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SPATIAL AND TEMPORAL VARIATION IN HISTORICAL FIRE REGIMES OF THE BLUE MOUNTAINS, OREGON AND WASHINGTON: THE INFLUENCE OF CLIMATE

by

Emily Katherine Heyerdahl

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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1997

Approved by Linda B. Brubaker
Chairperson of Supervisory Committee

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Doctoral Dissertation

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Date December 17, 1997

University of Washington

Abstract

SPATIAL AND TEMPORAL VARIATION IN HISTORICAL FIRE REGIMES OF THE BLUE MOUNTAINS, OREGON AND WASHINGTON: THE INFLUENCE OF CLIMATE

by Emily Katherine Heyerdahl

Chairperson of the Supervisory Committee
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To identify the influence of climate on spatial and temporal variation in fire, low- to high-severity fire regimes were reconstructed from tree-rings in the Blue Mountains. Fire recurrence, extent, severity and seasonality (low-severity fires only) were determined from fire scars and ages of 1426 trees sampled on 2914-8585 ha grids in 4 watersheds. Before 1900, fire regimes varied at regional (among watersheds) and local (within watersheds) spatial scales, although not all parameters of fire varied at both scales. Regionally, fires in ponderosa pine-dominated forests burned more frequently and earlier in the growing season in southern than northern watersheds, consistent with the occurrence of longer and drier fire seasons in the southern Blue Mountains. Fire extent did not vary regionally. Locally, fire recurrence varied with topography (aspect or elevation) in steep terrain but not in gentle terrain, while local variation in fire extent was unrelated to topography in any watershed. Temporal variation in the extent of low-severity fires was compared to existing tree-ring reconstructions of regional precipitation and an index of the Southern Oscillation (SOI). In southern watersheds, fire extent varied inversely with precipitation on annual and longer time scales. In northern watersheds, SOI tended to be low (El Niño conditions) during fire years, consistent with shorter snow-cover duration to the north during El Niño years. Prior year's climate (regional precipitation or SOI) did not influence fire extent in any watershed. Despite some regional synchrony in precipitation, fires rarely burned in more than one of the sampled watersheds during a given year, probably because processes that influence the ignition and/or spread of fire operate at sub-regional spatial

scales (e.g., lightning strikes, precipitation from convective storms). After about 1900, few fires occurred in any of the watersheds. These results suggest that to predict spatial variation in fire regimes within a given forest type, the spatial scales at which the controls of fire (e.g., climate and topography) operate must be considered. These results also imply that future fire regimes could be affected by changes in the duration of snow cover or by changes in the amount or timing of ignition.

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CHAPTER 1: INTRODUCTION

Concern over changing forest composition and structure in the Blue Mountains of northeastern Oregon and southeastern Washington, was one factor prompting the U.S. Forest Service to institute a nation-wide policy of ecosystem management (Everett et al. 1994). Designing implementation plans for this policy requires a broad range of social and scientific inputs (Bormann et al. 1994), one critical element of which is quantitative estimates of the range of historical variability of disturbance regimes such as forest fires (Everett et al. 1994, Swanson et al. 1994). Understanding what drives both the spatial and temporal variability in fire regimes will help land managers evaluate whether it will be feasible to maintain landscapes dramatically altered by twentieth-century land use within the range of historical disturbances, particularly if climate changes in the future. Based on the widespread evidence of historical fires in this region (e.g., fire scars and cohorts of early seral trees), fire is thought to have been the dominant disturbance type in most Blue Mountains forests prior to Euroamerican settlement (Agee 1994). However, because most of our current understanding of fire in this region comes from modern studies, little is known about the spatial and temporal scales over which historical fire regimes varied. Although modern fire behavior is clearly influenced by weather acting over short temporal and spatial scales (Schroeder et al. 1966, Deeming et al. 1977), studies of modern fire-weather relationships may not reflect the historical influence of climate on fire across the Blue Mountains for several reasons. First, forest composition and structure have changed dramatically due to a twentieth-century decline in fire occurrence caused by changes in land use. This change in fire regimes has altered fuel loads and changed fire behavior. Second, extrapolating fire-weather relationships observed at one study location to a larger region may not be valid because the climate of the Blue Mountains is variable across a range of spatial scales. Finally, short-term fire-weather relationships may not hold through time because the climate of the Blue Mountains has varied over the last few centuries (Graumlich 1987).

Fortunately multicentury records of fire and climate variability are preserved in tree rings in the Blue Mountains and can be used to understand the historical influence of climate on fire regimes. For example, despite many decades of logging, stands with tree-ring records of fire history are present throughout this region allowing the reconstruction of fire regimes over across multiple spatial scales. In addition, several existing tree-ring reconstructions of the climate of this region are suitable for comparison with fire histories. Annual precipitation has been reconstructed for the Blue Mountains region (1705-1979, Garfin and Hughes 1996) and an index of the Southern Oscillation has been reconstructed for western North America (1600-1963, Lough and Fritts 1985). In addition, the climate of the Blue Mountains is well-suited for exploring both spatial and temporal aspects of the climatic control of fire. At the regional scale, a north-south gradient in climate (higher precipitation, lower temperature and more persistent snow cover in the north than the south) potentially caused geographic variation in fire regimes. Nested within the regional gradient, are local topographically-generated variations in climate (northerly slopes cooler and moister than southerly slopes in steep terrain), which could result in variations in fire regimes at small spatial scales. Lastly, precipitation has fluctuated over the Blue Mountains region over the last few hundred years, providing an opportunity to explore the influence of climate on historical fire regimes across temporal scales.

The purpose of this study is to determine the influence of spatial (Chapter 2) and temporal (Chapter 3) variation in climate on historical fire regimes (recurrence, extent, severity and for some forest types seasonality) of the Blue Mountains. Tree-ring evidence of fire was sampled on grids covering the range of topography present in each of four watersheds distributed along 250 km of latitude. Fire scars were used to reconstruct low-severity regimes while the establishment date of early seral trees were used as evidence of moderate- and high-severity regimes. At regional scales (tens to hundreds of kilometers), the spatial variation of fire regimes among watersheds was compared to regional-scale patterns of climate. At local scales (kilometers to tens of kilometers), variation in fire extent within each watershed was compared to topographic variables (aspect, elevation)

that influence microclimate. Temporal variation in fire extent was assessed at local spatial scales by comparing annual fire extent in each watershed to existing tree-ring reconstructions of climate (regional precipitation and winter and spring indices of the Southern Oscillation) on annual and decadal time scales. Regionally, fire occurrence was compared among watersheds to identify years during which fires burned synchronously across the Blue Mountains.

Several appendices provide additional details about the sampled watersheds and their historical fire regimes. Appendix A contains topographic maps of the 4 watersheds showing sampled plots. This appendix also contains tables of the topography, vegetation and location for each sampled plot. Appendix B contains tables of fire extent and the number of trees and plots used to reconstruct each fire. Appendix C describes a comparison of three methods for determining fire extent (heuristic, Voronoi polygons and convex hull). Appendices D through G contain topographic maps for every fire year showing location and type of fire evidence and fire boundaries at each watershed. Finally, appendix H contains statistics of the distribution of fire intervals at forest plots with low-severity fire regimes.

CHAPTER 2: SPATIAL VARIATION IN HISTORICAL FIRE REGIMES

INTRODUCTION

In the Pacific Northwest, landforms cause climate to vary dramatically across a range of spatial scales, affecting forest composition and disturbance regimes at sub-continental to local scales (Schroeder et al. 1966, Bryson and Hare 1974, Gholz 1982, Agee 1993, Nielson 1995, Mock 1996). For example, at sub-continental scales (hundreds to thousands of kilometers), the Cascade Range intercepts moist, westerly Pacific air (Mock 1996). Consequently, many forests west of this range are dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) which burned infrequently, while many forests to the east are dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Loud.) that historically experienced frequent fires (Franklin and Dyrness 1988, Agee 1993). Historically, fire was the dominant disturbance type in most Pacific Northwest forests east of the Cascade Range (Agee 1993), and fire has thus had a greater influence than other disturbance types on the composition and structure of these forests. Although fire regimes have been characterized at local scales (kilometers to tens of kilometers) throughout the interior West (Heyerdahl et al. 1995), the influence of spatial variation in climate on fire regimes has not been studied at regional scales (tens to hundreds of kilometers) or across several scales simultaneously.

To detect variation in fire regimes that is due to spatial variation in climate, fire regimes must be examined at the same scales at which climate varies, and during periods when fire regimes are not changing due to factors other than climate (Urban et al. 1987, Wiens 1989). The Blue Mountains of northeastern Oregon and southeastern Washington are an ideal setting to examine the influence of climate on past fire regimes across a range of spatial scales. The Cascade Range and Columbia River Gorge to the west modify the atmospheric circulation, resulting in a north-south regional-scale gradient in climate, so that in the northern Blue Mountains precipitation is higher, temperature lower, and snow

cover persists longer than in the southern portion of this region. At the local scale, topographically-driven variations in microclimate are nested within the regional gradient. Northerly slopes, receiving less direct solar radiation, have lower temperature and higher relative humidity than southerly slopes. These spatial variations in climate affect the distribution of forest types. Throughout the Blue Mountains, forests on northerly slopes and at high elevations are dominated by grand fir (*Abies grandis* (Dougl.) Lindl.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), while southerly slopes and low elevations support ponderosa pine and western juniper (*Juniperus occidentalis* Hook.) forests (Johnson and Simon 1987, Johnson and Clausnitzer 1992). At the end of the nineteenth century, Euroamerican settlement dramatically altered fire regimes in many forest types, so that the relationship between fire and climate is obscured in the archival records that were kept after this time. Fortunately, a well-preserved, multicentury tree-ring record of fire pre-dates this period of change and has been successfully used to reconstruct fire regimes at small spatial scales (less than a kilometer; Hall 1976, Bork 1984, Maruoka 1994). However, these reconstructions are not sufficient for understanding the influence of variation in climate on fire regimes across spatial scales.

To identify the influence of spatial variation in climate on past fires, I reconstructed a multicentury history of fire regimes (occurrence, extent, severity and, for some forest types, seasonality) from tree rings at regional (50-250 km) and local (0.5-8 km) scales in the Blue Mountains. Fire scars and post-fire cohorts were sampled on a ≈1620 ha grid of ≈64 plots in each of four watersheds. At the regional scale, the influence of climate on fire was assessed by comparing fire recurrence, extent and seasonality among the four sampled watersheds in forests of similar composition. At the local scale, the influence of climate on fire was determined separately within each watershed by comparing fire recurrence, seasonality and severity among forest types and topographic settings.

STUDY AREA

Across the Blue Mountains, in northeastern Oregon and southeastern Washington (Figure 1), most precipitation falls during winter when the polar vortex expands, causing

the jet stream and its associated storm systems to flow over the Pacific Northwest (Bryson and Hare 1974). Summers are warm and dry due to subsidence from the North Pacific subtropical high lying off the coast of Alaska (Barry and Chorley 1992). The Cascade Range blocks much of the low-level, moist, westerly air flowing over the Pacific Ocean, consequently, annual precipitation throughout the Blue Mountains region is low (average of 446 mm for low elevation stations during the period 1895-1996; EarthInfo 1990, Mock 1996). Temperatures also reflect a reduced marine influence with low mean January temperature (-3.2°C) and high mean July temperature (18.8°C, 1895-1991, NOAA 1997). Although the climate across the Blue Mountains is generally continental, there is variation at both regional and local scales (Bryson and Hare 1974, Mock 1996). At the regional scale, precipitation decreases from north to south partly because moist, westerly Pacific air penetrates the Cascade Range via the Columbia River Gorge (Figure 1, Figure 2a) and flows across the northern Blue Mountains (Mock 1996). This regional gradient in precipitation is partly responsible for a regional gradient in the length of snow-cover duration, which is shorter in the south (Figure 2b, NRSC 1997). There is also a regional gradient in lightning storms, with more frequent lightning strikes in the southern than in the northern portion of the region (Morris 1934, Krider et al. 1980). At the local scale, steep gradients in elevation and abrupt transitions in aspect cause dramatic variation in microclimate over short distances. The study area spans 45°N, the latitude of maximum difference in solar energy input between slopes of different aspects (Holland and Steyn 1975). Here, steep northerly slopes annually receive about half as much direct, shortwave solar energy as southerly slopes (50% slope; Holland and Steyn 1975). Consequently, northerly slopes have lower surface temperature and higher relative humidity than southerly slopes at comparable elevation. Solar energy input does not vary as much in gentle terrain at this latitude where northerly slopes of 17% receive nearly as much solar energy (80%) as southerly slopes.

The forests of the Blue Mountains have been classified into five series of potential vegetation based on the tree species that would dominate the overstory in the absence of

disturbance (from mesic to dry): subalpine fir, grand fir, Douglas-fir, ponderosa pine and western juniper (Johnson and Simon 1987, Johnson and Clausnitzer 1992). Based on the composition of the understory, each series is subdivided into plant associations that occur over narrower ranges of environmental conditions than the forest series.

Land use changed rapidly in the Blue Mountains in the late 1800s. Prior to this time, this region was inhabited for many centuries by nomadic Native Americans, including the Cayuse, Nez Percé, Paiute, Umatilla and Shoshone tribes, whose economies were based on hunting and gathering (Schwantes 1989). Disease dramatically reduced their populations after the 1780s (Schwantes 1989). Between 1840 and 1860, some Euroamericans traveling the Oregon Trail settled in the Blue Mountains, but their population did not increase substantially until the completion of the transcontinental railroad in 1884 (Schwantes 1989, Evans 1990, Robbins and Wolf 1994, Langston 1995). This increase was accompanied by an eight- to tenfold rise in the number of grazing animals (Irwin et al. 1994). Timber harvesting began in the Blue Mountains in the late 1800s (Robbins and Wolf 1994, Langston 1995). A national policy of complete fire suppression was implemented shortly after the inception of the United States Forest Service in the early 1900s, but was not effective in many areas until the 1940s, with the advent of aerial drops of fire fighters and fire retardant (Pyne 1982).

METHODS

Sampling scales

Historical fire regimes were reconstructed at two spatial scales: regional and local. *Regional* variation in fire regimes was inferred by comparing evidence of fire from four watersheds distributed along 250 km of latitude in the Malheur, Wallowa-Whitman and Umatilla National Forests (Figure 1). The northern watersheds, Tucannon and Imnaha, are east-west trending river canyons embedded in complex landforms (Appendix A). Moist Pacific air flowing through the Columbia River Gorge causes greater precipitation in these areas relative to areas farther south. The other two watersheds, Baker and Dugout, lie in the dry southern Blue Mountains (Figure 1, Figure 2a). *Local* variation in

fire regimes was inferred within each watershed by comparing evidence of fire in different topographic settings and forest types. The sampling areas at the northern sites are located on slopes north and south of rivers. Elevations at Tucannon range from 1000 to 1800 m and slopes are dissected and steep (average sampled slope 47%). Elevations at Imnaha are comparable (1300-1900 m), but slopes are less steep (28%) and dissected. The Baker watershed lies on the northeastern face of the Elkhorn Mountains, and abuts the southern edge of the broad Baker Valley. This watershed has the greatest range in elevation of the four watersheds (1250-2300 m) and slope angles are intermediate (40%). The gentle landforms of the Dugout watershed straddle the North Fork of the Malheur River. This watershed has the smallest range in elevation (1400-1800 m) and the gentlest slopes (16%) of the four watersheds.

A ≈1620 ha area was selected to represent a range of topographic settings within minimally-harvested portions of each watershed. Each area was divided into a grid of 64 cells, each ≈25 ha, and a ≈1 ha plot was sampled near the center of each cell (Appendix A: Figure 23-26). Because many of the reconstructed fires intersected the boundaries of these sampling areas, an additional 10 to 19 plots per watershed were located at a lower density outside the grid to reconstruct the extent of large fires. This increased the size of the sampling areas to 2914-8585 ha each.

Topography and forest composition

Percentage cover of grass, forb, shrub and tree species was estimated at each plot, and slope, aspect, elevation, latitude and longitude were measured. This information was used with local keys to assign each plot to a forest series and plant association as indicators of potential vegetation (Johnson and Simon 1987, Johnson and Clausnitzer 1992). For some analyses, associations were assigned to two broad categories, *mesic* versus *dry* forest, based on local assessments of the microclimate occupied by each association (unpublished reports, Umatilla and Wallowa-Whitman National Forests). All associations in the subalpine fir series and some of those in the grand fir series were classified as mesic forest

(Table 1). All associations in the Douglas-fir and ponderosa pine series and the remaining associations in the grand fir series were classified as dry forest.

To evaluate the degree to which the topography of the sampled plots represents that of the Blue Mountains as a whole, the topography of the plots (elevation, aspect and slope) was graphically compared to that of the Blue Mountains, derived from a digital elevation model (DEM, 90 m resolution). Each topographic characteristic was categorized and the percentage of plots and land area were computed for each category and for all possible combinations of categories. Because only forested plots were sampled for this study and the DEM includes both forested and non-forested areas, land area below 600 and above 2500 m was eliminated (7% of total area), because these areas are unlikely to be forested (Johnson and Simon 1987).

To evaluate the degree to which the forests of the sampled plots represent the Blue Mountains as a whole, the overstory composition of the plots was graphically compared to that of the Blue Mountains. Using satellite imagery, the forests of the Blue Mountains have been assigned to one of 8 categories based on the overstory species that currently dominates: ponderosa pine, grand fir, Douglas-fir, lodgepole pine (*Pinus contorta* Dougl. ex Loud.), western juniper, aspen (*Populus tremuloides* Michx.), whitebark pine (*Pinus albicaulis* Engelm.) or a combined category for Englemann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (Loveland et al. 1991, Burgan et al. 1996). Sampled plots were assigned to these categories based on the tree species currently dominating the plot. Although potential vegetation was used for all other analyses, current vegetation was used here because it is the most readily available data on the composition of the forests of the Blue Mountains as a whole.

Evidence of fire

The type of evidence used to reconstruct fire regimes varied among plots depending on the severity of past fires. Fire intensity, interacting with tree morphology (e.g., bark thickness and crown height), dictates the effect of fire, and consequently the evidence of fire recorded by trees (Agee 1993). Low-severity fires often kill only a portion of the

cambium (Stokes 1980, McBride 1983). Subsequent annual rings produced by new cambium cover the dead cells, forming fire scars, which were used here as primary evidence of low-severity fires. Such fires can also cause abrupt increases or decreases in radial growth (Morris and Mowat 1958, Van Sickle and Hickman 1959, Weaver 1967, Landsberg et al. 1984, Sutherland et al. 1991). However, because other factors can also affect radial growth, an abrupt change in ring width in a given sample was used as evidence of a low-severity fire only when it coincided with a fire scar in other samples. In contrast to low-severity fires, high-severity fires kill most forest overstory trees and moderate-severity fires kill only a portion of the trees in a stand. The death of these trees opens growing space for a cohort of early seral, shade-intolerant trees whose date of establishment approximates the year of the fire (Barrett and Arno 1988, Oliver and Larson 1990, Arno et al. 1993). Cohorts of early seral trees were used as the only evidence of high- and moderate-severity fires for this study.

Fire scars

Where fire-scarred trees were present, scarred sections were removed with a chain saw from 1 to 8 logs, stumps, short snags or live trees (average: 3; Arno and Sneck 1977). Four trees sampled for a previous study at a single plot at Imnaha were also included (Maruoka 1994). All sections were sanded until the cell structure was visible and crossdated using a binocular microscope and existing tree-ring width chronologies, augmented by statistical crossdating for many samples (Holmes 1983, Swetnam et al. 1985, Yamaguchi 1991, Swetnam 1993a). Sections that could not be crossdated were excluded from further analyses (4%). Fire scars were identified by the presence of a discontinuity or gap within a ring or along a ring boundary followed by overlapping, curled rings (Stokes 1980, McBride 1983). The calendar year of fire occurrence was determined by noting the year in which each scar was located. As an indication of seasonality, scars were assigned to one of four intra-annular positions: earlywood, latewood, ring boundary or unknown (Weaver 1951, Ahlstrand 1980, Dieterich and Swetnam 1984). Scar position could not always be determined because rings were

narrow, especially in the vicinity of scars, or because scars were obscured by rot or insect galleries. The season of radial dormancy (i.e., the period represented by the ring boundary) spans two calendar years: from the time radial growth ceases in the summer of one year until it resumes in late spring of the following year. For this study, scars formed on the boundary between two rings were generally assigned to the *preceding* calendar year because most modern fires in the Pacific Northwest occur in the summer or fall (Agee 1993) and, over the last few hundred years, there is no evidence of changes in the seasonal timing of precipitation that might affect the seasonality of fire (Graumlich 1987). However, scars from a given fire can have a range of intra-annular positions because the timing of radial growth varies among trees and sites (Fritts 1976) and because fires may burn for several months (Parsons and van Wagtendonk 1996). For example, for several fires, scars occurred in the earlywood of many trees but on the preceding boundary in other trees. These fires were assumed to have occurred at the beginning of the radial growing season and ring-boundary scars for these fires were therefore assigned to the *following* calendar year.

To obtain the longest, most complete inventory of fires for each plot, the dates of scars and abrupt growth changes from all samples at a plot were combined into a single record of fire occurrence (Dieterich 1980). The records for each watershed were displayed on fire charts in which time lines with crossbars identify years with evidence of fire at each plot (Dieterich 1980, Grissino-Mayer 1995). These charts were used to assess general features of fire recurrence and extent in each watershed.

Cohorts

Where early seral cohorts were present, increment cores were removed from 5-10 of the largest diameter live trees (western larch (*Larix occidentalis* Nutt.) and lodgepole pine) to determine establishment dates. When more than one size class was present, the largest individuals in each class were sampled. Trees were cored near the ground to minimize errors in estimating establishment dates (average height: 23 cm). The cores were mounted on wooden holders, sanded and crossdated as described above. Those that could

not be crossdated were excluded from further analyses (5%). For cores that did not intersect the pith (60%), the number of rings to the pith was estimated based on the curvature of the innermost rings sampled (average correction: 4 years; Applequist 1958, Earle 1993). To correct for the number of years to reach coring height, one calendar year was subtracted from the pith date for every 5 cm between ground level and coring height. This correction factor was based on a previous analysis of early height growth for seral species in the Blue Mountains (Maruoka 1994).

The year during which fires occurred was estimated from establishment dates assuming that (1) trees in a post-fire cohort should be near one another on the ground because fires spread contiguously from a point of ignition, and (2) the ages of such trees should be similar, but not identical, because tree-ring reconstructions of establishment date are not exact and recolonization of a burned area may occur over a period of years (Oliver and Larsen 1990). Cohorts that established after moderate-severity fires in the sampled watersheds could not be mapped on aerial photographs because they spatially overlap cohorts that established after previous fires (Arno et al. 1995). Within each watershed, cohorts were identified using hierarchical agglomerative clustering of an index of proximity between pairs of trees (*sensu* Duncan and Stewart 1991). Because more than one post-fire cohort may co-exist at plots that experienced moderate-severity fires, proximity between trees within plots was also examined. Proximity was computed as a function of the difference in age and the distance between each pair of trees. Both terms were standardized and weighted equally so that temporal and spatial information contributed equally to the identification of cohorts (Gordon 1981):

$$c_{ij} = \frac{d_{ij}}{d_{max}} + \frac{a_{ij}}{a_{max}}$$

where: c_{ij} = index,

d_{ij} = difference in distance between trees *i* and *j*,

d_{max} = greatest distance between a pair of trees at the watershed,

a_{ij} = difference in age between trees *i* and *j*, and

a_{max} = greatest age difference between a pair of trees at the watershed.

After clustering, *groups* were selected by identifying a level of similarity that minimized both the number of groups and the range of establishment dates within those groups. Each group of trees identified by clustering was mapped to assess spatial proximity. Those groups containing trees that were both similar in age (≈ <40 years) and contiguous (in neighboring, or nearly neighboring, plots) were identified as post-fire *cohorts*. The earliest establishment date within each cohort was initially assigned as the year of fire occurrence. When this initial estimated year was similar to that of an adjacent large, low-severity fire, the year of occurrence was adjusted to coincide with the year of the low-severity fire, based on the assumption that scar dates are more accurate than tree-establishment dates (adjustments of 1-5 years, average: 3 years). Unlike low-severity fires, there is no record of the seasonality of high- and moderate-severity fires. The record of high- and moderate-severity fires at each plot was displayed on fire charts to assess general features of fire recurrence and extent.

Reconstructing fire regimes

Four parameters of fire regimes (recurrence, severity, annual extent and, for some forest types, seasonality) were reconstructed from fire scars, abrupt changes in ring width and the establishment dates of cohorts. Fire recurrence, which can loosely be thought of as fire frequency (Agee 1993), was computed as the number of fire years over a common time period because some plots experienced only one fire year during the period of record, precluding the computation of fire intervals. Fire severity was estimated based on the type of evidence of fire found at each plot. Plots with fire scars were considered to have experienced primarily low-severity fires, plots with multiple cohorts to have experienced primarily moderate-severity fires and plots with a single cohort to have experienced high-severity fires. Seasonality was determined for low-severity fires as described above. To determine annual fire extent, the tree-ring evidence of fire at each plot was mapped on the sampling grid for every year with evidence of fire. During a given fire year, no sampled trees may have been alive at some plots or these plots may contain only trees with a low probability of scarring (i.e., the fire year occurred before the year of first scarring; Gill

1974, Romme 1980). Such plots were considered unsampled for that fire year. Fire boundaries were drawn on the maps approximately halfway between plots with and without evidence of fire or along a perennial stream, if present. Plots lacking evidence of a fire during a given year but containing trees that could have recorded evidence of fire were included within fire boundaries only if they were surrounded by plots with evidence of fire. Plots were not included within the same fire boundary if they were separated by more than 3 plots without fire evidence or by more than 1.5 km without a sampled plot. Fire boundaries were not extended beyond the edges of the sampling areas and were not determined for years with fewer than three fire scars in the entire watershed. Annual fire extent was computed as the total area within the fire boundary (or boundaries) for each fire year. The period during which at least 30% of the plots within a watershed could show evidence of fire (i.e., cohorts had established or the plots had trees that had been previously scarred) was selected as the period with sufficient information to characterize fire regimes in that watershed.

Variation in fire regimes at regional and local scales

If fire regimes in the four watersheds changed differentially over the period of record, spatial variation among the watersheds could be masked when regimes are summarized through time. Therefore, plots of cumulative annual fire extent and fire charts were examined for evidence of changes in fire regimes through time. The record was evaluated only prior to 1900 because the fire regimes in each watershed underwent an obvious change in the late 1800s, a period of rapid change in land use in the Blue Mountains. Cumulative annual extent was computed for the full sampling area in each watershed and these data were regressed against calendar year using ordinary least squares. The record was examined for deviations of cumulative extent from the regression line that would indicate long-term shifts in the area burned per year. Fire charts for each watershed were visually examined for changes in fire recurrence or extent.

Regional variation in fire regimes was assessed by comparing fire recurrence, extent and seasonality among watersheds for the six plant associations that occur in all four

watersheds, the elk sedge (*Carex geyeri* Boott) and pine grass (*Calamagrostis rubescens* Buckl.) associations within the grand fir, Douglas-fir and ponderosa pine series (Table 1). The null hypothesis that fire recurrence (mean number of fire years per plot from 1687 to 1900) is the same in all four watersheds was tested with analysis of variance (ANOVA). To meet the assumptions of ANOVA, the number of fires was linearly transformed using a monotonic function to normalize the sampled distribution and stabilize its variance (equation 2 with λ=0.5 in Box and Cox 1964). There is no statistical interaction between watershed and forest type, indicating that the relative difference in fire recurrence among forest types *within* each watershed is consistent *among* the watersheds. Therefore, all plots within the six common plant associations were pooled for each watershed and ANOVA was performed using the four watersheds as levels of a single factor. Following rejection of the null hypothesis, a multiple range test was performed to identify which watersheds had significantly different mean fire recurrence (Tukey's honestly significant difference; Zar 1984). Regional variation in fire extent was assessed by graphically comparing the distribution of fire years by extent classes among watersheds. Regional variation in fire seasonality was assessed by comparing the distribution of scars by intra-annular position among watersheds.

Local variation in fire regimes was assessed separately for each watershed by graphically comparing the parameters of fire regimes (recurrence, severity and seasonality) with topography (elevation, aspect and slope) and forest type (subalpine fir, mesic grand fir, dry grand fir, Douglas-fir or ponderosa pine).

RESULTS

Topography and forest composition

At the regional scale, the distribution of sampled plots by topography and current forest overstory is similar to that of the Blue Mountains as a whole. Most of the plots and forested land area lie between 1000 and 2000 m, are equally distributed among all aspects, and have low to moderate slopes (<66% slope, Figure 3a, b, c). No combinations of elevation, aspect and slope were particularly over- or under-represented in the sampled

plots. The majority of plots and forested land area are currently dominated by ponderosa pine (≈43%, Figure 3d), Douglas-fir (≈17%) or grand fir (≈26%). Lodgepole pine, western juniper and Englemann spruce/subalpine fir comprise most of the remaining plots and land area. A small area of the Blue Mountains, but none of the plots, are dominated by aspen or whitebark pine (<1%).

