showed high interannual variation at the declining and healthy sites in both the white zone (Figure 8) and the green zone (Figure 9). There was also variation in the growth pattern among the individual sites in each class (Appendix 3).

In both zones, growth was strongly reduced in 1962-64, corresponding to a period of severe and extensive forest tent caterpillar defoliation (Table 6, Figure 4). This was followed by a period of excellent growth in the 1970s, especially 1977 in the white zone sites. However, both zones showed major growth reductions in 1979, corresponding to the first year of the most recent major outbreak of forest tent caterpillar that affected various portions of the study area until 1991.

A comparison of declining and healthy sites in the white zone (Figure 8) shows that growth was very similar during the period up to 1980. Since 1981, however, growth has been consistently less in the white zone declining sites. The most striking difference was observed for the period 1981-83, when healthy sites showed a strong recovery in growth, whereas growth continued to decrease in the declining sites. Because 1981 was a dry year (Figure 5), drought probably triggered this chronic reduction in growth of the declining stands. However, both healthy and declining stands have shown a general trend to growth recovery since the mid 1980s.

In the green zone (Figure 9), growth of declining and healthy stands was similar prior to 1966, but the growth of declining stands decreased sharply in 1966 and has since remained consistently reduced relative to the healthy stands. Since 1979, there have been several periods of declining growth followed by gradual recovery. In the 1990s, the overall growth of the green zone sites remained somewhat lower than it was during the 1970s. However, it should be noted from Table 3 that some of the green zone sites were reaching an old age (>90 years) when growth reductions would be expected, even in healthy aspen (Peterson and Peterson 1992).

The overall mean stem growth for all study sites (180 trees) is shown in Figure 10, based on tree-ring analysis of disks from the three heights. Growth in stem area increment tended to be greatest at the 1.3 m height, with a progressive decrease at the 5- and 10-m heights. This is especially noticeable during the earlier years, mainly because many of the trees had not yet reached these heights, thus contributing zero growth increments to the average for those years. However, there was a very similar pattern of year-to-year variation among the three heights. This becomes strikingly apparent when stem growth is plotted as a percentage change from the previous year's growth at each height (Figure 11).

Statistical modelling of aspen responses to climate and defoliation

The results of dynamic regression modelling indicated that most of the interannual variation in aspen growth could be explained by the following factors: forest tent caterpillar defoliation based on white rings (FTC), the Climatic Moisture Index (CMI), growing degree days (GDD) and the previous year's growth (G_{-1}). For all sites combined, the strongest relationship ($r^2 = 0.759$) was obtained using $\log_e$-transformed values of both observed and modelled aspen growth (Figure 12).

The regression coefficients used in this statistical model (Table 8) were all highly significant ($P<0.002$) for each of the above factors. Based on values of the Sensitivity Index (SI), aspen growth was most strongly sensitive to FTC (SI = 0.193) and G_{-1} (SI = 0.182), and somewhat less sensitive to CMI (SI = 0.083) and GDD (SI = 0.050).

The same models were also examined for each of the four site classes, using the same climate inputs but with FTC based on the mean proportion of white rings within the specific site class being modelled. In each site class, all four regression coefficents (Table 8) were statistically significant ($P < 0.01$) with the exception of the coefficient for the CMI in the healthy, green zone sites ($P = 0.053$).

In general, the regression coefficients were similar for all site classes; however, the CMI coefficients were larger and the GDD coefficients were smaller in the white zone sites compared to the green zone sites (Table 8). This suggests aspen growth was more strongly limited by moisture stress in the white zone, while cold growing seasons appeared to have a greater impact on growth in the green zone. These results are consistent with our analyses showing that the climate at higher elevations in the green zone is cooler and moister than that at lower elevations in the white zone (Figure 3).

Similar but marginally weaker relationships were obtained when annual precipitation (PREC) was used in place of the CMI and GDD ($r^2 = 0.754$ for all sites combined; results not shown). In contrast, no significant relationship was found between aspen growth and the Frost Index, which was intended to provide a measure of frost damage following aspen leafout.

Extreme climatic events

The tree-ring analysis and regression modelling indicates that the periods of reduced aspen growth were caused primarily by outbreaks of forest tent caterpillar, especially in the early 1960s and throughout the 1980s. There was also evidence that the drought of 1981 triggered a chronic reduction in the stem growth of declining stands in the white zone.

Normally, it would be expected that crown dieback and tree mortality should be most prevalent during periods of reduced stem growth. However, the available evidence indicates that the most recent aspen dieback event was not initiated until 1990-92, during a period of generally increasing growth following the defoliation events of the 1980s. This suggests that impacts other than those included in the regression model have contributed to the aspen dieback. These would include secondary invasions of insects such as poplar borers and fungal pathogens that have already been noted in the declining sites (Table 4). However, it is also important to consider the role of extreme weather events (hail and freeze-thaw events) and recent changes in other climatic factors (snow depth).

Hail

On average, about two severe hail events occur in the Grande Prairie forecast region each year. The most active hail year was 1987 when seven events were reported (Table 9). Within the Beaverlodge-Valleyview area, there were seven hail events in 1987 and 1991. Hail between 21 and 52 mm in diameter was reported at the Grande Prairie forestry station and near Valleyview in 1987, and at Sturgeon Lake and near Beaverlodge in 1991.

Most of the hailswaths in central Alberta are less than 30 km long and cover areas smaller than 200 sq. km (Alberta Research Council 1986). Hail occasionally causes significant damage in forest stands, as reported by Riley (1953) for mixedwood stands near Candle Lake in the 1940s. The only published recent record of hail damage near the study area was from 1994, when about 400 ha of forest was severely damaged in a 1994 storm northeast of Grande Cache (Brandt et al. 1996). However, none of the sites examined showed evidence of past hail damage, which is readily visible on aspen. Thus, hail could not have contributed significantly to the extensive dieback of aspen in the study area.

Snow depth and freeze-thaw events

During the period 1981-96, snowfall at Beaverlodge was 27% below the normal amount recorded during 1951-80 (Table 10). For the winters of 1989-90 to 1992-93, the cumulative snowfall from October to May was 19% to 52% below normal. Normally, there is a continuous cover of snow from November to March. However, the combination of below normal winter snowfall and above average temperatures during the winters from 1989-90 to 1992-93 resulted in a discontinuous snowcover with snow depths below normal during most months, especially in February and March (Table 11). Two of these winters (1989-90 and 1991-92) also showed sequences of major freeze-thaw events that could have contributed to the observed aspen dieback.

The winter of 1989-90 had exceptionally scant snow cover with generally mild conditions, except for a major cold period from late January to early February (minimum temperature of -43°C). March 1990 was the fourth warmest on record at Beaverlodge (mean of 0.3°C) and was followed by two freezing events in April, with temperatures dropping to -14°C on April 10.

Conditions were even more extreme during the winter of 1991-92, when there was an exceptional number of freeze-thaw events recorded between October and April (Figure 13). The first major freezing event was on 16-17 October 1991, when temperatures ranged from -2°C during the day to -10°C at night. A second, more significant cold period occurred from 21 October to 11 November, when temperatures averaged 10°C below normal, ranging from 0° to -14°C during the day and from -6° to -27°C at night. The third major event occurred during 2-7 December, when daytime maximum temperatures were 10 to 15 °C below normal, resulting in soil freezing to a depth of 5 cm (Figure 14).

Unseasonably mild weather with periodic short duration intrusions of cold temperatures characterized the fourth significant event between 15 December 1991 and 4 February 1992. During this period, mean temperature was 10°C above normal and soil frost penetration to 50 cm did not occur until early January, about three weeks later than normal. The fifth significant event was a cold period during 6-22 February followed by a rapid thaw, resulting in a 34°C increase in the daily maximum temperature from -22°C on 19 February to +12°C on 26 February.

The mild weather continued throughout March, which had 27 out of 31 days with maximum temperatures exceeding +5°C, compared to a long-term average of only 8 days. The mean temperature in March 1992 was +3.0°C (9.1°C above average), resulting in the warmest March ever recorded since weather records began at Beaverlodge in 1915. The soil was thawed to a depth of 50 cm by mid March, one month earlier than normal. Records of the Alberta Wildflower Survey also indicate that aspen in the Grande Prairie area were producing catkins by the end of March 1992, which is also much earlier than normal (Elizabeth Beaubien, University of Alberta, Pers. Comm.).

The last severe freezing event of the 1991-92 season occurred during 7-10 April, when the minimum temperature dropped to -16°C with daytime maximum temperatures as low as -4°C. Normally, such an event at this time of year would not cause damage to aspen. However, because the aspen were already flowering, the severe frost would have caused extensive damage to leaf buds. Furthermore, the frequent and severe frost events, coupled with dessication of soil in the absence of winter snow cover, would have led to cavitation of xylem and possible root damage.

Role of freeze-thaw events in forest decline

Our analysis suggests that unusual freeze-thaw events in the early 1990s contributed to the dieback of aspen forests in the Grande Prairie area. A similar combination of events was noted in southern Manitoba during the winter and spring of 1957-58, when buds of both conifers and aspen were killed by a severe frost in April following a long period when conditions were much warmer and drier than normal (Cayford et al. 1959). This led to the formation of abnormally foliage in aspen, browning of conifer foliage and reduced stem growth in both the aspen and conifers.

Several studies have shown that winter thaw followed by severe spring frost has been a major cause of dieback in various forest types in Canada and the northern United States. These include the widespread dieback of white and yellow birch in eastern Canada (Braathe 1995) and dieback of western white pine in southern British Columbia (Auclair et al. 1990), both of which occurred following anomalous thaw-freeze conditions during the 1930s. More recently, thaw-freeze events during the winter of 1980-81 have been implicated as a major cause of the sugar maple dieback that occurred throughout the 1980s in southern Quebec (Auclair et al. 1992). Experimental work (Braathe 1995, Cox and Malcolm 1997) indicates that the dieback was likely caused by cavitation of xylem in the stem and damage to roots, both of which reduce the ability of trees to supply water and nutrients to emerging buds and leaves.

Comparison with aspen decline in western Saskatchewan

In general, the level of dieback observed in the Grande Prairie area was much less than that recorded in a previous study of aspen decline in the Bronson Forest near St. Walburg, Saskatchewan in 1995 (Hogg and Schwarz, 199-). The mean percentage of live trees with severe (>40%) crown dieback was 25% in the declining stands studied in the Bronson forest, compared with 9% in the declining stands examined in the present study (Table 5).

As in the Grande Prairie area, aspen in the Bronson Forest were defoliated by forest tent caterpillar during the period 1979-90. However, the average frequency of years with defoliation in the Bronson Forest (4.1 ± 0.3) was more than twice as high as in the stands examined in the present study (1.9 ± 0.3, Table 7). This may largely account for the difference in the severity of crown dieback between these two areas. In addition, the climate since 1980 has been drier at St. Walburg, Saskatchewan (mean CMI = -8) than at Grande Prairie (mean CMI = -1, Figure

5), which would have resulted in greater drought stress on the aspen stands examined in the Saskatchewan study.

CONCLUSIONS

Crown dieback of aspen forests has occurred in the Grande Prairie area of northwestern Alberta, especially in areas dominated by agricultural land use (the white zone). However, the degree of aspen dieback observed in 1997 was relatively light, and dieback was found to be uncommon in the areas of continuous forest at higher elevation (the green zone).

The results of this study indicate that several factors have contributed to the observed dieback of aspen in the Grande Prairie area. Forest tent caterpillar defoliation occurred sporadically over a 12-year period (1979-90), causing severe reductions in stem growth in some years. Although the recent climate has been relatively moist, a drought in 1981 was followed by reduced growth of most declining stands in the climatically-drier white zone. Although it appears that drought and defoliation did not directly cause the aspen dieback, these stresses would have predisposed some stands to secondary invasions by wood-boring insects and fungal pathogens. Forest health assessments indicate that these insects and diseases were important contributors to aspen dieback, especially in those few areas where it was noted in the green zone.

The results also indicate that thaw-freeze events during dry, mild winters in the early 1990s, especially 1991-92, caused additional stress on aspen stands in the region. March 1992 was the warmest ever recorded, resulting in soil thaw about one month earlier than normal. This was followed by severe cold period in April 1992, which probably triggered crown dieback, especially at low elevations in the white zone where aspen had already started flowering.

Houston (1992) provides several examples where such a combination of events has led to forest dieback and decline in other regions of North America. However, it appears that most stands in the Grande Prairie area recovered significantly between 1993 and 1997, because of moist climatic conditions and a greatly reduced incidence of defoliation by forest tent caterpillar. The future health of aspen stands in the region will likely depend on the frequency and severity of a) defoliation by forest tent caterpillar and other insects, b) thaw-freeze events during late winter and spring, and c) summer drought.

ACKNOWLEDGEMENTS

This work was conducted as part of a Collaborative Research Agreement between Weyerhaeuser Canada Ltd. (Grande Prairie Operations) and the Canadian Forest Service (CFS). Howard Gates and Roger Brett (CFS, Edmonton) conducted the aerial surveys and field sampling was conducted with the assistance of Howard Gates, Brad Tomm, Brooke Bennett and Sherri Dunne. Sample preparation, laboratory analyses and ring-width measurements were conducted by Trisha Hook. Weather and soil temperature data were provided by Pat Kyle, Jacques LaFlamme and Monique Lapalme (Climate Services, Environment Canada, Edmonton). Assistance with preparation of figures was provided by Roger Brett, Mike Michaelian and Bob Crawford (Environment Canada, Downsview). Elizabeth Beaubien of the Devonian Botanic Garden, University of Alberta provided valuable information on the dates of aspen flowering. We also thank the landowners and provincial government officials for giving the permission necessary to conduct this study.

LITERATURE CITED

Alberta Research Council. 1986. Weather modification in Alberta - Research and Operations 1980-1985, Summary report and recommendations. Natural Resources Division, Atmospheric Sciences Department Report. 18pp.

Auclair, A.N.D.; Martin, H.C.; Walker, S.L. 1990. A case study of forest decline in western Canada and the adjacent United States. Water, Air, Soil Pollut. 53: 13-31.

Auclair, A.N.D.; Worrest, R.C.; Lachance, D.; Martin, H.C. 1992. Climatic perturbation as a general mechanism of forest dieback. Pages 38-58 *in* P.D. Manion and D. Lachance, eds. Forest decline concepts. Am. Phytopathol. Soc., St. Paul, Minnesota.

Batzer, H.O.; Hodson, A.C.; Schneider, A.E. 1954. Preliminary results of an inquiry into effects of defoliation of aspen trees by the forest tent caterpillar. Sch. For., Univ. Minnesota, St. Paul. Minnesota. Minnesota For. Notes 31.

Beckingham, J.D.; Archibald, J.H. 1996. Field guide to ecosites of northern Alberta. Nat. Resour. Can., Can. For. Serv., Northwest Reg., North. For. Cent., Edmonton, Alberta. Spec. Rep. 5.

Beckingham, J.D.; Corns, I.G.W.; Archibald, J.H. 1996. Field guide to ecosites of west-central Alberta. Nat. Resour. Can., Can. For. Serv., Northwest Reg., North. For. Cent., Edmonton, Alberta. Spec. Rep. 9.

Bird, R.D. 1961. Ecology of the aspen parkland of western Canada in relation to land use. Research Branch, Canada Department of Agriculture, Ottawa, Ont. Contrib. No. 27.

Braathe, P. 1995. Birch dieback – caused by prolonged early spring thaws and subsequent frost. Norwegian Journal of Agricultural Sciences, Supplement No. 20.

Brandt, J.P., 1995. Forest insect- and disease-caused impacts to timber resources of west-central Canada: 1988-1992. Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Information Report NOR-X-341.

Brandt, J.P.; Knowles, K.R.; Larson, R.M.; Ono, H.; Walter, B.L., 1996. Forest insect and disease conditions in west-central Canada in 1995 and predictions for 1996 Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta. Information Report NOR-X-347.

Cayford, J.H.; Hildahl, V.; Nairn, L.D.; Wheaton, P.H. 1959. Injury to trees from winter drying and frost in Manitoba and Saskatchewan in 1958. Forestry Chronicle 35: 282-290.

Churchill, G.B.; John, H.H.; Duncan, D.P.; Hodson, A.C. 1964. Long-term effects of defoliation of aspen by the forest tent caterpillar. Ecol. 45: 630-633.

Cox, R.M.; Malcolm, J.W. 1997. Effects of duration of a simulated winter thaw on dieback and xylem conductivity of *Betula papyrifera.* Tree Physiology 17: 389-396.

Environment Canada. 1983. Canadian climate normals, temperature and precipitation, prairie provinces. Environ. Can., Atmos. Environ. Serv., Downsview, Ontario.

Hildahl, V.; Campbell, A.E. 1975. Forest tent caterpillar in the prairie provinces. Can. For. Serv., Northern Forestry Centre, Edmonton, Alberta. Information Report NOR-X-135.

Hildahl, V.; Reeks, W.A. 1960. Outbreaks of the forest tent caterpillar, *Malacosoma disstria* Hbn., and their effects on stands of trembling aspen in Manitoba and Saskatchewan. Ca. Entomol. 92:199-209.

Hogg, E.H. 1994. Climate and the southern limit of the western Canadian boreal forest. Canadian Journal of Forest Research 24: 1835-1845.

Hogg, E.H. 1997. Temporal scaling of moisture and the forest-grassland boundary in western Canada. Agricultural and Forest Meteorology 84: 115-122.

Hogg, E.H.; Hurdle, P.A. 1995. The aspen parkland in western Canada: A dry-climate analogue for the future boreal forest? Water, Air, and Soil Pollution 82: 391-400.

Hogg, E.H.; Schwarz, A.G. 199-. Tree-ring analysis of declining aspen stands in west-central Saskatchewan. Northern Forestry Centre, Edmonton, Alberta. Information Report NOR-X (submitted).

Houston, D.R. 1992. A host–stress–saprogen model for forest dieback–decline diseases. Pages 3-25 *in* P.D. Manion and D. Lachance, eds. Forest decline concepts. Am. Phytopathol. Soc., St. Paul, Minnesota.

Joe, P.; Crozier, C.; Donaldson, N.; Etkin, D.; Brun, E.; Clodman, S.; Abraham, J.; Siok, S.; Biron, H-P; Leduc, M.; Chadwick, P.; Knott, S.; Archibald, J.; Vickers, G.; Blackwell, S.; Drouillard, R.; Whitman, A.; Brooks, H.; Kouwen, N.; Verret, R.; Fournier, G.; Kochtubajda, B. 1995. Recent progress in the operational forecasting of summer severe weather. Atmosphere-Ocean 33: 249-302.

Kalra, Y.P.; Maynard, D.G. 1991. Methods manual for forest soil and plant analysis. For. Can., Northwest Reg., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-319.

Kozlowski, T.T.; Kramer, P.J.; Pallardy, S.G. 1991. The physiological ecology of woody plants. Academic Press, New York.

Peterson, E.B.; Peterson, N.M. 1992. Ecology, management, and use of aspen and balsam poplar in the Prairie Provinces, Canada. Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, Special Report 1.

Philips, D. 1990. The Climates of Canada. Supply and Services Canada, Ottawa. 176pp.

Riley, C.G. 1953. Hail Damage in Forest Stands. Forestry Chronicle. 139-143.

Rowe, J.S. 1972. Forest regions of Canada. Dep. Environ., Can. For. Serv., Ottawa, Ont. Publ. 1300.

Zoltai, S.C.; Singh, T.; Apps, M.J. 1991. Aspen in a changing climate. In: Aspen management for the 21st century. Proceedings of a symposium, 20-21 Nov. 1990, Edmonton AB. Edited by S. Navratil and P.B. Chapman. Forestry Canada, Northern Forestry Centre, Edmonton AB, pp. 143-152.

Table 1. Summary of current long-term climate stations within 160 km of Grande Prairie.

ID	Station name	Lat (°N)	Long (°W)	Elev (m)	Start of Record
A	BALD MOUNTAIN	54 49	118 55	939	June 1954
B*	BEAVERLODGE CDA	55 12	119 24	745	Aug 1915
C	ECONOMY LO	54 47	118 14	800	Aug 1953
D*	GRANDE PRAIRIE A	55 11	118 53	669	Jan 1942
E	KAKWA LO	54 26	118 58	1213	Apr 1956
F	NOSE MOUNTAIN LO	54 33	119 35	1574	May 1949
G	PINTO LO	54 47	119 24	1067	June 1959
H	PUSKWASKAU LO	55 13	117 30	972	Aug 1944
I	SNUFF MOUNTAIN LO	54 41	117 32	969	May 1953
J*	WANHAM CDA	55 47	118 24	607	Jan 1955
K	WHITE MOUNTAIN LO	55 42	119 14	1093	July 1954
L*	FAIRVIEW	56 05	118 32	646	Oct 1931
M	SIMONETTE LO	54 14	118 25	1274	May 1956
N	SWEATHOUSE LO	54 55	116 45	853	Aug 1953
O	TONY LO	54 23	117 24	1036	May 1957
P	BERLAND LO	54 15	117 24	1219	May 1958
Q	HUCKLEBERRY LO	53 59	118 11	1429	June 1958
R*	PEACE RIVER A	56 14	117 26	571	Jan 1944
S	WHITEMUD LO	56 26	118 01	853	June 1954

*climate stations operating year round.