Plots were sampled in 4 of the 5 series of potential vegetation found in the Blue Mountains (Table 1). Although 30 plant associations were sampled, only 16 of these were common (95% of plots). Ten associations were classified as mesic forest and 6 as dry. Regardless of forest series, ponderosa pine currently dominates, or codominates, almost all dry forest plots (88%) and is present in most others (8%). In contrast, this species is absent from the majority of mesic forest plots (75%), where grand fir, subalpine fir or lodgepole pine dominate. At the regional scale, more plant associations occur at Tucannon, Imnaha and Baker than at Dugout (Table 1). Many of the 16 common associations occur at Tucannon, Imnaha and Baker, although ponderosa pine associations are uncommon in all three watersheds and subalpine fir associations are uncommon at Imnaha. In contrast, all of the dry, but none of the mesic associations occur at Dugout. At the local scale, plant associations vary with topography in most of the sampled watersheds. At the northern watersheds (Tucannon and Imnaha), most mesic associations are on north and east aspects (87%), while most dry associations are on south and west aspects (81%). At Baker, mesic associations only occur above >1700 m (88%). Dry associations occur on all aspects at this watershed, but on south and west aspects are limited to <1700 m. At Dugout, dry associations occur on all aspects and elevations and mesic forests are not present in the sampling area.

Evidence of fire

Fire scars were collected from 524 trees (Table 2), most of which were ponderosa pine (98%). Scarred trees were present in all plots at Dugout, but in less than half the plots at Tucannon (38%), Imnaha (46%) and Baker (49%, Table 1). The period 1687-1994 was identified as the period during which fire regimes could be reliably reconstructed from fire

scars at all watersheds (Table 2). Within this period, 3659 fire scars and 306 growth changes were dated to 121 separate calendar years (32 to 65 years per watershed, Appendix B).

The establishment dates of 616 trees were estimated from roughly equal numbers of western larch and lodgepole pine at the northern watersheds, Tucannon and Imnaha (Table 2). Cluster analysis revealed 4 post-fire cohorts in each watershed (1798-1994, Figure 4, Appendix B). Each cohort contains 16 to 192 trees (average: 66) whose establishment dates differ by 14 to 42 years (average: 30). There is no temporal overlap in the establishment dates of trees assigned to different cohorts within either watershed. The earliest establishment date within most cohorts coincided with adjacent low-severity fires so the year of the low-severity fires was assigned as the fire year for the cohort (1774, 1888 at Tucannon; 1798, 1834, 1886 at Imnaha). At Tucannon, most plots (67%) had only a single cohort, indicating that high-severity fires were most common at this watershed (Figure 5a). In contrast, half the plots (52%) at Imnaha had multiple cohorts (2 or 3), indicating that moderate- and high-severity fires were equally common at this watershed (Figure 5b).

The establishment dates of 286 trees were estimated from roughly equal numbers of western larch and lodgepole pine at Baker (Table 2). However, post-fire cohorts could not be discerned at this watershed because no level of similarity yielded groups with a narrow range of ages. At Dugout, despite the occurrence of individuals of early seral species such as lodgepole pine and western larch, cohorts of these species were not found so cluster analysis was not used at this watershed.

Variation in fire regimes at regional and local scales

In each watershed, cumulative fire extent fit a straight line (r_a^2 = 0.97 to 0.99) from 1687 to 1900, indicating that fire regimes did not change substantially over this period (Figure 6). This lack of change in fire regimes prior to 1900 was confirmed by a lack of changes in fire recurrence and extent shown by the fire charts (Figure 7 and 8). However, after this time, an abrupt decrease in the slope of cumulative extent indicates that fire

regimes changed around 1900. Only a few small fires burned in any of the watersheds after this time.

Regional variation (comparison of dry forest types among watersheds)

Fire recurrence in dry forests varied among watersheds. The null hypothesis of no difference in the mean number of fires per dry forest plot among watersheds was rejected (Table 3). Furthermore, fire recurrence differed between all pairs of watersheds except Baker and Dugout. Fire recurrence varied more strongly with location within the region (north versus south) than with forest type (dry grand fir, Douglas-fir or ponderosa pine, Figure 9). For example, at Dugout, in the south, the mean number of fire years is similar in the Douglas-fir and dry grand fir forest types (19 and 14, respectively) but more than twice as high as the mean number of fire years in the same forest type at Imnaha, in the north (7 and 3, respectively).

In dry forests at all four watersheds, many fires probably burned in the summer or early fall, after the end of the growing season, because most scars for which seasonality could be determined were found on ring boundaries (35-83% per watershed, Figure 10). However, seasonality varied among watersheds. To the north (Tucannon and Imnaha) few fires burned during the growing season (8% earlywood and latewood scars) whereas to the south (Baker and Dugout) many fires burned during the growing season (48% earlywood and latewood scars). In addition, the few fire years (17%) that had a majority of scars in the early- and/or latewood were found only in the southern watersheds (12 fire years at Dugout and 9 at Baker).

Annual extent was small relative to the size of the sampling area during most fire years in all watersheds (Figure 11). For approximately half the fire years, extent was <525 ha at Tucannon and Imnaha, <930 ha at Baker and <1730 ha at Dugout, or ≈20% of each sampling area. Nevertheless, at most watersheds some fires were very large. During at least one year at most watersheds (Imnaha, Baker and Dugout), a fire burned the entire sampling area. At Tucannon, the greatest annual extent was 70% of the sampling area. During some fire years (23%, mostly at Dugout), more than one fire boundary was

identified, indicating that several fires may have burned the watershed at different times during that fire year. Most fire boundaries at all watersheds intersected the edge of the sampling area (82%), indicating that annual extents were probably larger than reconstructed. Although fire extent was smaller at the northern than the southern watersheds, the sampling area in these watersheds is also smaller than that to the south so that differences in extent may be an artifact of sampling design.

Local variation (comparison of all forest types within each watershed)

At the northern watersheds (Tucannon and Imnaha), fire recurrence and severity varied most strongly with aspect. Fires were more frequent and less severe on south and west aspects (average of 2 and 4 fires per plot, 1798-1900, respectively) than on north and east aspects (average of 1 and 2 fires, respectively), regardless of elevation (Figure 12). At Baker, fire recurrence and severity varied most strongly with elevation. Fires were more common below than above 1500 m (average of 6 versus 4 fires per plot). Although low-severity fires occurred on all sampled aspects at Baker, they were limited to <1500 m on north and east aspects. Moderate- and high-severity fires occurred primarily on north and east aspects >1500 m but fire recurrence could not be reconstructed in these areas. Fire recurrence at Dugout ranged from 2 to 10 fires per plot but did not vary consistently with either aspect or elevation. Only low-severity fires were found in this watershed. Seasonality (low-severity fires only) did not vary with either aspect or elevation in any watershed.

Fire severity also varied with forest type. Most plots with mesic associations had cohorts of western larch and/or lodgepole pine but no fire scars (96% of plots), indicating that historical fires were predominantly of moderate or high severity. In contrast, fire scars were found in most plots with dry associations (93% of plots), indicating that historical fires were predominantly of low severity. Only 2% of all plots had both fire-scarred trees and cohorts of western larch and/or lodgepole pine.

DISCUSSION

Fire regimes did not change from 1687 to 1900

Fire extent and recurrence did not change dramatically from 1687 to ≈1900 in any sampled watershed. This stability indicates that fire regimes can be characterized and compared among watersheds for this period. Differences in fire recurrence before and after ≈1900 are much greater than any spatial variation, either among or within watersheds, prior to this time. I speculate that fire extent and occurrence were initially reduced by high precipitation, and perhaps domestic livestock grazing, in the late 1800s, followed by effective fire suppression by federal land-management agencies in the mid-1900s (Chapter 3). As a consequence, spatial variation in climate or other factors no longer influences fire regimes as it did before ≈1900, either regionally or locally. This dramatic change in fire recurrence has profoundly affected forest composition and structure, most notably in dry forests where shade-tolerant understory trees have established in the absence of fire (Agee 1994), as they have in similar forest types throughout the western United States where fire has been excluded for many decades (Weaver 1959, 1961, Cooper 1960, Mutch et al. 1993, Agee 1994, Covington and Moore 1994). This change in forest composition and structure has shifted the fire regime of the dry forests from frequent, low-severity fires to infrequent, high-severity fires that kill large areas of multiply-scarred ponderosa pine trees (Agee 1993, 1994).

Variation in fire regimes was consistent with spatial variation in climate

Fire recurrence varied both regionally and locally

At the regional scale, fires were less frequent in the dry forests of the northern watersheds than in similar forest types to the south (Figure 9), consistent with regional gradients in climate (Figure 2). Summer precipitation is higher in the northern than in the southern Blue Mountains (Figure 2a). Precipitation increases fuel moisture by directly wetting soil and ground fuels and also by increasing relative humidity, in response to which fuels absorb more moisture from the surrounding air (Schroeder and Buck 1970).

The moisture content of fuel critically affects all aspects of fire behavior, including the probability that fuel will combust and the rate at which fire spreads (Blackmarr 1972, Rothermel 1983, Latham 1989). To the south, low precipitation resulted in lower fuel moisture which is more conducive to fire ignition and spread than high fuel moisture. Snow cover persists longer in the northern than the southern Blue Mountains. Snow-cover duration may be an important control on fire regimes because melting snow wets ground fuels directly. Shorter durations in the southern Blue Mountains result in longer seasons during which fuels are dry enough to combust. Lastly, summer lightning is more frequent in the south (Morris 1934, Krider et al. 1980), probably resulting in more frequent ignitions in the southern than the northern watersheds. The consequence of these regional gradients in climate was more frequent fires in the southern than the northern Blue Mountains.

In addition to influencing fire indirectly by modifying climate, regional-scale landforms within the Blue Mountains may have affected fire recurrence directly by facilitating or stopping the spread of individual fires (Swanson et al. 1988, Agee 1993, Swetnam and Baisan 1996). Both northern watersheds are embedded in complex topography where ridges and barren rocky slopes interrupt the continuity of ground fuels and may have limited fire spread and occurrence. In contrast, to the south, Dugout lies in an area of gentle topography and Baker is at the edge of a broad, flat valley. Consequently, fires ignited at a distance may have spread into these watersheds more often than distant fires spread into the northern watersheds, resulting in more frequent fires to the south.

Nested within the regional variation, fire recurrence was also variable at the local scale. Because the four watersheds are topographically unique, the relationship of fire recurrence to topography varied among watersheds even though it was locally consistent with spatial variation in microclimate. Aspect had the greatest influence on recurrence at Tucannon and Imnaha (Figure 12). Aspect may be particularly important at these watersheds because the slopes are steep. In steep terrain, aspect affects fuel moisture by controlling the input of direct solar radiation which heats fuels hence lowers fuel moisture (Hayes 1941, 1942, Countryman 1978). Steep slopes with south and west aspects are

also free of snow earlier in the year because they receive more direct solar energy and consequently have a longer fire season than north and east aspects. Furthermore, the east-west trending rivers at these watersheds act as fire breaks between northerly and southerly slopes and probably prevented the spread of frequent fires from the southerly slopes to the northerly ones.

Elevation was the most important topographic control of fire recurrence in dry forests at Baker, with fires most frequent at low elevation (Figure 12). Temperature generally decreases and relative humidity increases with increasing elevation, so that fuel moistures generally increase with elevation, regardless of aspect (e.g., Hayes 1941, 1942). Furthermore, the gradient in temperature causes snow cover to melt sooner at low than high elevations, contributing to the gradient in fuel moisture. Although I was unable to reconstruct individual fires in mesic forests at high elevations at Baker, I speculate that fires were more frequent in mesic forests at this watershed than in similar forests at Tucannon and Imnaha because precipitation is lower at Baker and no topographic barrier prevents fire spread from dry to mesic forests. Consequently, the frequent fires in dry forest may have spread or spotted upslope into mesic forests but failed to attain large size because higher fuel moistures impeded fire spread (Agee et al. 1990, Agee 1993).

At Dugout, recurrence did not vary with aspect or elevation because the gentle slopes sampled at this watershed (average: 16%) result in only small differences in microclimate and there is only a small range in elevation compared to the other watersheds.

At the local scale, forest structure also influences microclimate, hence fire recurrence. Variation in microclimate controls the distribution of vegetation within watersheds (Holland and Steyn 1975, Pope and Lloyd 1975) so that in steep terrain in the Blue Mountains, dry grand fir, Douglas-fir and ponderosa pine forests grow on warm, dry slopes (south and west aspects and low elevations) and mesic grand fir and subalpine fir grow on cool, moist slopes (north and east aspects and high elevations). However, ground fuels are drier, hence fires are more likely to ignite and/or spread, under the relatively open canopies of dry forests than the closed canopies of mesic forests (Rothermel 1983). Forest structure (closed or open canopy) therefore enhances the

microclimate resulting from topography alone so that variation of fire recurrence within watersheds results from microclimates determined by both topography and vegetation.

Seasonality varied regionally

At the regional scale, fire seasonality in dry forests varied among watersheds with more fires burning during the radial growing season in the southern than in the northern watersheds (Figure 10). This indicates that either the timing of radial growth varies regionally, or the timing of fire varies regionally or both vary simultaneously. Fires may have burned at similar times throughout the Blue Mountains while radial growth continued later into the year in the south. The southern Blue Mountains receive a greater proportion of annual precipitation during the spring (May/June) than do the northern Blue Mountains (Mock 1996), so that radial growth of ponderosa pine may continue longer into the year to the south (Fritts 1976). As a consequence, fires burning simultaneously across the Blue Mountains could have created early- and latewood scars in the south but scars on the ring boundary to the north. Alternatively, radial growth may have ceased at similar times throughout the Blue Mountains while fires burned earlier in the year in the south, as do modern fires (1986-1993, E. Alvarado personal communication), possibly due in part to earlier melting of snow cover.

Variation in fire seasonality reconstructed from tree rings in the Blue Mountains and elsewhere in western North America is consistent with continental-scale variation in climate (Figure 13, Baisan and Swetnam 1990, Brown and Swetnam 1994, Grissino-Mayer 1995, Wright 1996, Heyerdahl et al., unpublished data). Most of these studies assume that scars in earlywood were created by fires that burned in the spring or early summer while those in latewood or on the boundary between two rings were created by fires that burned in the late summer or early fall. The three northern-most studies (Washington, Oregon, northern California), all conducted in areas with relatively dry summers and a maximum in precipitation during the winter (Karl and Koscielny 1982, Mock 1996), have a majority of scars (>90%) in the latewood or on ring boundaries. In contrast, the three southern studies, in areas which have relatively dry winters and a

precipitation maximum during the summer monsoon (Karl and Koscielny 1982, O'Hara and Metcalfe 1995, Mock 1996), have less than half of the scars in the latewood or on the boundary between two rings. As a consequence, fires occurred primarily in late summer or fall at the northern sites, but commonly in the spring or early summer at the southern sites.

Extent varied locally

Annual fire extent varied locally although that variation was not consistent with topography. Although most fire extents were small relative to the size of the sampling area in all watersheds, they were large relative to twentieth century fires. The majority of fire years in all watersheds had extents corresponding to the largest classes in a modern classification of fire size (E and above; A: <0.10 ha, B: 0.11-4 ha, C:5-40 ha, D:41-121 ha, E:122-404 ha, F:405-2300 ha, G:>2300 ha; USDAFS 1993). Fire extent was variable within watersheds, although this variation is more likely due to temporal than spatial variation in climate because fires of similar extent occurred in different portions of the watershed and vice versa (Chapter 3).

Extent may vary regionally, but that variation was not detected because the full extent of most fires was not reconstructed. For example, at Tucannon steep, rocky slopes may have prevented some fires from spreading whereas the gentle topography at Dugout may not. Annual fire extent had a similar distribution in dry forests in the eastern Cascade Range of Washington where most extents (95% of fires from 1700-1900) were small relative to the sampling area size (<2400 ha out of 10,000 ha) but many fires intersected the boundary of the study area so that fire extents are probably underestimated at this site as well (Wright 1996).

Implications for understanding regional fire regimes

Although variation in fire regimes is evident at the continental scale, such variation has not been well-characterized at regional or even local scales. For example, even within similar forest types, fire recurrence was twice as frequent in the southern as in the northern

Blue Mountains (Figure 9) so that even within this relatively small region, recurrence cannot be predicted on forest type alone. Furthermore, the locally consistent but regionally variable relationships between fire recurrence and topography found in the Blue Mountains (Figure 12) indicates that fire recurrence cannot always be predicted on the basis of simple relationships with topography. Instead, predicting fire regimes in unsampled watersheds requires an understanding of the controls of fire and the spatial scales over which those controls operate.

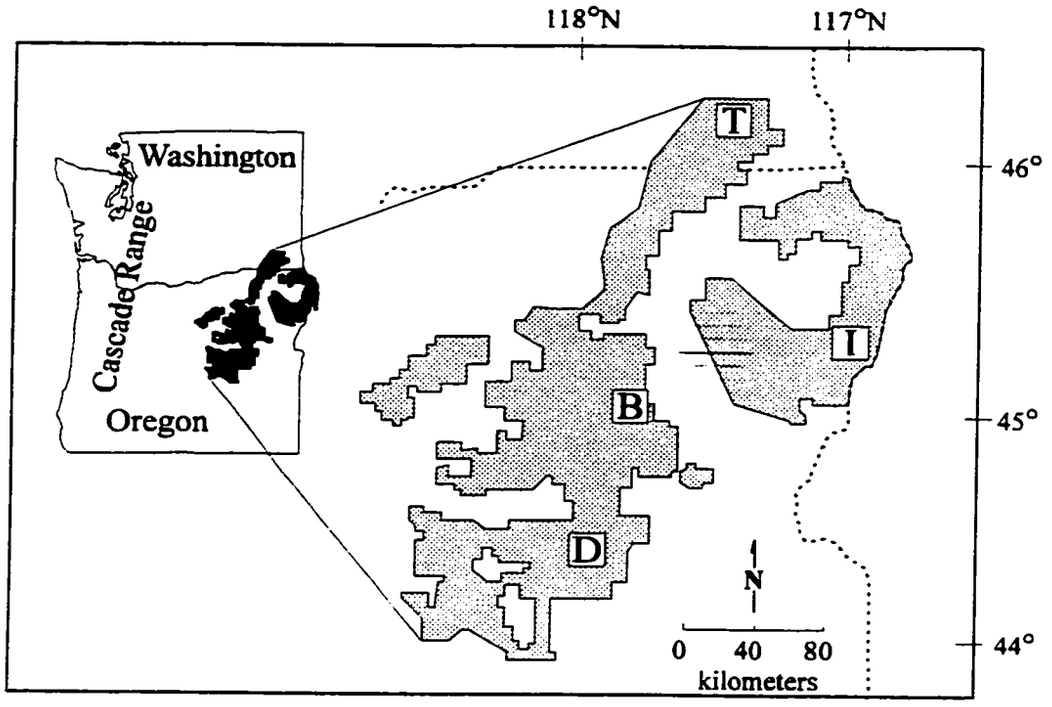

Figure 1. The Blue Mountains of Oregon and Washington, showing the location of the four sampled watersheds (T = Tucannon, I = Imnaha, B = Baker and D = Dugout). The Columbia River flows through the Cascade Range along the border between Oregon and Washington. Shaded areas indicate land managed by the U.S. Forest Service.

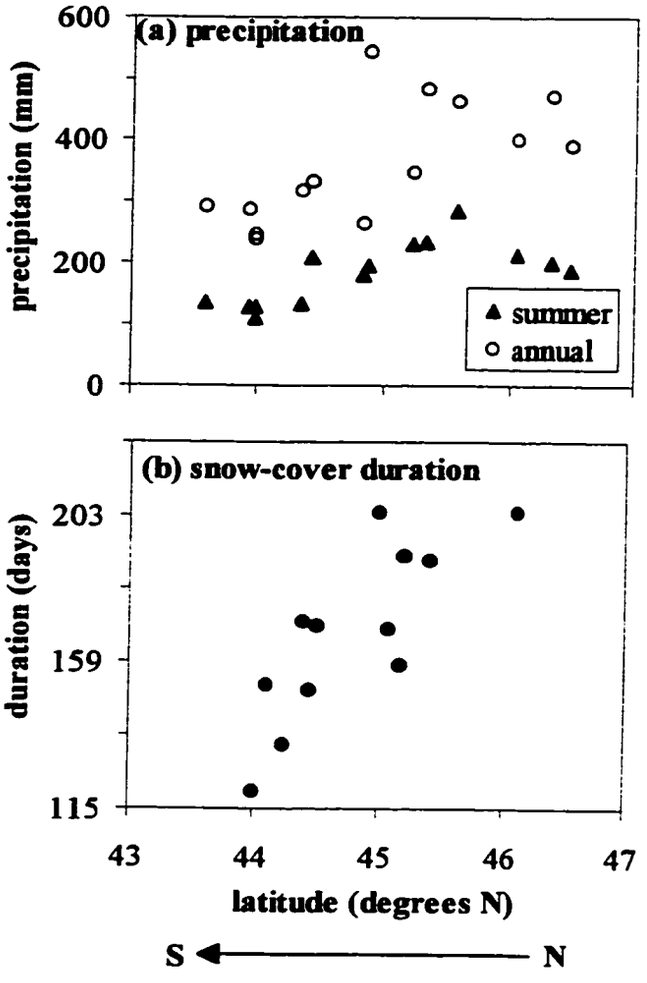

Figure 2. Regional variation in the modern climate of the Blue Mountains: (a) summer (July-September) and annual precipitation (previous October-current September; 1949-1979; NOAA 1997) and (b) length of period without continuous snow cover (1979-1996; NRSC 1997) at individual weather or snow telemetry stations in the Blue Mountains.

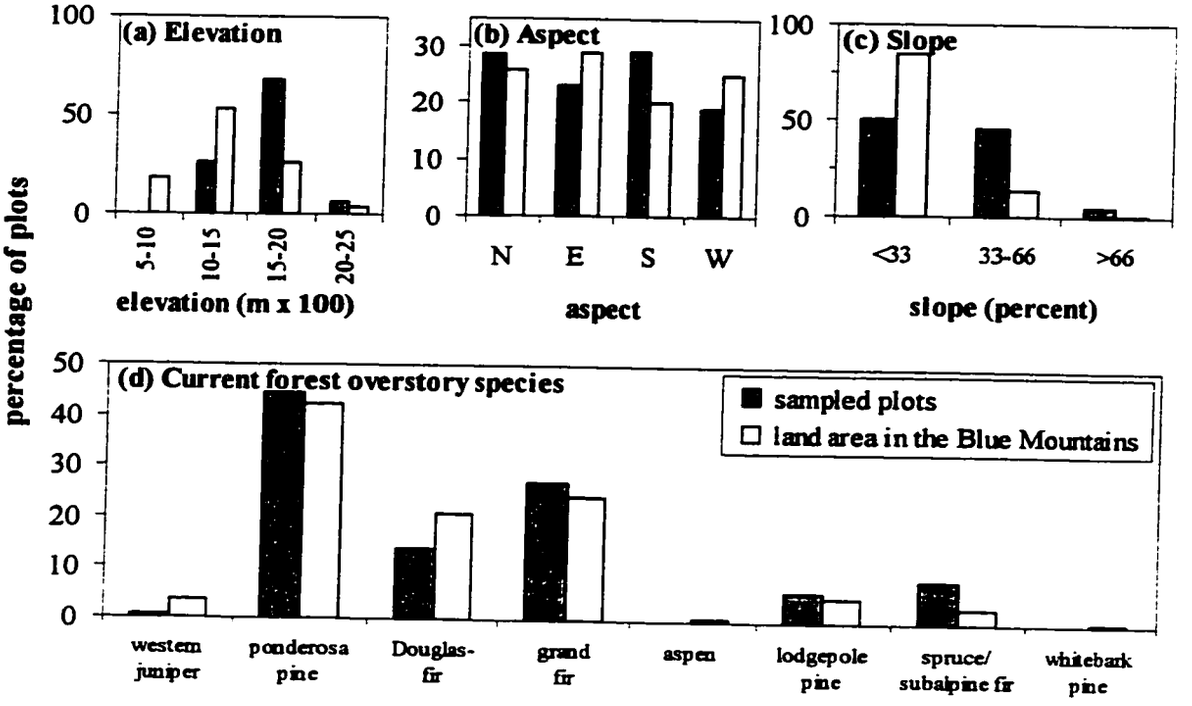

Figure 3. Distribution by topography and current forest overstory for plots and for forested land in the Blue Mountains. Aspect classes are 90° wide, beginning with 46° for E (east). Topography for the Blue Mountains was derived from a digital elevation model and current forest overstory from satellite data.

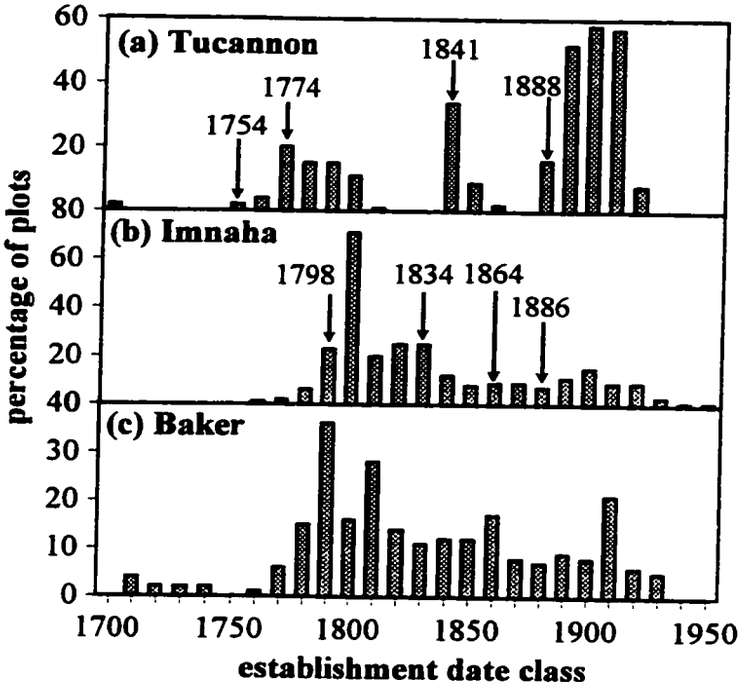

Figure 4. Distribution of plots by establishment date classes. Estimated dates of high- and moderate-severity fires, reconstructed from spatially-clustered cohorts of early seral trees, are indicated by arrows for (a) Tucannon and (b) Imnaha. Cohorts could not be identified at (c) Baker.

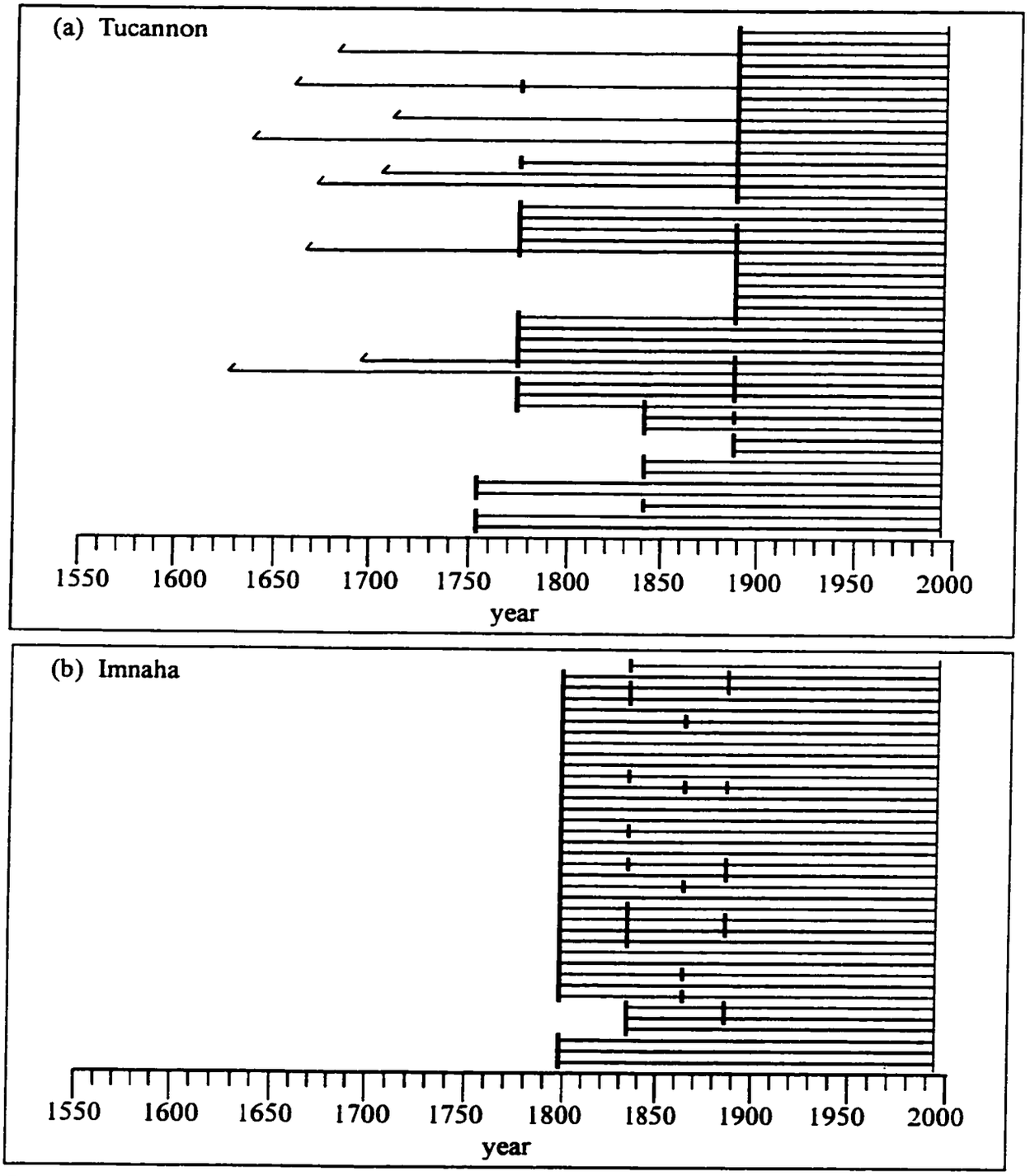

Figure 5. Fire chart for mesic forest plots at (a) Tucannon and (b) Imnaha. Each horizontal line shows the composite tree-ring record at a single sampling plot through time. The lines are arranged roughly north (top) to south (bottom) within each watershed. Short vertical lines indicate an estimated year of fire. Fine diagonal lines indicate the earliest establishment date at a given plot.