Table 2. Location, elevation and soil texture of the study sites.

Site class and name	Site No.	Latitude (degrees N)	Longitude (degrees W)	Altitude (m)	Soil texture
White zone declining:					
Young's Point (D)	3	55.12	117.58	690	silty loam
Saskatoon Island	16	55.21	119.08	700	clay
NW Wembley (D)	17	55.20	119.17	790	clay
Bear Hill	25	55.41	119.08	760	clay
East Smokey	27	55.23	118.25	580	sandy loam
White zone healthy:					
Young's Point (H)	4	55.13	117.59	690	silty loam
NW Wembley (H)	19	55.20	119.25	820	sandy loam
Saskatoon Hill	20	55.22	119.30	930	loam
W Beaverlodge	21	55.23	119.56	770	clay
Valhalla Lake	24	55.39	119.44	750	clay loam
Green zone declining:					
Campbell Ridge	12	54.92	118.80	730	clay
N Economy Lake	14	54.94	118.26	700	loam
Spring Lake (D)	23	55.51	119.53	850	silty loam
SW Bad Heart	26	55.46	118.38	760	clay loam
Green zone healthy:					
E Pinto Creek	8	54.86	119.35	820	silty loam
Iroquois Creek	9	54.87	119.14	810	loam
S Simonette River	15	55.03	118.23	650	silty loam
Spring Lake (H)	22	55.51	119.57	840	clay
Means by site class:					
white zone declining:				704	
white zone healthy:				792	
green zone declining:				760	
green zone healthy:				780	

Table 3. General stand characteristics of study sites. Sites were sampled in July 1997 using circular plots with a diameter of 20 m.

Site class and name	Site No.	mean stand origin	mean DBH (cm)	mean ht (m)	live stems in plot	dead stems in plot
White zone declining:						
Young's Point (D)	3	1945	15.0	16.9	27	24
Saskatoon Island	16	1925	18.3	16.7	30	13
NW Wembley (D)	17	1934	13.5	13.4	53	24
Bear Hill	25	1929	12.8	10.7	67	16
East Smokey	27	1954	11.5	13.9	46	18
White zone healthy:						
Young's Point (H)	4	1944	13.0	15.4	80	13
NW Wembley (H)	19	1947	10.8	15.8	72	22
Saskatoon Hill	20	1933	12.8	16.2	102	32
W Beaverlodge	21	1936	18.0	17.0	35	7
Valhalla Lake	24	1932	15.0	17.4	59	18
Green zone declining:						
Campbell Ridge	12	1906	21.3	19.8	17	12
N Economy Lake	14	1939	14.5	17.9	37	10
Spring Lake (D)	23	1898	19.8	24.5	23	19
SW Bad Heart	26	1944	11.4	14.9	67	36
Green zone healthy:						
E Pinto Creek	8	1908	22.9	23.0	33	2
Iroquois Creek	9	1907	20.2	25.6	41	3
S Simonette River	15	1944	13.1	19.3	70	14
Spring Lake (H)	22	1944	12.6	18.9	77	24
Means by site class:						
white zone declining:		1937	14.2	14.3	45	19
white zone healthy:		1938	13.9	16.4	70	18
green zone declining:		1922	16.8	19.3	36	19
green zone healthy:		1926	17.2	21.7	55	11

Table 4. Aspen trees affected by forest insects, fungal pathogens and other damage, expressed as a percentage of the total number of aspen in 20-m diameter circular plots, including standing dead aspen. Live trees with damage refer to those affected by insects (excluding current year defoliation), fungal pathogens and other sources of damage.

	White zone										Green zone							
	Declining sites					Healthy sites					Declining sites				Healthy sites			
Site:	3	16	17	25	27	4	19	20	21	24	12	14	23	26	8	9	15	22
% Live with damage	43	30	22	37	42	10	13	22	9	2	31	30	29	62	17	9	9	5
% Live without damage	10	40	47	45	30	76	64	54	74	74	28	49	26	3	77	84	74	71
% Dead	47	30	31	18	28	14	23	24	17	24	41	21	45	35	6	7	17	24
% with insect damage:																		
Poplar borer	53	5	-	-	31	2	1	-	-	-	3	15	-	-	-	-	2	-
Bronze poplar borer	-	-	12	-	-	-	-	-	-	-	-	-	2	-	-	-	-	-
Large Aspen Tortrix	-	-	-	-	-	-	-	-	81	-	-	-	-	-	-	-	-	-
% with fungal pathogens:																		
Armillaria root rot	22	9	4	13	22	-	-	-	-	-	14	-	-	35	-	-	1	-
False tinder conk	4	33	5	10	2	1	-	-	2	-	24	2	-	8	14	2	1	-
Hypoxylon canker	-	-	-	-	-	-	-	-	-	-	-	-	10	-	-	-	-	-
Leaf and twig blight	-	-	-	-	-	-	-	-	-	-	-	-	24	62	-	-	-	2
% with other damage:																		
Frost cracks	4	-	1	9	16	1	2	-	5	-	-	2	-	6	-	-	1	-
Stem breaks	8	-	-	-	-	4	-	-	-	-	-	-	-	-	-	-	-	-
Mechanical damage	6	-	8	32	6	1	10	22	2	-	7	13	-	5	6	5	2	2
Total no. of trees in plot	51	43	77	82	64	93	94	134	42	78	29	47	42	103	35	44	84	101

Table 5. Percentage of live stems showing severe dieback (>40%), light dieback (>10-40%) and minimal dieback (<10%) of crowns at 18 sites in July 1997.

Site class and name	Site No.	% severe crown dieback	% light crown dieback	% minimal crown dieback	*estimated mean % crown dieback*
White zone declining:					
Young's Point (D)	3	4	26	70	*7*
Saskatoon Island	16	17	47	37	*19*
NW Wembley (D)	17	6	28	66	*9*
Bear Hill	25	6	39	55	*11*
East Smokey	27	11	30	59	*12*
White zone healthy:					
Young's Point (H)	4	0	8	93	*1*
NW Wembley (H)	19	4	51	44	*12*
Saskatoon Hill	20	9	43	48	*14*
W Beaverlodge	21	0	3	97	*1*
Valhalla Lake	24	0	17	83	*4*
Green zone declining:					
Campbell Ridge	12	12	41	47	*13*
N Economy Lake	14	3	38	59	*8*
Spring Lake (D)	23	13	65	22	*25*
SW Bad Heart	26	6	66	28	*16*
Green zone healthy:					
E Pinto Creek	8	3	21	76	*6*
Iroquois Creek	9	2	20	78	*5*
S Simonette River	15	3	39	59	*10*
Spring Lake (H)	22	3	21	77	*6*
Means by site class:					
white zone declining:		8.8	34.0	57.4	*11.6*
white zone healthy:		2.6	24.4	73.0	*6.4*
green zone declining:		8.5	52.5	39.0	*15.5*
green zone healthy:		2.8	25.3	72.5	*6.8*
All sites:		**5.7**	**34.0**	**60.5**	**10.1**

Table 6. Percentage of aspen stems with white rings at each site, based on tree-ring analysis of disks from 1.3-m height. White rings are typically formed during years of severe defoliation by forest tent caterpillar and other insects. Percentages are based on a maximum of 20 radii per site (two radii for each of ten stems), with reduced sample sizes in years with very narrow rings or prior to stems reaching 1.3 m height. No white rings were observed for years not listed. "-" denotes no white rings and "N" denotes no data (for period prior to stand establishment).

	White zone										Green zone							
	Declining sites					Healthy sites					Declining sites				Healthy sites			
Site	3	16	17	25	27	4	19	20	21	24	12	14	23	26	8	9	15	22
1997	-	-	-	-	-	-	-	-	-	-	-	-	-	50	-	-	-	-
1995	-	-	-	-	-	-	-	-	-	-	-	-	-	100	-	-	-	-
1991	-	-	-	-	-	-	-	-	-	-	-	-	5	-	-	-	-	-
1990	-	-	10	-	-	-	-	-	60	-	-	-	100	-	-	-	-	50
1989	-	-	17	28	100	-	-	-	-	100	-	17	-	15	-	-	-	80
1988	10	-	-	10	95	-	-	-	5	-	-	-	-	15	-	-	95	10
1987	-	-	-	-	-	-	-	-	-	-	-	38	-	75	-	-	100	-
1986	-	-	-	-	-	-	-	-	-	-	-	42	-	10	-	-	-	-
1985	-	-	-	-	-	-	14	-	-	-	-	90	-	-	-	-	-	-
1984	-	100	60	50	85	60	-	-	-	100	-	100	-	5	-	-	-	-
1983	63	-	-	-	100	90	-	-	-	-	-	-	-	100	-	-	40	-
1982	100	-	-	-	40	100	-	-	-	-	-	-	-	90	-	-	-	-
1981	67	-	-	-	-	30	-	-	-	-	-	-	-	-	-	-	-	-
1980	-	-	11	-	-	-	33	-	-	-	-	10	-	-	100	-	-	78
1979	-	-	-	15	-	-	100	-	-	-	75	10	-	25	-	100	-	90
1964	14	5	-	-	-	56	-	-	-	-	-	11	-	-	-	81	-	-
1963	100	89	100	100	94	100	100	15	90	100	5	58	-	100	95	70	-	89
1962	100	100	-	10	63	100	-	-	-	-	-	63	-	-	-	-	80	55
1961	10	-	-	-	-	-	-	-	-	-	-	83	-	-	-	-	-	-
1960	-	-	-	-	6	-	-	65	-	-	-	22	-	-	-	-	-	-
1959	-	-	10	-	-	-	-	-	-	-	90	-	-	-	-	-	-	-
1958	-	-	-	-	-	-	-	50	-	-	-	-	-	13	100	-	-	-
1943	N	69	-	55	N	N	N	90	-	-	-	N	-	N	-	-	N	N
1942	N	75	90	50	N	N	N	90	-	-	100	N	95	N	-	-	N	N
1929	N	N	N	N	N	N	N	N	N	N	-	N	-	N	-	36	N	N
1928	N	N	N	N	N	N	N	N	N	N	-	N	90	N	-	100	N	N
1927	N	N	N	N	N	N	N	N	N	N	86	N	-	N	-	25	N	N
1918	N	N	N	N	N	N	N	N	N	N	-	N	70	N	-	-	N	N

Table 7. Mean (± SE) number of years with defoliation by forest tent caterpillar, based on frequency of white rings in disks from the 1.3-m height.

	Years with defoliation		No. of
	1979-1997	1958-1997	sites
White zone declining	1.9 ± 0.6	3.5 ± 0.7	5
White zone healthy	1.4 ± 0.4	2.7 ± 0.6	5
Green zone declining	2.4 ± 0.8	3.5 ± 1.1	4
Green zone healthy	1.9 ± 0.4	3.3 ± 0.4	4
All sites	**1.9 ± 0.3**	**3.3 ± 0.4**	**18**

Table 8. Coefficients for dynamic regression of aspen growth in response to insect defoliation and variation in moisture and warmth during the growing season. Regression equations are of the form $\log_e (G) = a*FTC + b*CMI + c*GDD + d*\log_e (G_{-1})$; where FTC is estimated percentage incidence of defoliation by forest tent caterpillar based on white rings, CMI is the Climatic Moisture Index (Hogg 1997) for the period 1 September (previous year) to 31 August (current year), GDD is the annual number of growing degree days; G and G_{-1} are aspen growth for the current and previous years respectively, based on mean stem area increment at the 1.3-m height.

	Regression coefficients				
Site class	a	b	c	d	r^2
White zone declining	-0.0141	0.0105	0.00036	0.574	0.854
White zone healthy	-0.0136	0.0116	0.00038	0.619	0.706
Green zone declining	-0.0159	0.0084	0.00052	0.509	0.640
Green zone healthy	-0.0145	0.0072	0.00057	0.547	0.630
All sites	**-0.0153**	**0.0088**	**0.00048**	**0.559**	**0.759**

Table 9. Severe hail events in the Grande Prairie region for the period 1982-1997. The number of hail events in the study area are given in parentheses.

Year	No. of events	Size (mm)	Locations
1982	0		
1983	2	25 - 40	Crooked Creek, Guy, Whitmud, Nampa, Whitecourt
1984	1	52	High Prairie
1985	0		
1986	2 (1)	30	Grande Prairie, High Prairie
1987	7 (4)	21 - 52	High Prairie, Peace River - 2, Valleyview - 2, Grande Prairie Forestry Stn - 2
1988	1 (1)	30	Grande Prairie Forestry Stn
1989	2	25 - 40	Peace River, Hines Creek
1990	2	52	Grimshaw - 2
1991	3 (3)	25 - 52	Sturgeon Lake - 2, Beaverlodge
1992	3	52	High Prairie - 2, Grimshaw
1993	0		
1994	3	40-45	Manning - 3
1995	0		
1996	0		
1997	2 (2)	40 - 52	Beaverlodge, White Mountain

Table 10. Monthly snowfall (cm) at Beaverlodge, showing comparison between the period 1981-1996 and the climate normals for 1951-1980. Monthly snowfall is also shown for each of the four winter periods from October 1989 to May 1993.

	Climatology		Monthly snowfall amounts			
Month	1951-80 Mean	1981-96 Mean	1989-90	1990-91	1991-92	1992-93
October	14	9	11	12	18	3
November	29	25	20	67	30	11
December	36	26	25	54	44	28
January	39	33	45	10	21	12
February	28	20	11	2	21	6
March	28	16	8	10	13	6
April	14	9	4	tr	5	26
May	4	3	9	0	7	0
Totals	192	141	133	155	142	92

Table 11. Snow depth on ground (cm) for the last day of the month at Beaverlodge, showing comparison between the period 1981-1996 and the climate normals for 1951-1980. Snow depths (end of each month) are also shown for each of the four winter periods from October 1989 to May 1993.

Month	Climatology		Snow depth (end of month)			
	1951-80 Mean	1981-96 Mean	1989-90	1990-91	1991-92	1992-93
October	2	3	5	0	12	tr
November	16	13	0	35	17	0
December	26	19	1	26	16	23
January	35	24	20	16	18	8
February	35	18	1	6	8	0
March	24	11	0	3	0	0
April	1	2	0	0	0	0
May	0	0	0	0	0	0

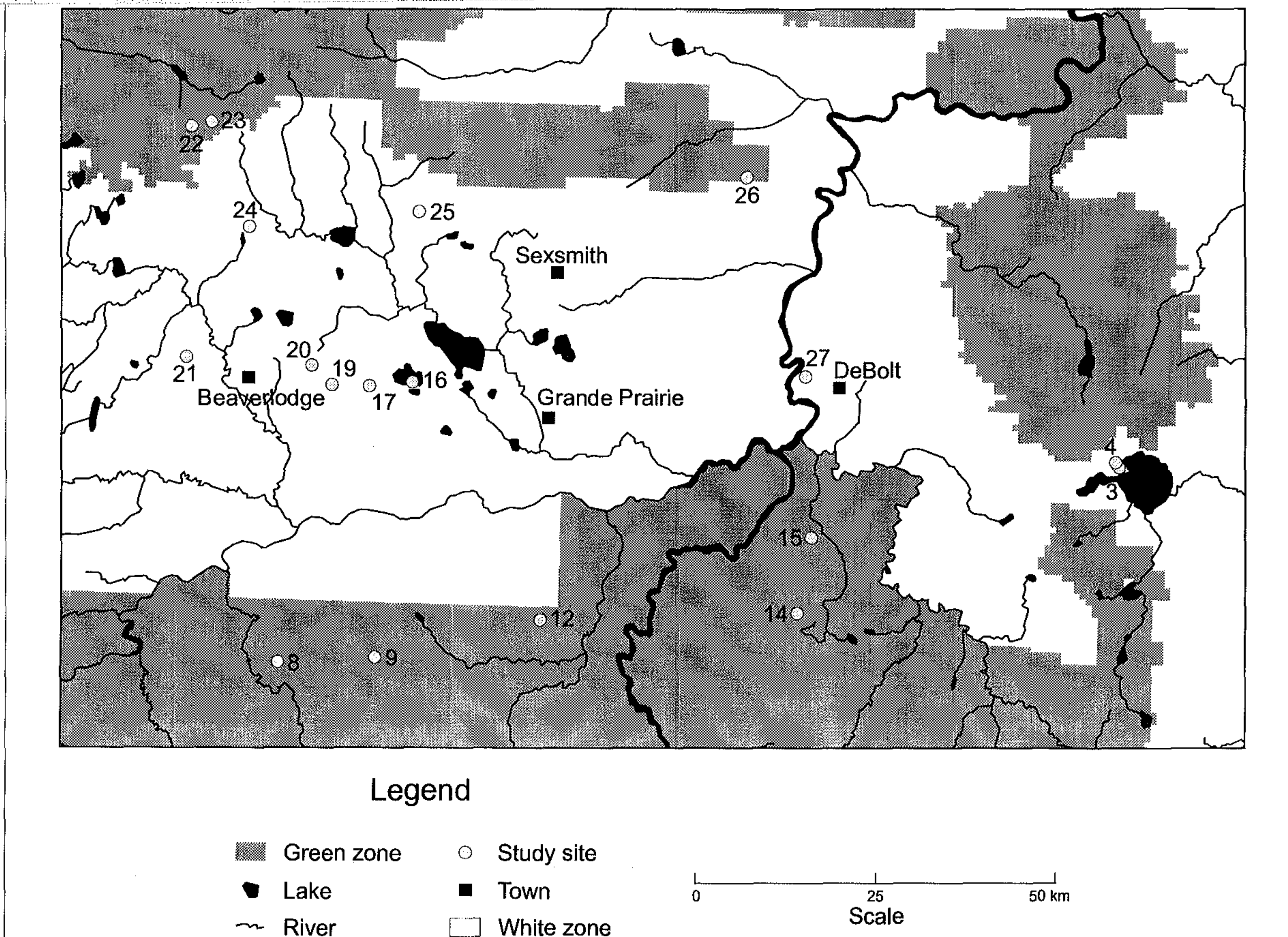


Fig. 1. Locations of study sites within the study area.

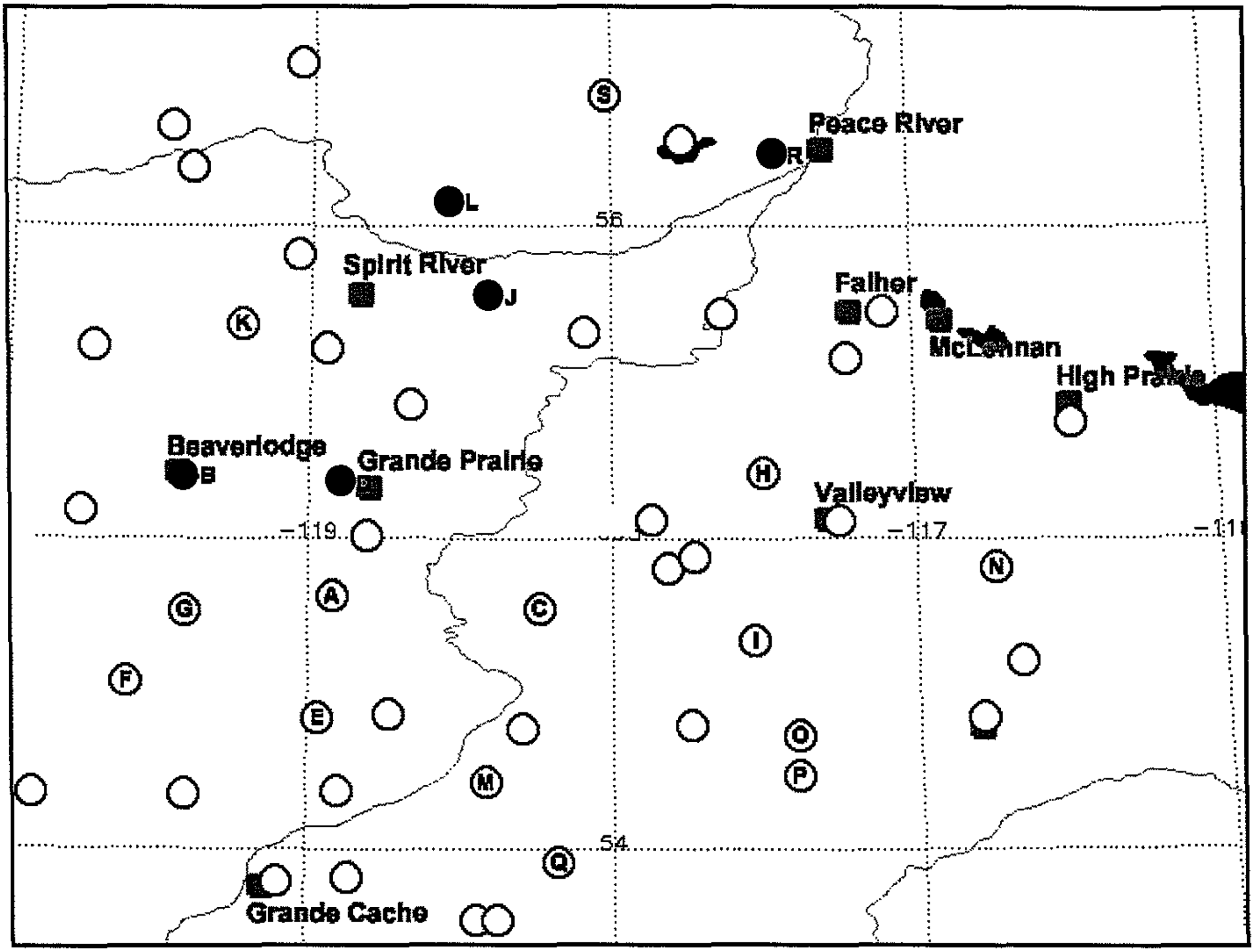
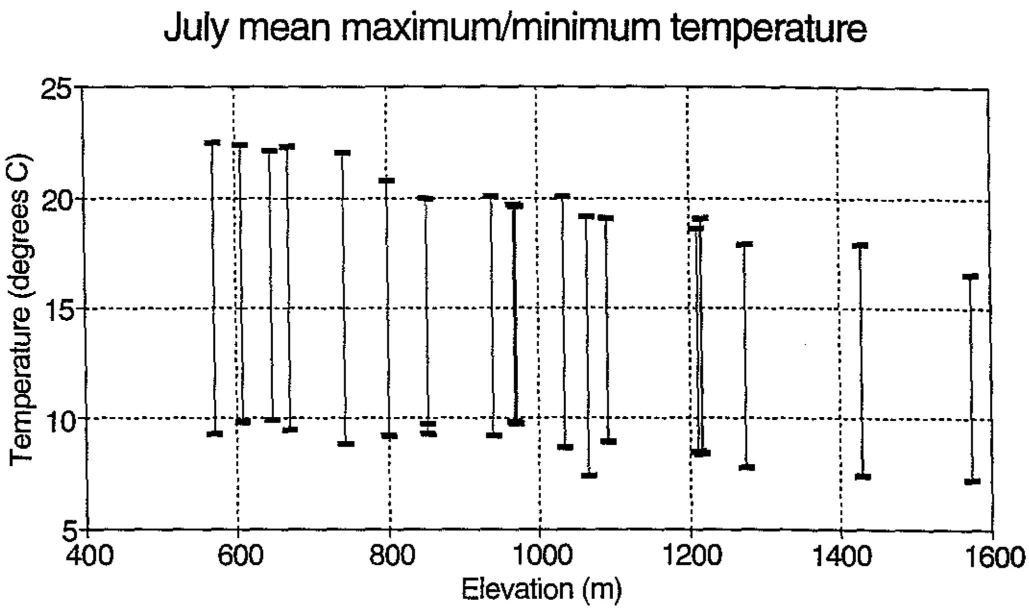


Figure 2 . Map showing location of climate stations including fire lookouts (summer only) in the Grande Prairie area. Letters refer to stations listed in Table 1.



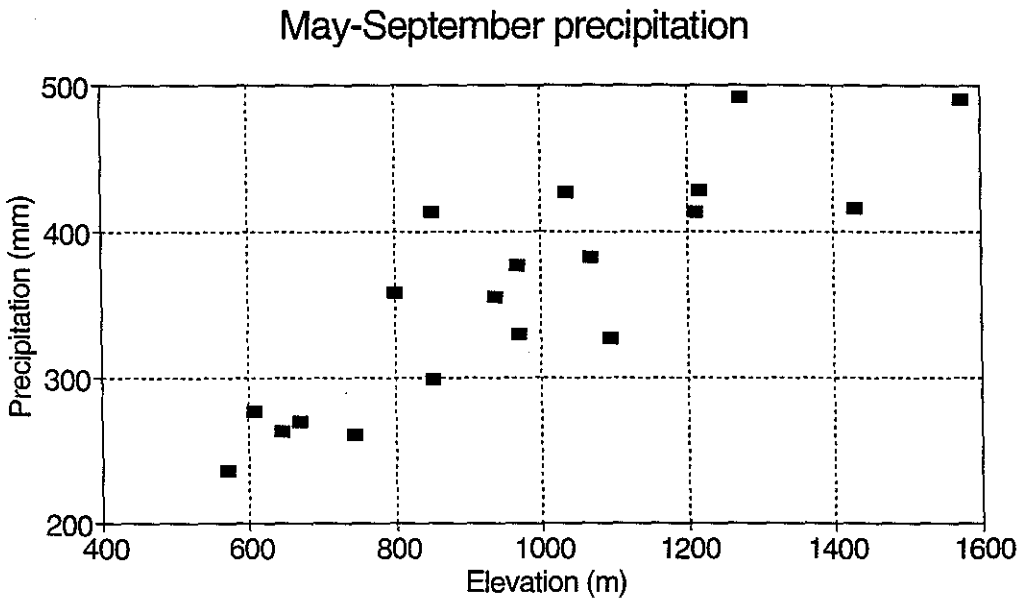


Figure 3. Effect of elevation on climate characteristics for weather stations in the Grande Prairie area, based on the 1951-80 period.

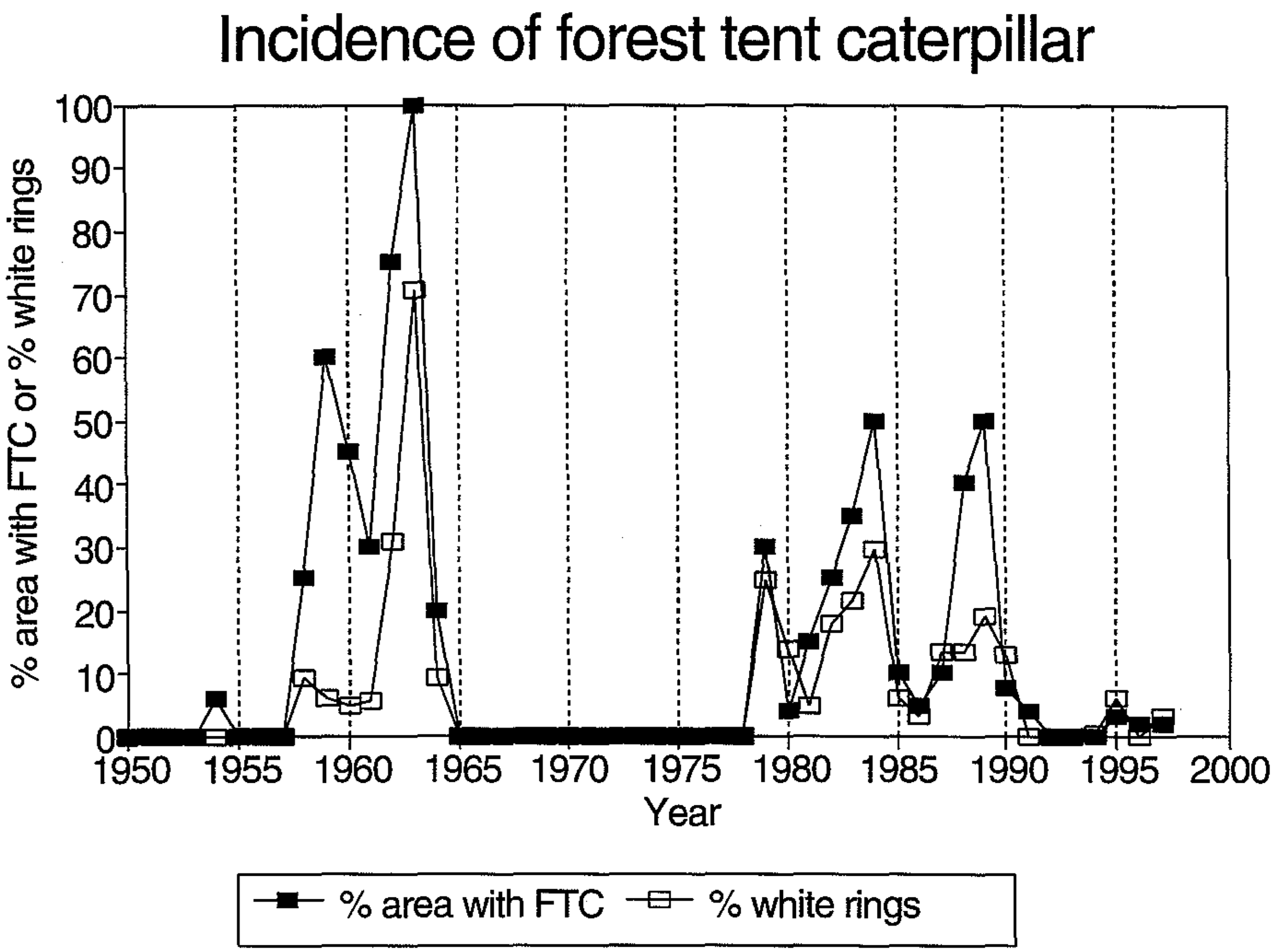


Figure 4. Annual incidence of defoliation of aspen by forest tent caterpillar (FTC) based on a) estimated percentage of study area where defoliation was recorded during surveys by the Canadian Forest Service, and b) percentage of aspen stems (N=180) showing white rings in disks collected at breast height (1.3 m).

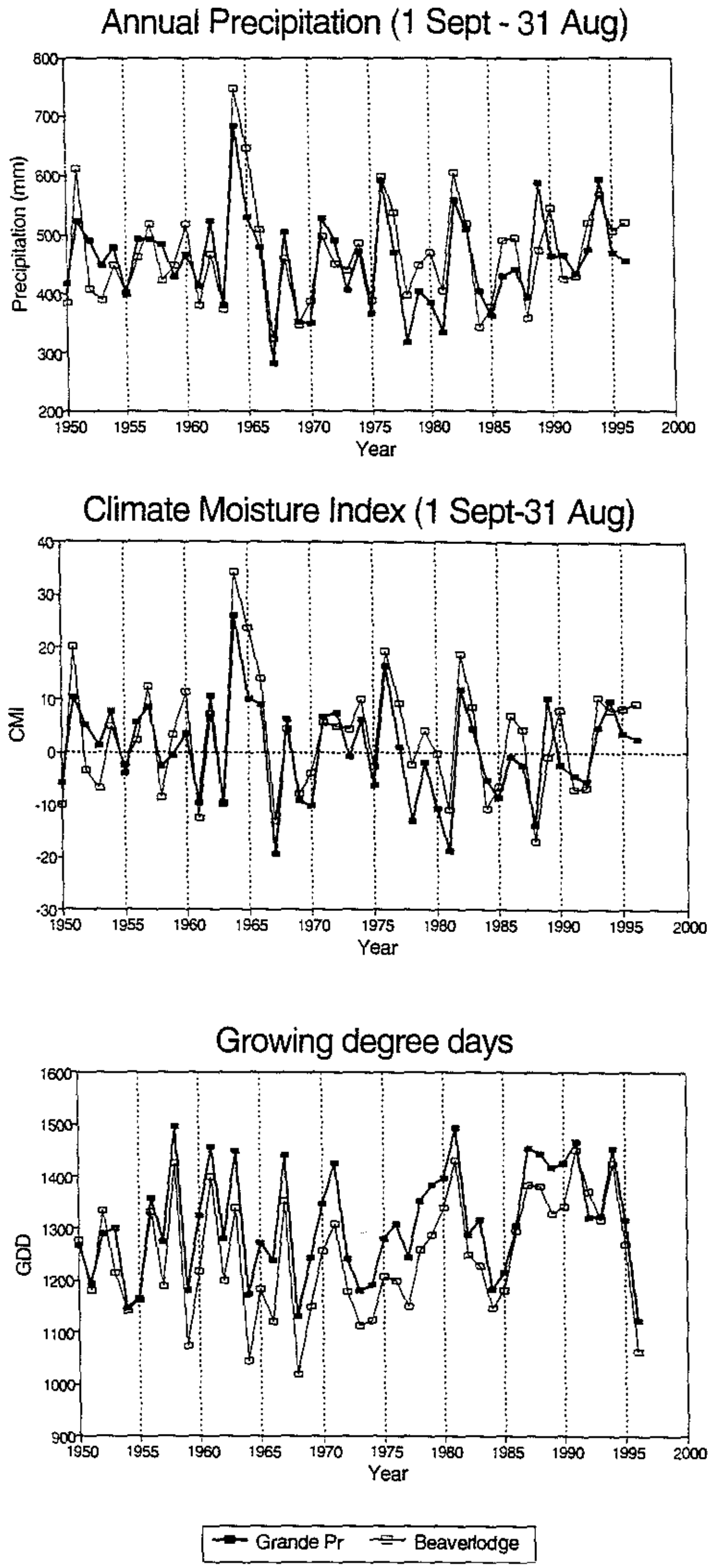


Figure 5. Trends in annual climate characteristics for Grande Prairie and Beaverlodge (1950-1996) used as input for the dynamic regression model of aspen growth: a) precipitation, b) the Climate Moisture Index (Hogg 1997) and c) growing degree days.

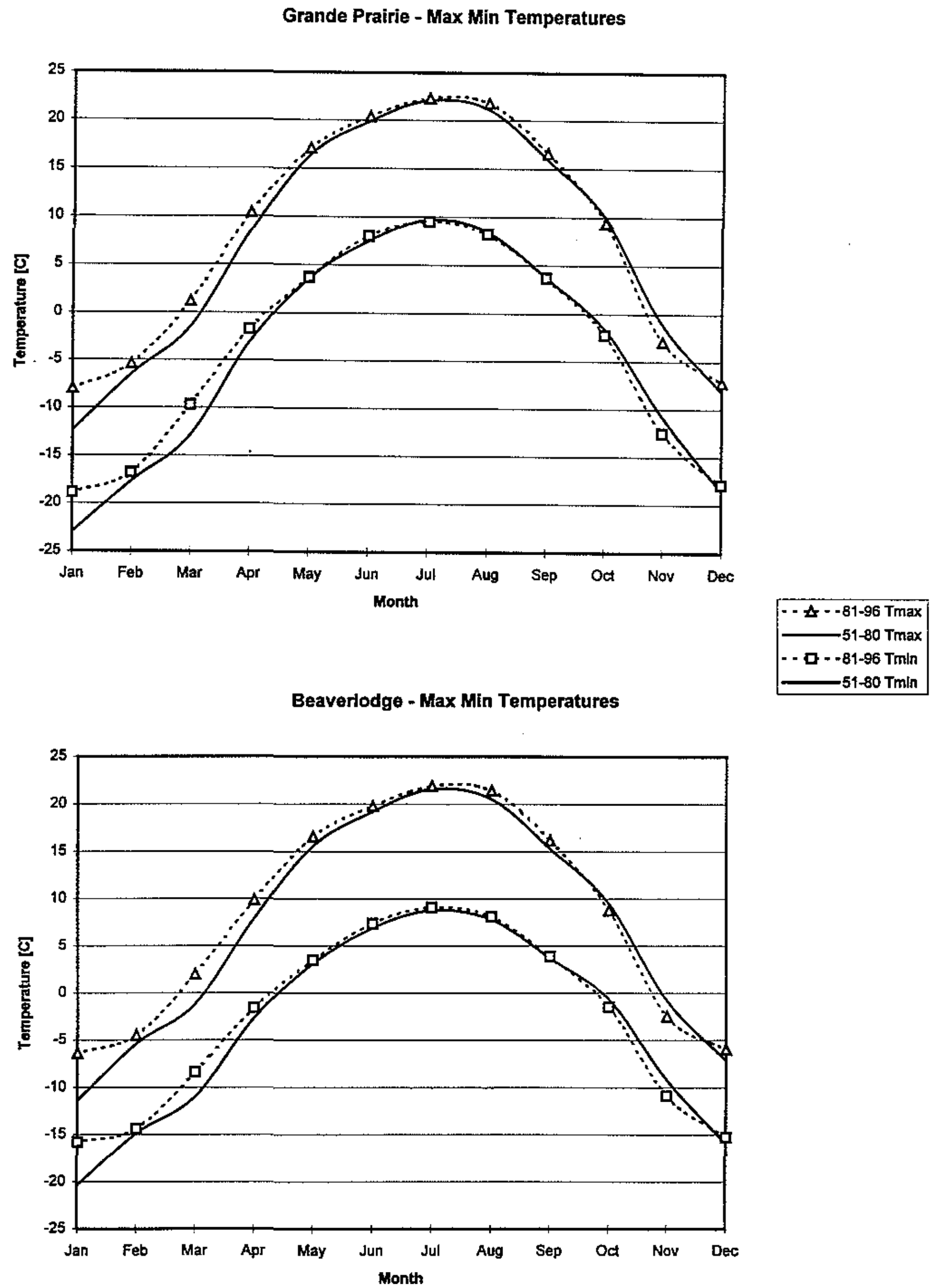
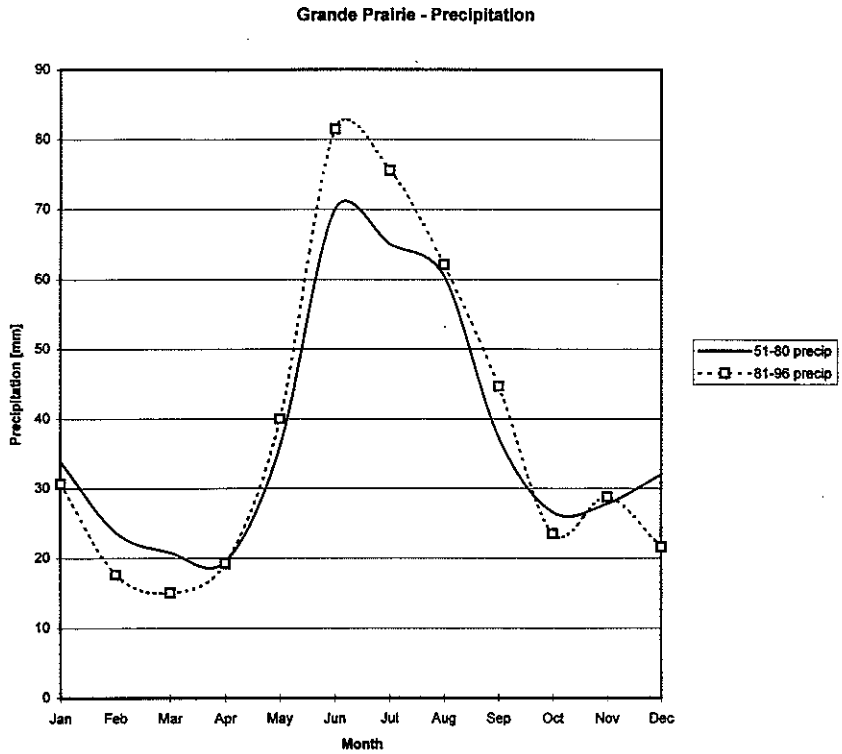


Figure 6. Mean daily maximum and minimum temperatures (°C) at Grande Prairie and Beaverlodge for the period 1981-1996, compared to the 30-year climate normals for 1951-1980.