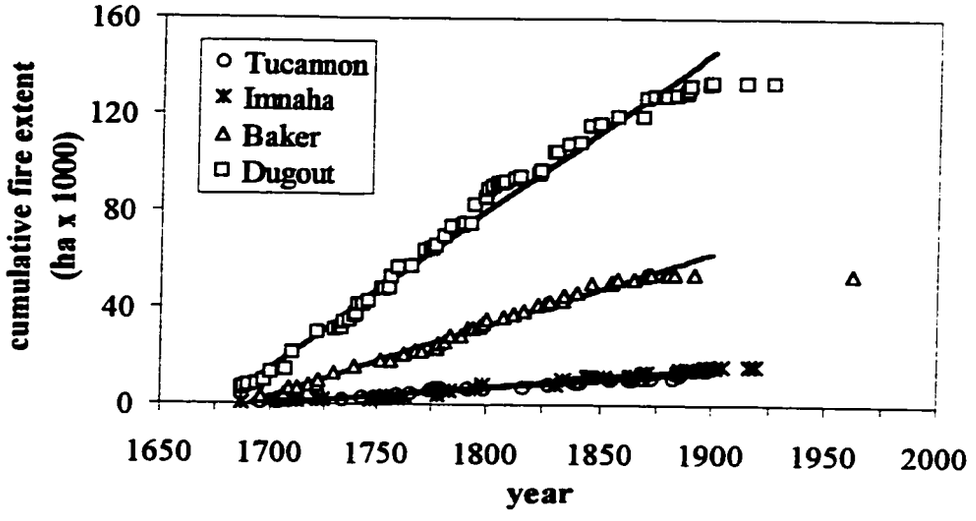

Figure 6. Cumulative fire extent by watershed for fires occurring since 1687. Regression lines were determined using ordinary least squares from 1687 to 1900 (r_a^2 = 0.97 to 0.99). The slopes of the lines are partially dependent on sampling area size, which is not the same for all watersheds (see Table 2).

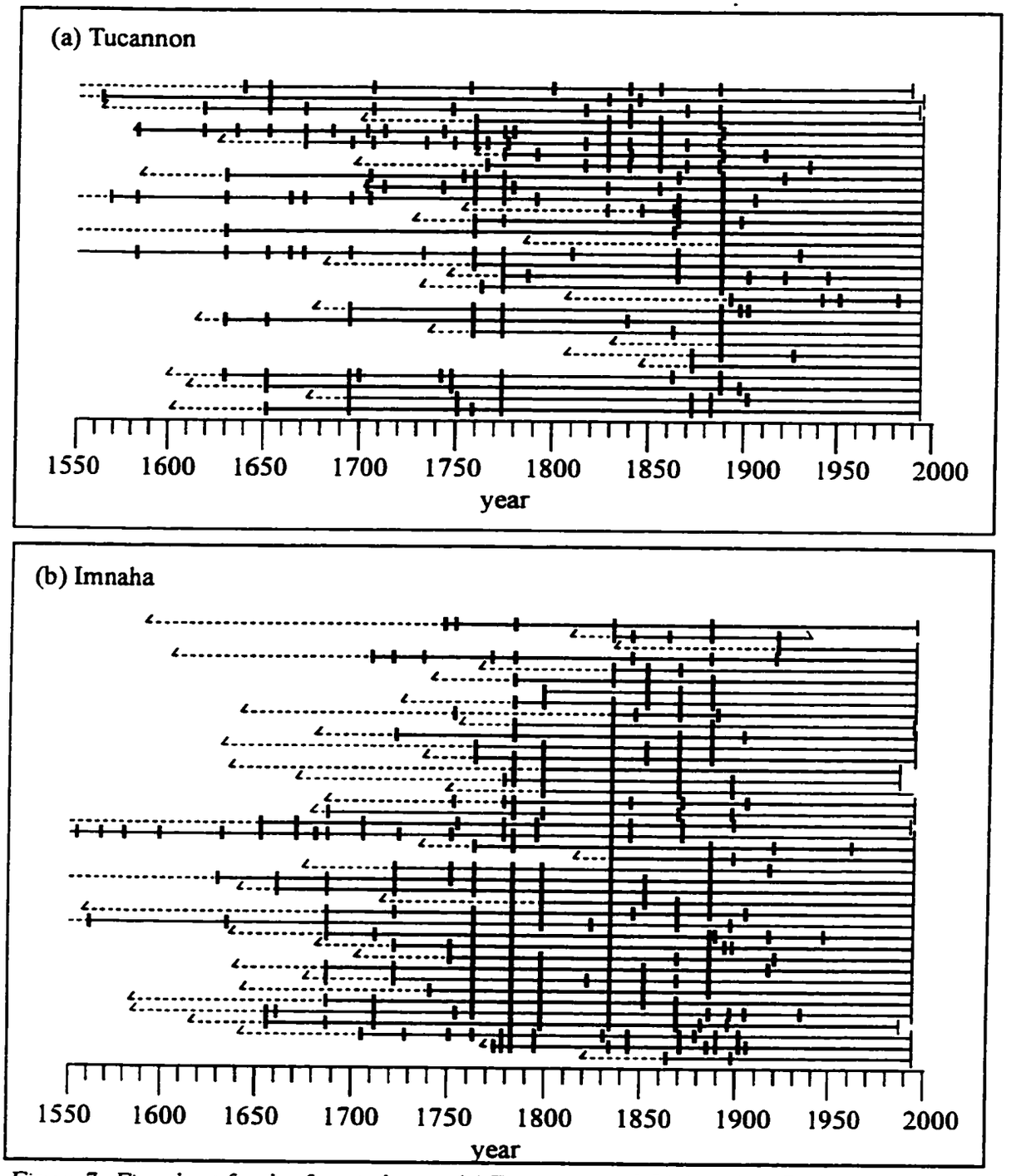

Figure 7. Fire chart for dry forest plots at (a) Tucannon and (b) Imnaha. Each horizontal line shows the composite tree-ring record at a single sampling plot through time. The lines are arranged roughtly north (top) to south (bottom) within each watershed. A fire may have scarred more than one tree per plot. Dashed horizontal lines indicate years that preceeded the formation of the first fire scar on samples from that plot. Solid vertical bars mark fire years. Fine vertical lines at the beginning and end of each chronology mark pith or bark dates, while fine diagonal lines mark the earliest or latest ring dates when pith or bark was not sampled. All dated scars are shown, whether or not they were mapped as part of a fire.

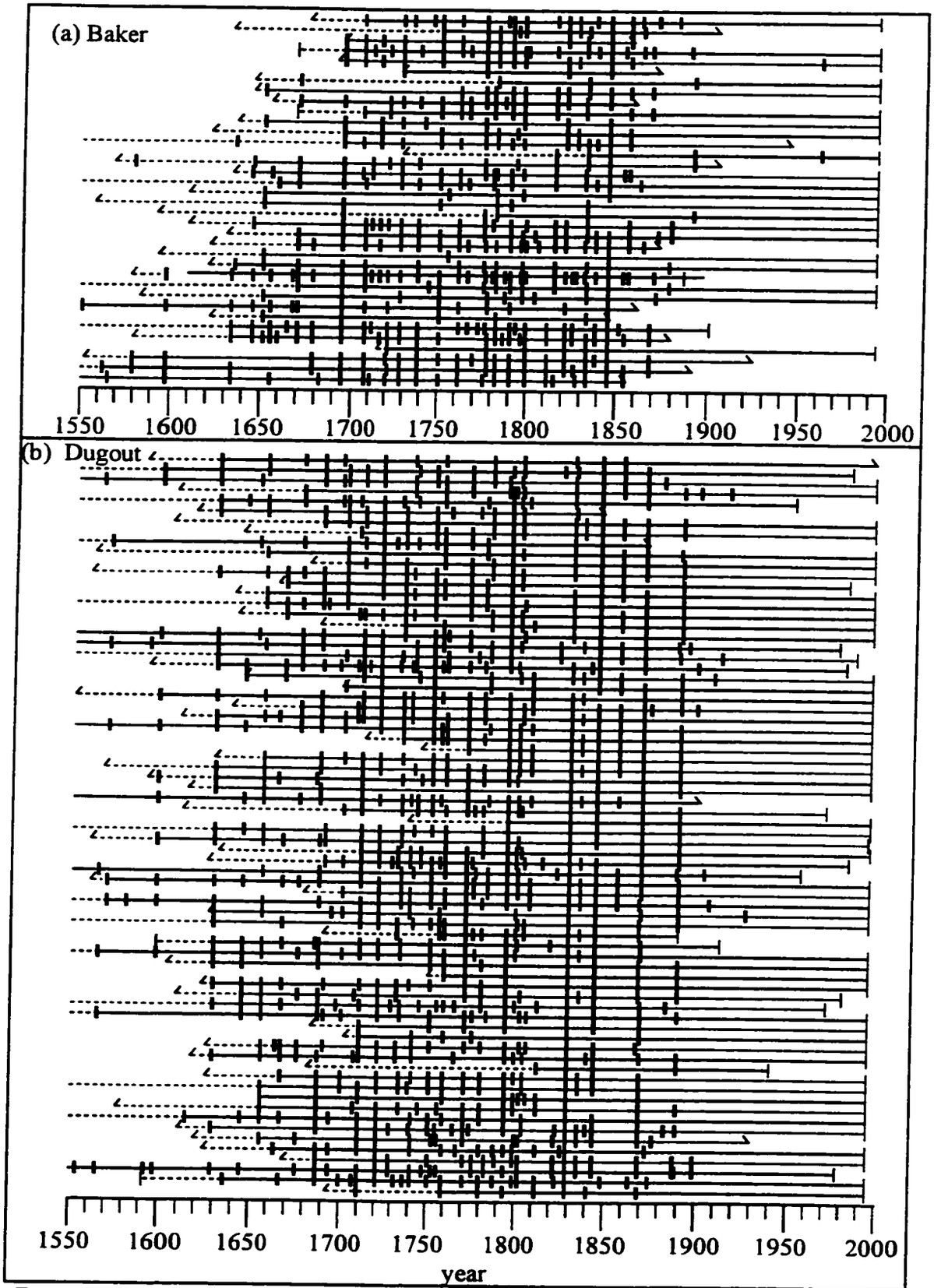

Figure 8. Fire chart for dry forests at (a) Baker and (b) Dugout (see Figure 7 for explanation).

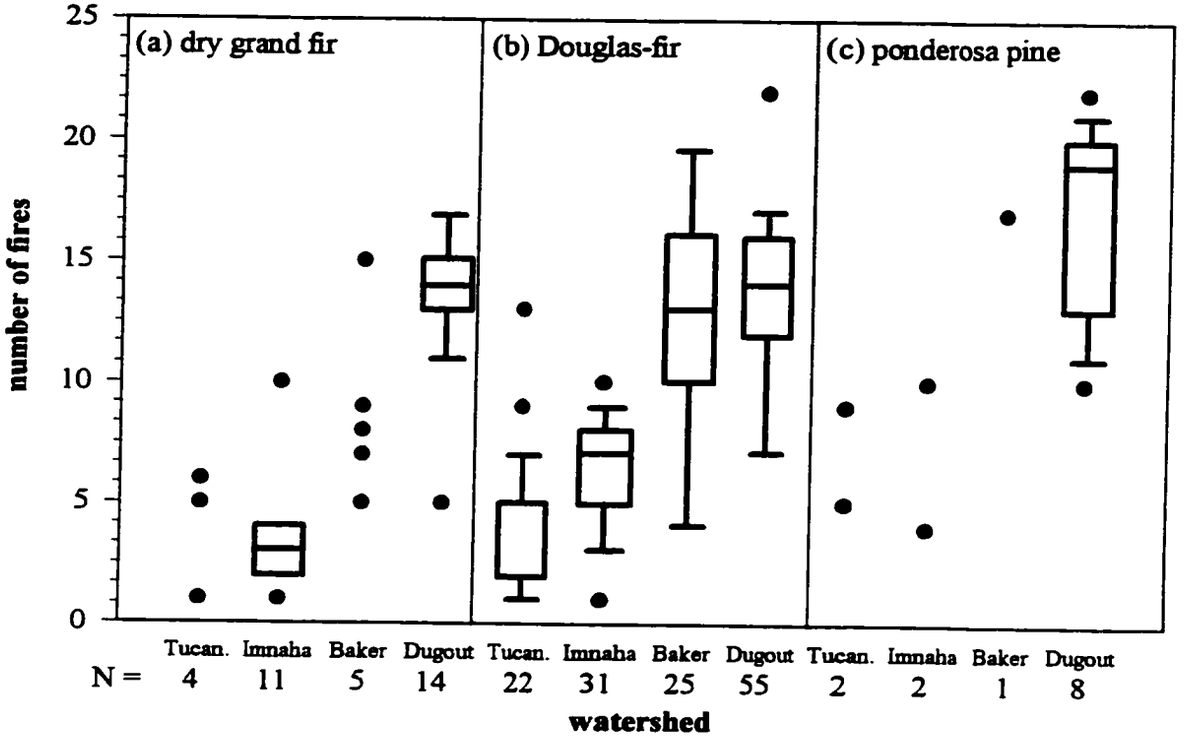

Figure 9. Regional variation in fire recurrence in dry forest plots (1687-1900). Only pinegrass and elk sedge associations of the grand fir, Douglas-fir and ponderosa pine series are included. The boxes enclose the 25th to 75th percentiles, the whiskers enclose the 10th to 90th percentiles, the horizontal line across each box indicates the median and all values falling outside the 10th to 90th percentiles are shown as dots. Where <6 plots were sampled in a forest type at a watershed, the number of fires is indicated by dots for all the plots that were sampled.

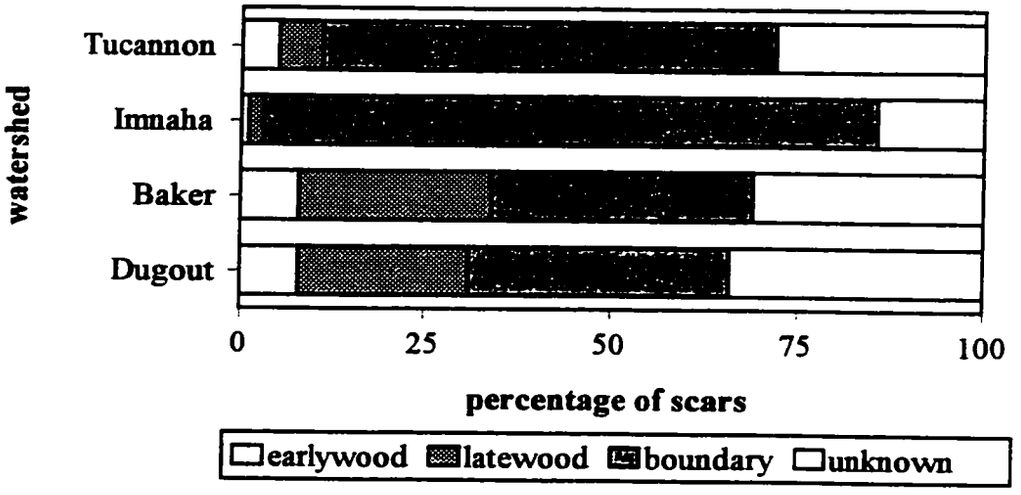

Figure 10. Regional variation in fire seasonality. Intra-annular position of scars as a percentage of total scars (1687-1900) at each watershed. The watersheds are ordered from north (top) to south (bottom).

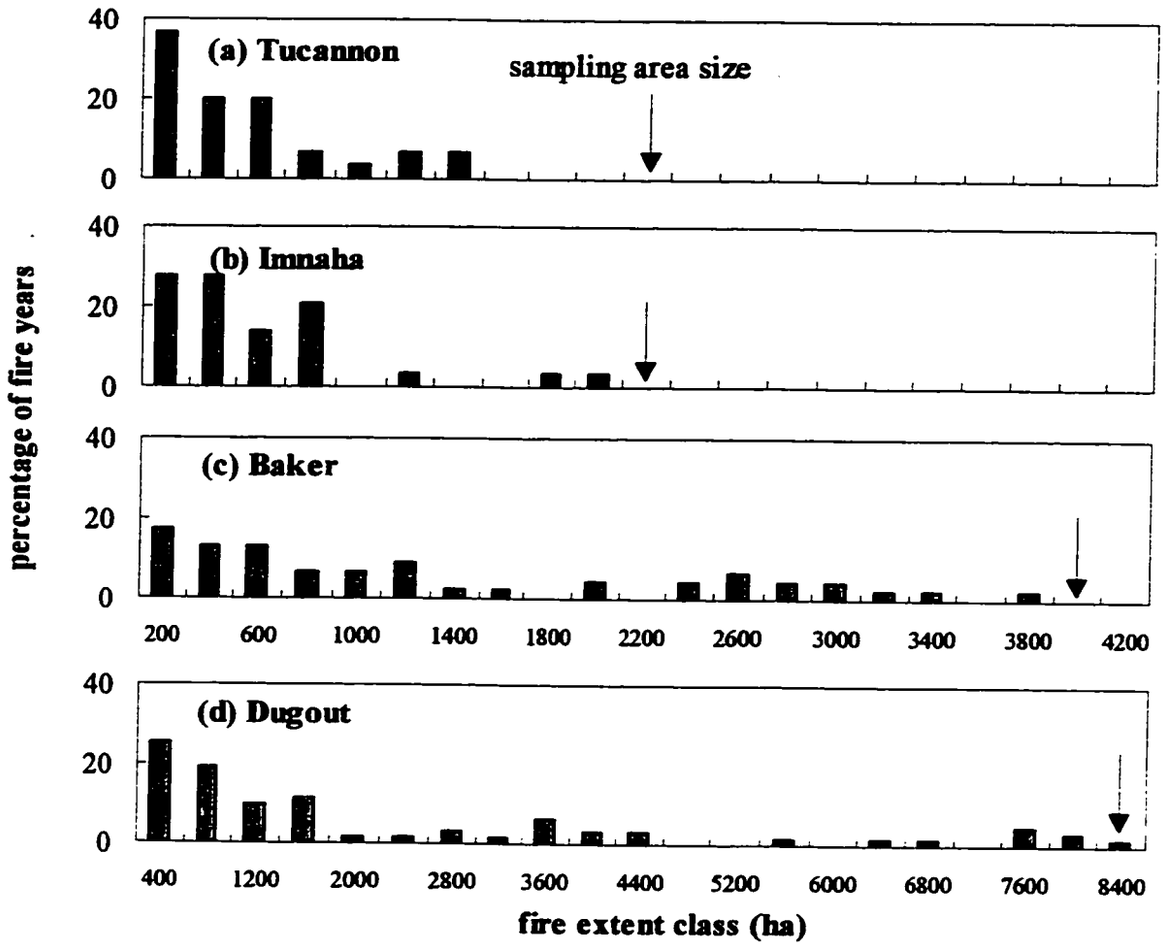

Figure 11. Regional variation in fire extent. Distribution of fire years by extent classes for low severity fires (1687-1900). Extent classes for Dugout are twice as large as the classes for the other three watersheds. The size of the sampling area is indicated by an arrow.

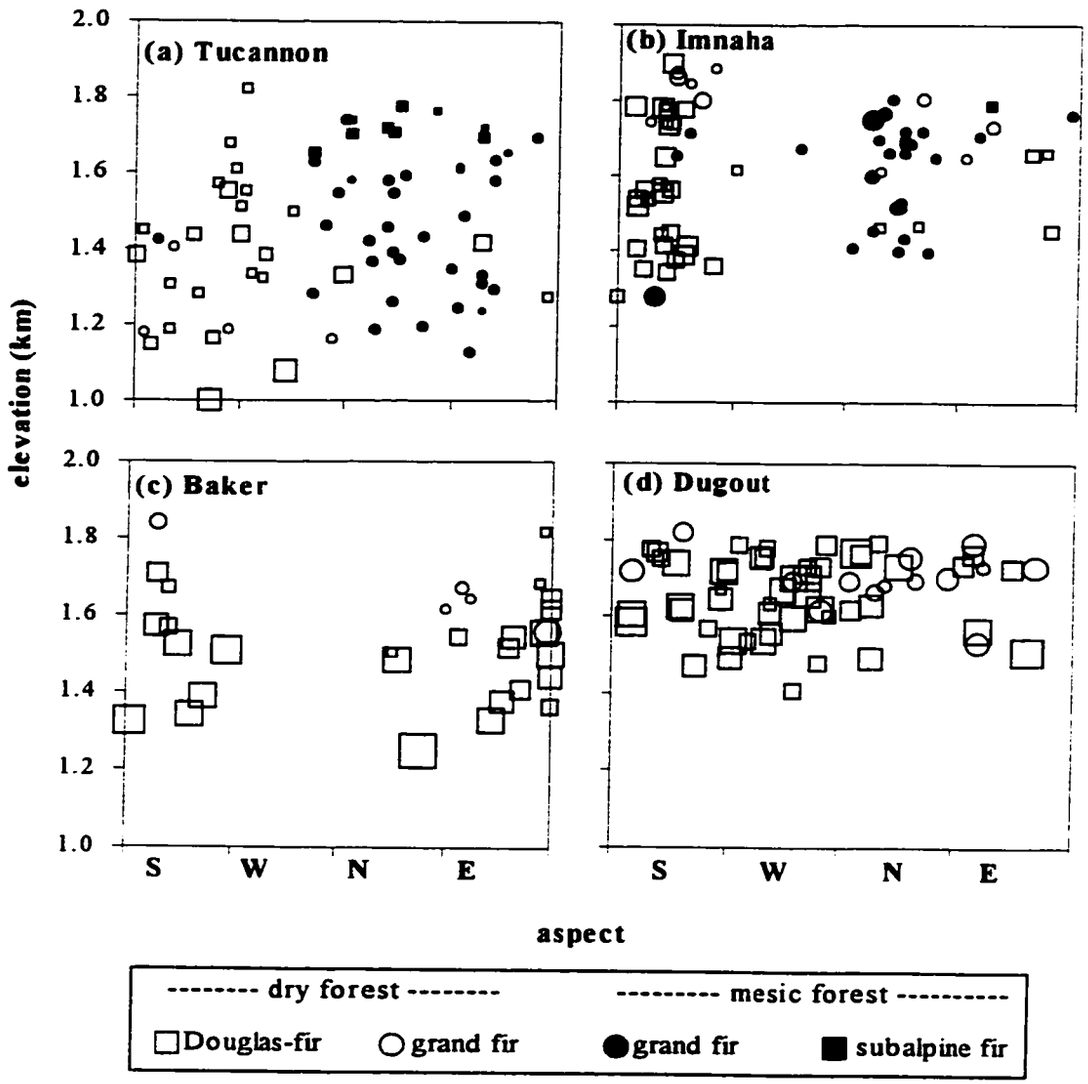

Figure 12. Local variation in fire recurrence. Distribution of plots by elevation and aspect at each watershed. The size of the symbols is proportional to the number of fires (1798-1900), with the smallest symbol representing no fires and the largest 10 fires. At Baker, subalpine fir and mesic grand fir forests occur primarily on north and east aspects above 1500 m but are not shown because fire recurrence could not be reconstructed for these plots.

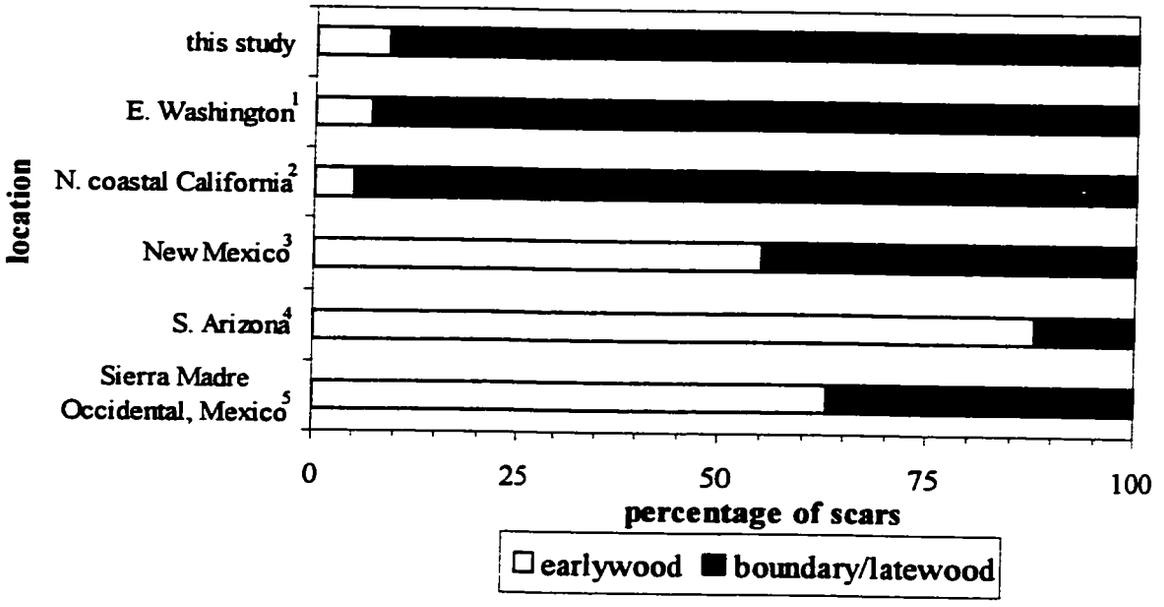

Figure 13. Seasonality of historical fire regimes of selected sites in western North America. Sites are ordered from north (top) to south (bottom). (1) 1319 scars, Wright 1996; (2) 56 scars, Brown and Swetnam 1994; (3) 1623 scars, Grissino-Mayer 1995; (4) > 900 scars, Baisan and Swetnam 1990; (5) 1384 scars, Heyerdahl et al., unpublished data.

Table 1. Distribution of plots by plant association and evidence of fire. Only associations found at more than 2 plots are included (95% of all plots sampled). Forest series for each association correspond to the tree species in the association name. The plant associations are ordered from those growing in mesic to dry environments (top to bottom).