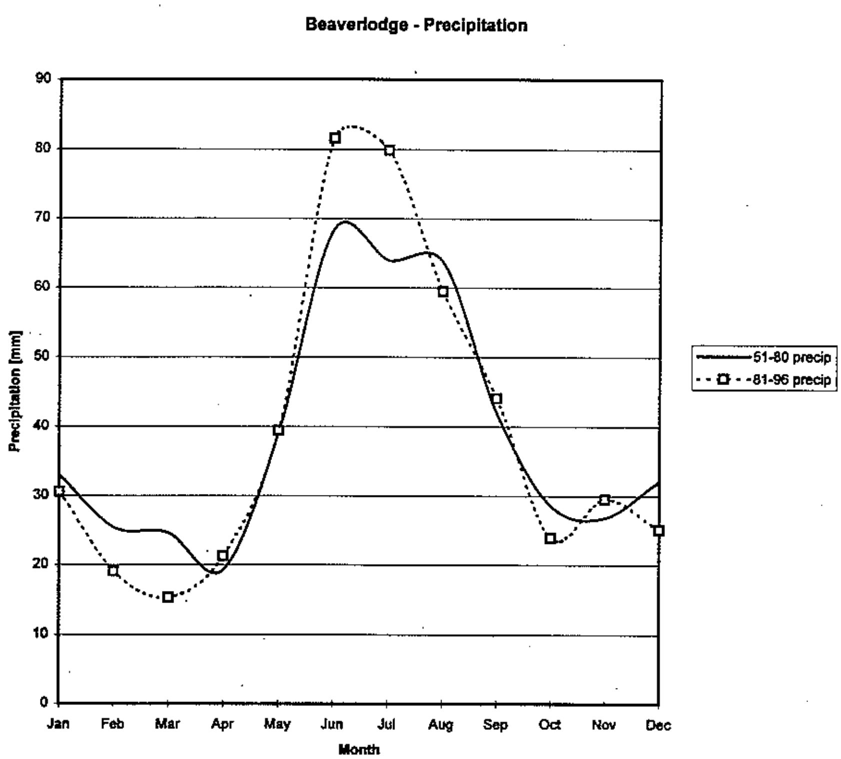


Figure 7. Monthly precipitation (mm) at Grande Prairie and Beaverlodge for the period 1981-1996, compared to the 30-year climate normals for 1951-1980.

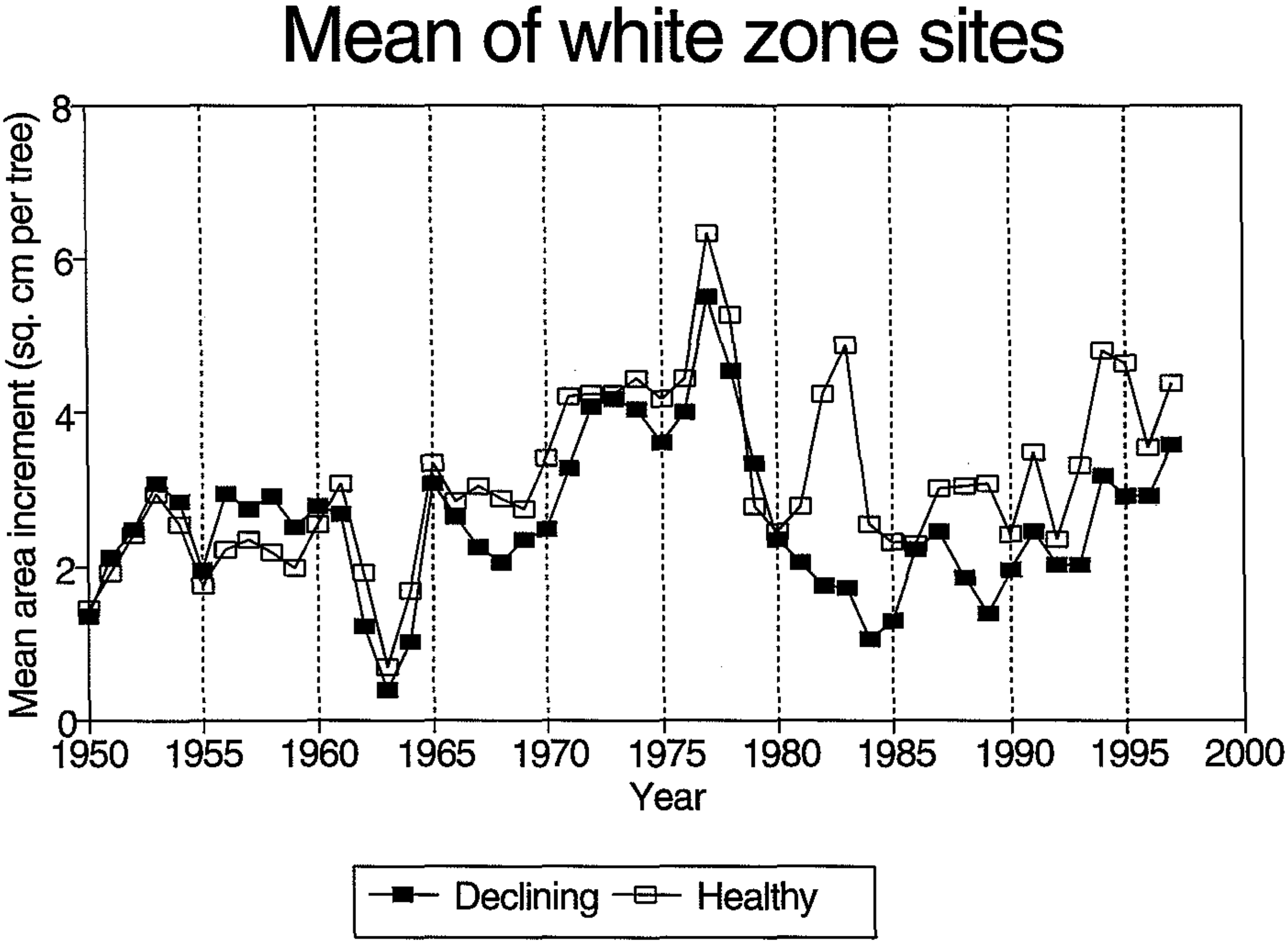


Figure 8. Trends in average stem area increment of aspen from five declining sites and five healthy sites in the white zone, based on tree-ring analysis of disks collected from breast height (total of 100 trees).

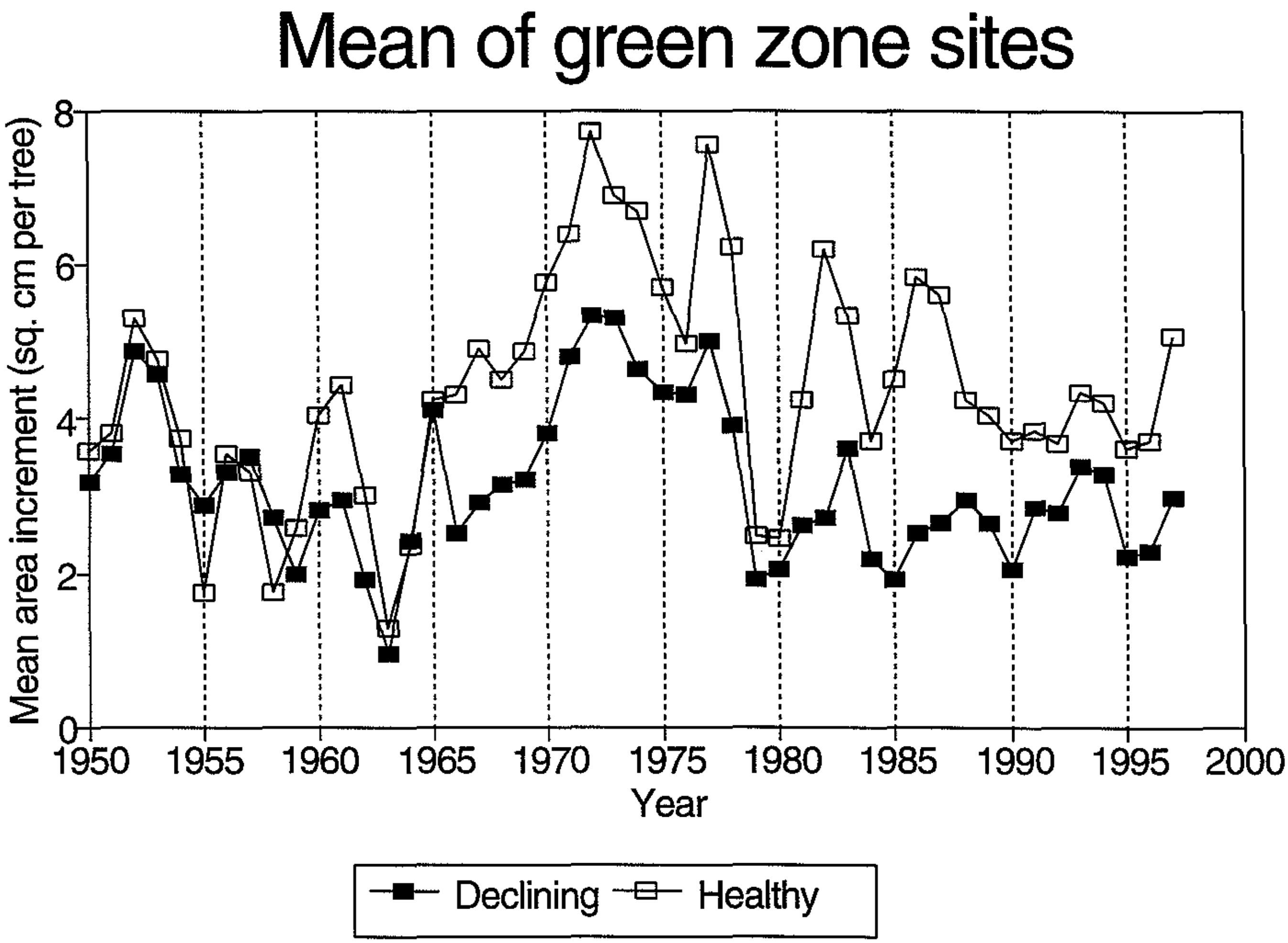


Figure 9. Trends in average stem area increment of aspen from four declining sites and four healthy sites in the green zone, based on tree-ring analysis of disks collected from breast height (total of 80 trees).

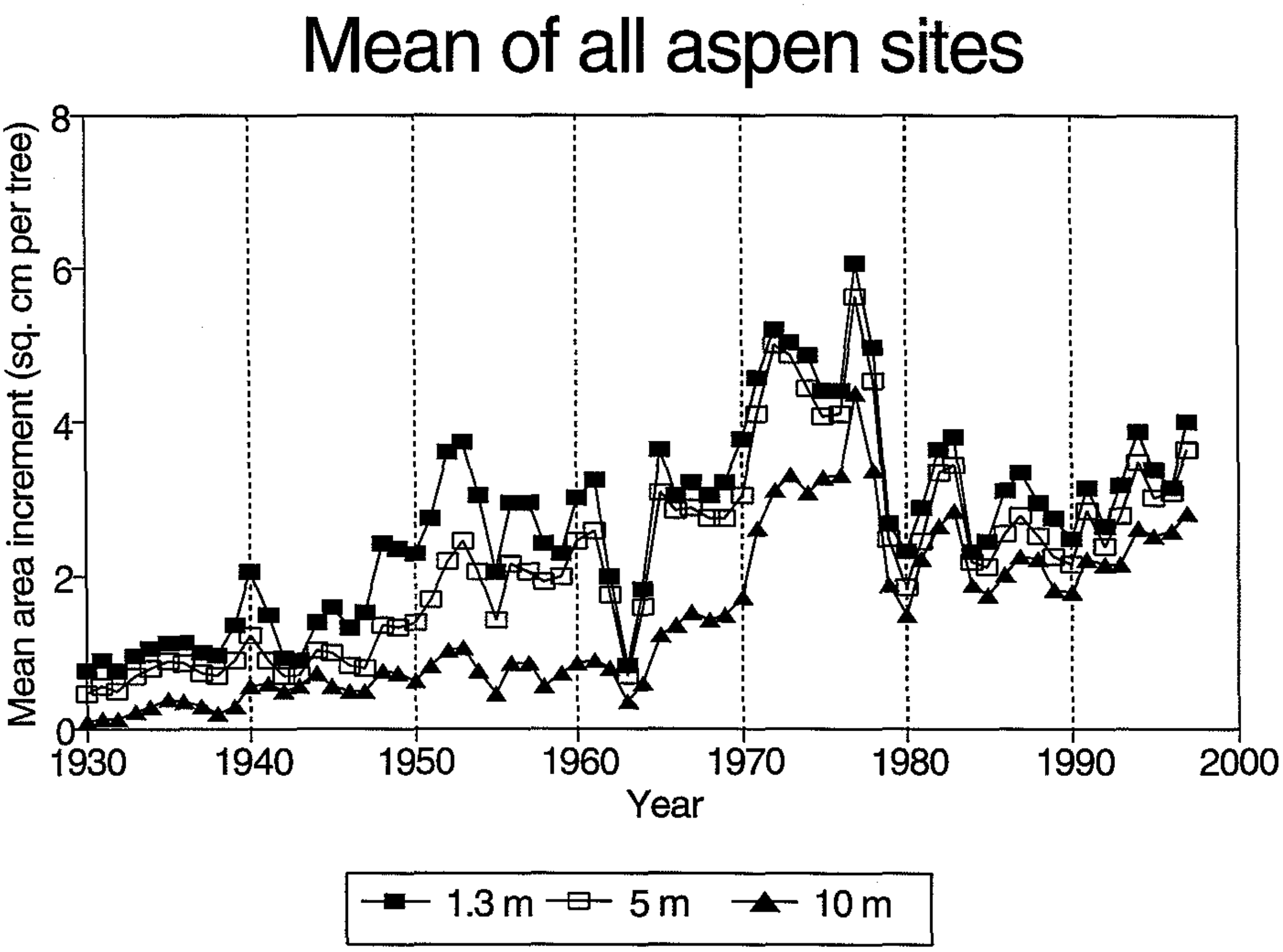


Figure 10. Trends in stem area increment at three different heights (1.3 m, 5 m, and 10 m), averaged for all aspen sampled (N=180).

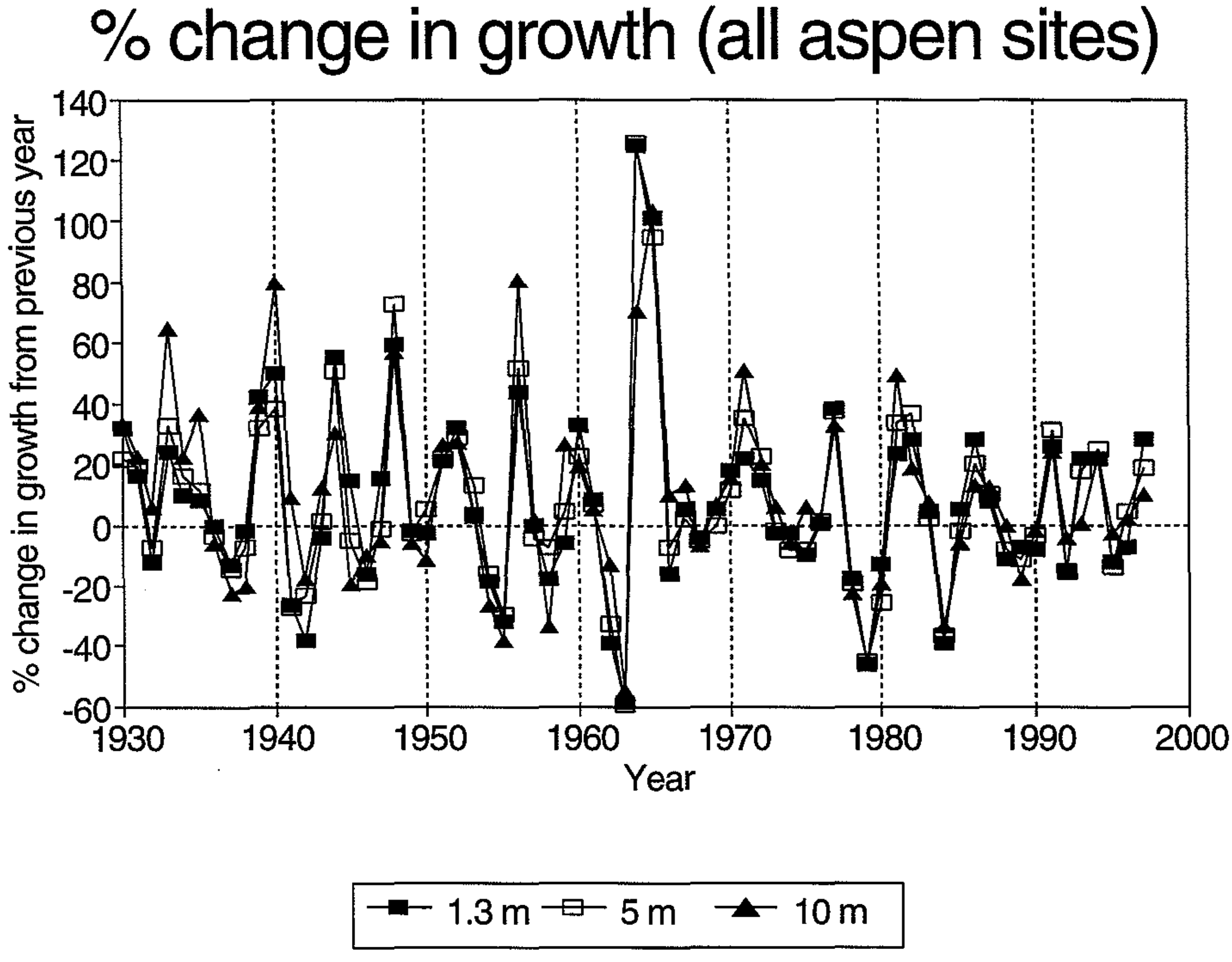


Figure 11. Interannual variation in stem at three different heights (1.3 m, 5 m, and 10 m), averaged for all aspen sampled (N=180). Growth for each year is expressed as a percentage change from the previous year's growth.

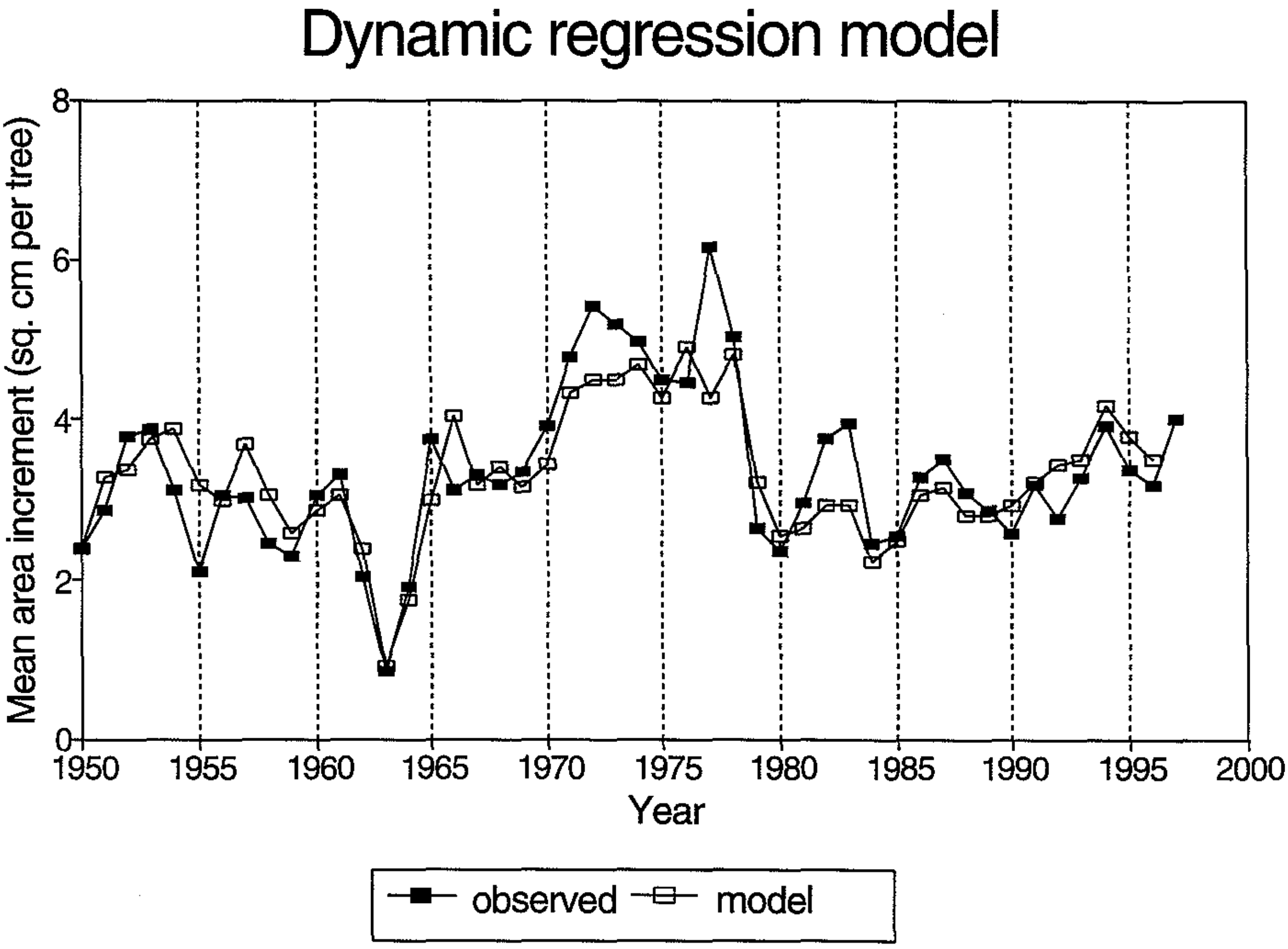


Figure 12. Observed and modelled stem growth of aspen (mean of all sites). Observed stem growth is based on tree-ring analysis of disks collected at breast height (1.3 m, Figure 10); modelled stem growth was obtained using dynamic regression using the equation described in Table 8 (all sites)

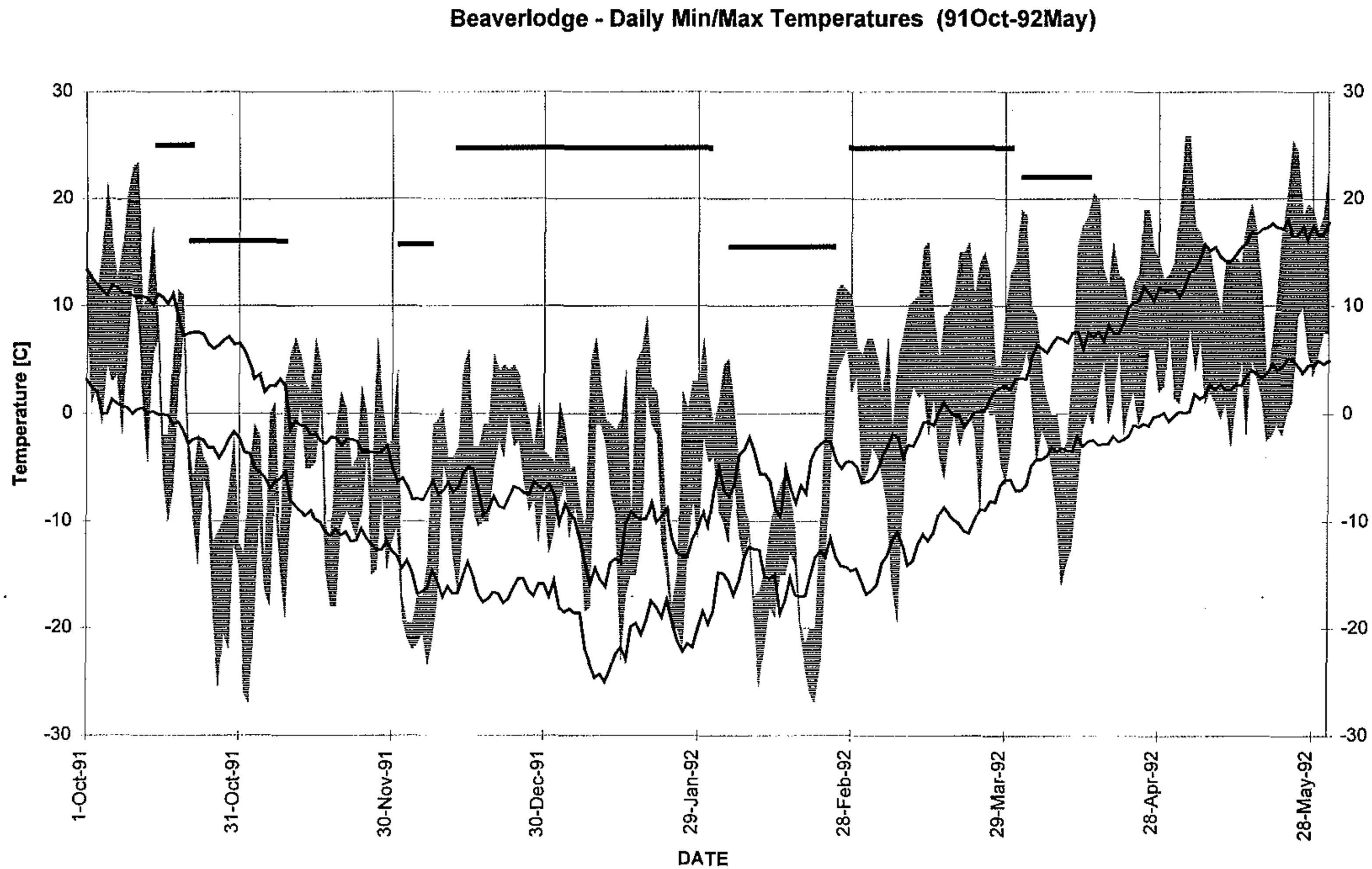


Figure 13. Daily maximum and minimum temperatures [in shaded area] at Beaverlodge for the period October 1991 to May 1992, showing the extreme climatic events. The 30-year climate normals [solid continuous lines] for 1951-1980 are shown for comparison.

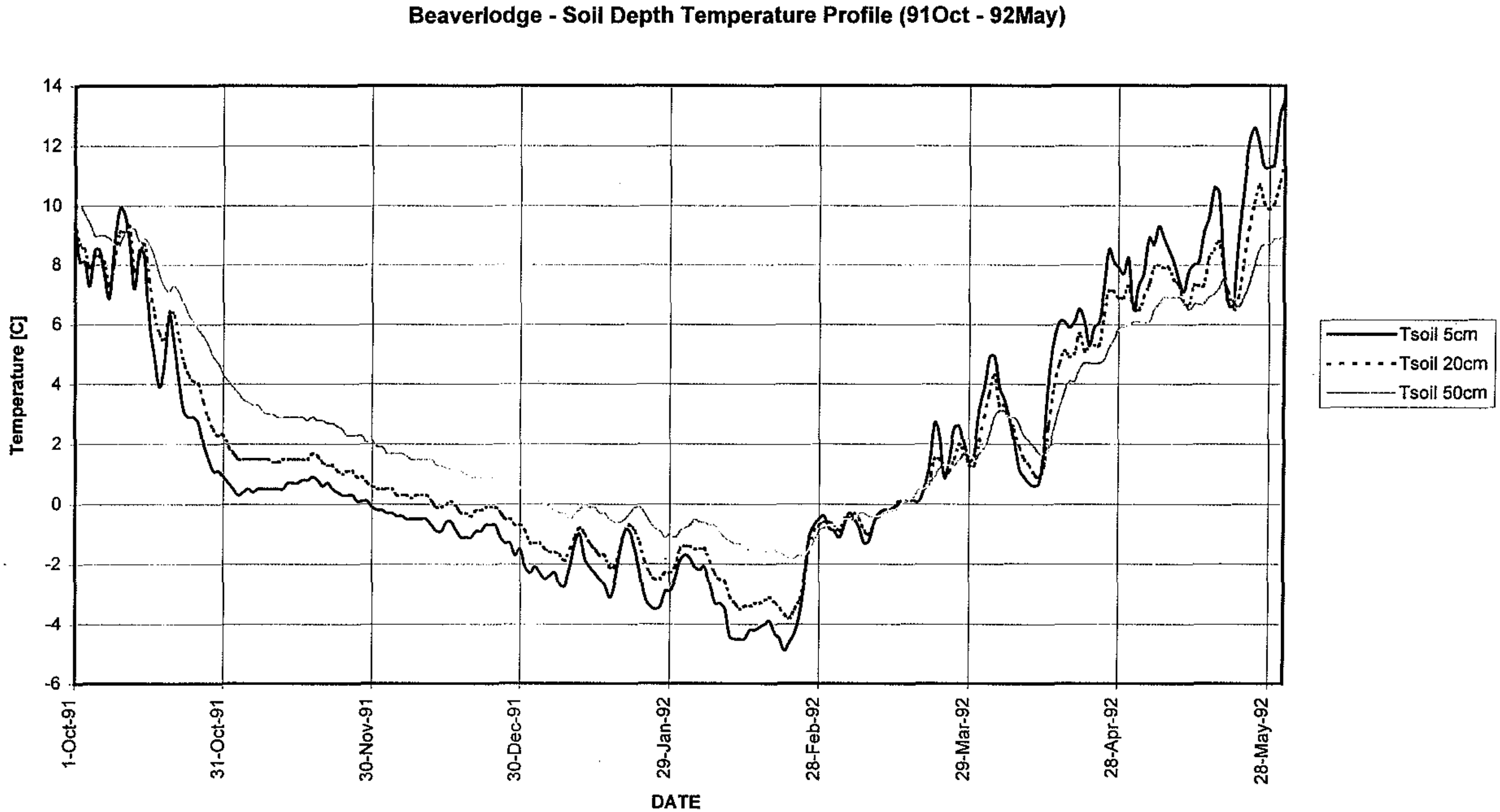
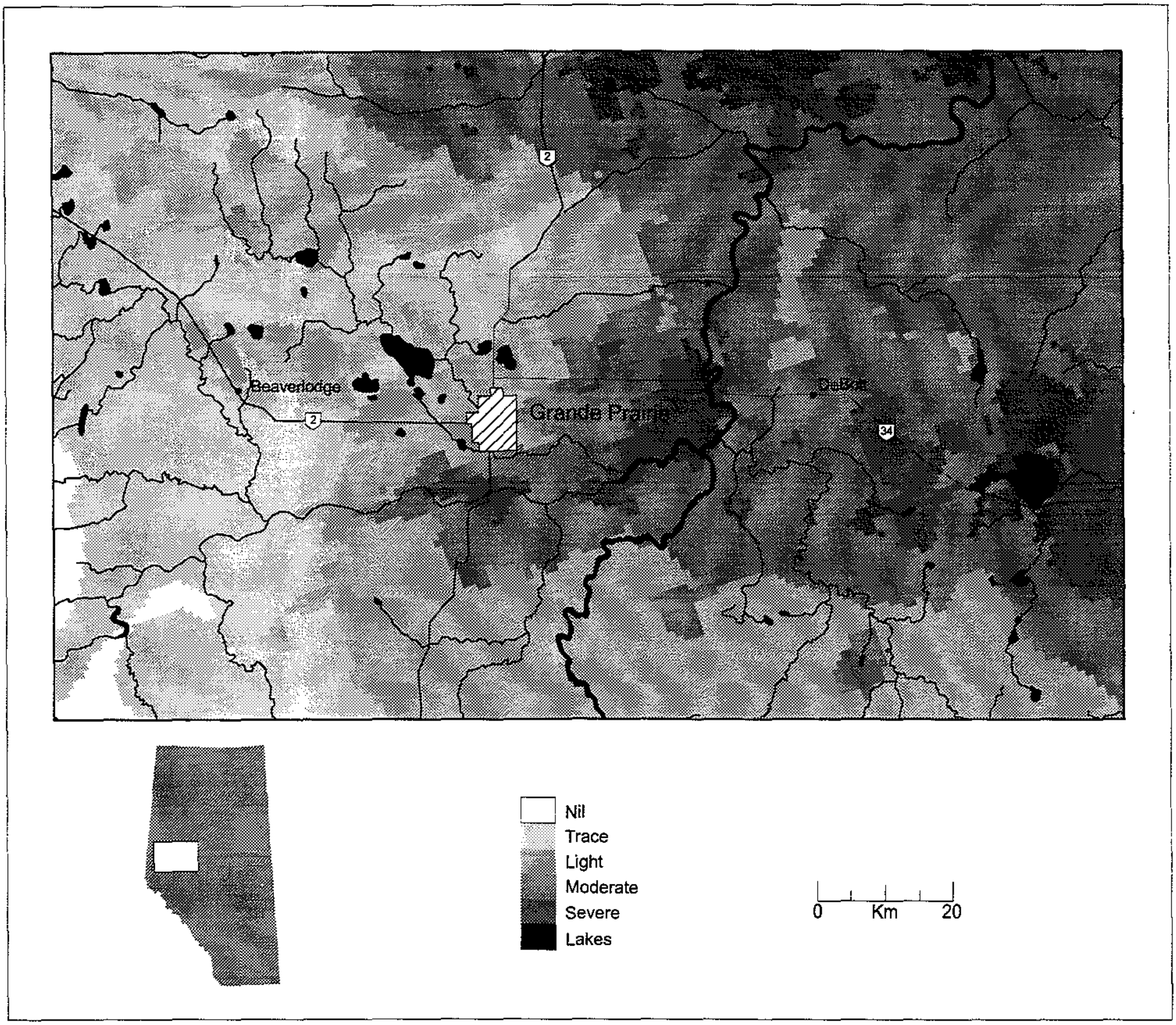


Figure 14. Soil temperature at three depths for the period October 1991 to May 1992 at Beaverlodge.

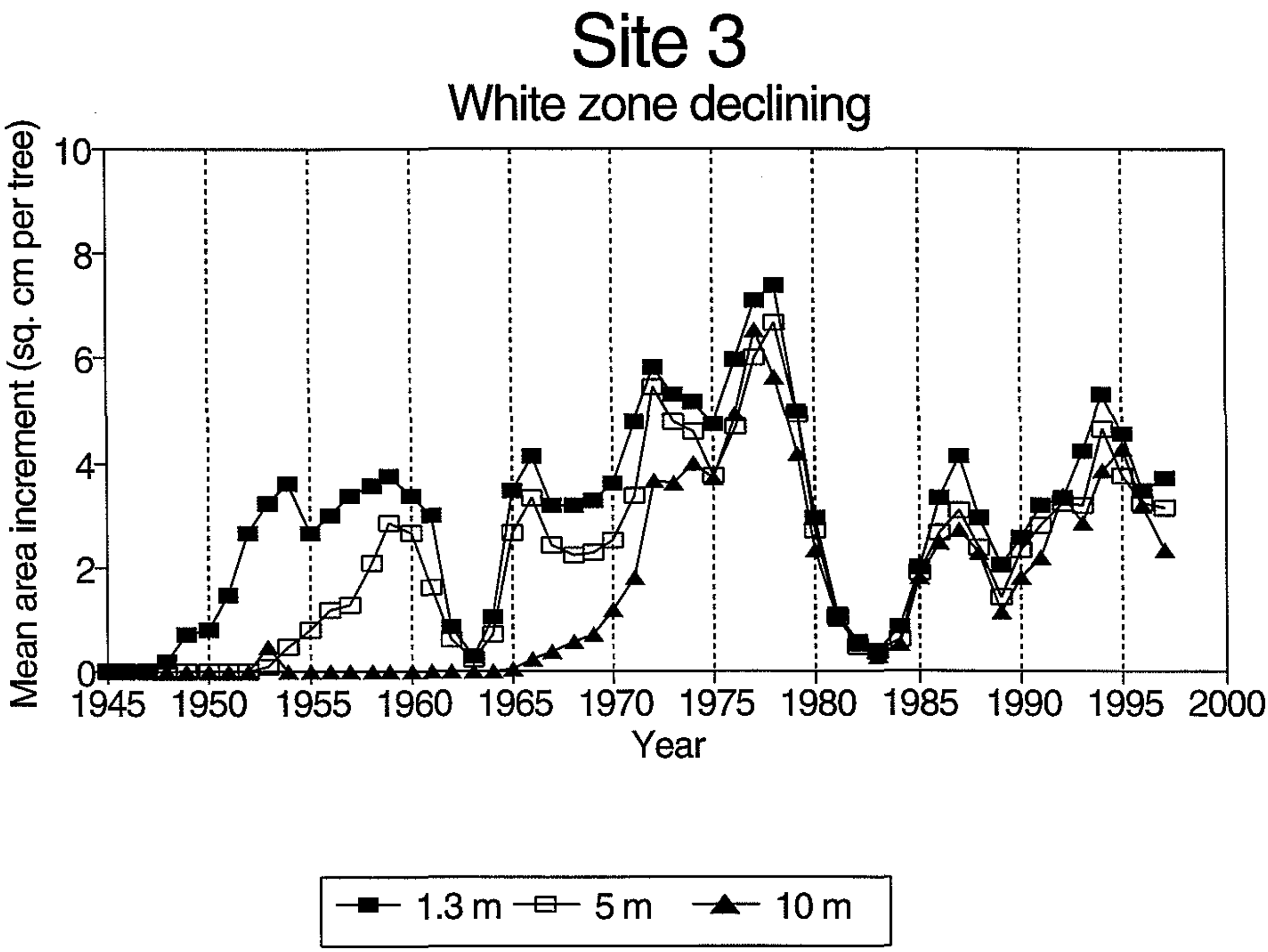
Appendix 1. Area of trembling aspen defoliated by forest tent caterpillar, 1988-1992 (From Brandt 1995).