Common name	Scientific name	Number of plots: Watershed				Evidence of fire	
		Tucannon	Imnaha	Baker	Dugout	age cohorts	fire scars
Mesic forest associations:		0	0	0	0	0	0
subalpine fir/fool's huckleberry	*A. lasiocarpa/Menziesia ferruginea*	3	0	0	0	3	0
subalpine fir/big huckleberry	*A. lasiocarpa/Vaccinium membranaceum*	9	1	4	0	14	0
subalpine fir/grouse huckleberry	*A. lasiocarpa/Vaccinium scoparium*	0	0	12	0	12	0
subalpine fir/elk sedge	*A. lasiocarpa/Carex geyeri*	1	0	4	0	5	0
grand fir/Pacific yew/twinflower	*A. grandis/T. brevifolia/Linnaea borealis*	3	0	0	0	3	0
grand fir/queen's cup beadlily	*A. grandis/Clintonia uniflora*	2	2	0	0	4	0
grand fir/twinflower	*A. grandis/Linnaea borealis*	4	0	4	0	6	2
grand fir/big huckleberry	*A. grandis/Vaccinium membranaceum*	14	24	7	0	43	2
grand fir/Columbia brome	*A. grandis/Bromus vulgaris*	2	0	2	0	4	0
grand fir/birchleaf spiraea	*A. grandis/Spiraea betulifolia*	5	0	0	0	5	0
Dry forest associations:		0	0	0	0	0	0
grand fir/pinegrass	*A. grandis/Calamagrostis rubescens*	4	9	5	11	10	19
grand fir/elk sedge	*A. grandis/Carex geyeri*	0	2	1	3	0	6
Douglas-fir/pinegrass	*P. menziesii/Calamagrostis rubescens*	19	30	21	44	3	111
Douglas-fir/elk sedge	*P. menziesii/Carex geyeri*	3	1	4	11	0	19
ponderosa pine/pinegrass	*P. ponderosa/Calamagrostis rubescens*	1	2	0	9	0	12
ponderosa pine/elk sedge	*P. ponderosa/Carex geyeri*	1	0	1	2	0	4

Table 2. Size of sampling areas (18,904 ha total) and amount of fire evidence sampled. Potential evidence of fire is abrupt increases or decreases in ring width. Begin and end years are dates of first and last rings found at each watershed and the period of reliability is the span of time during which at least 30% of dry forest plots were susceptible to scarring. Numbers of plots and trees given are for the entire period of record. More than half of the trees (55%) from which fire-scarred sections were removed were stumps, logs or snags and multiple sections were removed from one-third of these.

	Sampled area (ha)		Number of plots		Number of trees		Number	Potential	Fire scars			
	age	fire	age	fire	age	fire	of fire	evidence	Begin	End	Period of reliability	
Watershed	class	scar	class	scar	class	scar	scars	of fire	Year	Year	Begin	End
Tucannon	912	2,002	46	28	334	86	382	21	1487	1994	1639	1994
Imnaha	860	2,095	40	34	282	109	517	48	1480	1994	1687	1994
Baker	638	3,812	37	36	286	114	1,258	88	1403	1994	1646	1994
Dugout	0	8,585	0	82	0	215	2,156	124	1346	1994	1629	1994
Total	2,410	16,494	123	180	902	524	4,313	281				

Table 3. Regional variation in fire recurrence. Results of ANOVA among watersheds in the number of fires per dry forest plot (1687-1900).

Source of variation	Sum of squares	Degrees of freedom	mean square	F-ratio	p-value
Between watersheds	346.935	3	115.645	70.742	<0.001
Within watersheds	279.543	171	1.635		
Total	626.478	174			

CHAPTER 3: TEMPORAL VARIATION IN HISTORICAL FIRE REGIMES

INTRODUCTION

Historically, low-severity fires affected the composition and structure of ponderosa-pine (*Pinus ponderosa* Dougl. ex Loud.) dominated forests of interior western North America (Smith 1983, Keane et al. 1990, Agee 1993). However, timber harvesting, grazing, fire exclusion and other land-use practices over the last ≈100 years have nearly eliminated the low-severity fire regimes that were common in these forests, resulting in dramatic changes in forest composition and structure (Cooper 1960, Mutch et al. 1993, Covington and Moore 1994, Chapter 2). Federal land-management agencies may reintroduce fire to the forests of the interior West in the hope of restoring the range of compositions and structures that existed prior to Euroamerican settlement (USDAFS and USDIPS 1995). Although the range of variation in pre-settlement fire regimes provides a context for this restoration (Fulé et al. 1997), the past range alone is of little use in anticipating changes in forests as a consequence of changes in climate, such as changes in the frequency of lightning strikes and weather conducive to fire spread (Flannigan and Van Wagner 1991, Price and Rind 1994). Anticipating the consequences of climate change requires that we understand the *causes* of pre-settlement variation in fire regimes, including variation in past climate.

The influence of weather acting on modern fires over short time scales (minutes, hours, days) is well documented at local scales (e.g., Schroeder et al. 1966, Deeming et al. 1977). However, to understand how climate controls fire regimes over longer time scales (years, decades, centuries), we need long-term evidence of the relationship between climate and fire during periods when forests were not highly altered by twentieth century fire exclusion. Archival records of fire and climate begin in the early twentieth century and are therefore too short for this purpose. Fortunately, multicentury records of both fire and climate are recorded in tree rings. These records have been used in the southwestern United States to elucidate past relationships between fire and both local climate and

features of global atmospheric circulation such as the Southern Oscillation (Swetnam and Betancourt 1990, Swetnam 1993b, Swetnam and Baisan 1996). The occurrence of archival years during which fires burned synchronously across the western United States (e.g., 1910; Plummer 1912) implies that there may be large-scale climatic controls of fire (Swetnam and Betancourt 1990, Swetnam 1993b).

The Blue Mountains in northeastern Oregon and southeastern Washington, provide an opportunity to study historical interactions of climate and fire, because independent multicentury records of both have been reconstructed from annually-dated tree-ring series for the region. Fire regimes have been reconstructed in four watersheds (1687-1994, Chapter 2), a single time series of annual precipitation has been reconstructed for the Blue Mountains region (1705-1979, Garfin and Hughes 1996) and an index of the Southern Oscillation has been reconstructed for western North America (1600-1963, Lough and Fritts 1985).

This study has three objectives. First, to describe temporal variation in historical fire extent within each watershed and to explore the influence of climate (precipitation and an index of the Southern Oscillation). Second, to identify whether fires historically burned synchronously across the Blue Mountains. Finally, based on the past influence of climate in this region, to identify which parameters of climate could affect future fire regimes in the Blue Mountains.

STUDY AREA

The Blue Mountains, in northeastern Oregon and southeastern Washington, lie east of the Cascade Range which blocks much of the low-level, moist westerly flow from the Pacific Ocean (Mock 1996, Figure 14). Consequently, annual precipitation is low across the study area (446 mm at low elevation stations, 1895-1996, EarthInfo 1990). Most precipitation falls as snow in winter; summer (July-September) precipitation averages only 12% of annual precipitation (1895-1996, EarthInfo 1990, NCDC 1996). Mean temperatures are high in July (18.8°C) and low in January (-3.2°C at low elevation stations, 1895-1991, EarthInfo 1990).

Temporal variation in the climate of the Blue Mountains is partially explained by the Southern Oscillation, an intermittent fluctuation of sea-level pressure, surface wind and sea-surface temperature over the tropics and South Pacific Ocean that influences surface climate over much of the globe (Ropelewski and Halpert 1986, 1987; Kiladis and Diaz 1989), including the Pacific Northwest (Redmond and Koch 1991, Cayan and Webb 1992). During the warm phase of the Southern Oscillation, typically El Niño years, winters are warmer and sometimes drier than during other years in northeastern Oregon and southeastern Washington (October-March, 1931-1984, Redmond and Koch 1991). Consequently, spring snow cover is low, particularly in the northern Blue Mountains (Redmond and Koch 1991, Cayan and Webb 1992). There is a 3 to 5 month delay before fluctuations of the Southern Oscillation affect the climate of the Pacific Northwest (Redmond and Koch 1991).

Despite regional consistency, some aspects of climate vary across the Blue Mountains because this region lies at the interface of three distinctly different air masses: westerly marine air, easterly and southerly continental air and northerly arctic air (Mitchell 1976, Mock 1996, Ferguson 1997). These air masses interact with landforms so that fluctuations in climate are not always synchronous across the region. For example, the Columbia River breaches the Cascade Range west of the northern end of the study area so moist, westerly Pacific air sometimes brings precipitation to the northern but not the southern Blue Mountains (Mock 1996).

Forest composition is comparable among the sampled watersheds (Chapter 2). Ponderosa pine dominates (by height and basal area) or is present in the overstory of most of the sampled plots (96% of plots). The remaining plots are dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) or grand fir (*Abies grandis* (Doug.) Lindl.). Creeping Oregon grape (*Berberis repens* Lindl.), snowberry (*Symphoricarpos albus* (L.) Blake), birchleaf spiraea (*Spiraea betulifolia* (Pall.) var. *lucida* (Dougl.) C.L. Hitchc.), serviceberry (*Amelanchier alnifolia* (L.)), pinegrass (*Calamagrostis rubescens* Buckl.), elk sedge (*Carex geyeri* Boott), yarrow (*Achillea millefolium* var. *lanulosa* Piper),

western hawkweed (*Hieracium albertinum* Farr) and heartleaf arnica (*Arnica cordifolia* Hook.) occur in many of the sampled plots.

Historical fire regimes have been reconstructed in four watersheds in the Malheur, Wallowa-Whitman and Umatilla National Forests (Figure 14, Chapter 2). The northern watersheds, Tucannon and Imnaha, are east-west trending river canyons embedded in complex landforms (Figure 23 and 24). Most ponderosa-pine dominated forests at these watersheds are on southerly slopes. Elevations at Tucannon range from 1000-1800 m and slopes are dissected and steep (average slope at sampled plots: 47%). Elevations are similar at Imnaha (1300-1900 m), but slopes are more gentle (28%) and less dissected. In the southern Blue Mountains, Baker lies on the northeastern face of the Elkhorn Mountains, with slopes averaging 40% (Figure 25). Ponderosa-pine dominated forests are found on all aspects at this site but are limited to 1250 to 1700 m. The Dugout watershed lies in an area of gentle landforms straddling the North Fork of the Malheur River in the southern Blue Mountains, and has the smallest range in elevation (1400-1800 m) and the gentlest slopes (16%) of the four watersheds (Figure 26). Ponderosa pine-dominated forests occur on all aspects and elevations at Dugout.

METHODS

Fire and climate records

Fire extent and occurrence

Annual fire extent, the total area burned each year, was reconstructed from fire-scarred trees in the four sampled watersheds (1687-1994, Chapter 2). An approximately 600 ha grid of ≈25 plots was sampled at Tucannon, Imnaha and Baker. The number of plots and size of the sampling area were approximately twice this at Dugout. Because many of the reconstructed fires intersected the boundary of the grids (82%), an additional 10 to 19 plots per watershed were located at a lower density outside the grid at each watershed to reconstruct the extent of large fires. This increased the size of the sampling areas to 2002-8585 ha with a minimum of one plot per 370 ha. Fire-scarred sections were

removed from 524 ponderosa pine trees, from which 3659 fire scars were dendrochronologically dated to the correct calendar year (Stokes and Smiley 1968, Yamaguchi 1991). Fires occurred during 121 separate calendar years (32 to 65 years per watershed). Annual fire extent for each watershed was estimated on maps by assuming that fire boundaries lay halfway between sampled plots with and without evidence of fire for a given year.

To identify potential trends in each watershed, the time series of fire extent was examined for conformance to the properties of a stationary random sequence, white noise, using its autocorrelation function (Diggle 1990). The portmanteau Q-statistic was computed from autocorrelation coefficients for 15 lags of the time series of fire extent. This statistic was used because it accounts for the possibility that in computing a large number of autocorrelation coefficients, some may be significant even when the time series is in fact a white noise sequence. Because of an obvious change in fire extent at each watershed in the late 1800s, during a period of changing land use in the Blue Mountains (Figure 15, Schwantes 1989, Irwin et al. 1994, Robbins and Wolf 1994, Langston 1995), the Q-statistic was computed only for the period 1687-1900. This statistic is distributed approximately as chi-squared with the degrees of freedom equal to the number of lags computed. The null hypothesis that the time series is a white noise sequence, was rejected with significance level α=0.05 when the Q-statistic was greater than 25.00.

Climate

Reconstructed climate. An existing index of the seasonal strength and phase of the Southern Oscillation (SOI), computed as the difference in normalized monthly surface pressure between Tahiti and Darwin, Australia, has been reconstructed from a network of 65 tree-ring chronologies in western North America (1600-1963, Lough and Fritts 1985). Low values of SOI correspond to the warm phase of the Southern Oscillation, typically El Niño years. The reconstruction explains 49% of the variance in western North American SOI during winter (December-February) and 52% in spring (March-May, 1908-1963).

The portmanteau Q-statistic was computed for 15 lags of the autocorrelation function for SOI during both seasons (1705-1963).

Annual precipitation (previous October to current September) has been reconstructed for the Blue Mountains region from a network of 13 tree-ring chronologies in the Pacific Northwest, three of which are in the southern Blue Mountains (Garfin and Hughes 1996). This reconstruction (1705-1979) explains 37% of the variance in modern precipitation (Oregon climate division 8, 1931-1979). The portmanteau Q-statistic was computed for 15 lags of the autocorrelation function (1705-1979).

Modern climate. The instrumental record of modern climate was examined to determine the ways in which tree-ring reconstructions of annual precipitation are related to parameters of climate that are likely to influence fire. In particular, annual records of precipitation potentially contain information about variation in precipitation during the fire season and about snow-cover duration. Precipitation during the fire season (July-September) affects fuel moisture directly while snow-cover duration (fall to late spring/early summer) influences the number of days each summer during which fuels are conducive to fire ignition and spread. To assess how well annual precipitation reflects variation in these climatic parameters that can affect fire, annual precipitation for the Blue Mountains region was correlated with (i) summer precipitation for the region and (ii) snow-cover duration at 12 snow-telemetry sites across the region (Figure 14). Annual (previous October-current September) and summer (fire season: July-September, Agee 1993) precipitation were computed as sums of monthly values for the Blue Mountains (Oregon climate division 8, 1895-1988 with no missing data, EarthInfo 1990). The elevation of the snow-telemetry stations is similar to that of the watersheds from which fire extent was reconstructed (1500-1675 m versus 1470-1731 m, respectively; Figure 14; NRSC 1997). Daily snow cover is available from 1979 or 1981 to 1996, with few missing years (Table 4).

The instrumental record of modern climate was also examined to assess whether the tree-ring reconstruction of regional precipitation available to this study is representative of local climate at the watersheds in which fire regimes were reconstructed. Modern

precipitation (1949-1979) at each of the 14 weather stations was correlated with regional precipitation, both reconstructed and modern (Spearman rank correlation, Oregon climate division 8). The effects of the Southern Oscillation on the climate of the Blue Mountains has been explored elsewhere (Redmond and Koch 1991, Cayan and Webb 1992) and is described above (see Study area).

Relationship between fire and climate

The relationship between fire and climate records was examined at two spatial scales: local (within watersheds) and regional (among watersheds). Locally, fire extent was compared to climate (precipitation or SOI) at both annual and decadal time scales. Regionally, the annual synchrony of fire occurrence among watersheds was assessed to identify the potential effects of regional-scale influences such as climate.

Local

The relationship between reconstructed climate (regional precipitation or SOI) and fire extent was examined using cross-correlation and superposed epoch analysis (SEA, Haurwitz and Brier 1981, Grissino-Mayer 1995, Prager and Hoenig 1989, 1992). Cross-correlation was used to assess the strength of the linear relationship between climate and fire extent for concurrent and lagged years (±5 years, 1705-1900). If these two series are linearly related, changes in climate would be associated with proportional changes in fire extent. However, the relationship between fire and climate is probably nonlinear for several reasons. First, fires will not burn (fire extent will be zero) if fuel moisture is above the moisture of extinction (typically 12 to 40% of dry weight; Albini 1976), so that if additional precipitation increases fuel moisture above this level, fire extent cannot be reduced proportionally. Second, precipitation is not the only aspect of weather that influences fire extent. For example, a larger area may burn on windy than calm days during years with similarly low annual precipitation or lightning storms may not occur during a years of low annual precipitation. Lastly, a methodological constraint may affect the relationship between fire extent and climate. In all sampled watersheds, the full extent

of many fires was probably not reconstructed, so that the area burned was likely underestimated for most fire years (Chapter 2).

To identify possible nonlinear associations, SEA was used to examine the relationship between climate and fire (Haurwitz and Brier 1981, Grissino-Mayer 1995). Four null hypotheses were tested at each watershed: there is no association between climate and key-event years, where climate is either reconstructed precipitation or reconstructed SOI and key-event years are either fire years (years with annual extents ≥370 ha) or non-fire years (years with annual extents 0-370 ha). An extent of 370 ha (4-19% of sampling areas) was used to distinguish between fire and non-fire years because fires smaller than this could not be detected in all portions of each watershed under the sampling scheme used for this study. Because fire years are defined by this minimum extent, the results are comparable among watersheds with different-sized sampling areas and should not be strongly affected by inaccuracies in maximum fire extent. For each watershed, windows of time (11-year epochs) were identified. These epochs were centered around years during which key events occurred (fire or non-fire years) and included adjacent background years (±5 years from key-event years). The difference between climate during key-event years and average climate during the corresponding 11-year epoch was then averaged for all key-event years. In order to eliminate the requirements for random sampling, normality, homogeneity of variance and independence of observations, statistical significance was determined by bootstrapping (Haurwitz and Brier 1981, Prager and Hoenig 1989). This was achieved by 1000 trials of randomly selecting the same number of 11-year epochs as were present in the time series of interest (fire years or non-fire years), and computing the average difference between climate during the key-event year and its adjacent background years, using normal approximation and percentile-and-rank methods (Haurwitz and Brier 1981, Mooney and Duval 1993, Grissino-Mayer 1995). The null hypothesis was rejected if the average difference between climate during key-event years and its adjacent background years was outside confidence intervals (99%) identified from the bootstrapped null distribution.

Longer-term relationships between fire and climate were examined visually by smoothing the raw series of fire extent at each watershed, regional precipitation and SOI. To emphasize decadal variations, each time series was smoothed using cubic splines that retain 50% of the variance present in the original series at periods of 20 years (Cook and Peters 1981, Diggle 1990).

Regional

To identify regional patterns of fire occurrence, the significance of annual synchrony between all possible pairs of watersheds was evaluated for both fire and non-fire years using contingency tables and for fire years only using the Ochiai index, a measure of similarity used in ecology (Hubalek 1982, Grissino-Mayer 1995). Contingency tables tested the null hypothesis that fire years (≥370 ha in extent) and non-fire years (0-370 ha) were independent between all pairs of watersheds ($\alpha<0.01$, Swetnam 1993b, Grissino-Mayer 1995). The four cells of each 2x2 table contained the number of fire or non-fire years for the two watersheds being compared and a chi-squared statistic was computed from the expected joint probabilities of the table. The Ochiai index was computed using only fire years and was transformed to lie between 0 and 1 (Hubalek 1982, Grissino-Mayer 1995). Values greater than 0.5 indicate more synchronous than nonsynchronous years while values less than 0.5 indicate the reverse.

RESULTS

Fire and climate records

Fire extent and occurrence

Prior to ≈1900, fire extent was stationary in all of the sampled watersheds ($Q>9.03$, 1687-1900, Figure 15). In each watershed, extent varied about a constant mean (Tucannon=59 ha, Imnaha=66 ha, Baker=253 ha, Dugout=623 ha; 3-7% of the sampled areas). Beginning in the late 1800s, the occurrence and extent of fires decreased dramatically at every sampled watershed. Only 7 small fires (4% of total fire years)

burned during the last third of the period of record (1900-1994). This decline occurred several decades earlier in the southern watersheds (Baker and Dugout) than in the northern watersheds (Tucannon and Imnaha). However, at Baker this early decline may be an artifact of an eroding tree-ring record, because record at this watershed was found on old stumps that have lost outer rings and scars to decay or fire.

Climate

Annual precipitation reconstructed for the Blue Mountains region was stationary with a constant mean of 452 mm (Q=20.00, Figure 16). Reconstructed winter and spring SOI are also stationary (Q=13.02, 6.20, respectively) with constant means of 0.02 and 0.04, respectively (Figure 17).

In modern instrumental records, annual precipitation is significantly correlated ($p<0.05$) with summer precipitation in the Blue Mountains region ($r=0.48$) and with snow-cover duration at most (75%) stations ($r=0.53$ to 0.74). Neither precipitation (annual or summer) nor snow-cover duration are significantly correlated with station elevation ($p=0.28$, 0.96 and 0.14, respectively).

Modern precipitation for the Blue Mountains region was significantly correlated with local precipitation at 13 of the 14 weather stations in that region (Figure 18), but reconstructed regional precipitation was significantly correlated with local precipitation at only the 7 weather stations in the southern Blue Mountains (south of latitude ≈44.85°N, $p<0.01$).

Relationship between fire and climate

Local

As expected, the linear relationship between climate and fire extent was weak. At the southern watersheds (Baker and Dugout), reconstructed regional precipitation and fire extent were significantly ($p<0.01$), but not highly, correlated during concurrent years but not during lagged years ($r=-0.19$ and -0.25, respectively). In contrast, at the northern watersheds (Tucannon and Imnaha), precipitation was not significantly correlated with fire

extent for either concurrent or lagged years. Furthermore, reconstructed SOI (spring or fall) and fire extent were not significantly correlated during concurrent or lagged years at any of the sampled watersheds ($p>0.01$).

The nonlinear relationship between fire and precipitation was different in the southern versus the northern watersheds. To the south (Baker and Dugout), reconstructed precipitation was significantly low during fire years, and high during non-fire years, compared to precipitation during adjacent background years ($p<0.01$, Figure 19c, d). In contrast, to the north (Tucannon and Imnaha), reconstructed precipitation during either fire or non-fire years was not significantly different from that during adjacent background years (Figure 19a, b).

The nonlinear relationship between fire and SOI was also different in the southern versus the northern watersheds. To the north (Tucannon), reconstructed winter SOI was significantly low during fire years, and significantly high during non-fire years, as compared to SOI during adjacent background years ($p<0.01$). Similarly, reconstructed spring SOI was significantly lower during fire years at Tucannon and also at Imnaha, and higher during non-fire years at Tucannon, than during adjacent background years (Figure 20a, b). In contrast, to the south (Baker and Dugout), neither winter (not shown) nor spring reconstructed SOI were different from adjacent background years during either fire or non-fire years at either watershed (Figure 20c, d). These results indicate that fires tended to occur during El Niño years at the northern watersheds but not at the southern ones.

The degree of similarity between decadal fluctuations in fire extent and precipitation differed among watersheds. Decadal variations in the smoothed series of regional precipitation and fire extent are strikingly consistent and opposite in sign from the beginning of the period of record until the late 1800s at Dugout (Figure 21). Similarly, these fluctuations are consistent from the mid-1700s to the mid-1800s at Baker and Imnaha. The series are much less consistent at Tucannon. Decadal variations in either winter or spring SOI and fire extent were not consistent at any of the watersheds (not shown).

Regional

Fire and non-fire years were independent between all pairs of watersheds, with the exception of Baker with Tucannon and Imnaha (Table 5). This general lack of synchrony is corroborated by low values of the Ochiai index (<0.5 for all watershed pairs), indicating that there were more nonsynchronous than synchronous fire years (Table 5). Fires burned at least 370 ha in all four watersheds during only one year (1869), and in three of the four watersheds during only 2 years (1751 and 1783).

DISCUSSION

What was the historical relationship between fire and climate?

To detect past relationships between climate and fire, proxy records of climate must be representative of the area within which fire regimes are reconstructed. Comparisons between modern precipitation for the Blue Mountains region and local precipitation at weather stations indicated that the tree-ring reconstruction of precipitation used in this study more strongly reflects variation to the south than the north (Figure 18). Thus, while the precipitation reconstruction used in this study is adequate for examining fire-climate relationships in the southern watersheds, it is probably not sufficiently representative of precipitation variation in the north to allow detection of such relationships in that area. In contrast, fluctuations in the Southern Oscillation have a greater influence on the climate of the northern Blue Mountains (Cayan and Webb 1992) so that the reconstructions of SOI are expected to be related to fire regimes in the north more strongly than in the south.

Local

Annual time scale. Reconstructed precipitation tended to be low during fire years in the southern watersheds, Baker and Dugout (Figure 19). This relationship could be the result of either lower precipitation during the fire season or shorter snow-cover duration, or a combination of both these factors. The effects of fluctuations in these climate parameters has been discussed above (see Modern climate). SOI tended to be low (El Niño years) during fire years at the northern watersheds. In the north, snow cover and

SOI are positively correlated so that snow cover tends to be low during years of low SOI (Cayan and Webb 1992). This is probably because winter temperature is higher than average and winter precipitation is sometimes lower (October to March, Redmond and Koch 1991). Shallow snow covers are likely to ablate earlier, resulting in longer fire seasons which have more days during which all the conditions necessary for fire may occur simultaneously. Alternatively, or additionally, fire extent may have been greater because relatively long fire seasons may have allowed fires to burn for a greater number of days during years of low SOI than during other years.

The climate of the southwestern United States is also affected by fluctuations in the Southern Oscillation (Redmond and Koch 1991, Cayan and Webb 1992). However, these fluctuations have an opposite effect on fire occurrence in this region as compared to the Pacific Northwest. During the low phase of the Southern Oscillation, winter temperature is above average in the Pacific Northwest and winter precipitation is sometimes below average, while the Southwest receives *more* precipitation during such years (Redmond and Koch 1991, Cayan and Webb 1992). These differences in the effect of the Southern Oscillation on the climate of the northwestern versus southwestern United States is reflected in the occurrence of historical fires in these two regions. Of the 24 fire years (extents ≥370 ha) in the northern Blue Mountains (1700-1900), only 1 was a large fire year in the southwestern United States (Swetnam and Baisan 1996). Conversely, of the 20 years during which the most sites experienced fire across Arizona and New Mexico, only 1 was a large fire year in the northern Blue Mountains.

Fire extent in all four watersheds was more strongly influenced by climate (either regional precipitation or SOI) during the fire year than by climate during preceding years (Figure 19 and 20). These results are likely because winter conditions replenish soil and fuel moisture each year. The watersheds are relatively high in elevation (1470-1731 m) and covered by snow each winter. The melting of this snow cover in spring increases soil and fuel moistures at the beginning of every fire season, so that precipitation during preceding years has little effect on the potential for fire during the current year.

Decadal time scale. Given the lack of lagged relationships between climate and fire on annual time scales (Figure 19 and 20), the decadal consistency between fire and regional precipitation at Dugout (1687 to ≈1900), and during some time periods at Baker and Imnaha (mid-1700s to mid-1800s), does not reflect the cumulative effect of multiple years of low or high precipitation. Rather it probably reflects the fact that low precipitation over the Blue Mountains (leading to low fuel moisture and relative humidity) is a necessary but not sufficient condition for fire occurrence and spread. In the Blue Mountains, as elsewhere, an ignition source and adequate fuel with a low moisture content are also necessary (Rothermel 1983). Consequently, fires cannot occur at a given watershed when any of these conditions are lacking, even during years that are generally dry throughout the region. This lack of fire during some dry years is evident at Baker (e.g., 1756, 1787, 1856, 1880 and 1889; Figure 22). In addition, precipitation and lightning strikes do not occur uniformly across the Blue Mountains during the fire season because they derive from convective storms (Morris 1934, Krider et al. 1980, Mock 1996), so that some watersheds may receive more precipitation and/or lightning strikes than others during a given year. The high fuel moisture and relative humidity resulting from summer storms in some watersheds may have prevented fires from starting or spreading into them despite generally low annual precipitation across the region. Similarly, convective storms may ignite fires in some watersheds but not others during these regionally dry years. In a given watershed, there is a low probability of satisfying all the conditions necessary for fire in a single year. However, when multi-year periods of low average regional precipitation are considered, the probability of satisfying the necessary conditions during one of those years increases. Consequently, fluctuations in fire and climate are consistent at decadal scales.

Regional

Historically, fires rarely burned in more than one of the sampled watersheds during the same year in the Blue Mountains (Table 5), despite regional fire years in the archival record (e.g., 1910; Plummer 1912). These results are consistent with a previous study of fire history at 15 sites (≈ 2 ha each) in the Blue Mountains. Although fires occurred at 3

or more sites during 7 years between 1800 and 1900, the majority of fire years occurred at single sites (35 fire years; samples crossdated from Maruoka 1994). This lack of annual synchrony implies that regional-scale fluctuations in climate were not the strongest control of past fire regimes in the Blue Mountains. Although low precipitation may have resulted in low fuel moisture across the region as a whole, the patchy occurrence of convective storms resulted in similar patchiness in summer precipitation and lightning strikes, limiting the occurrence and/or spread of fires in individual watersheds as described above. In addition to patchiness in ignition and fuel condition, the lack of synchrony in past fire occurrence across the region may have been due to a lack of synchrony in annual and/or summer precipitation across the Blue Mountains. This lack of synchrony is likely because the climate of this region is influenced by three separate air masses (Mitchell 1976, Mock 1996, Ferguson 1997) so that during a given year, the weather of different portions of this area could be dominated by different air masses.

In contrast to the lack of annually synchronous fires in the Blue Mountains, historical fires were often synchronous across a broad region of the southwestern United States (Swetnam and Baisan 1996). More frequent ignition of fires by lightning in the Southwest than the Pacific Northwest is one possible explanation for the differences observed in synchrony within these two regions. Arizona and New Mexico experience many more thunderstorms than the Pacific Northwest (20-90 *vs.* 10-30 annually; 1948-1977; Changery 1981), resulting in a higher frequency of cloud-to-ground lightning flashes that could ignite fires (1-5 versus <0.5 flashes/km^2, respectively; 1989-1995; Orville 1994, Orville and Silver 1997). The higher lightning flash densities in the Southwest probably result in a higher probability that fires would ignite simultaneously across a region.

Did non-climatic factors influence fire?