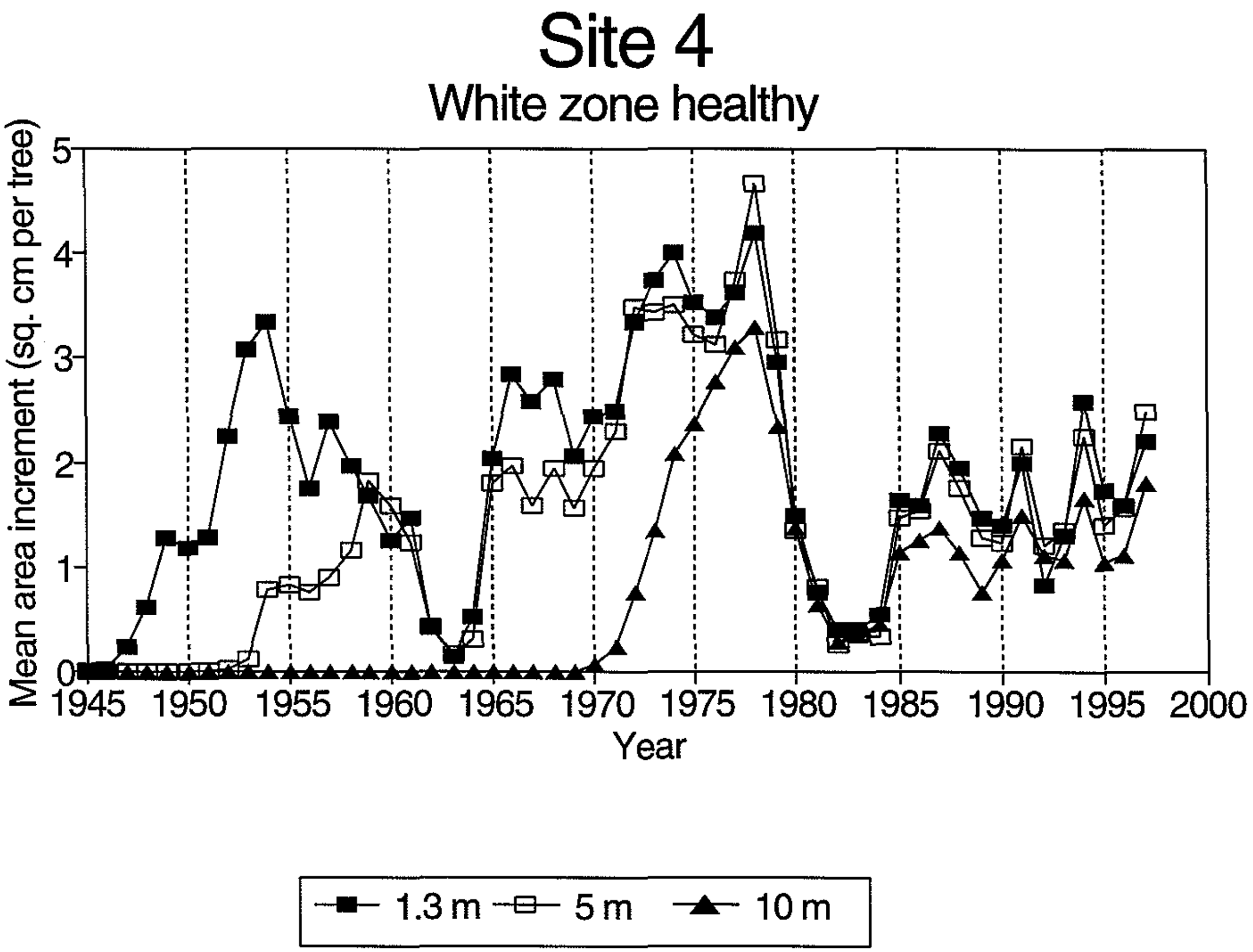


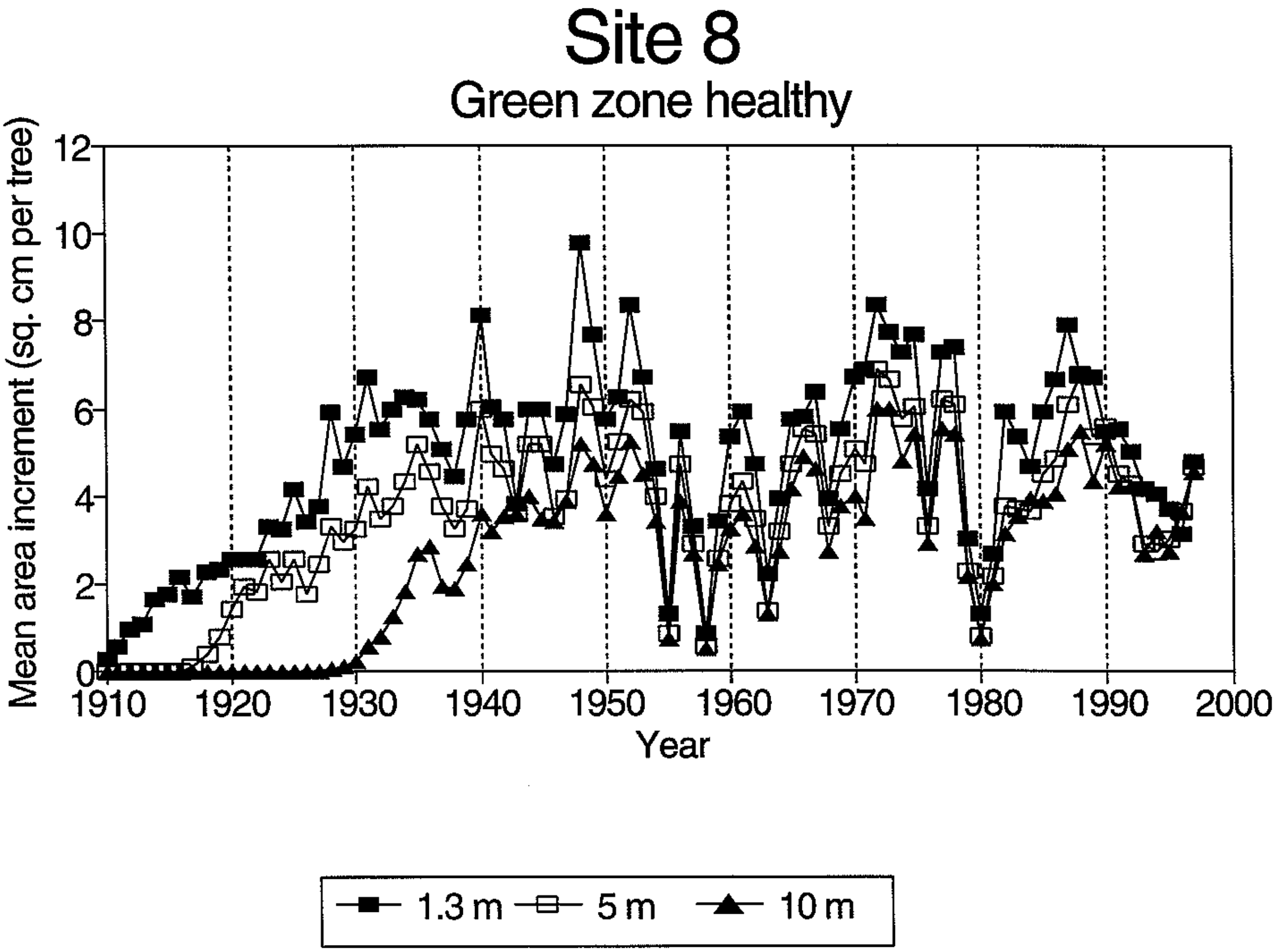
Appendix 2. Relative level of forest tent caterpillar defoliation, 1937-1997
(Defoliation level as a combination of years and severity of defoliation)

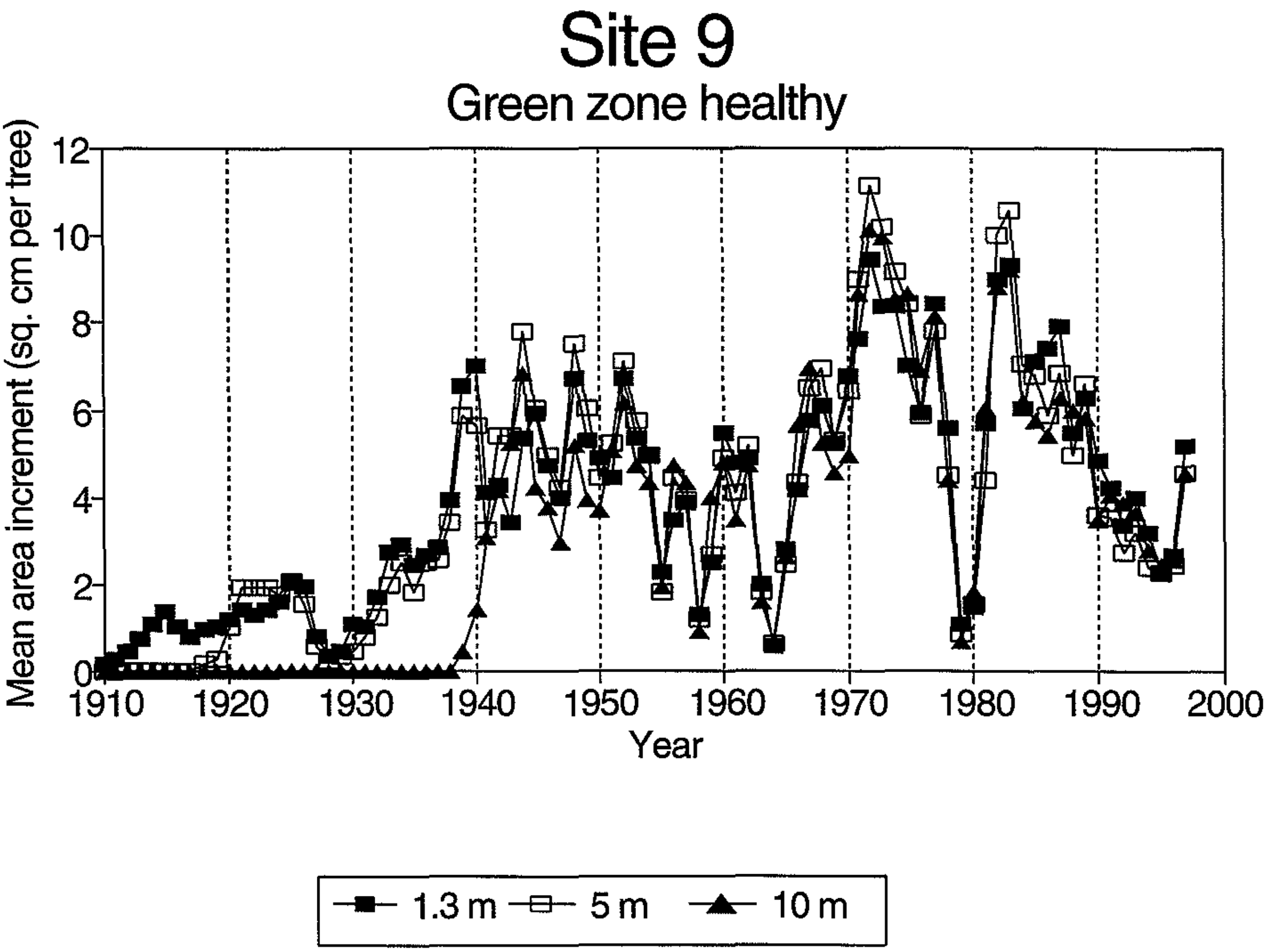
APPENDIX 3

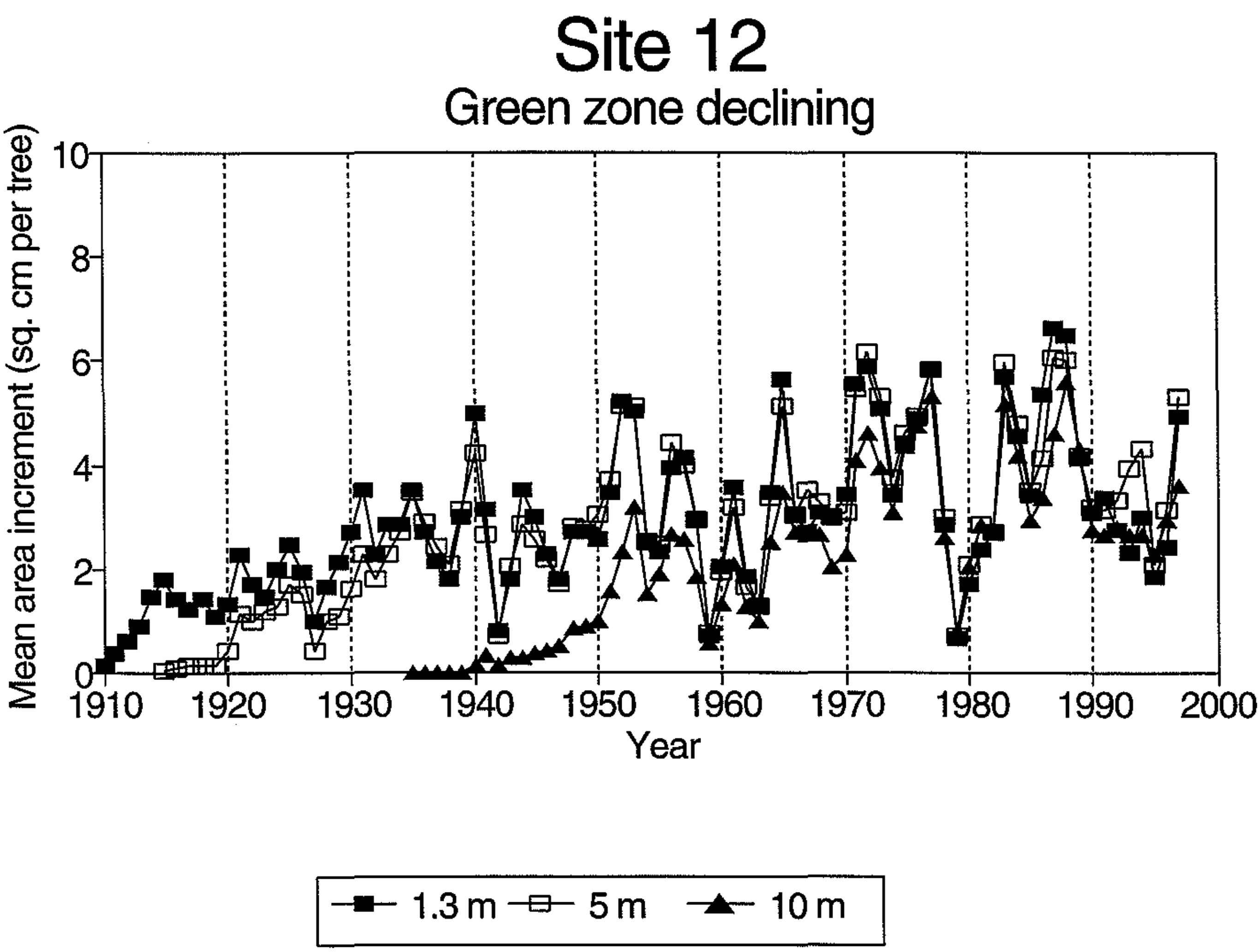
Trends in stem area increment of aspen based on tree-ring analysis of disks collected at three heights (1.3 m, 5 m and 10 m) for each of the study sites (averages based on N=10 trees per site).

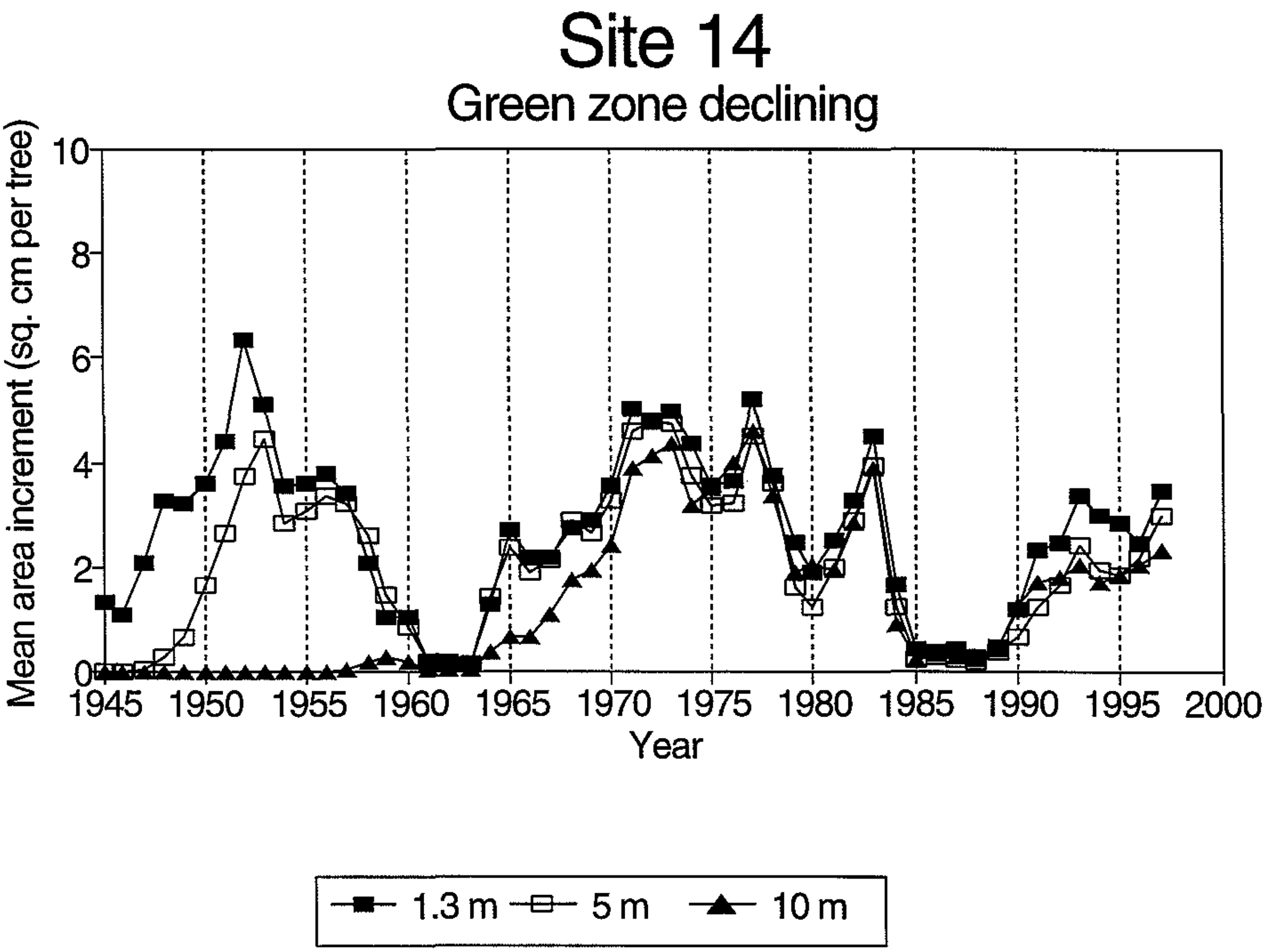

Site 3
White zone declining
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m

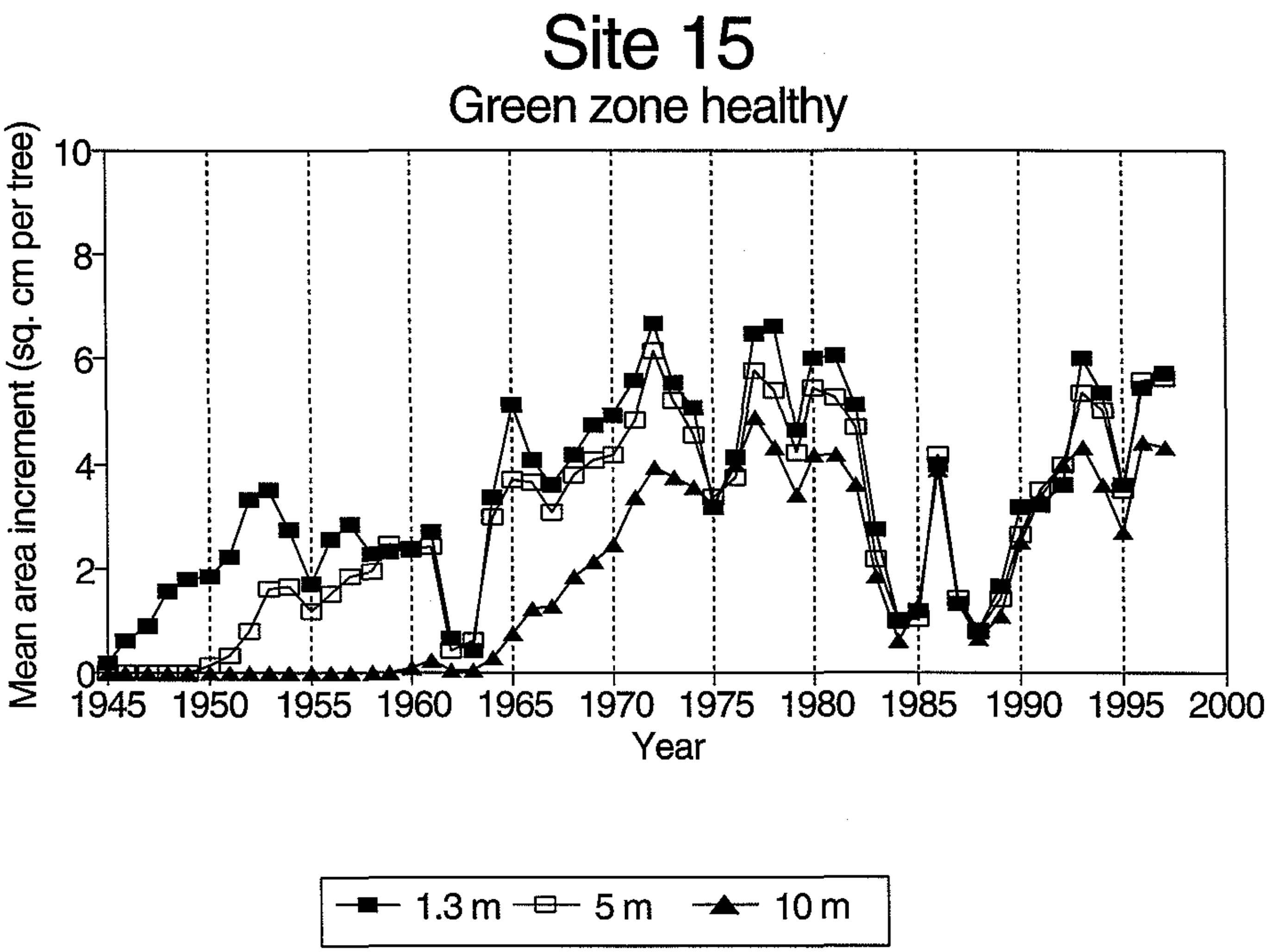

Site 4
White zone healthy
Mean area increment (sq. cm per tree)
0
1
2
3
4
5
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m