The abrupt decrease in annual fire extent in all watersheds during the late 1800s indicates that climate no longer drives temporal variation in fire extent as it did before 1900 (Figure 21). This dramatic change was probably caused by a shift in both the human and non-human factors controlling fire. The initial abrupt decline in fire coincided with the

wettest period in the 275 year reconstruction of precipitation (mid-1880s-1910s, Figure 16 and 21). Fuel moisture was probably higher during this period than during other periods, inhibiting the ignition and/or spread of fires as high precipitation did during other periods (e.g., early 1800s). However, fire extent did not increase at the end of this wet period when precipitation dropped to its lowest values during the period of record (≈1920s). This unexpected absence of fire was probably not due to fire suppression by federal land-management agencies because efforts to extinguish fires were not effective until the 1940s-1950s (Pyne 1982). Declines in fire occurrence have been attributed to reduction of herbaceous fuel by domestic livestock grazing in the southwestern United States (Madany and West 1983, Savage and Swetnam 1990, Savage 1991, Touchan et al. 1995). Woody fuel comprises a greater proportion of the total fuel load and herbaceous fuel less so in grazed versus nearby ungrazed areas in the Pacific Northwest (Rummel 1951, Zimmerman and Neuenschwander 1984). Because herbaceous fuels carry some low-severity fires in some forest types, these changes in fuel suggest that grazing may reduce the potential for such fires. In the Blue Mountains, Euroamerican settlers increased the number of domestic grazing animals eight- to ten-fold in the 1870s and 1880s and the number of these animals remained at these levels into the mid-twentieth century (Irwin et al. 1994). Consequently, reduced herbaceous fuel loads in the study areas may also have persisted well into the twentieth century, lowering the potential for fire occurrence and/or spread during the dry years of the 1920s-1930s. After this time, fire exclusion undoubtedly became the primary cause of low fire occurrence and spread.

As in the past, fires still burn during years of low precipitation. However, changes in forest structure and composition during the last ≈100 years of low fire occurrence have dramatically increased both vertical and horizontal fuel loads in the ponderosa pine-dominated forests of the Blue Mountains. Many stands in the Blue Mountains and throughout the interior West that historically were composed of large, widely-spaced ponderosa pine now have dense understories of shade-tolerant species such as grand fir and Douglas-fir (Weaver 1959, 1961, Cooper 1960, Mutch et al. 1993, Covington and

Moore 1994). The ladder fuels provided by these understory trees result in high-severity fires in stands that have survived many low-severity fires over the past few hundred years (Agee 1997).

Implications for the future

The atmospheric concentration of greenhouse gases is predicted to double over historical levels within the next 50 to 100 years (Houghton et al. 1996). Although the climate of the Blue Mountains is expected to change under such an atmosphere, predictions for areas this size are not considered reliable because they are below the spatial resolution of general circulation models and because the influence of complex regional-scale topography, such as that of the Blue Mountains, has not been fully modeled (Houghton et al. 1996, Ferguson 1997). Despite this uncertainty in predicted climate, understanding past fire-climate relationships allows us to identify those parameters of climate that are likely to affect future fire regimes if they were to change in the future. For example, under a $2xCO_2$ climate, snow-cover duration in the Blue Mountains and elsewhere is predicted to decrease due to increases in winter and spring temperature (Karl et al. 1993, Brown et al. 1995). Changes in the frequency, intensity or effects of fluctuations in the Southern Oscillation could further impact the duration of snow cover in the northern Blue Mountains. Snow cover duration appears to have been an important control of fire recurrence in the northern Blue Mountains, so that if durations are shorter and summers continue to be dry, fire seasons will be longer and the potential for larger and/or more frequent fires could increase. Historically, climate in preceding years did not affect fire during the current year because fuel moisture was moderated by melting snow at the beginning of each fire season. Consequently, a change in the duration of snow cover could change the relationship between fire and climate if the watersheds, or portions of them, are no longer covered by snow every winter. In this case, lagged relationships in climate might become important in that below-average precipitation in a single year, or over a period of years, could increase the potential for fire in a subsequent year.

A doubling of CO_2 is also predicted to affect the density of lightning strikes across the globe which could also affect future fire regimes in the Blue Mountains. The proportion of cloud-to-ground lightning is predicted to increase for extra-tropical thunderstorms while its seasonality remains the same (Price and Rind 1994). If the density of summer lightning strikes increases across the Blue Mountains and the incidence of summer conditions conducive to fire occurrence and spread remains constant or increases, the potential for synchronous fires across the region could also increase, especially in light of the continuous fuels now present in many forests (Swetnam 1993b).

Past climate clearly influenced historical fire regimes in the Blue Mountains, indicating that future climate has the potential to do so as well. Even if predictions of regional climate change were currently reliable, the exact nature of changes in fire regimes is not easy to predict from the past because forest composition, structure and fuel loads have changed dramatically since the late 1800s. As a result of such uncertainties, predicting actual fire regimes for these forests remains one of the major challenges to predicting future forest conditions under an altered climate.

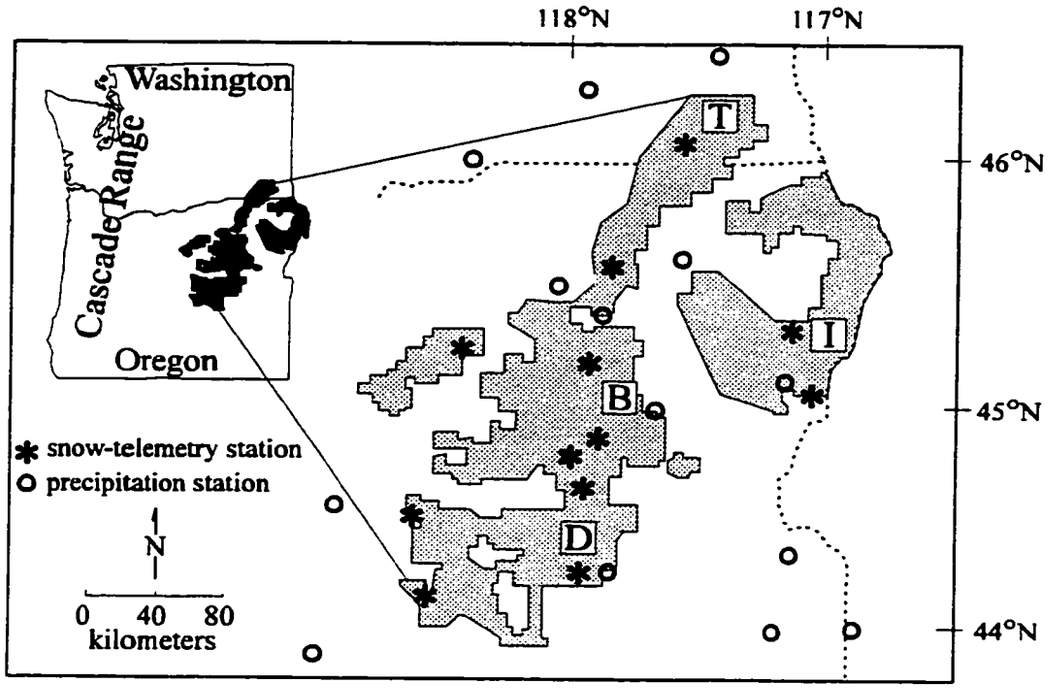

Figure 14. The Blue Mountains of Oregon and Washington, showing the location of the four watersheds in which fire extent was reconstructed (T = Tucannon, I = Imnaha, B = Baker, D = Dugout); the 14 stations with modern precipitation records and the 12 stations with modern snow cover records. Shaded regions indicate land managed by the U.S. Forest Service.

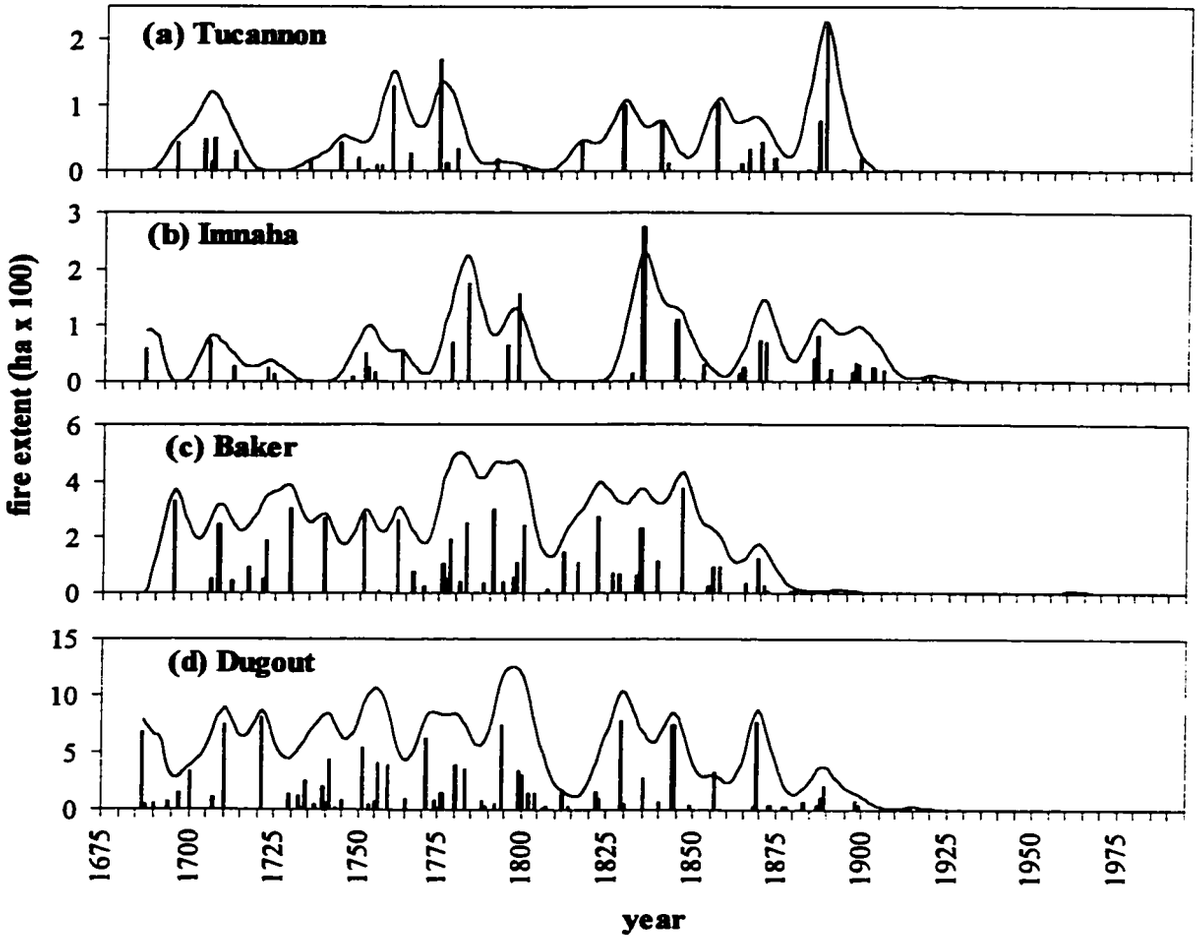

Figure 15. Annual fire extent by watershed. Both raw and smoothed time series are shown (cubic spline with 50% frequency cutoff at 20 years).

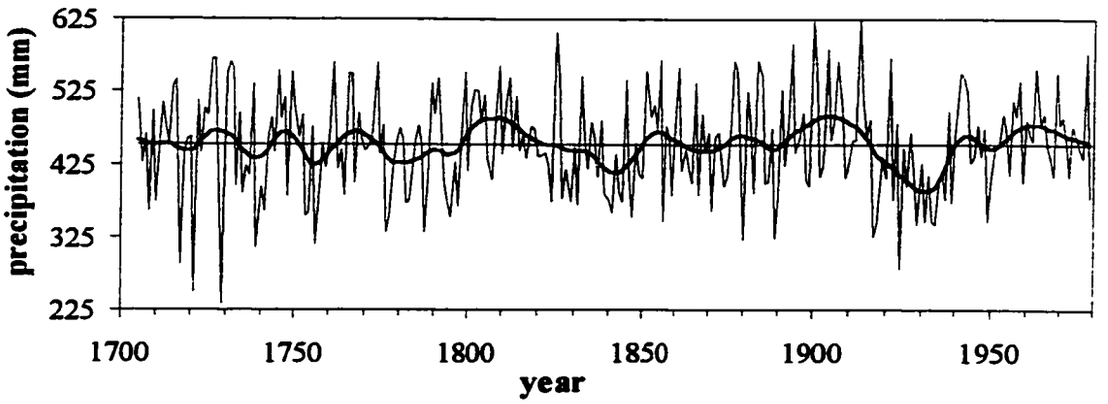

Figure 16. Annual precipitation (previous October to current September), reconstructed from tree rings in the Blue Mountains (from Garfin and Hughes 1996). Both raw and smoothed time series are shown (cubic spline with 50% frequency cutoff at 20 years).

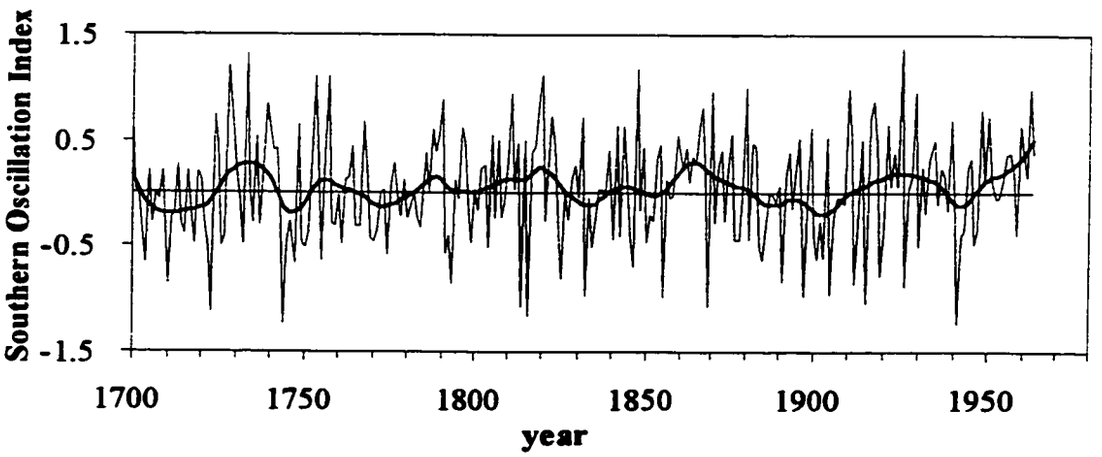

Figure 17. Southern Oscillation Index (spring: March to May), reconstructed from tree rings in western North America (from Lough and Fritts 1985). Both raw and smoothed time series are shown (cubic spline with 50% frequency cutoff at 20 years).

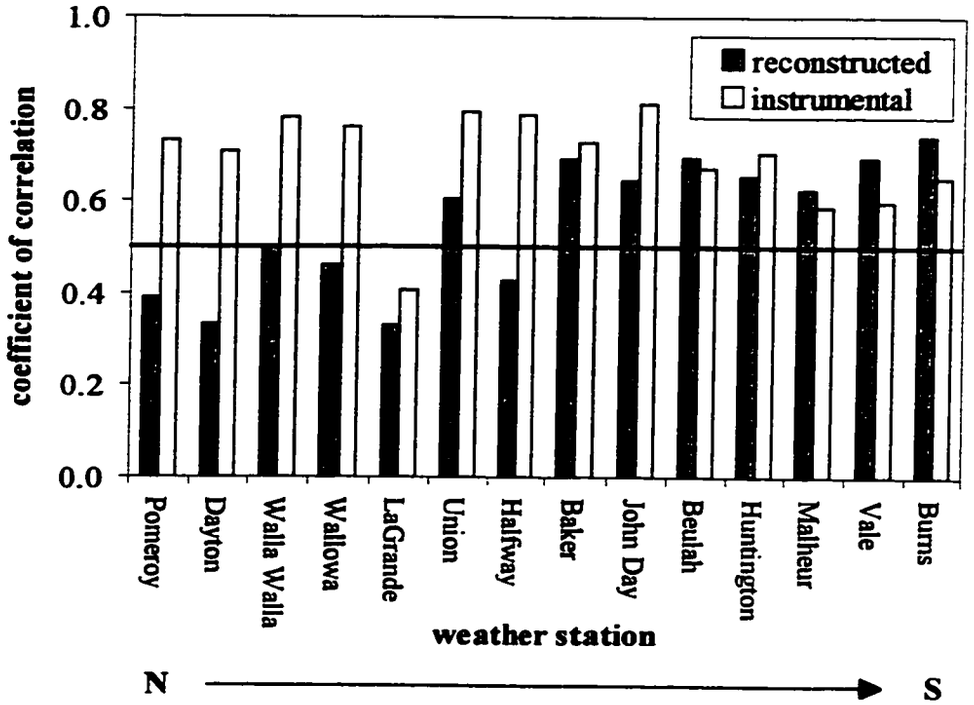

Figure 18. Coefficients of non-parametric (Spearman rank) correlation of modern precipitation at weather stations in the Blue Mountains with modern *precipitation in Oregon climate division 8 and precipitation* reconstructed *for the same climate division (1949-1979). Coefficients greater than ≈0.50 (indicated as heavy line) are significant ($p<0.01$).*

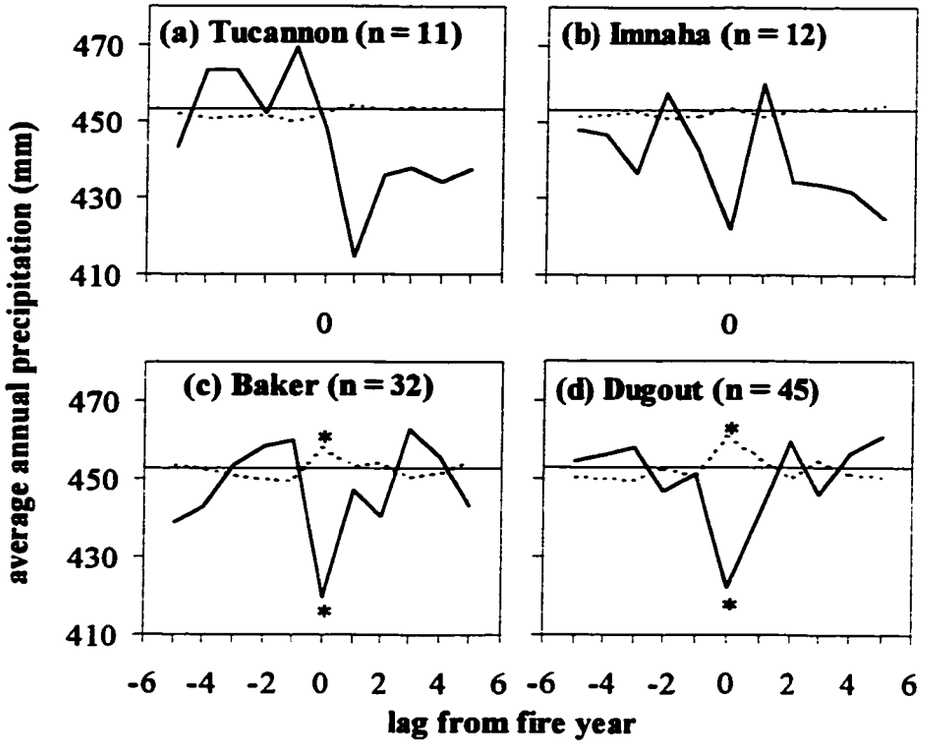

Figure 19. Average reconstructed annual precipitation during years with fire extent ≥370 ha (solid line, number of years in parentheses) and years with fire extent 0-370 ha (dashed line) and for years before and after these years. Stars mark lags for which the average precipitation is significantly different from the mean for the period of analysis (1705-1900, $p<0.01$). Horizontal line indicates annual precipitation averaged over 1705-1900.

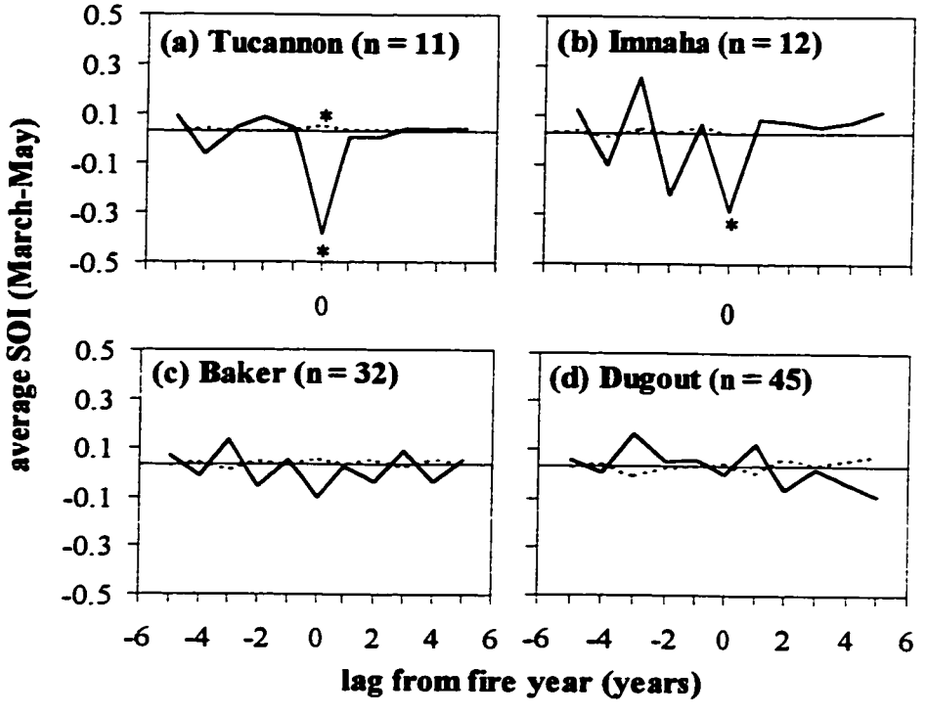

Figure 20. Average reconstructed spring Southern Oscillation Index (March through May) during years with fire extent ≥370 ha (solid line, number of years in parentheses) and years with fire extent 0-370 ha (dashed line) and for years before and after these years. Stars mark lags for which the average index is significantly different from the mean for the period of analysis (1705-1900; $p<0.01$). Horizontal line indicates average SOI from 1705-1900. The index tends to be negative during El Niño years.

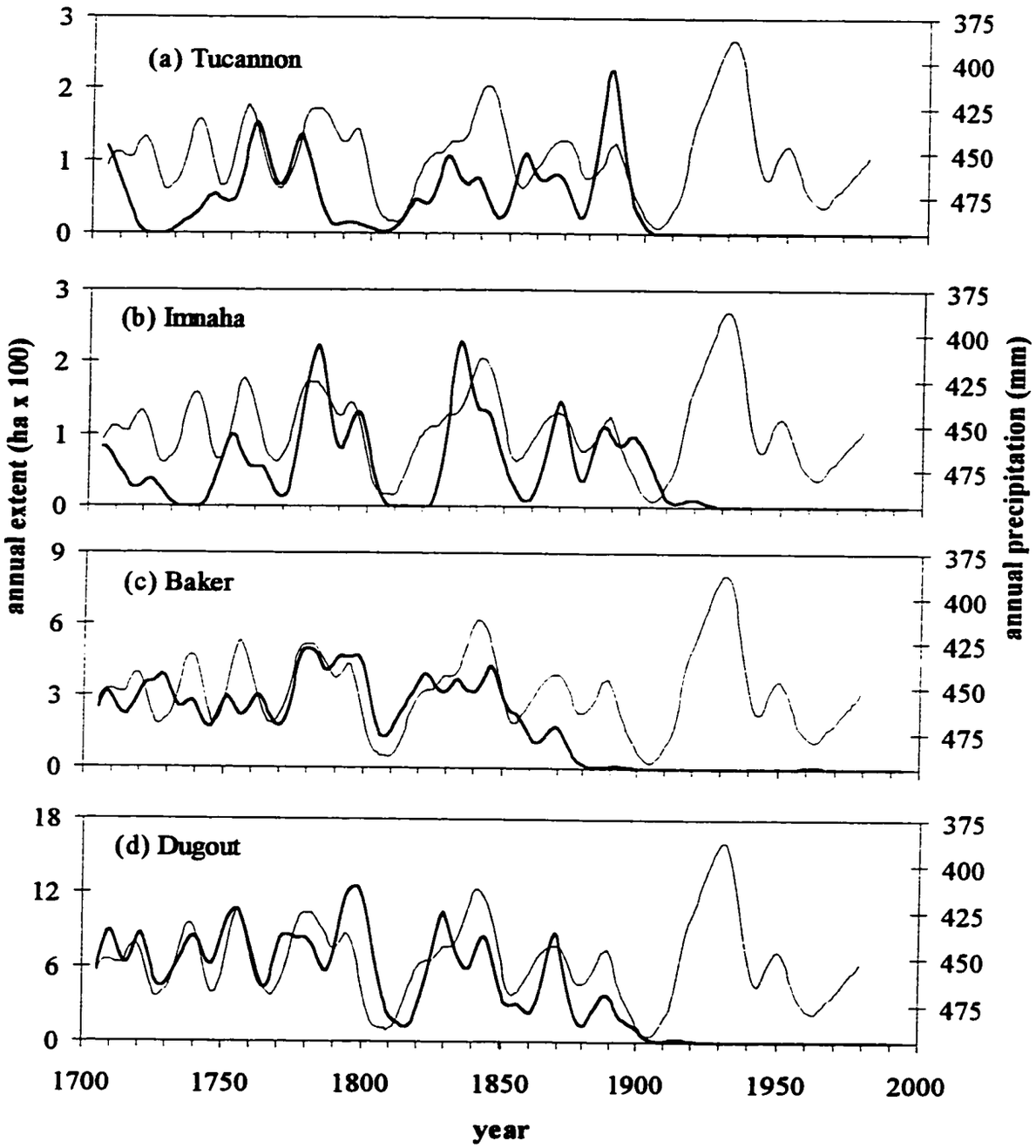

Figure 21. Decadal fluctuations in fire exent and precipitation. Fire extent (heavy line) and annual precipitation (light line), smoothed with cubic splines (50% frequency cutoff at 20 years). The precipitation axis is inverted.

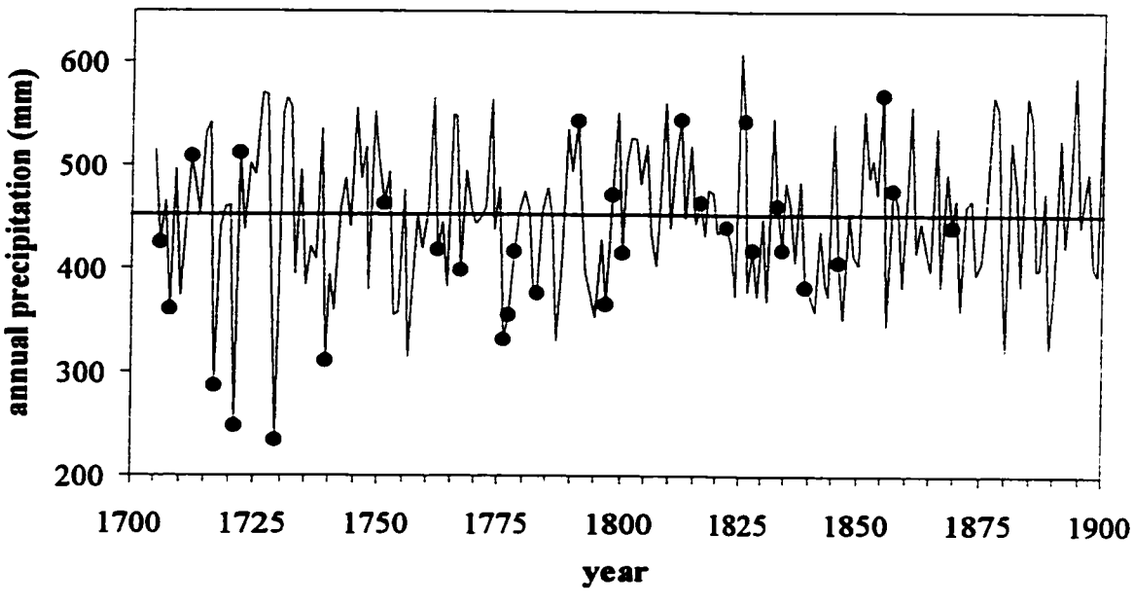

Figure 22. Annual precipitation reconstructed from tree rings for the Blue Mountains region (from Garfin and Hughes 1996). Dots indicate years during which fires >370 ha in extent burned at Baker.

Table 4. Precipitation and snow-telemetry stations (location, elevation, period of record and number of years without data) used for this study.