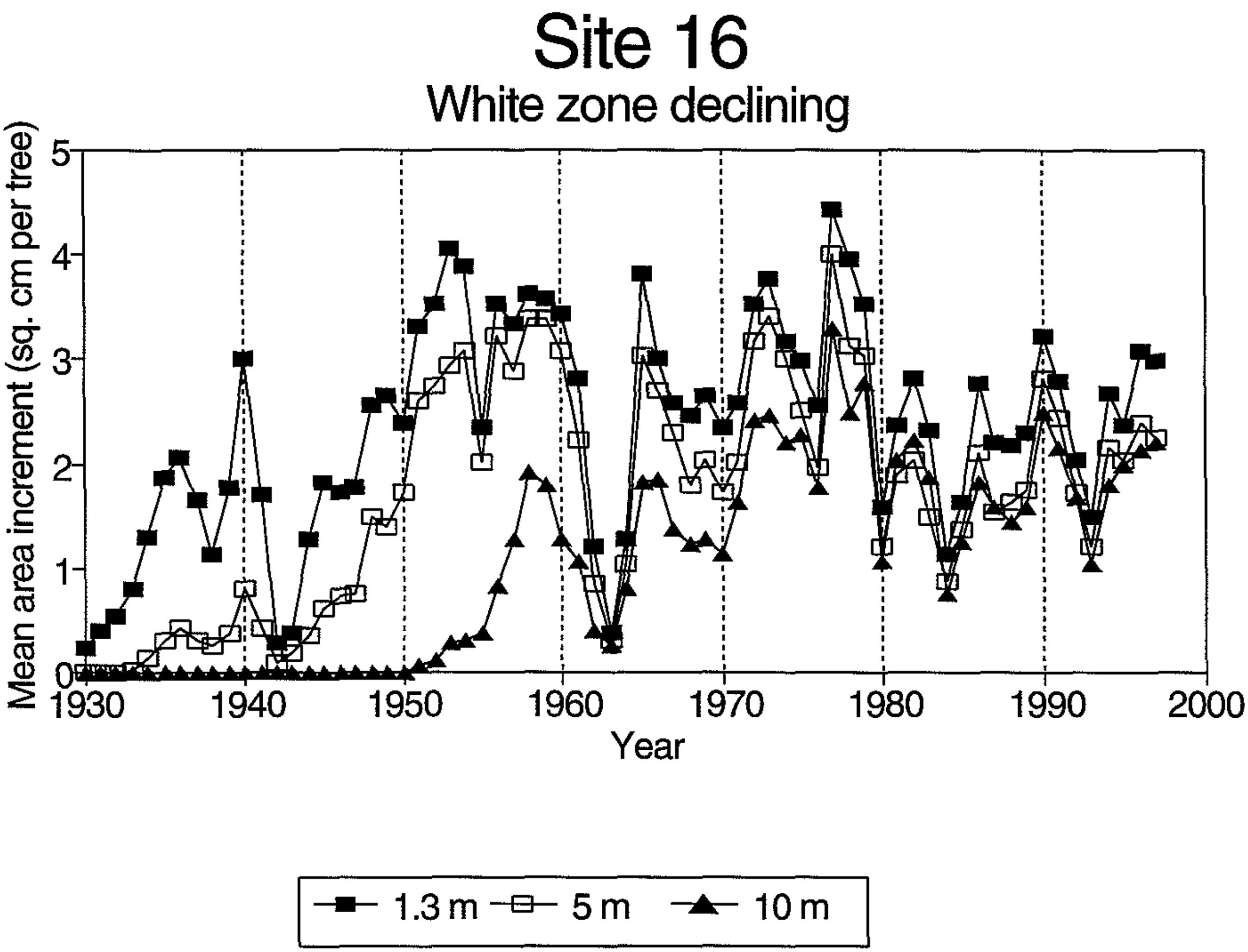

Site 8
Green zone healthy
Mean area increment (sq. cm per tree)
Year
0
2
4
6
8
10
12
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
1.3 m
5 m
10 m


Site 9
Green zone healthy
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
12
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year
1.3 m
5 m
10 m

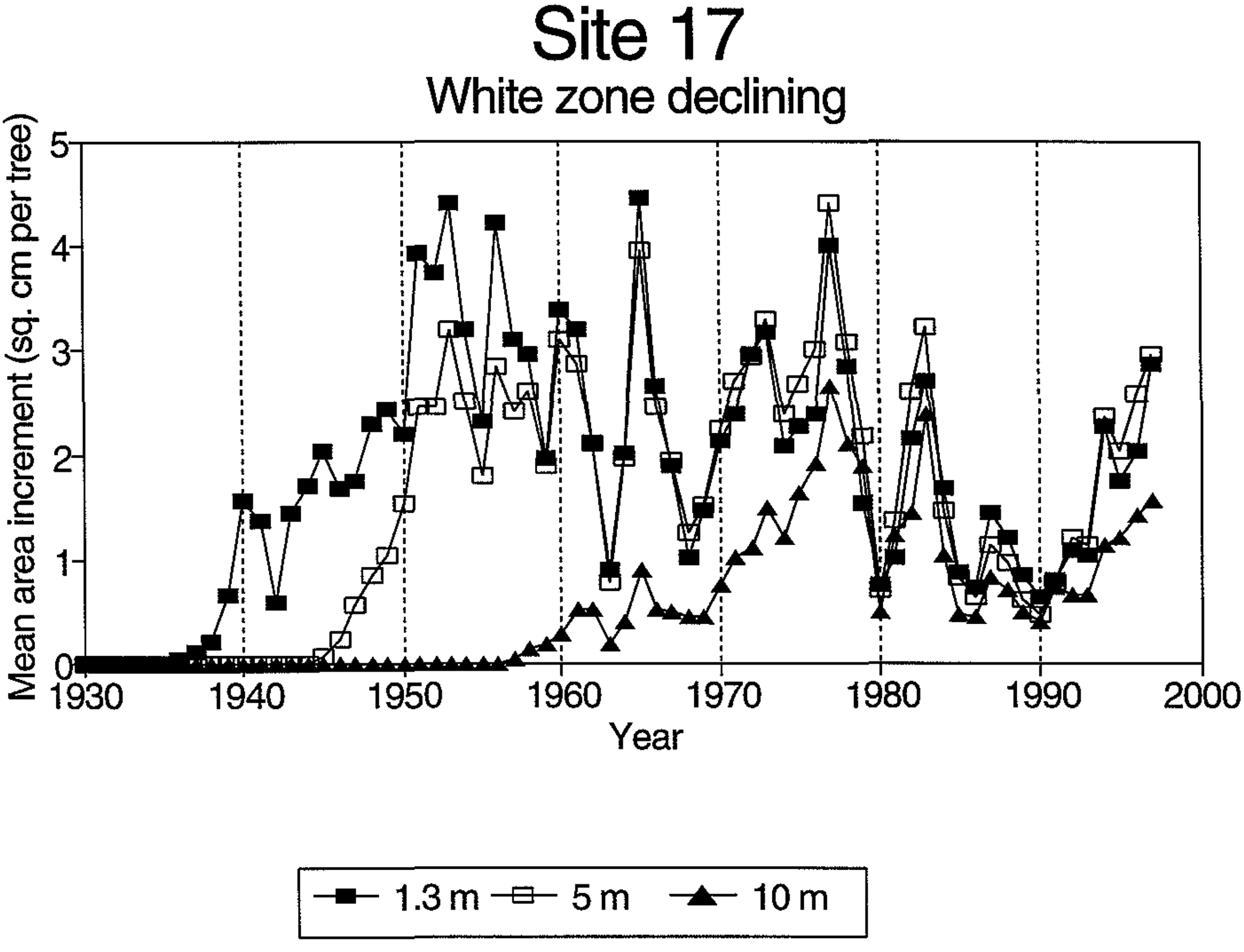

Site 12
Green zone declining
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year
1.3 m
5 m
10 m

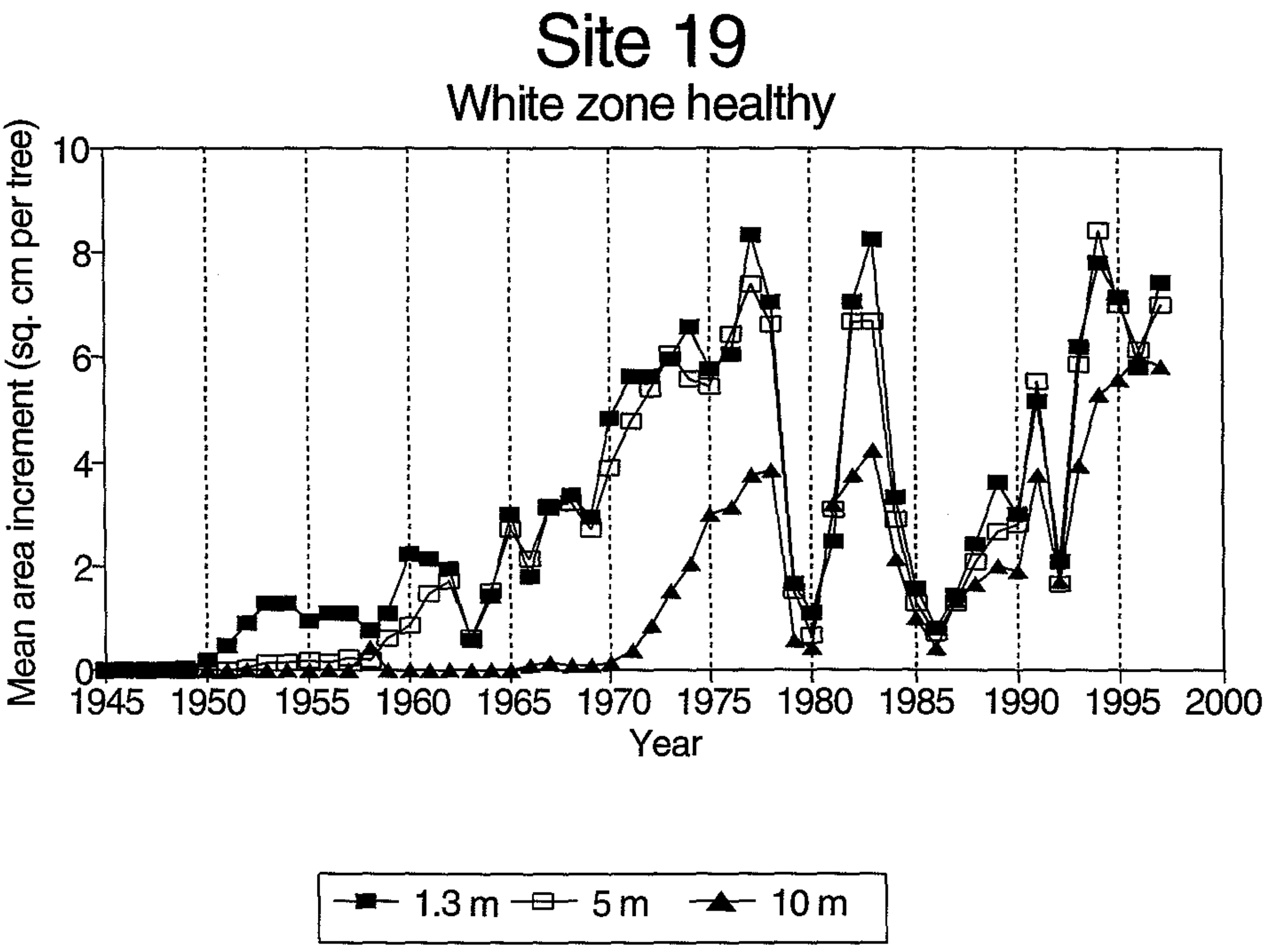

Site 14
Green zone declining
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m


Site 15
Green zone healthy
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m

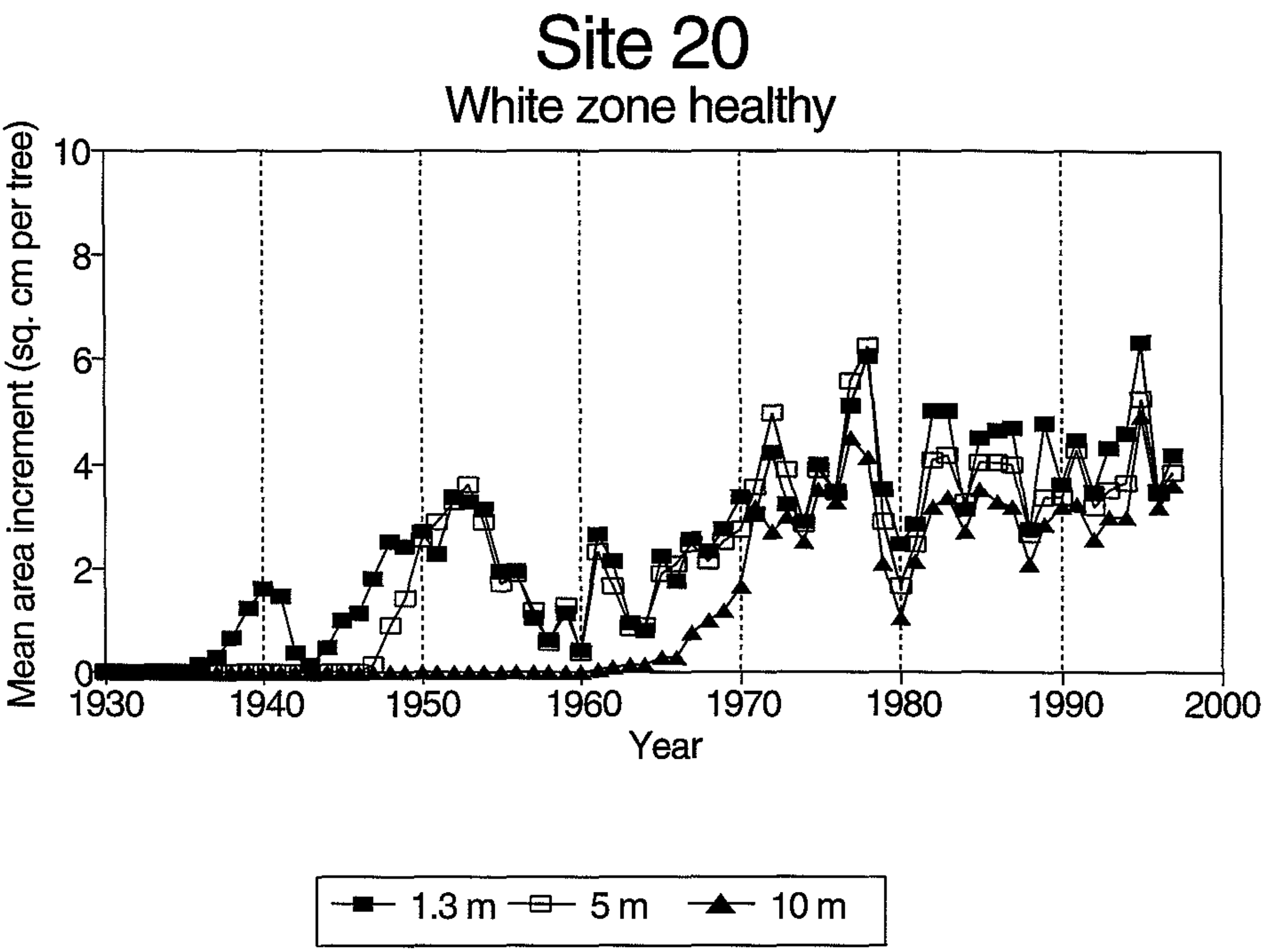


Site 16
White zone declining
Mean area increment (sq. cm per tree)
0
1
2
3
4
5
1930
1940
1950
1960
1970
1980
1990
2000
Year
1.3 m
5 m
10 m

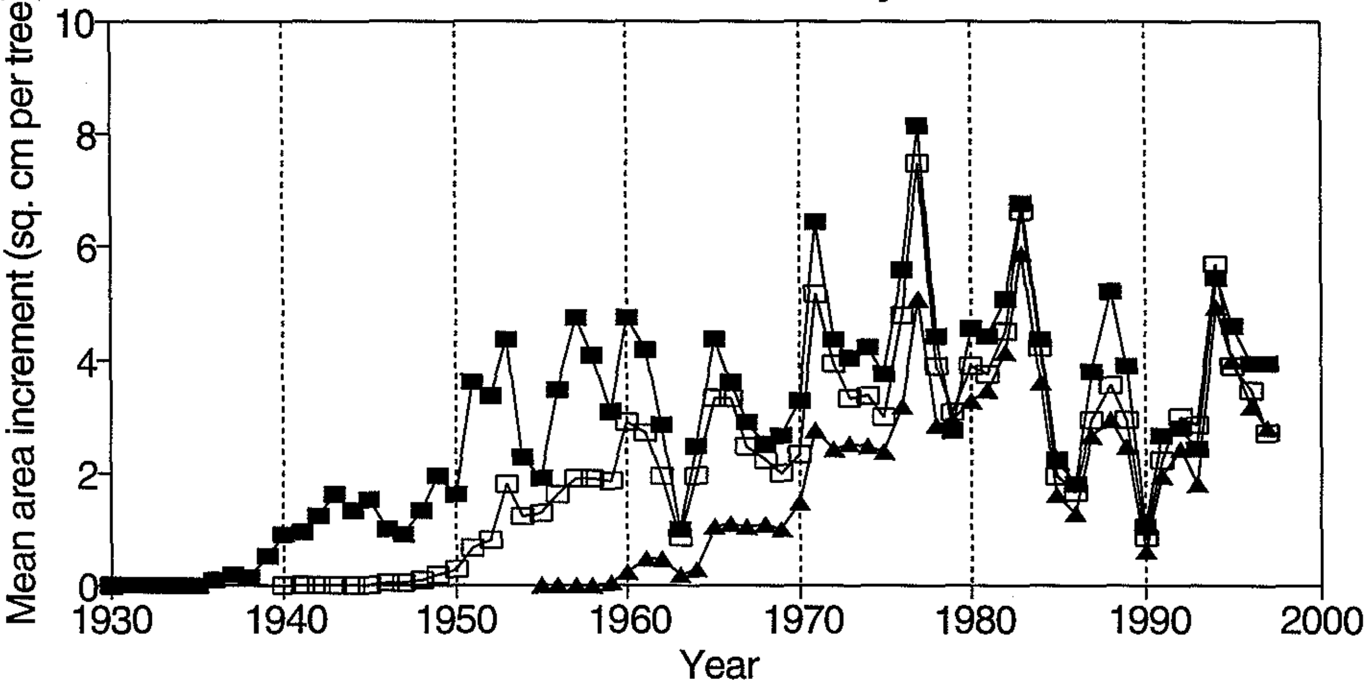

Site 17
White zone declining
Mean area increment (sq. cm per tree)
0
1
2
3
4
5
1930
1940
1950
1960
1970
1980
1990
2000
Year
1.3 m
5 m
10 m



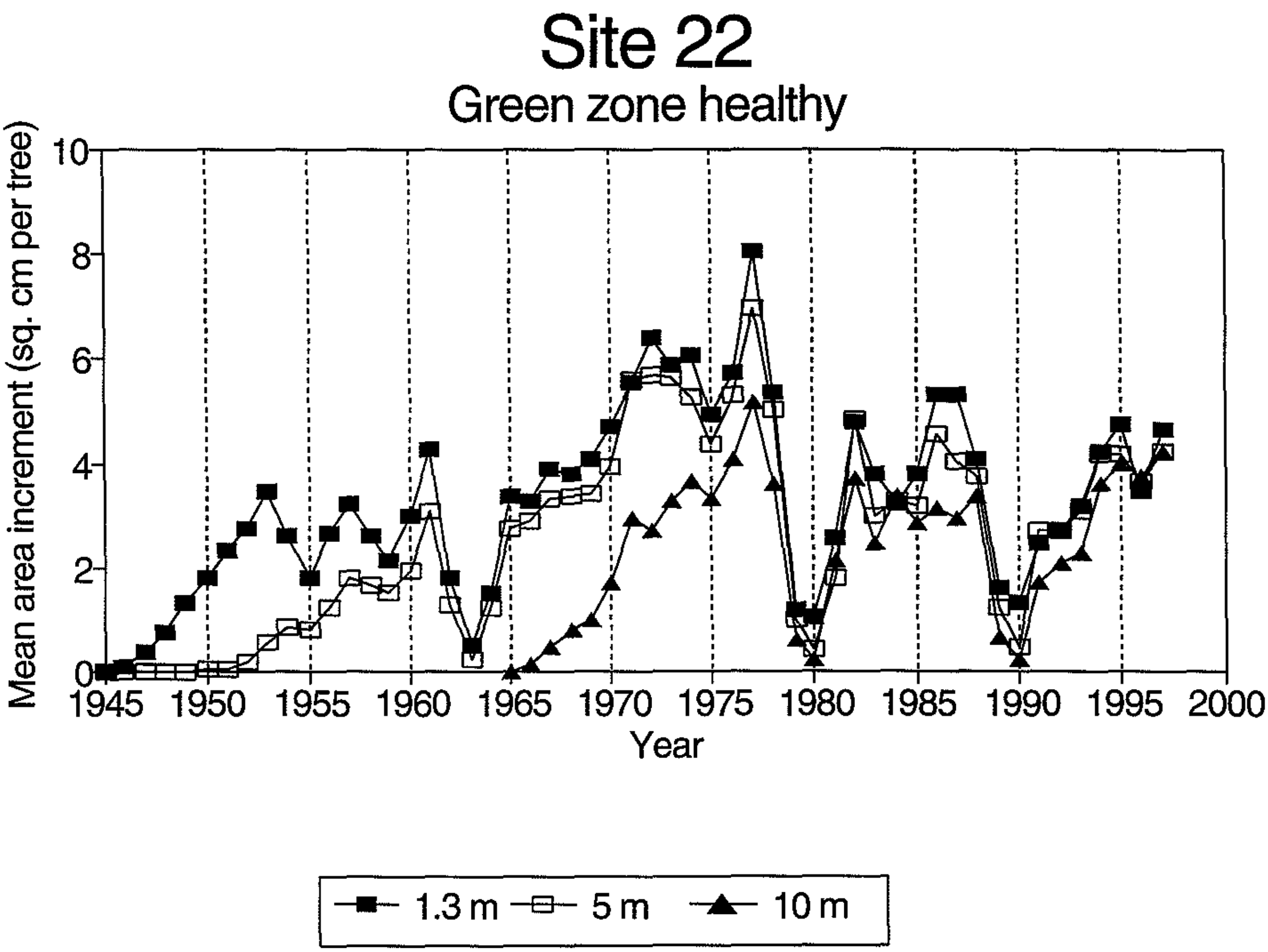
Site 19
White zone healthy
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m