Station	Latitude (°N)	Longitude (°W)	Elevation (m)	Period of record	Number of missing years
Precipitation stations:					
Pomeroy	46.50	-117.63	576	1920-1992	21
Dayton	46.33	-117.95	476	1920-1995	4
Walla Walla	46.05	-118.33	357	1940-1990	22
Wallowa	45.57	-117.53	890	1903-1996	18
LaGrande	45.32	-118.08	841	1900-1996	20
Union	45.22	-117.88	845	1912-1996	6
Halfway	44.88	-117.12	814	1941-1996	17
Baker City	44.83	-117.82	1027	1943-1994	1
John Day	44.43	-118.95	933	1953-1996	10
Huntington	44.35	-117.25	643	1910-1996	28
Malheur	43.98	-117.03	689	1942-1996	6
Vale	43.98	-117.25	683	1910-1996	26
Beulah	43.93	-118.17	997	1939-1996	14
Burns	43.58	-118.95	1262	1910-1994	10
Snow-telemetry stations:					
Beaver Reservoir	45.08	-118.13	1570	1981-1996	0
Eilertson Meadows	44.51	-118.07	1646	1981-1996	0
Gold Center	44.46	-118.17	1628	1981-1996	0
High Ridge	45.41	-118.06	1518	1979-1996	1
Lake Creek Ranger Stn.	44.11	-118.36	1585	1979-1996	0
Lucky Strike	45.17	-118.51	1540	1979-1996	0
Rock Springs	44.00	-118.83	1555	1981-1996	0
Schneider Meadows	45.00	-117.09	1646	1981-1996	0
Starr Ridge	44.25	-119.02	1616	1981-1996	0
Tipton	44.40	-118.22	1570	1981-1996	0
Touchet	43.12	-117.85	1686	1981-1996	3

Table 5. Synchroneity of fire (≥370 ha) and non-fire (0-370 ha) years between all pairs of watersheds (1687-1900). There were 13 fire years at Tucannon, 14 at Imnaha, 32 at Baker and 51 at Dugout. Starred values indicate that fire years were significantly synchronous ($p<0.01$). Values of the Ochiai index <0.5 indicate more asynchronous than synchronous years.

Watershed pair		No. of synchronous years	χ^2	Ochiai index
Tucannon	Imnaha	2	0.57	0.15
Tucannon	Baker	7	16.46*	0.34
Tucannon	Dugout	4	0.37	0.16
Imnaha	Baker	6	9.17*	0.28
Imnaha	Dugout	5	1.17	0.19
Baker	Dugout	10	1.14	0.25

CHAPTER 4: IMPLICATIONS FOR MANAGEMENT AND FUTURE RESEARCH

The spatially-explicit, multi-scale sampling design used in this study, coupled with annual accuracy in reconstructing low-severity fire regimes, permitted a demonstration that climate influenced both spatial and temporal variation in historical fire regimes in the Blue Mountains. The understanding of fire-climate relationships provided by this study has several implications for fire management and future research in the Blue Mountains and elsewhere in the interior West:

Management implications

- Reconstructions of historical fire regimes are useful for ecosystem management because they can serve both as benchmarks against which current forest conditions can be compared and as goals for the restoration of fire (Fulé et al. 1997). As a benchmark, the history of fire regimes that I reconstructed in the Blue Mountains clearly shows that fires that were once frequent, even in mesic forests, have now largely been eliminated. However, within dry forests, the change is most dramatic in the southern Blue Mountains because fires were most frequent there historically. Consequently, restoration efforts might have the greatest impact in dry forests of the southern Blue Mountains.
- The reconstruction of fire seasonality in dry forests can be used in establishing goals for the restoration of fire to the Blue Mountains. These results demonstrate that there is some historical precedent for burning during the growing season in the southern but not the northern Blue Mountains (Figure 10). However, fuel loads have increased in the dry forests of the Blue Mountains due to fire exclusion so that early season burning may be more severe now than it was historically (e.g., Grier 1989).
- Historically, fires tended to occur during El Niño years in the northern Blue Mountains (Figure 20). Because there is a 3 to 5 month delay before fluctuations of the Southern Oscillation affect the climate of the Pacific Northwest, the potential for large fire years may be predictable in the northern Blue Mountains. This information might be useful

for allocating fire management resources, as proposed elsewhere in the western United States where fluctuations in El Niño/Southern Oscillation affect fire occurrence (Swetnam and Betancourt 1990).

- This study provides the first data on the distribution of historical fire extent in dry forests of the Pacific Northwest. Historically, fires in the Blue Mountains were large relative to modern fires (Figure 11). While it may not be feasible to prescribe single fires of such large extent due to the impact of smoke on human communities, this information provides a benchmark against which fire prescriptions can be measured. If the goal is to restore annual fire extents to their historical levels, such goals might be achieved by burning small, adjacent areas at different times during the year or over a period of several years.
- This study has demonstrated that even at regional scales, fire regimes vary within forest types in response to spatial variation in climate (Figure 9). Based on these results, plans to restore fire to dry forests across regions such as the Blue Mountains may need to consider the spatial scale at which the drivers of fire operate.
- Predictions of future fire regimes must be made using models that combine current forest structure with predications of future regional climate. The long-term fire-climate relationships developed by this study can be used to test retrodictions from these models and to provide guidance on which parameters of climate may influence fire regimes in the future. For example, fires tended to burn during El Niño years in the northern Blue Mountains so that changes in fire regimes in this area can be modeled as a response to changes in the frequency and/or intensity of fluctuations in the El Niño/Southern Oscillation. Also, fires did not occur during every dry year but rather fire occurrence was limited by ignition so that changes in fire regimes may be more accurately modeled as responses to changes in the frequency of lightning strikes than changes in the frequency of dry conditions. However, future fire regimes of the Blue Mountains cannot be predicted solely on the basis of past relationships between fire

and climate because forest composition and structure have changed dramatically over the last hundred years, especially in ponderosa pine dominated forests.

Future research implications

- Historical fire regimes in the Blue Mountains varied across a range of spatial scales in response to landform-driven variations in climate. Because the complex landforms elsewhere in the interior West cause climate to vary spatially, I assume that historical fire regimes were also spatially variable elsewhere. Consequently, future tree-ring reconstructions of fire regimes would benefit from clearly defining the spatial scale (or scales) of interest before the start of the study and also the relationship of the scale of interest to the drivers of fire. This may require pilot studies at different spatial scales. The scale of interest will depend on the potential uses of the reconstructed fire regimes. Will the reconstructions be used to restore fire to the sampled area only or will it be used to restore fire to a larger region?
- Dendrochronological techniques were critical to reconstructing fire recurrence and extent for low-severity fire regimes. Crossdating was essential for obtaining an adequate characterization of recurrence because not every fire scars every tree, especially where fires were frequent. Consequently, fire recurrence would have been underestimated for this study if I had computed it from simple ring and scar counts. Furthermore, without crossdating, when fires were frequent, annual fire extent could not be confidently reconstructed because scars cannot be confidently assigned to a single year. Thus, future reconstructions of fire regimes in dry forests should include dendrochronological techniques.
- Although this study elucidated important aspects of historical fire-climate relationships in the Blue Mountains, these relationships could be further clarified by improved tree-ring reconstructions of both climate and fire, particularly in the northern Blue Mountains. For example, the history of annual precipitation in the northern Blue Mountains is not well-characterized by existing tree-ring reconstructions because they were developed from tree-ring chronologies in the southern Blue Mountains. In

addition, reconstructed spring temperature, an important control of snow-cover duration, may allow a better understanding of temporal variation in fire extent in the northern Blue Mountains.

- Although the results presented here provide the first information that the extent of historical fires in dry forests of the Pacific Northwest were large compared to modern fires, the full extent of most fires reconstructed for this study was probably underestimated. This underestimation is probably greatest in the northern Blue Mountains where the study areas were small relative to those in the south. Future studies of fire extent would benefit from pilot studies that characterize the range of distributions in this parameter. In forests that historically experienced low- or moderate-severity fires, this information must come from field sampling because the structural legacy of these fires is not evident in aerial photographs. In addition to underestimating fire extents, this study did not reconstruct fire extents smaller than ≈25 ha. Consequently, to explore the historical importance of very small fires, fire extents should be reconstructed at small scales in some portions of each watershed.

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APPENDIX A: SAMPLING PLOT DESCRIPTIONS AND WATERSHED MAPS

Table 6. Sampling plot characteristics for ***Tucannon****. The abbreviations for plant association follow Johnson and Clausnitzer (1992).*

Plot ID	Elevation (m)	Aspect (deg.)	Slope (%)	Longitude (deg.)	Latitude (deg.)	Albers-x (m)	Albers-y (m)	Plant Association
1.5	1609	221	62	-117.596	46.195	654,034	577,396	PSME/CARU
1.6	1695	--	0	-117.586	46.196	654,806	577,502	PICO(ABLA2)/VAME
2.4	1436	185	58	-117.598	46.193	653,878	577,175	PSME/CARU
2.5	1417	70	66	-117.594	46.190	654,184	576,839	PSME/CARU
2.6	1500	273	37	-117.588	46.189	654,646	576,724	PSME/CARU
2.7	1692	--	0	-117.579	46.191	655,342	576,942	PICO(ABLA2)/VAME
3.3	1189	216	48	-117.604	46.187	653,411	576,511	ABGR/CARU
3.4	1189	165	62	-117.600	46.187	653,719	576,509	PSME/CARU
3.5	1304	165	33	-117.594	46.184	654,179	576,171	PSME/CARU
3.7	1820	230	49	-117.581	46.187	655,184	576,498	PSME/CARU
3.8	1512	225	64	-117.574	46.186	655,724	576,383	PSME/CARU
3.9	1731	--	0	-117.567	46.187	656,264	576,490	PICO(ABLA2)/CAGE
4.3	1189	340	35	-117.606	46.183	653,253	576,067	ABGR/TABR/LIBO2
4.4	1128	60	85	-117.601	46.183	653,639	576,064	ABGR/TABR/LIBO2
4.5	1161	305	62	-117.593	46.182	654,255	575,948	ABGR/CARU
4.6	1274	127	51	-117.586	46.182	654,795	575,944	PSME/CARU
4.7	1323	246	64	-117.582	46.182	655,103	575,942	PSME/CARU
4.8	1448	142	59	-117.574	46.184	655,722	576,160	PSME/CARU
4.9	1573	205	51	-117.570	46.182	656,029	575,936	PSME/CARU
4.10	1676	215	58	-117.561	46.182	656,724	575,931	PSME/CARU
5.3	1280	290	70	-117.606	46.178	653,248	575,511	ABGR/SPBE
5.4	1390	355	75	-117.599	46.178	653,789	575,507	ABGR/BRVU
5.5	1262	355	60	-117.592	46.177	654,328	575,391	ABGR/LIBO2
5.6	1195	20	40	-117.587	46.178	654,715	575,500	ABGR/TABR/CLUN
5.7	1180	144	55	-117.582	46.179	655,101	575,609	ABGR/CARU
5.8	1280	190	42	-117.576	46.177	655,563	575,383	PSME/CARU
6.2	1365	337	60	-117.611	46.174	652,860	575,069	ABGR/CLUN
6.3	1402	168	60	-117.608	46.173	653,090	574,956	ABGR/CARU
6.4	1457	350	50	-117.600	46.174	653,708	575,062	ABGR/VAME
6.5	1329	70	50	-117.593	46.174	654,248	575,058	ABGR/LIBO2
6.6	1432	20	70	-117.588	46.173	654,633	574,944	ABGR/SPBE
6.7	1292	80	40	-117.580	46.174	655,251	575,051	ABGR/SPBE
6.8	1244	50	60	-117.573	46.172	655,790	574,825	ABGR/TABR/CLUN
6.9	1335	235	38	-117.567	46.174	656,254	575,044	PSME/CARU
6.10	1372	0	35	-117.564	46.173	656,485	574,931	ABGR/LIBO2

Table 6 (continued). Sampling plot characteristics for ***Tucannon.***

Plot ID	Elevation (m)	Aspect (deg.)	Slope (%)	Longitude (deg.)	Latitude (deg.)	Albers-x (m)	Albers-y (m)	Plant Association
7.1	1579	350	65	-117.618	46.168	652,315	574,405	ABGR/BRVU
7.2	1579	320	53	-117.611	46.170	652,856	574,624	ABGR/VAME
7.3	1548	310	63	-117.606	46.168	653,240	574,398	ABGR/VAME
7.4	1548	355	50	-117.600	46.169	653,704	574,506	ABGR/VAME
7.5	1420	335	65	-117.593	46.169	654,244	574,502	ABGR/CLUN
7.6	1591	5	40	-117.586	46.169	654,784	574,498	PICO(ABGR)/VAME
7.7	1426	155	65	-117.582	46.168	655,092	574,385	ABGR/SPBE
7.8	1347	45	55	-117.570	46.169	656,019	574,489	ABGR/SPBE
7.9	1311	70	60	-117.566	46.169	656,327	574,487	ABGR/LIBO2
7.10	1237	70	57	-117.562	46.168	656,636	574,374	ABGR/TABR/LIBO2
8.1	1701	320	7	-117.619	46.164	652,234	573,961	ABLA2/VAME
8.2	1652	90	45	-117.612	46.166	652,776	574,180	ABGR/VAME
8.3	1615	50	30	-117.608	46.163	653,082	573,843	ABGR/VAME
8.4	1609	50	70	-117.601	46.164	653,623	573,951	ABGR/VAME
8.5	1628	290	65	-117.593	46.164	654,240	573,946	ABGR/VAME
8.6	1579	80	58	-117.588	46.164	654,626	573,943	ABGR/VAME
8.7	1487	55	60	-117.581	46.166	655,168	574,162	ABGR/GYDR
9.1	1695	117	27	-117.619	46.160	652,230	573,516	ABGR/VAME
9.2	1719	348	25	-117.612	46.160	652,771	573,512	ABLA2/VAME
9.3	1652	290	25	-117.605	46.159	653,310	573,397	PICO(ABLA2)/VAME
9.4	1634	80	50	-117.601	46.160	653,620	573,506	ABGR/VAME
9.5	1737	315	40	-117.595	46.161	654,083	573,613	ABGR/VAME
9.6	1463	300	53	-117.585	46.160	654,854	573,496	ABGR/VAME
10.2	1695	70	25	-117.613	46.155	652,689	572,956	PICO(ABLA2)/VAME
10.3	1707	355	38	-117.606	46.157	653,231	573,175	ABLA2/VAME
10.4	1707	320	30	-117.599	46.156	653,771	573,059	ABLA2/MEFE
10.5	1719	70	15	-117.593	46.155	654,233	572,945	ABLA2/MEFE
11.3	1774	0	18	-117.607	46.152	653,150	572,619	ABLA2/VAME
11.4	1737	320	15	-117.600	46.152	653,690	572,615	ABLA2/MEFE
11.5	1762	30	25	-117.593	46.151	654,229	572,500	ABLA2/VAME
1	1161	203	37	-117.623	46.191	651,948	576,967	PIPO/CARU
2	1146	150	55	-117.643	46.193	650,408	577,202	PSME/CARU
3	1076	267	47	-117.668	46.200	648,486	577,996	PSME/CARU
4	975	200	44	-117.695	46.201	646,405	578,125	PSME/CAGE
5	1551	214	28	-117.674	46.219	648,041	580,114	PSME/CARU
6	1551	230	47	-117.650	46.212	649,885	579,320	PSME/CAGE
7	1384	248	54	-117.630	46.201	651,417	578,084	PIPO/CAGE
8	1439	225	50	-117.671	46.211	648,265	579,222	PSME/CAGE
9	1384	137	47	-117.613	46.204	652,741	578,370	--
10	1329	314	57	-117.654	46.203	649,605	578,279	PSME/CARU

Table 7. Sampling plot characteristics for ***Imnaha****. The abbreviations for plant association follow Johnson and Simon (1987). Samples and site information from plot 9 were collected by a previous study (Maruoka 1994).*

Plot ID	Elevation (m)	Aspect (deg.)	Slope (%)	Longitude (deg.)	Latitude (deg.)	Albers-x (m)	Albers-y (m)	Plant Association
1.1	1844	190	37	-117.023	45.126	698,192	458,314	ABGR/CARU
1.2	1859	--	0	-117.016	45.126	698,742	458,347	ABGR/CARU
1.3	1871	--	0	-117.009	45.126	699,292	458,302	ABGR/CAGE
1.4	1887	210	27	-117.002	45.126	699,843	458,280	ABGR/CARU
1.5	1896	175	37	-116.996	45.125	700,314	458,191	PSME/CARU
2.1	1798	199	34	-117.022	45.125	698,270	458,191	ABGR/CAGE
2.2	1737	171	28	-117.016	45.123	698,742	457,957	PSME/CARU
2.3	1737	177	28	-117.012	45.123	699,057	457,969	PSME/CARU
2.4	1783	147	62	-117.003	45.124	699,764	458,046	PSME/CARU
2.5	1777	168	38	-116.997	45.123	700,236	457,980	PSME/CARU
2.6	1786	171	36	-116.989	45.124	700,865	458,046	PSME/CARU
2.7	1771	171	45	-116.984	45.124	701,258	458,091	PSME/CARU
2.8	1774	186	37	-116.978	45.124	701,730	458,058	PSME/CARU
3.1	1658	112	57	-117.024	45.119	698,113	457,524	PSME/CARU
3.2	1573	167	27	-117.016	45.119	698,742	457,513	PSME/CARU
3.3	1536	157	42	-117.009	45.118	699,292	457,468	PSME/CARU
3.4	1536	150	47	-117.004	45.118	699,686	457,457	PSME/CARU
3.5	1560	175	28	-116.997	45.119	700,236	457,568	PSME/CARU
3.6	1554	169	49	-116.992	45.119	700,629	457,513	PSME/CARU
3.7	1646	170	37	-116.985	45.119	701,179	457,579	PSME/CARU
3.8	1560	155	49	-116.979	45.118	701,651	457,391	PSME/CARU
4.1	1457	115	12	-117.021	45.114	698,349	456,990	PSME/CARU
4.2	1442	168	13	-117.016	45.115	698,742	457,057	PSME/CARU
4.3	1445	175	20	-117.011	45.116	699,135	457,146	PSME/CARU
4.4	1413	170	7	-117.004	45.115	699,686	457,034	PSME/CARU
4.5	1390	186	28	-116.997	45.114	700,236	457,012	PSME/CARU
4.6	1405	149	47	-116.990	45.115	700,786	457,068	PSME/CARU
4.7	1378	180	45	-116.984	45.116	701,258	457,146	PSME/CARU
4.8	1414	189	46	-116.977	45.117	701,808	457,246	PSME/CARU
5.1	1728	71	6	-117.022	45.108	698,270	456,345	ABGR/CARU
5.2	1432	--	0	-117.016	45.110	698,742	456,545	ABGR/CLUN
5.3	1399	20	32	-117.010	45.107	699,214	456,222	ABGR/VAME
5.4	1402	356	18	-117.004	45.110	699,686	456,567	ABGR/VAME
5.5	1463	342	15	-116.998	45.109	700,157	456,434	PSME/CARU
5.6	1457	337	48	-116.991	45.109	700,708	456,445	ABGR/VAME
5.7	1411	321	53	-116.983	45.109	701,337	456,445	ABGR/ACGL
	1466	12	23	-116.979	45.109	701,651	456,456	PSME/VAME

Table 7 (continued) Sampling plot characteristics for ***Imnaha.***

Plot ID	Elevation (m)	Aspect (deg.)	Slope (%)	Longitude (deg.)	Latitude (deg.)	Albers-x (m)	Albers-y (m)	Plant Association
6.1	1804	351	11	-117.021	45.105	698,348	455,978	ABGR/VAME
6.2	1515	355	19	-117.016	45.105	698,742	456,011	ABGR/VAME
6.3	1516	357	57	-117.010	45.106	699,214	456,055	ABGR/VAME
6.4	1530	357	63	-117.004	45.106	699,686	456,111	ABGR/VAME
6.5	1609	342	57	-116.997	45.106	700,236	456,033	ABGR/CARU
6.6	1682	5	25	-116.990	45.104	700,787	455,900	ABGR/CLUN
6.7	1682	0	60	-116.984	45.105	701,258	455,922	ABGR/VAME
6.8	1658	348	18	-116.978	45.104	701,730	455,889	ABGR/VAME
7.1	1597	335	27	-117.021	45.100	698,348	455,444	ABGR/VAME
7.2	1646	50	5	-117.016	45.100	698,742	455,466	ABGR/CARU
7.3	1695	340	8	-117.010	45.100	699,213	455,444	ABGR/VAME
7.4	1713	190	12	-117.004	45.100	699,686	455,366	ABGR/VAME
7.5	1749	335	25	-116.997	45.100	700,236	455,455	ABGR/VAME
7.6	1768	345	6	-116.990	45.101	700,787	455,522	PICO(ABGR)/VAME
7.7	1804	15	4	-116.985	45.099	701,180	455,344	ABGR/CARU
7.8	1786	70	10	-116.978	45.101	701,730	455,555	ABLA2/VAME
8.1	1646	25	20	-117.022	45.096	698,270	454,910	ABGR/VAME
8.2	1658	0	35	-117.016	45.096	698,742	454,932	ABGR/VAME
8.3	1695	0	30	-117.009	45.096	699,292	454,998	ABGR/VAME
8.4	1670	280	15	-117.005	45.095	699,607	454,865	ABGR/VAME
8.5	1652	180	10	-116.997	45.097	700,236	455,065	ABGR/VAME
8.6	1743	159	10	-116.990	45.097	700,787	455,021	ABGR/CARU
8.7	1783	170	12	-116.985	45.097	701,180	455,021	ABGR/CARU
8.8	1762	130	10	-116.977	45.096	701,809	454,955	ABGR/VAME
9.1	1719	15	32	-117.024	45.091	698,112	454,432	ABGR/VAME
9.2	1719	--	0	-117.017	45.091	698,663	454,454	ABGR/VAME
9.3	1707	60	18	-117.010	45.091	699,213	454,465	ABGR/VAME
1	1353	155	52	-116.886	45.141	708,958	459,977	PIPO/CARU
2	1280	--	0	-116.903	45.122	707,625	457,862	PIPO/CARU
3	1344	173	38	-116.924	45.111	705,975	456,637	PSME/CARU
4	1734	173	28	-116.972	45.123	702,201	457,969	PSME/CARU
5	1655	101	37	-116.914	45.123	706,760	457,972	PSME/CARU
6	1570	171	48	-116.894	45.143	708,330	460,199	PSME/CARU
7	1362	209	58	-116.964	45.114	702,831	456,968	PSME/CAGE
8	1518	150	25	-116.943	45.122	704,481	457,859	PSME/CARU
9	1280	164	2	-116.916	45.109	706,605	456,415	ABGR/VAME
10	1615	226	19	-116.878	45.126	709,590	458,310	PSME/CARU

*Table 8. Sampling plot characteristics for **Baker**. The abbreviations for plant association follow Johnson and Clausnitzer (1992).*

Plot ID	Elevation (m)	Aspect (deg.)	Slope (%)	Longitude (deg.)	Latitude (deg.)	Albers-x (m)	Albers-y (m)	Plant Association
2.5	1615	330	45	-118.016	44.801	619,684	422,660	ABGR/BRVU
2.6	1634	355	38	-118.011	44.803	620,082	422,878	PICO(ABGR)/CARU
2.7	1567	70	40	-118.002	44.803	620,794	422,869	ABGR/VAME
2.8	1439	135	55	-117.997	44.802	621,187	422,752	PSME/CARU
2.9	1365	135	20	-117.994	44.803	621,426	422,861	PSME/CARU
2.10	1329	85	43	-117.984	44.803	622,216	422,851	PSME/CARU
3.4	1634	350	55	-118.022	44.798	619,205	422,333	ABGR/VAME
3.5	1682	330	55	-118.016	44.799	619,681	422,438	ABGR/VAME
3.6	1615	135	35	-118.007	44.797	620,390	422,206	PSME/CARU
3.7	1481	136	49	-118.001	44.798	620,866	422,312	PSME/CARU
3.8	1506	0	50	-117.996	44.797	621,259	422,196	PSME/CARU
3.9	1484	5	38	-117.990	44.799	621,737	422,412	PSME/CARU
3.10	1408	109	48	-117.985	44.799	622,132	422,407	PSME/CARU
3.11	1515	100	49	-117.982	44.798	622,367	422,293	PSME/CARU
4.2	1884	321	37	-118.034	44.794	618,251	421,900	ABGR/VAME
4.3	1890	330	39	-118.028	44.793	618,724	421,782	ABGR/VAME
4.5	1670	170	51	-118.018	44.793	619,515	421,772	PSME/CARU
4.6	1570	170	45	-118.010	44.796	620,151	422,098	PSME/CARU
4.7	1524	180	44	-118.005	44.796	620,547	422,093	PSME/CARU
4.8	1475	13	67	-118.000	44.794	620,939	421,866	ABGR/LIBO2
4.9	1594	306	35	-117.991	44.793	621,649	421,746	ABGR/LIBO2
4.10	1545	103	37	-117.987	44.795	621,968	421,964	PSME/CARU
4.11	1542	57	12	-117.982	44.792	622,359	421,626	PSME/CARU
5.2	2066	331	36	-118.035	44.789	618,165	421,345	ABLA2/VASC
5.3	1945	80	63	-118.027	44.789	618,797	421,337	ABLA2/ARCO
5.5	1634	10	45	-118.015	44.789	619,746	421,325	ABGR/LIBO2
5.6	1682	125	40	-118.011	44.787	620,060	421,098	PSME/CARU
5.7	1548	330	35	-118.003	44.789	620,695	421,313	ABGR/LIBO2
5.8	1646	310	45	-117.998	44.790	621,092	421,419	ABGR/VAME
5.9	1573	160	25	-117.988	44.789	621,881	421,298	PSME/CELE/CAGE
5.10	1500	135	45	-117.984	44.788	622,196	421,183	PSME/CARU
6.1	2188	293	72	-118.040	44.783	617,761	420,683	ABLA2-PIAL/POPU
6.2	2152	120	50	-118.034	44.785	618,239	420,899	ABLA2/VASC
6.3	2005	140	37	-118.028	44.784	618,711	420,782	ABGR/ARCO
6.4	1877	340	47	-118.022	44.785	619,187	420,887	PICO(ABLA2)/VASC
6.5	1817	130	18	-118.015	44.787	619,743	421,102	PSME/CARU
6.6	1664	290	45	-118.010	44.785	620,136	420,875	ABGR/BRVU
6.9	1707	160	50	-117.994	44.786	621,402	420,970	PSME/CARU

Table 8 (continued). Sampling plot characteristics for ***Baker****.*

Plot ID	Elevation (m)	Aspect (deg.)	Slope (%)	Longitude (deg.)	Latitude (deg.)	Albers-x (m)	Albers-y (m)	Plant Association
7.1	2322	55	26	-118.041	44.780	617,678	420,350	PICO(ABLA2)/CAGE
7.2	2115	70	30	-118.037	44.781	617,995	420,457	PICO(ABLA2)/VASC
7.3	2073	4	37	-118.030	44.781	618,549	420,450	PICO(ABLA2)/VASC
7.4	1859	120	25	-118.022	44.782	619,183	420,553	ABLA2/VAME
7.5	1871	5	40	-118.014	44.779	619,811	420,211	ABLA2/VAME
7.6	1877	5	53	-118.010	44.781	620,130	420,430	ABLA2/VAME
7.7	1877	350	50	-118.007	44.782	620,369	420,538	PICO(ABGR)/VAME
7.8	1646	135	60	-117.995	44.783	621,319	420,638	PSME/CELE/CAGE
8.1	2249	110	35	-118.041	44.776	617,672	419,905	PICO(ABLA2)/CAGE
8.2	2082	122	24	-118.034	44.776	618,226	419,898	PICO(ABLA2)/CAGE
8.3	2012	80	20	-118.029	44.776	618,621	419,893	PICO(ABLA2)/VAME
8.4	1969	20	37	-118.022	44.776	619,174	419,886	PICO(ABLA2)/VASC
8.5	2018	10	50	-118.017	44.777	619,571	419,992	PICO(ABLA2)/VASC
8.6	1695	60	35	-118.009	44.776	620,202	419,873	ABGR/CARU
8.8	1615	45	54	-117.996	44.777	621,232	419,971	ABGR/CARU
9.1	2249	5	60	-118.041	44.773	617,667	419,571	ABLA2/VASC
9.2	2167	52	28	-118.036	44.772	618,061	419,455	PICO(ABLA2)/VASC
9.3	2155	355	28	-118.028	44.772	618,694	419,447	ABLA2/VASC
9.4	2179	310	18	-118.023	44.771	619,088	419,331	PICO(ABLA2)/VASC
9.5	2079	165	45	-118.015	44.772	619,722	419,434	PSME/CARU
9.6	2012	180	40	-118.010	44.773	620,119	419,540	PSME/CARU
10.3	2207	50	35	-118.028	44.767	618,687	418,891	PICO(ABLA2)/VASC
10.4	2231	320	5	-118.021	44.768	619,242	418,995	PICO(ABLA2)/CAGE
1	1670	59	54	-117.981	44.778	622,419	420,068	ABGR/CARU
2	1643	66	42	-117.964	44.777	623,763	419,940	ABGR/CARU
3	1560	132	54	-118.026	44.810	618,906	423,671	ABGR/CARU
4	1326	139	38	-117.959	44.787	624,171	421,048	PSME/CAGE
5	1250	24	21	-117.946	44.784	625,195	420,702	PSME/CARU
6	1341	189	31	-117.927	44.774	626,684	419,572	PIPO/FEID
7	1509	221	22	-117.940	44.763	625,642	418,361	PSME/CAGE
8	1554	130	22	-117.959	44.742	624,111	416,043	PSME/CAGE
9	1387	200	25	-117.945	44.731	625,205	414,807	PIPO/CAGE
10	1841	161	22	-117.982	44.761	622,317	418,178	ABGR/CAGE
11	1375	94	45	-117.921	44.757	627,138	417,676	PSME/CAGE

Table 9. Sampling plot characteristics for ***Dugout****. The abbreviations for plant association follow Johnson and Clausnitzer (1992).*

Plot ID	Elevation (m)	Aspect (deg.)	Slope (%)	Longitude (deg.)	Latitude (deg.)	Albers-x (m)	Albers-y (m)	Plant Association
2.1	1597	280	22	-118.379	44.230	589,902	359,597	PSME/CARU
2.2	1658	290	35	-118.374	44.231	590,303	359,701	PSME/CARU
2.3	1719	150	0	-118.366	44.233	590,946	359,913	ABGR/CARU
2.4	1719	225	2	-118.359	44.231	591,500	359,681	PSME/CARU
3.1	1615	300	20	-118.378	44.227	589,976	359,262	ABGR/CAGE
3.2	1731	290	15	-118.372	44.227	590,455	359,254	PSME/CARU
3.3	1725	90	2	-118.366	44.229	590,938	359,468	PSME/CARU
3.4	1734	53	16	-118.362	44.227	591,253	359,240	PSME/CARU
4.1	1609	260	25	-118.377	44.223	590,048	358,816	PSME/CARU
4.2	1701	290	40	-118.372	44.220	590,442	358,476	PSME/CARU
4.3	1756	255	10	-118.364	44.223	591,086	358,798	PSME/CARU
5.1	1536	255	12	-118.379	44.218	589,879	358,263	PSME/CARU
5.2	1731	300	20	-118.372	44.218	590,438	358,253	PSME/CARU
5.3	1762	60	10	-118.364	44.219	591,079	358,354	PSME/CARU
5.4	1768	328	9	-118.358	44.217	591,554	358,123	PSME/CARU
5.5	1743	--	0	-118.355	44.217	591,793	358,119	PSME/CARU
6.1	1536	230	20	-118.378	44.213	589,949	357,706	PSME/CARU
6.2	1625	189	22	-118.372	44.213	590,428	357,697	PSME/CARU
6.3	1670	270	17	-118.368	44.213	590,748	357,692	PSME/CARU
6.4	1701	280	23	-118.359	44.214	591,468	357,791	PSME/CAGE
6.5	1737	185	22	-118.353	44.212	591,944	357,561	PSME/CARU
6.6	1768	170	12	-118.346	44.213	592,505	357,662	PSME/CARU
6.7	1786	234	10	-118.344	44.213	592,664	357,660	PSME/CARU
7.1	1609	--	6	-118.377	44.210	590,024	357,370	PSME/CARU
7.2	1628	340	20	-118.371	44.207	590,497	357,029	PSME/CARU
7.3	1664	342	16	-118.364	44.208	591,058	357,131	ABGR/CARU
7.4	1695	14	14	-118.358	44.209	591,539	357,234	ABGR/CARU
7.5	1695	278	32	-118.353	44.208	591,937	357,116	ABGR/CARU
7.6	1756	315	15	-118.347	44.209	592,417	357,219	PSME/CARU
7.7	1786	305	6	-118.341	44.210	592,898	357,322	PSME/CARU
8.1	1621	300	32	-118.378	44.204	589,932	356,705	PSME/CARU
8.2	1670	270	30	-118.372	44.205	590,413	356,808	PSME/CARU
8.3	1731	0	10	-118.365	44.205	590,973	356,799	PSME/CAGE
8.4	1762	332	3	-118.359	44.204	591,450	356,679	PSME/CARU
8.5	1792	60	15	-118.353	44.204	591,929	356,671	ABGR/CAGE
8.6	1756	253	13	-118.350	44.205	592,170	356,778	PSME/CAGE
9.1	1536	242	35	-118.378	44.200	589,925	356,260	PSME/CARU
9.2	1615	324	20	-118.372	44.200	590,404	356,252	PSME/CARU
9.3	1749	173	7	-118.365	44.201	590,965	356,354	PSME/CAGE
9.4	1737	--	0	-118.358	44.200	591,522	356,233	PSME/CARU
9.5	1792	345	8	-118.353	44.200	591,922	356,226	PSME/CAGE

Table 9 (continued). Sampling plot characteristics for ***Dugout.***

Plot ID	Elevation (m)	Aspect (deg.)	Slope (%)	Longitude (deg.)	Latitude (deg.)	Albers-x (m)	Albers-y (m)	Plant Association
9.6	1774	--	0	-118.347	44.200	592,401	356,218	PSME/CARU
10.1	1493	228	18	-118.378	44.195	589,915	355,704	PSME/CARU
10.2	1600	307	28	-118.372	44.197	590,398	355,918	PSME/CARU
10.3	1689	--	0	-118.365	44.196	590,956	355,798	PSME/CAGE
10.4	1670	220	15	-118.362	44.193	591,189	355,460	PSME/CAGE
10.5	1774	165	11	-118.353	44.197	591,916	355,893	PSME/CAGE
10.6	1780	--	0	-118.345	44.195	592,551	355,660	PSME/CARU
10.7	1780	258	6	-118.340	44.195	592,951	355,653	PSME/CAGE
11.1	1493	340	20	-118.378	44.191	589,908	355,260	PSME/CARU
11.2	1524	--	0	-118.374	44.189	590,223	355,032	PSME/CARU
11.3	1670	220	8	-118.367	44.190	590,784	355,133	PIPO/AGSP
11.4	1646	220	15	-118.361	44.191	591,265	355,237	PSME/CAGE
11.5	1780	--	0	-118.353	44.191	591,905	355,226	PSME/CARU
11.6	1780	355	8	-118.346	44.191	592,464	355,217	PSME/CARU
11.7	1774	--	0	-118.341	44.190	592,861	355,098	PSME/CARU
12.1	1408	280	50	-118.379	44.187	589,820	354,816	PSME/CAGE
12.2	1548	230	12	-118.373	44.187	590,299	354,808	PSME/CARU
12.3	1570	245	12	-118.366	44.187	590,859	354,799	PSME/CARU
12.4	1634	260	50	-118.359	44.187	591,418	354,789	PSME/CARU
12.5	1713	255	14	-118.355	44.187	591,737	354,784	PIPO/CARU
12.6	1695	100	20	-118.348	44.186	592,295	354,663	PIPO/CARU
12.7	1756	268	12	-118.342	44.186	592,774	354,655	PIPO/CARU
1	1756	10	8	-118.354	44.250	591,935	361,786	ABGR/CARU
2	1719	222	12	-118.372	44.245	590,489	361,255	PIPO/CARU
3	1682	350	20	-118.348	44.232	592,380	359,777	ABGR/CARU
4	1728	69	12	-118.409	44.239	587,525	360,639	ABGR/CARU
5	1701	40	27	-118.401	44.220	588,126	358,516	ABGR/CARU
6	1731	107	22	-118.402	44.206	588,019	356,960	ABGR/CARU
7	1817	190	18	-118.417	44.219	586,847	358,427	ABGR/CARU
8	1481	299	33	-118.353	44.173	591,871	353,225	PIPO/CARU
9	1628	--	0	-118.410	44.179	587,327	353,970	PSME/CARU
10	1564	65	18	-118.403	44.167	587,864	352,626	PSME/CARU
11	1509	103	38	-118.386	44.171	589,230	353,047	PSME/CARU
12	1615	190	17	-118.335	44.219	593,394	358,315	PIPO/CAGE
13	1603	150	33	-118.330	44.207	593,771	356,974	PIPO/CARU
14	1554	261	46	-118.307	44.198	595,592	355,943	PIPO/CARU
15	1585	150	35	-118.311	44.185	595,249	354,503	PIPO/CARU
16	1472	200	12	-118.295	44.160	596,483	351,703	PIPO/CARU
17	1692	323	18	-118.322	44.239	594,469	360,521	ABGR/CARU
18	1567	210	25	-118.393	44.267	588,856	363,729	PIPO/CAGE
19	1533	65	6	-118.400	44.251	588,266	361,960	ABGR/CAGE

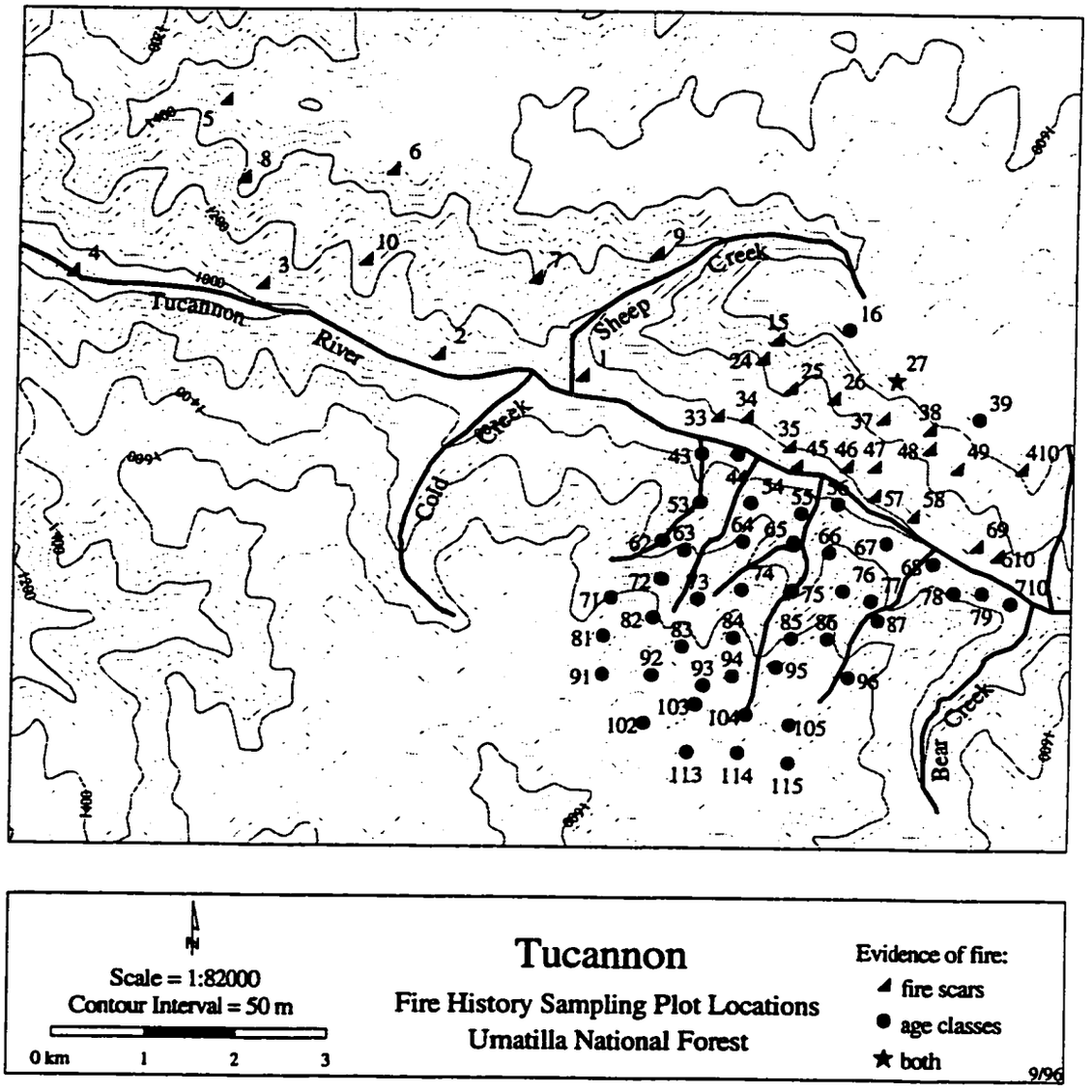


Figure 23. Map of sampling plot locations for Tucannon.

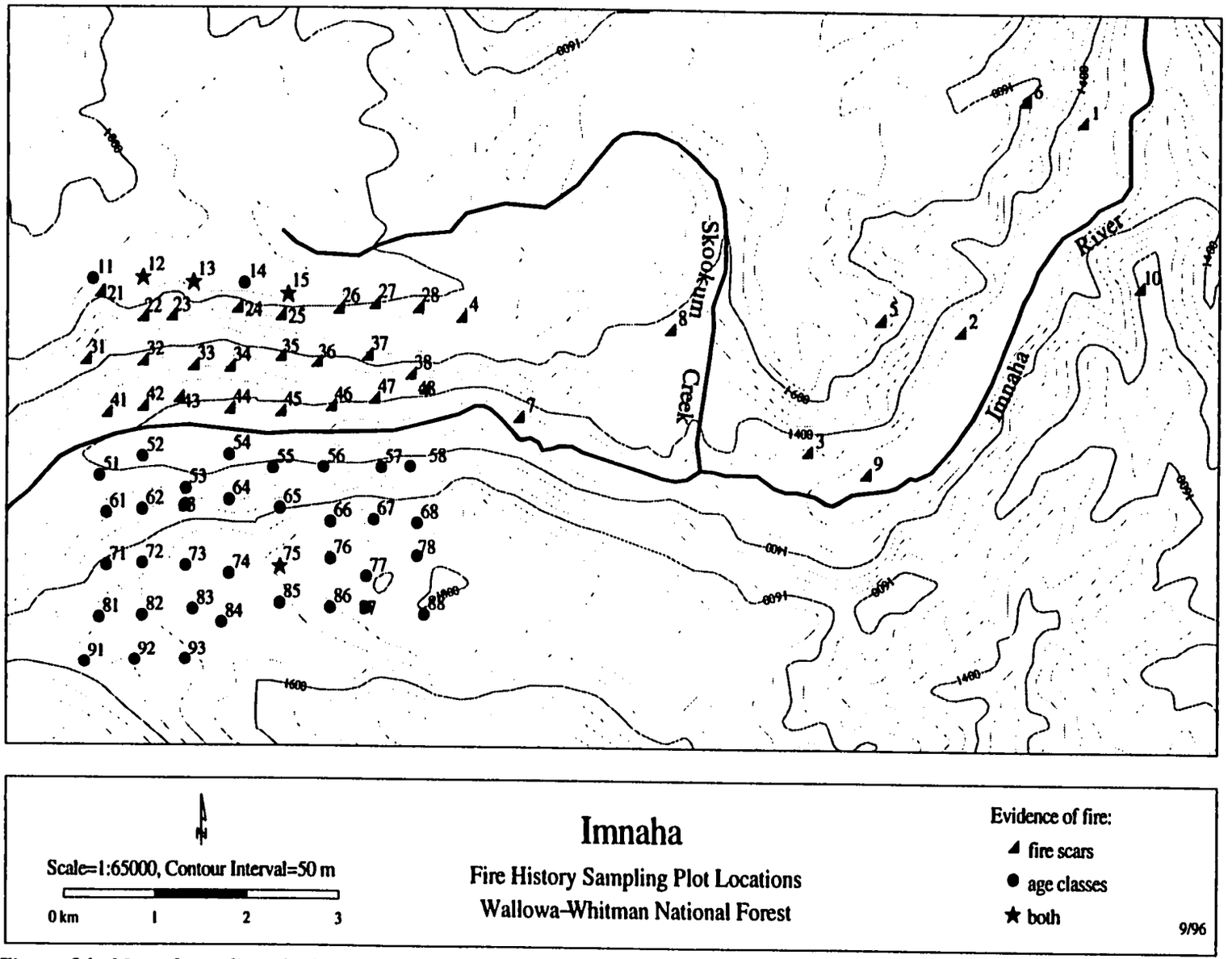


Figure 24. Map of sampling plot locations for Imnaha.

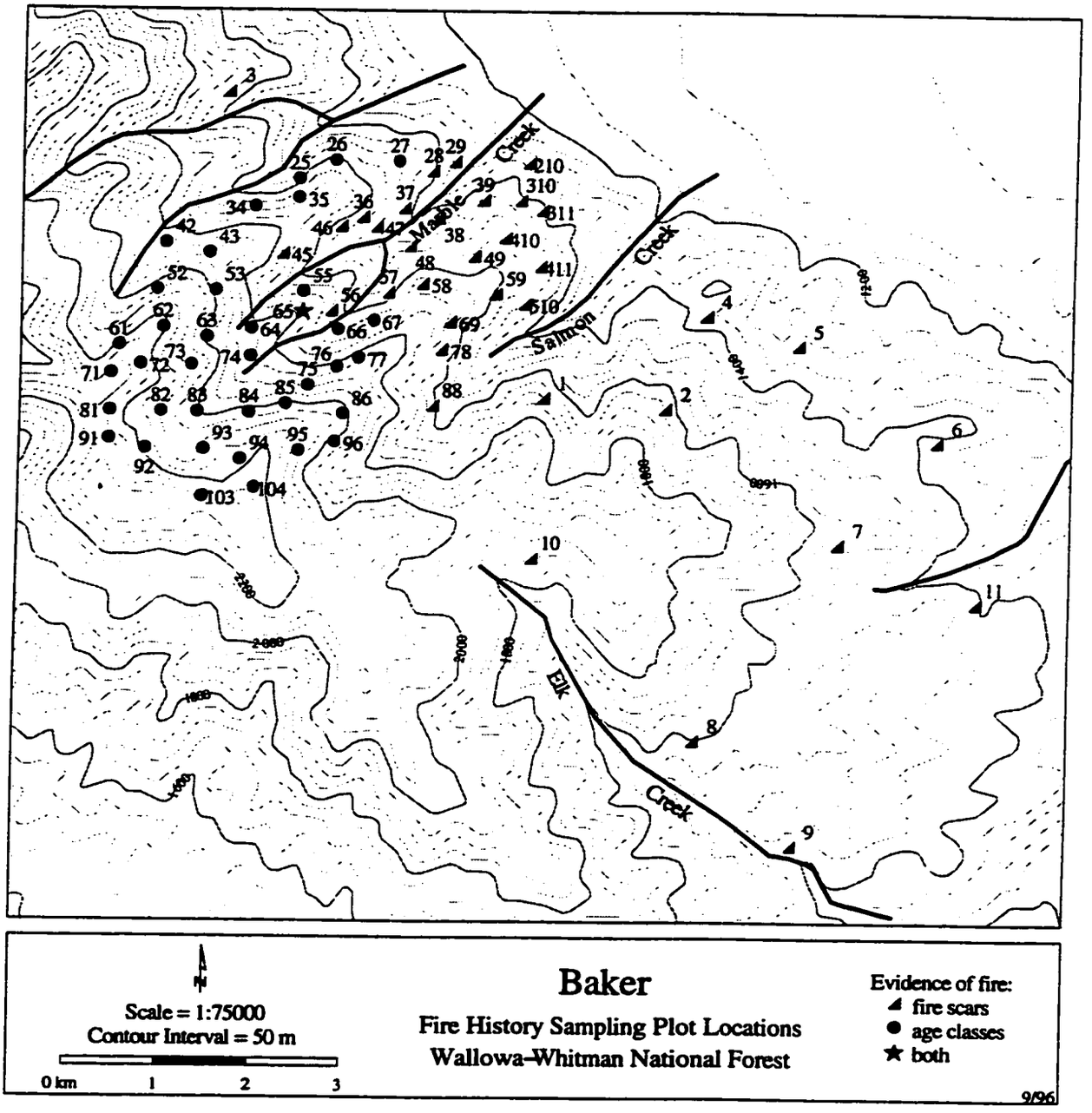


Figure 25. Map of sampling plot locations at Baker.

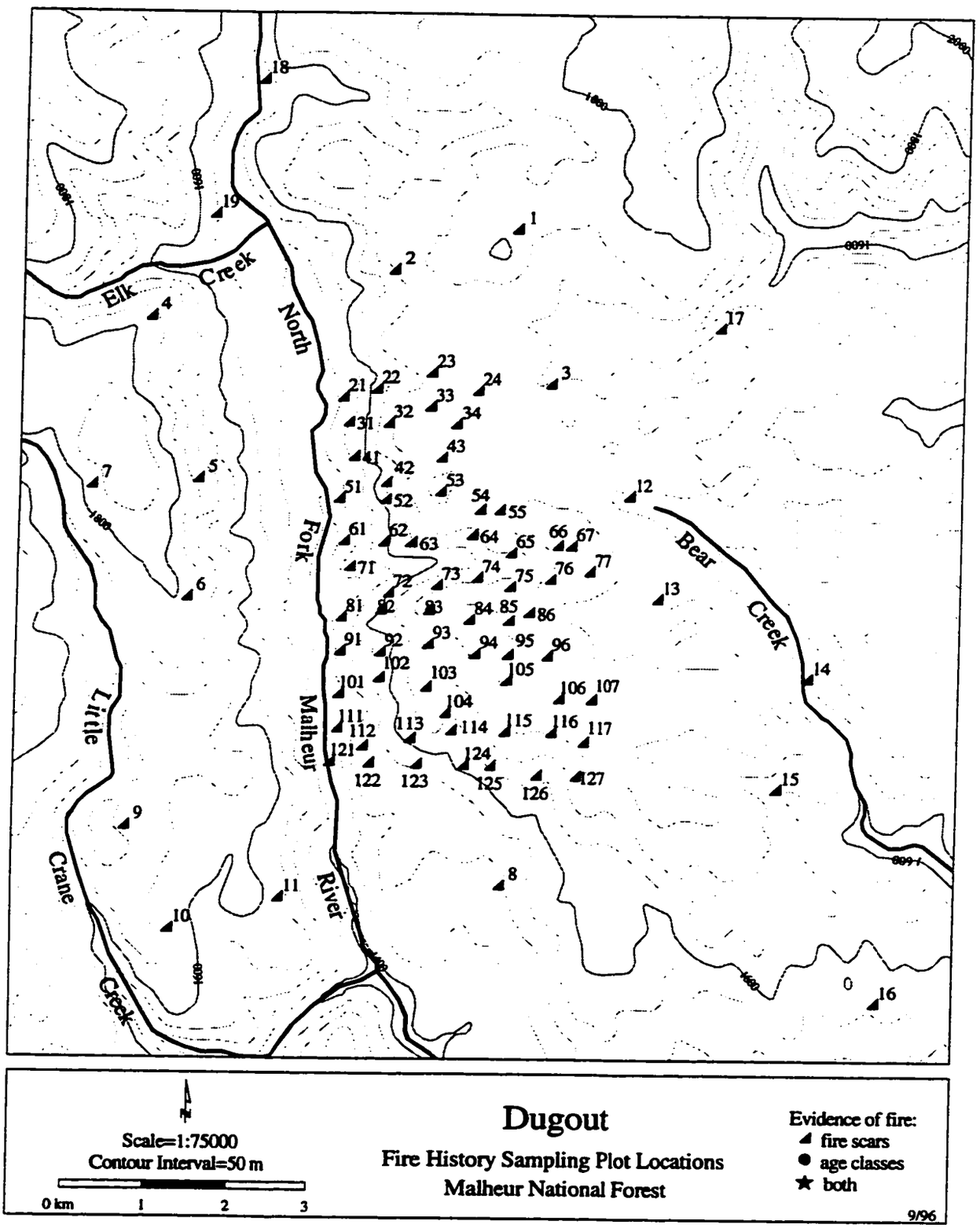


Figure 26. Map of sampling plot locations for Dugout.

APPENDIX B: SUMMARY STATISTICS FOR FIRE YEARS, BY WATERSHED

Table 10. Summary statistics for fire years at ***Tucannon.***

	Fire year	Extent			No. of plots		No. of trees	
		Total (ha)	Dry forests (ha)	Mesic forests (ha)	Dry	Mesic	Dry	Mesic
1	1583	365	365	--	3	--	5	--
2	1618	386	386	--	2	--	3	--
3	1630	394	394	--	6	--	9	--
4	1635	143	143	--	1	--	2	--
5	1652	784	784	--	9	--	12	--
6	1664	220	220	--	2	--	3	--
7	1671	781	781	--	5	--	9	--
8	1685	161	161	--	1	--	2	--
9	1695	425	425	--	9	--	15	--
10	1703	480	480	--	2	--	5	--
11	1705	129	129	--	2	--	4	--
12	1706	488	488	--	3	--	5	--
13	1712	286	286	--	2	--	2	--
14	1734	152	152	--	1	--	3	--
15	1743	428	428	--	3	--	8	--
16	1748	209	209	--	3	--	5	--
17	1751	30	30	--	2	--	3	--
18	1754	101	--	101	--	4	--	26
19	1756	101	101	--	1	--	4	--
20	1759	1292	1292	--	14	--	27	--
21	1765	271	271	--	2	--	2	--
22	1774	1683	1013	670	17	15	39	45
23	1776	120	120	--	1	--	3	--
24	1779	333	333	--	2	--	4	--
25	1791	172	172	--	2	--	2	--
26	1799	70	70	--	1	--	4	--
27	1816	458	458	--	3	--	7	--
28	1828	989	989	--	7	--	25	--
29	1839	736	736	--	5	--	13	--
30	1841	120	--	120	--	6	--	42
31	1855	1030	1030	--	7	--	24	--
32	1863	109	109	--	4	--	7	--
33	1865	347	347	--	7	--	18	--
34	1869	441	441	--	3	--	8	--
35	1873	205	205	--	4	--	7	--
36	1883	30	30	--	2	--	3	--
37	1886	756	756	--	5	--	15	--
38	1888	2080	1384	696	20	31	55	192
39	1893	19	19	--	1	--	2	--
40	1898	198	198	--	3	--	3	--

Table 11. Summary statistics for fire years at ***Imnaha.***

	Fire year	Extent			No. of plots		No. of trees	
		Total (ha)	Dry forests (ha)	Mesic forests (ha)	Dry	Mesic	Dry	Mesic
1	1632	39	39	–	1	–	2	–
2	1652	39	39	–	1	–	3	–
3	1661	119	119	–	3	–	3	–
4	1671	274	274	–	2	–	3	–
5	1681	39	39	–	1	–	2	–
6	1687	581	581	–	11	–	16	–
7	1705	716	716	–	3	–	7	–
8	1712	261	261	–	4	–	6	–
9	1722	246	246	–	8	–	13	–
10	1724	122	122	–	1	–	2	–
11	1747	81	81	–	1	–	3	–
12	1751	506	506	–	6	–	8	–
13	1752	245	245	–	2	–	6	–
14	1754	158	158	–	2	–	2	–
15	1763	545	545	–	17	–	27	–
16	1778	701	701	–	6	–	13	–
17	1783	1736	1736	–	30	–	51	–
18	1795	641	641	–	4	–	9	–
19	1798	1532	748	784	20	33	49	117
20	1831	128	128	–	1	–	4	–
21	1834	2206	1953	253	35	13	84	45
22	1844	1081	1081	–	7	–	18	–
23	1846	25	25	–	1	–	2	–
24	1852	282	282	–	12	–	20	–
25	1863	133	133	–	1	–	4	–
26	1864	140	–	140	–	6	2	16
27	1869	714	714	–	18	–	33	–
28	1871	681	681	–	5	–	17	–
29	1885	393	393	–	4	–	13	–
30	1886	701	538	163	20	11	42	45
31	1889	40	40	–	2	–	3	–
32	1890	220	220	–	2	–	3	–
33	1896	148	148	–	1	–	3	–
34	1897	306	306	–	6	–	11	–
35	1898	281	281	–	5	–	7	–
36	1902	243	243	–	2	–	4	–
37	1905	177	177	–	3	–	4	–
38	1917	40	40	–	2	–	2	–
39	1919	78	78	–	2	–	4	–