Site 20
White zone healthy
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1930
1940
1950
1960
1970
1980
1990
2000
Year
1.3 m
5 m
10 m

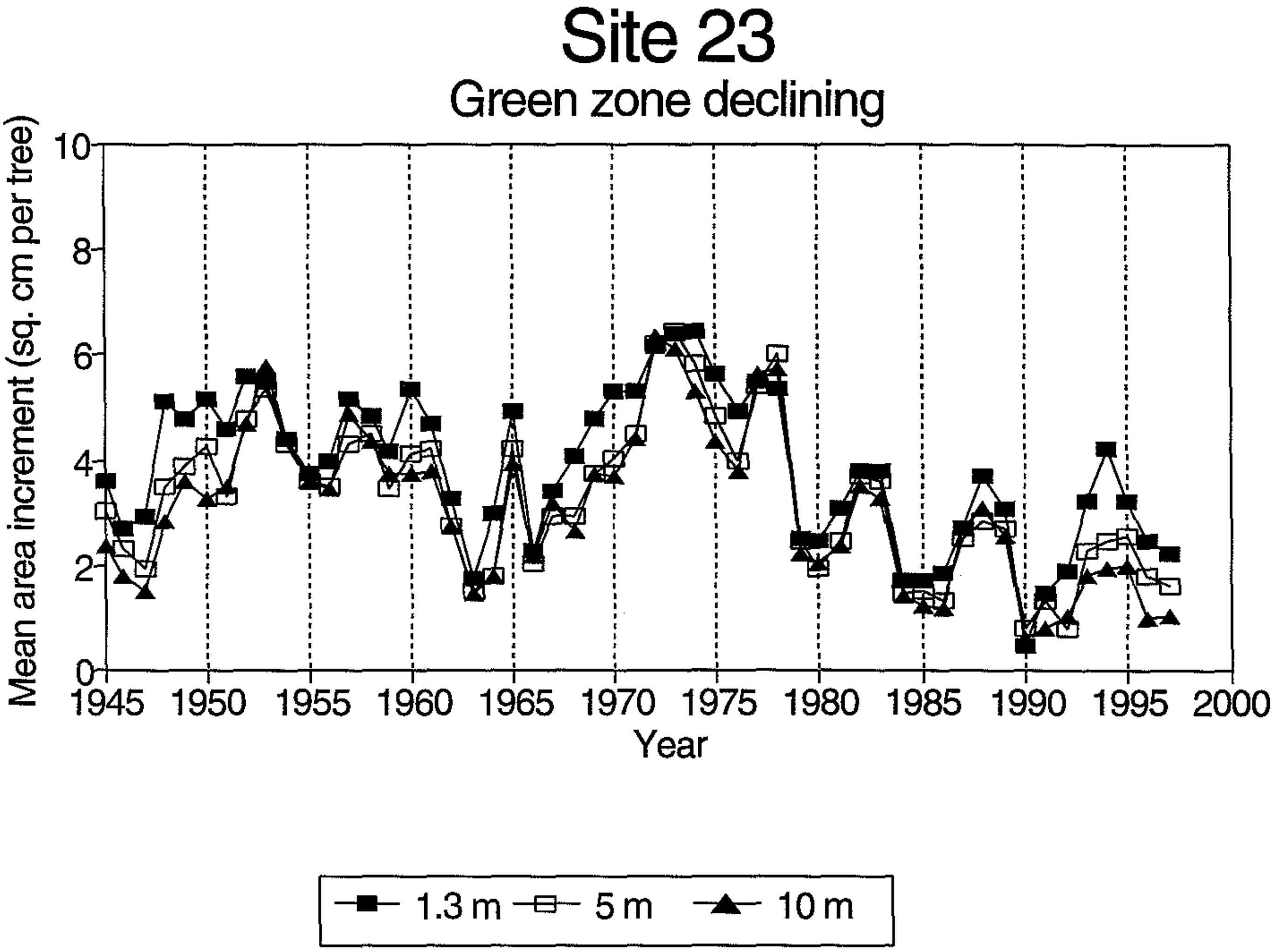
Site 21
White zone healthy

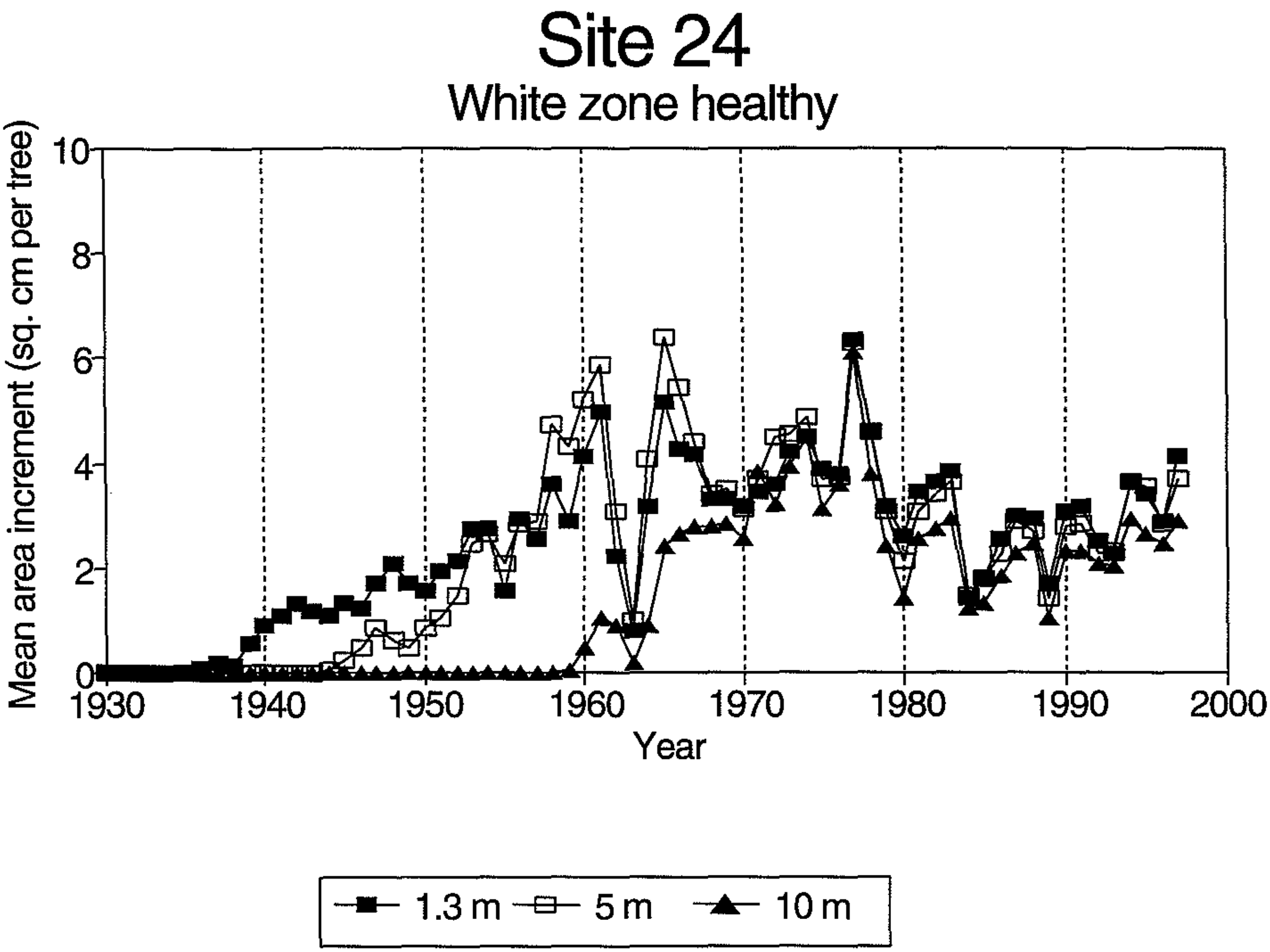


1.3 m — 5 m — 10 m

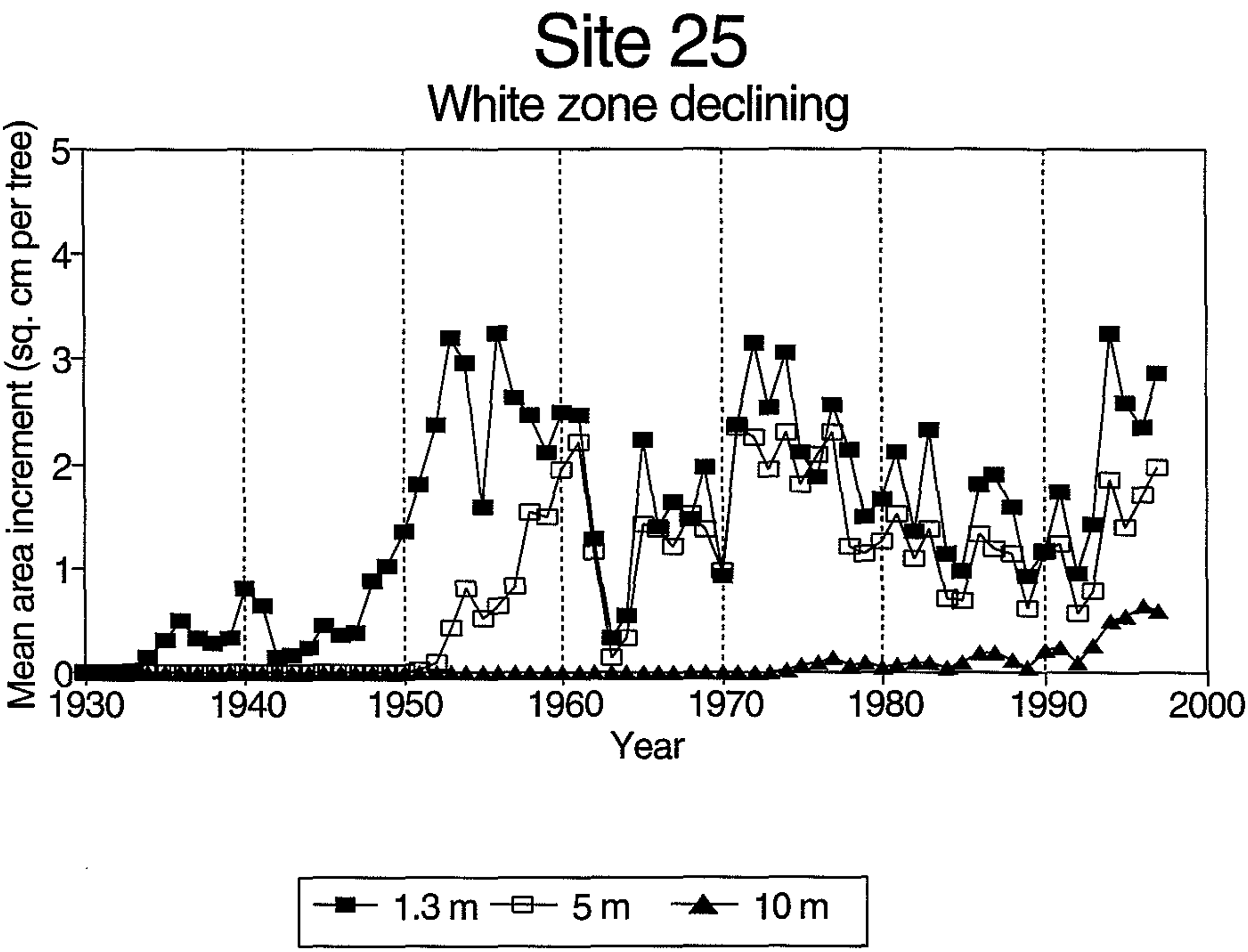


Site 22
Green zone healthy
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m

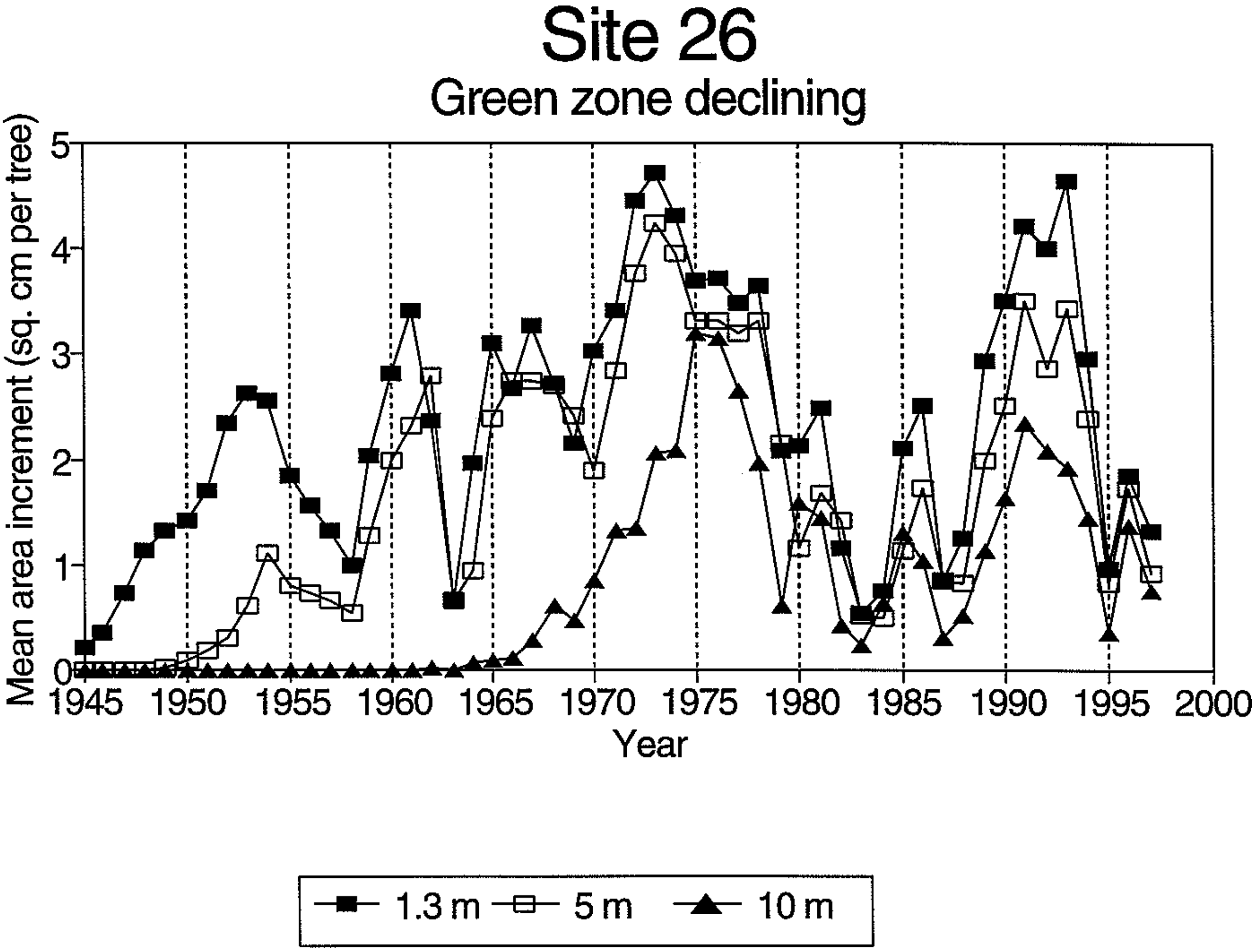

Site 23
Green zone declining
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m

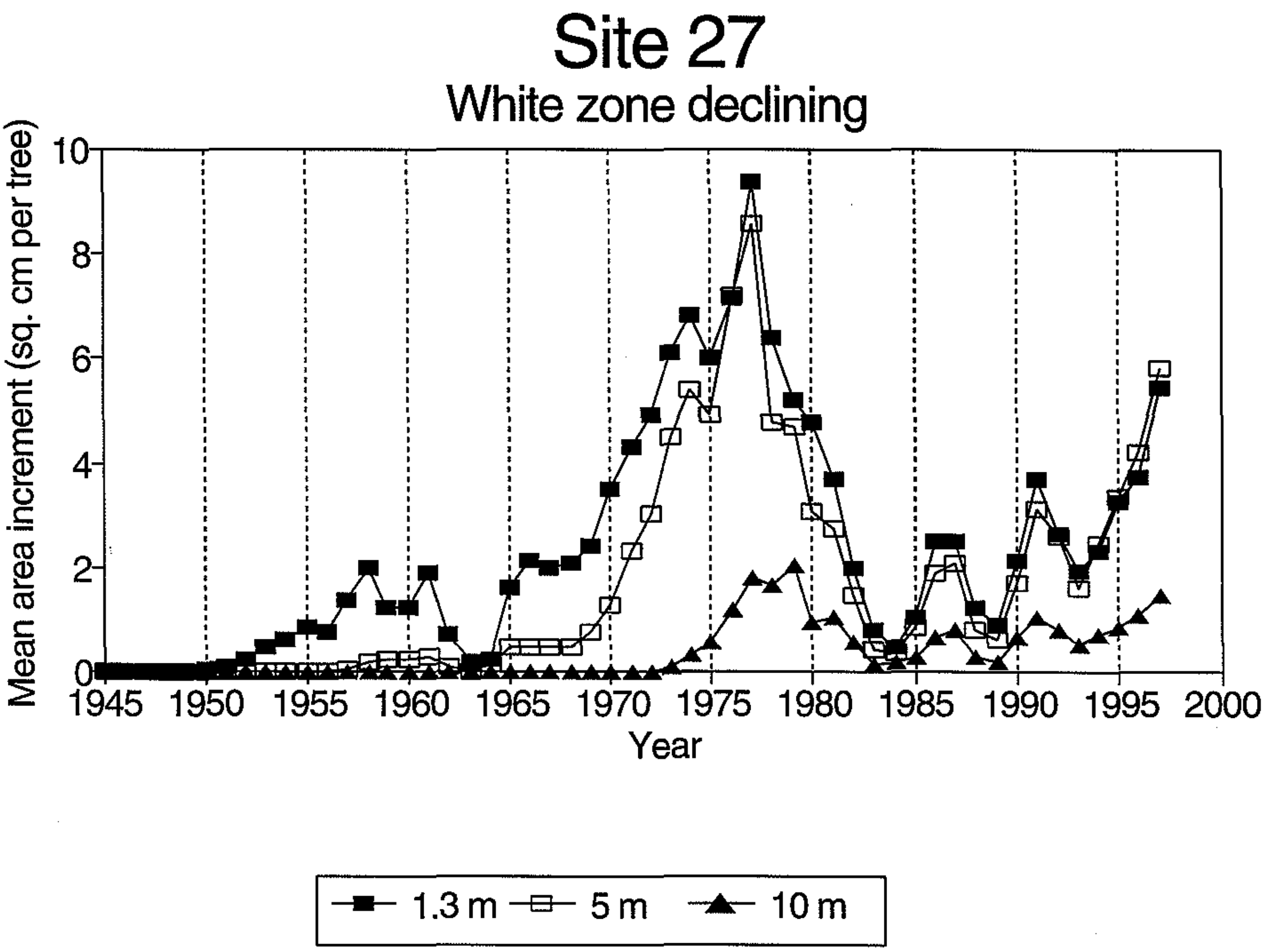


Site 24
White zone healthy
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1930
1940
1950
1960
1970
1980
1990
2000
Year
1.3 m
5 m
10 m



Site 25
White zone declining
Mean area increment (sq. cm per tree)
5
4
3
2
1
0
1930
1940
1950
1960
1970
1980
1990
2000
Year
1.3 m
5 m
10 m


Site 26
Green zone declining
Mean area increment (sq. cm per tree)
0
1
2
3
4
5
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m


Site 27
White zone declining
Mean area increment (sq. cm per tree)
0
2
4
6
8
10
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
1.3 m
5 m
10 m