Table 12. Summary statistics for fire years at ***Baker.***

	Fire year	Extent			No. of plots		No. of trees	
		Total (ha)	Dry forests (ha)	Mesic forests (ha)	Dry	Mesic	Dry	Mesic
1	1634	1508	1508	–	6	–	10	–
2	1646	1400	1400	–	6	–	9	–
3	1652	1187	1187	–	9	–	12	–
4	1656	1408	1408	–	6	–	7	–
5	1668	400	400	–	2	–	3	–
6	1671	1394	1394	–	13	–	19	–
7	1679	1384	1384	–	6	–	11	–
8	1695	3313	3313	–	26	–	58	–
9	1706	454	454	–	7	–	9	–
10	1708	2448	2448	–	13	–	27	–
11	1712	424	424	–	6	–	10	–
12	1717	922	922	–	9	–	14	–
13	1721	467	467	–	2	–	4	–
14	1722	1846	1846	–	11	–	14	–
15	1729	3030	3030	–	21	–	45	–
16	1739	2631	2631	–	15	–	33	–
17	1751	2803	2803	–	22	–	52	–
18	1756	49	49	–	2	–	3	–
19	1762	2581	2581	–	19	–	55	–
20	1767	769	769	–	7	–	17	–
21	1770	223	223	–	1	–	4	–
22	1776	1004	1004	–	19	–	35	–
23	1777	467	467	–	3	–	11	–
24	1778	1887	1887	–	6	–	20	–
25	1781	368	368	–	7	–	14	–
26	1783	2492	2492	–	21	–	38	–
27	1788	341	341	–	3	–	8	–
28	1791	2963	2963	–	23	–	57	–
29	1794	355	355	–	4	–	5	–
30	1797	535	535	–	3	–	13	–
31	1798	1046	1046	–	15	–	31	–
32	1800	2399	2399	–	10	–	24	–
33	1807	114	114	–	1	–	3	–
34	1812	1430	1430	–	5	–	16	–
35	1816	1063	1063	–	16	–	35	–

Table 12 (continued). Summary statistics for fire years at ***Baker.***

	Fire year	Extent			No. of plots		No. of trees	
		Total (ha)	Dry forests (ha)	Mesic forests (ha)	Dry	Mesic	Dry	Mesic
36	1822	2727	2727	--	20	--	45	--
37	1826	704	704	--	3	--	6	--
38	1828	639	639	--	7	--	15	--
39	1833	571	571	--	8	--	22	--
40	1834	2264	2264	--	19	--	36	--
41	1839	1097	1097	--	8	--	17	--
42	1846	3700	3700	--	31	--	64	--
43	1854	197	197	--	3	--	9	--
44	1855	917	917	--	3	--	7	--
45	1857	920	920	--	13	--	23	--
46	1865	293	293	--	1	--	3	--
47	1869	1225	1225	--	7	--	15	--
48	1871	262	262	--	1	--	3	--
49	1872	38	38	--	1	--	3	--
50	1879	77	77	--	2	--	5	--
51	1880	49	49	--	2	--	3	--
52	1883	33	33	--	1	--	4	--
53	1892	94	94	--	4	--	6	--
54	1962	38	38	--	2	--	3	--

Table 13. Summary statistics for fire years at ***Dugout.***

	Fire year	Extent			No. of plots		No. of trees	
		Total (ha)	Dry forests (ha)	Mesic forests (ha)	Dry	Mesic	Dry	Mesic
1	1529	317	317	--	3	--	3	--
2	1540	434	434	--	3	--	3	--
3	1547	49	49	--	2	--	2	--
4	1565	1190	1190	--	5	--	6	--
5	1570	702	702	--	5	--	5	--
6	1593	217	217	--	2	--	3	--
7	1598	1258	1258	--	12	--	12	--
8	1629	5534	5534	--	30	--	38	--
9	1645	2683	2683	--	16	--	17	--
10	1652	596	596	--	3	--	3	--
11	1656	4988	4988	--	34	--	48	--
12	1664	324	324	--	4	--	4	--
13	1667	1188	1188	--	17	--	24	--
14	1676	3846	3846	--	21	--	30	--
15	1685	38	38	--	2	--	3	--
16	1687	6725	6725	--	40	--	65	--
17	1688	343	343	--	1	--	3	--
18	1690	483	483	--	7	--	7	--
19	1694	653	653	--	3	--	3	--
20	1697	1426	1426	--	5	--	7	--
21	1700	3202	3202	--	26	--	30	--
22	1707	1075	1075	--	10	--	12	--
23	1710	7416	7416	--	47	--	76	--
24	1721	8081	8081	--	54	--	91	--
25	1729	1256	1256	--	6	--	7	--
26	1732	1115	1115	--	11	--	17	--
27	1733	131	131	--	1	--	2	--
28	1734	2421	2421	--	34	--	48	--
29	1737	370	370	--	1	--	2	--
30	1739	1917	1917	--	18	--	29	--
31	1740	544	544	--	1	--	3	--
32	1741	4287	4287	--	19	--	30	--
33	1743	101	101	--	3	--	3	--
34	1745	784	784	--	5	--	7	--
35	1751	5324	5324	--	47	--	83	--
36	1753	377	377	--	2	--	2	--
37	1755	679	679	--	2	--	3	--
38	1756	4038	4038	--	25	--	36	--
39	1759	3865	3865	--	31	--	50	--
40	1765	869	869	--	3	--	4	--

Table 13 (continued). Summary statistics for fire years at ***Dugout.***

	Fire year	Extent			No. of plots		No. of trees	
		Total (ha)	Dry forests (ha)	Mesic forests (ha)	Dry	Mesic	Dry	Mesic
41	1771	6245	6245	--	51	--	94	--
42	1774	777	777	--	2	--	3	--
43	1775	158	158	--	6	--	7	--
44	1776	1433	1433	--	5	--	11	--
45	1780	3850	3850	--	31	--	48	--
46	1783	3562	3562	--	22	--	42	--
47	1788	762	762	--	2	--	7	--
48	1789	297	297	--	1	--	3	--
49	1792	578	578	--	2	--	4	--
50	1794	7402	7402	--	60	--	112	--
51	1799	3340	3340	--	17	--	20	--
52	1800	2971	2971	--	27	--	43	--
53	1802	1471	1471	--	14	--	18	--
54	1804	1427	1427	--	9	--	15	--
55	1806	105	105	--	3	--	4	--
56	1807	322	322	--	13	--	24	--
57	1812	1569	1569	--	7	--	17	--
58	1814	225	225	--	1	--	3	--
59	1822	1573	1573	--	6	--	16	--
60	1823	975	975	--	3	--	9	--
61	1829	7811	7811	--	66	--	151	--
62	1830	461	461	--	2	--	2	--
63	1835	2776	2776	--	23	--	34	--
64	1840	617	617	--	3	--	4	--
65	1844	7464	7464	--	64	--	132	--
66	1849	370	370	--	1	--	3	--
67	1856	3224	3224	--	29	--	56	--
68	1868	201	201	--	7	--	13	--
69	1869	7656	7656	--	57	--	125	--
70	1873	428	428	--	2	--	3	--
71	1877	239	239	--	1	--	3	--
72	1878	296	296	--	1	--	2	--
73	1883	623	623	--	2	--	4	--
74	1887	343	343	--	1	--	4	--
75	1888	1040	1040	--	4	--	20	--
76	1889	2046	2046	--	43	--	76	--
77	1898	811	811	--	3	--	4	--
78	1899	372	372	--	2	--	3	--
79	1914	257	257	--	1	--	2	--
80	1926	23	23	--	1	--	2	--

APPENDIX C. COMPARISON OF THREE METHODS OF DETERMINING FIRE EXTENT

There are many methods for reconstructing fire boundaries from tree-ring evidence of fire. The location of fire boundaries determines the extent of the reconstructed fires and consequently has great influence on the results of any analyses of fire extent. I compared the results of three methods of determining fire extents: the heuristic method used in my analyses in Chapters 2 and 3 and two common computer methods of determining extent, Voronoi (Thiessen) polygons and convex hulls. All three methods yielded essentially the same fire extents at the four sampled watersheds in the Blue Mountains.

Determination of fire extent

In addition to the heuristic method described in Chapter 2, fire extent was determined by computing Voronoi (Thiessen) polygons and convex hulls. The location of sampled plots and evidence of fire was used to determine fire extent for every fire year at each site by the program SPANFIRE (Swetnam and Holmes 1994). To compute fire extent with Voronoi polygons, each site was divided into polygons, each of which contains only one of the sampling plots. These polygons completely cover the site and do not overlap spatially (Mark 1987). The sides of the polygons lie halfway between the sampling plot and each of its nearest neighbor plots. Fire extent was determined for every fire year by summing the area of all polygons that contain evidence of fire in that year. Plots lacking trees with recorder years for a given fire year were considered unsampled for that year. Polygon boundaries were re-determined for every fire year to account for changing sample size through time. Convex hulls determine fire extent using a single polygon rather than dividing the entire site into multiple polygons. Fire extent for a given year is the area of the smallest convex polygon containing all the sampling plots that have evidence of fire in that year (Sedgewick 1988). Although Voronoi polygons can be identified for any number of plots, identification of a convex hull requires at least three plots with evidence of fire so the extent of the smallest fires could not be determined using convex hulls. The pixel size for both methods, a measure of the spatial resolution used by SPANFIRE, was 10 ha.

Comparison of methods

Fire extent determined by SPANFIRE was significantly and highly correlated with the fire extents determined heuristically (heuristic method described in Chapter 2, Figure 27, Table 14). There are some outliers in the comparison between the methods for the entire sampling area. At Tucannon and Imnaha, the greatest differences occur between fire extents determined heuristically and using Voronoi polygons. The difference between the two methods is due to the complex shape of the sampling area perimeter at both Tucannon and Imnaha (Figure 23 and 24). The years with the greatest difference in fire extent calculated by the two methods all have large fire extents (Tucannon 1774, Imnaha 1763, 1783, 1798). In determining fire boundaries subjectively, we did not extrapolate to the unsampled areas south of the dry forest sampling areas at either site but the Voronoi method did. The difference between the methods is reduced when the sampling area perimeter has a simple shape. For example, the correlation between the methods improves for Imnaha and Tucannon when only fires from the dense sampling area are included. At Baker and Dugout the greatest differences occur for annual fire extents determined heuristically and with convex hulls. The years for which fire extent differ the most when calculated by the two methods all have isolated points that were subjectively mapped with multiple fire boundaries but were included within a single convex hull (Dugout 1700, 1741, 1802, Baker 1776, 1816, 1828, 1869).

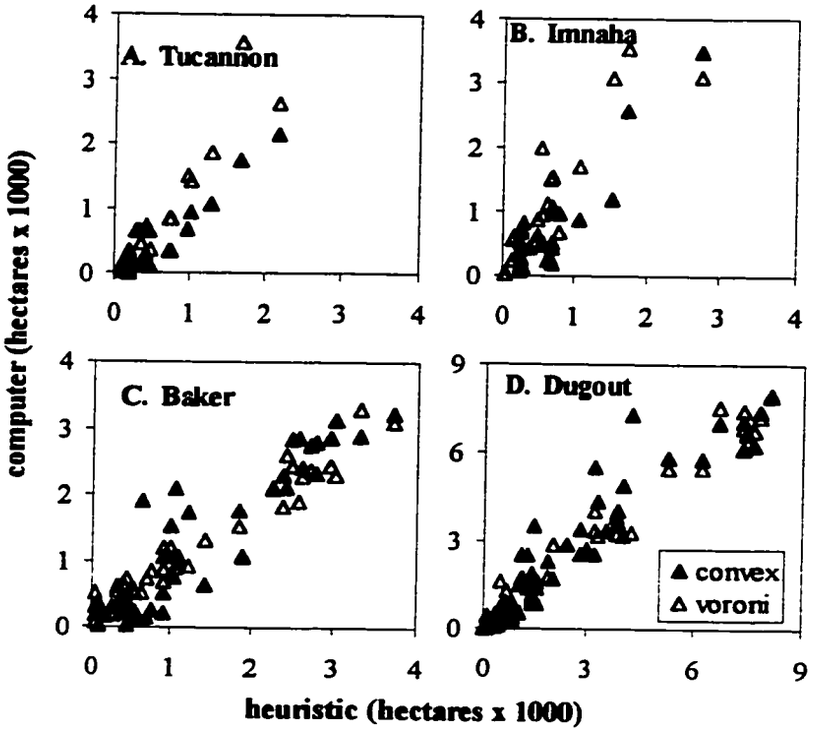


Figure 27. Scatter plots of heuristically- versus computer-determined annual fire extent for the entire sampling area, by site (1687-1994). Two computer methods were used: convex hull and Voronoi polygons. Both mesic and dry forests were included.

Table 14. Correlation of heuristically- and computer-determined fire extents. The nonparametric (Spearman rank) correlation coefficient (r) of annual fire extent is given. Convex hull and Voronoi polygon are the computer methods. Both mesic and dry forests were included. All correlations are significant ($p < 0.01$). The number of fire years correlated is given in parentheses.

	Entire sampling site			Dense sampling area		
	Subjective with:		Voronoi with:	Subjective with:		Voronoi with:
	convex hull	Voronoi	convex hull	convex hull	Voronoi	convex hull
Tucannon	0.89 (19)	0.92 (24)	0.94 (19)	0.90 (8)	0.97 (13)	0.95 (8)
Imnaha	0.74 (20)	0.87 (26)	0.65 (20)	0.93 (14)	0.97 (18)	0.98 (14)
Baker	0.90 (36)	0.96 (44)	0.87 (36)	0.91 (27)	0.90 (33)	0.85 (27)
Dugout	0.95 (43)	0.96 (46)	0.94 (43)	0.97 (34)	0.96 (40)	0.95 (34)

APPENDIX D: TUCANNON FIRE MAPS

Evidence of fire was mapped at Tucannon for every year in dry forests that had at least two scars and for every fire event identified in mesic forests. Symbols indicate whether the evidence of fire was cohorts or scars. If the later, the intra-annular position of the scar is also indicated. Plots indicating as having probable evidence of fire are those for which the only evidence was an abrupt increase or decrease in ring width. Plots having no evidence of fire in a given year include plots at which no sampled trees were alive during that year as well as plots with trees that were less susceptible to scarring (i.e., the fire year occurred before the first scar). Plots indicated as having no record for a given year are plots that were sampled but had no trees recording during that year. Fire boundaries are shown as a heavy line.

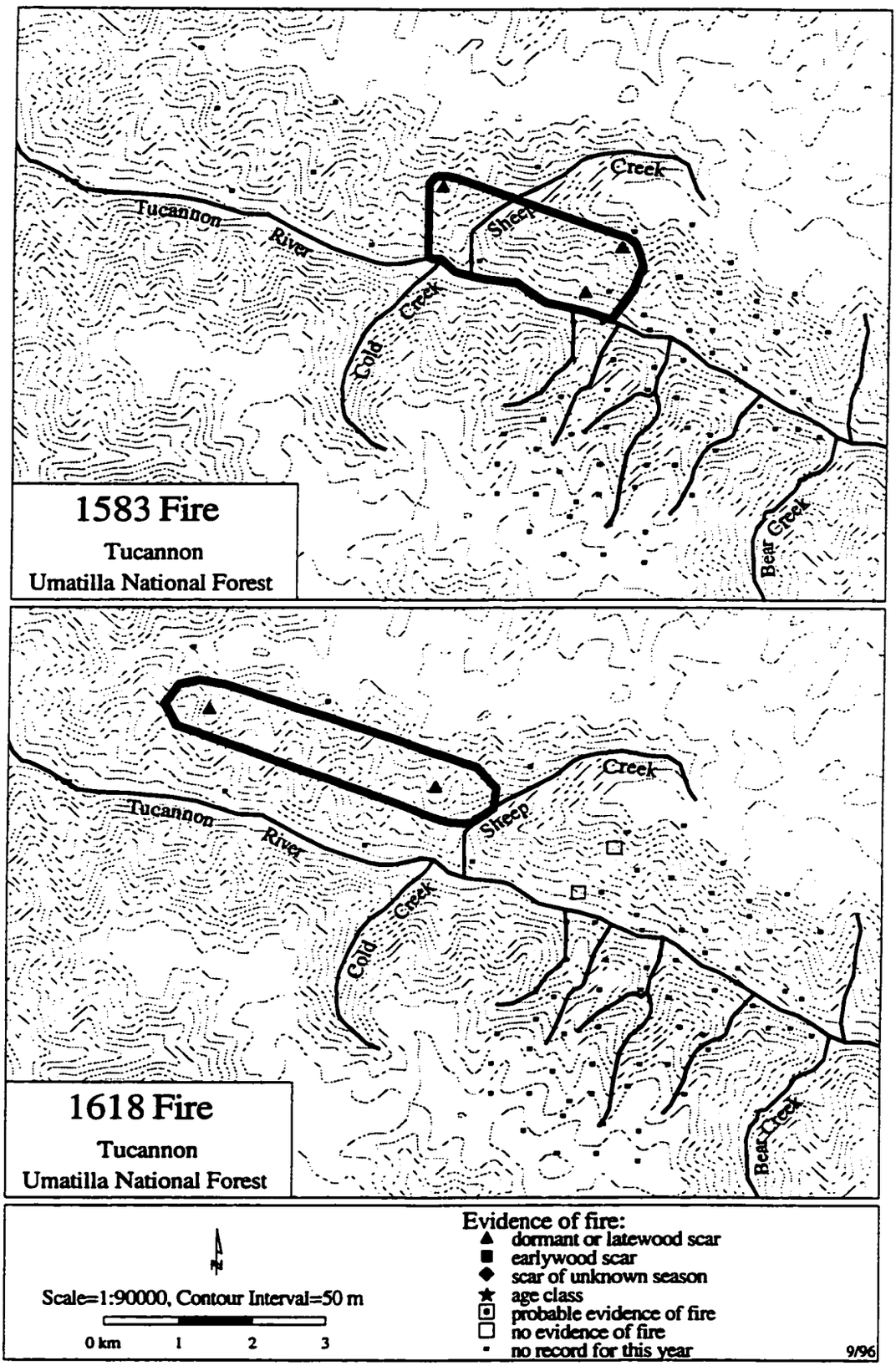


Figure 28. Tucannon fire maps for 1583 (top) and 1618 (bottom).

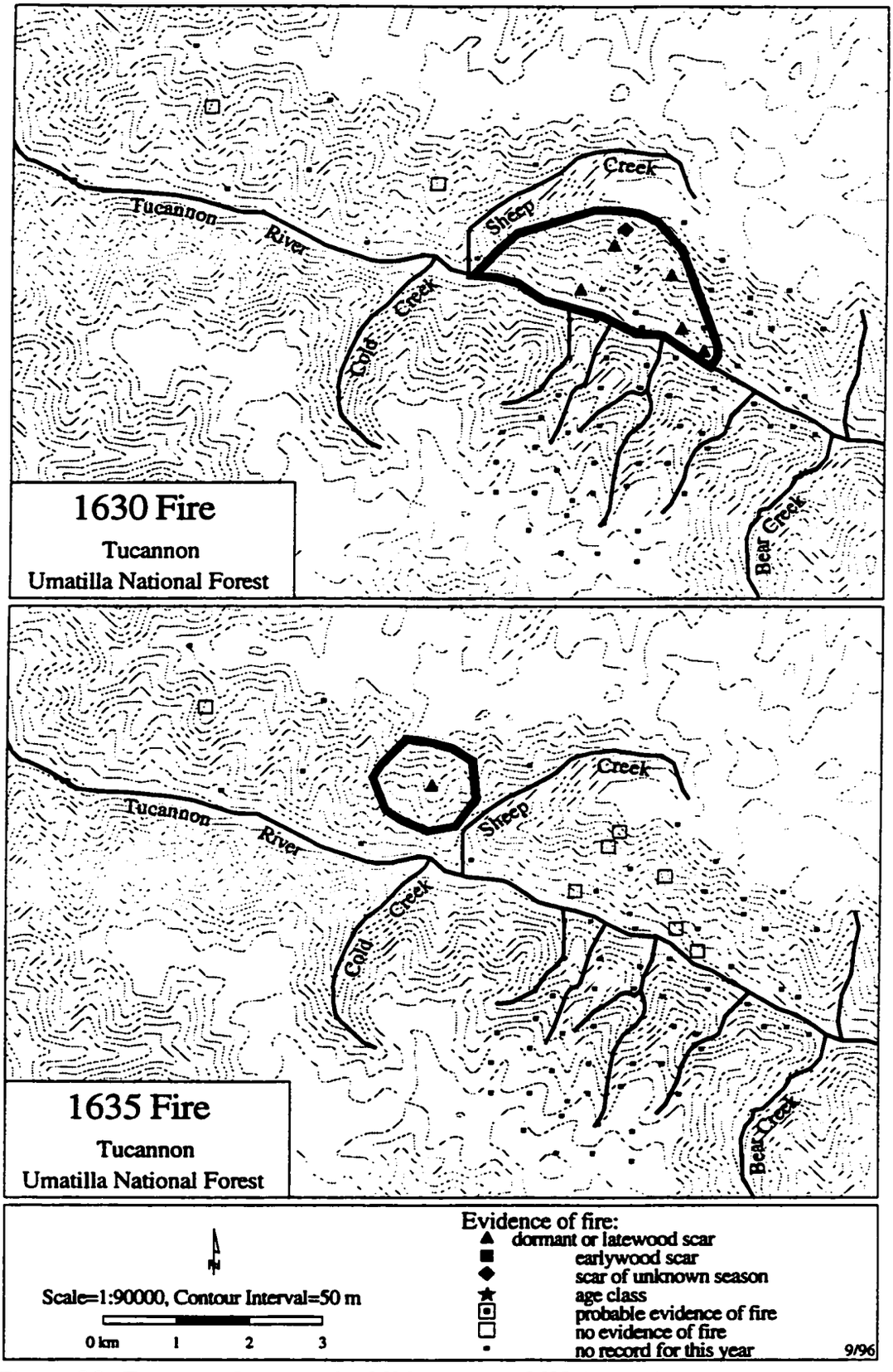


Figure 29. Tucannon fire maps for 1630 (top) and 1635 (bottom).

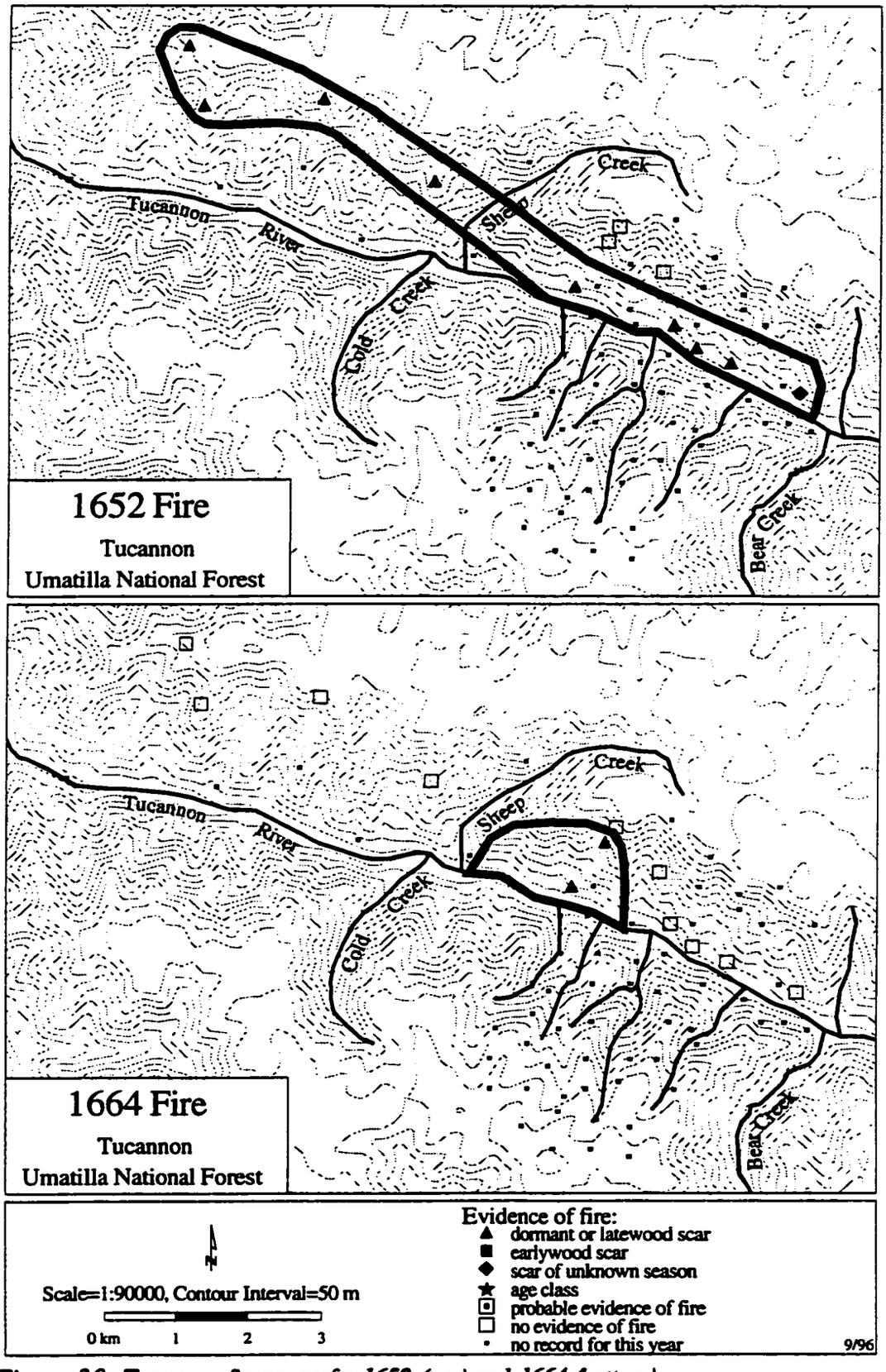


Figure 30. Tucannon fire maps for 1652 (top) and 1664 (bottom).

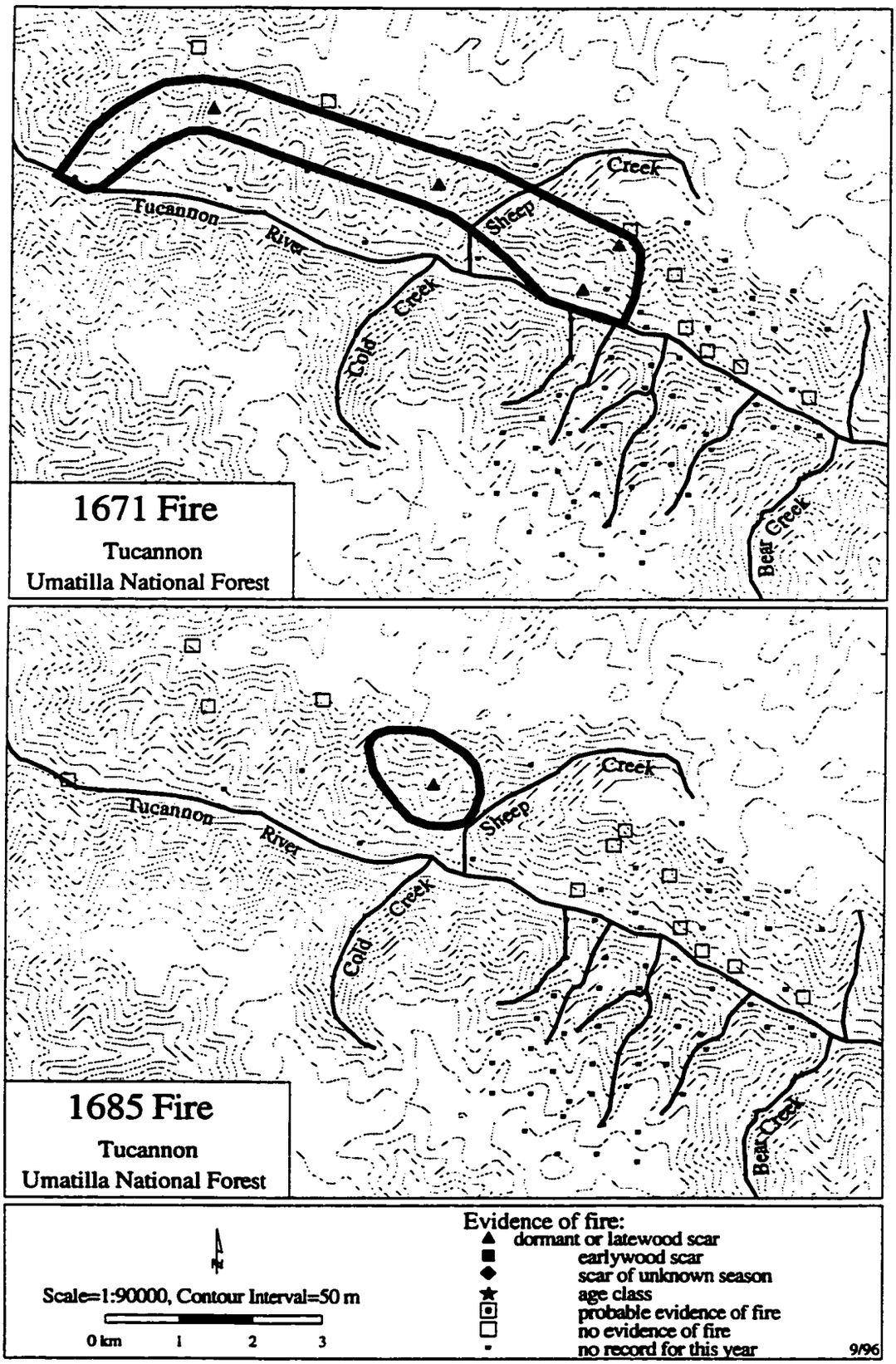


Figure 31. Tucannon fire maps for 1671 (top) and 1685 (bottom).

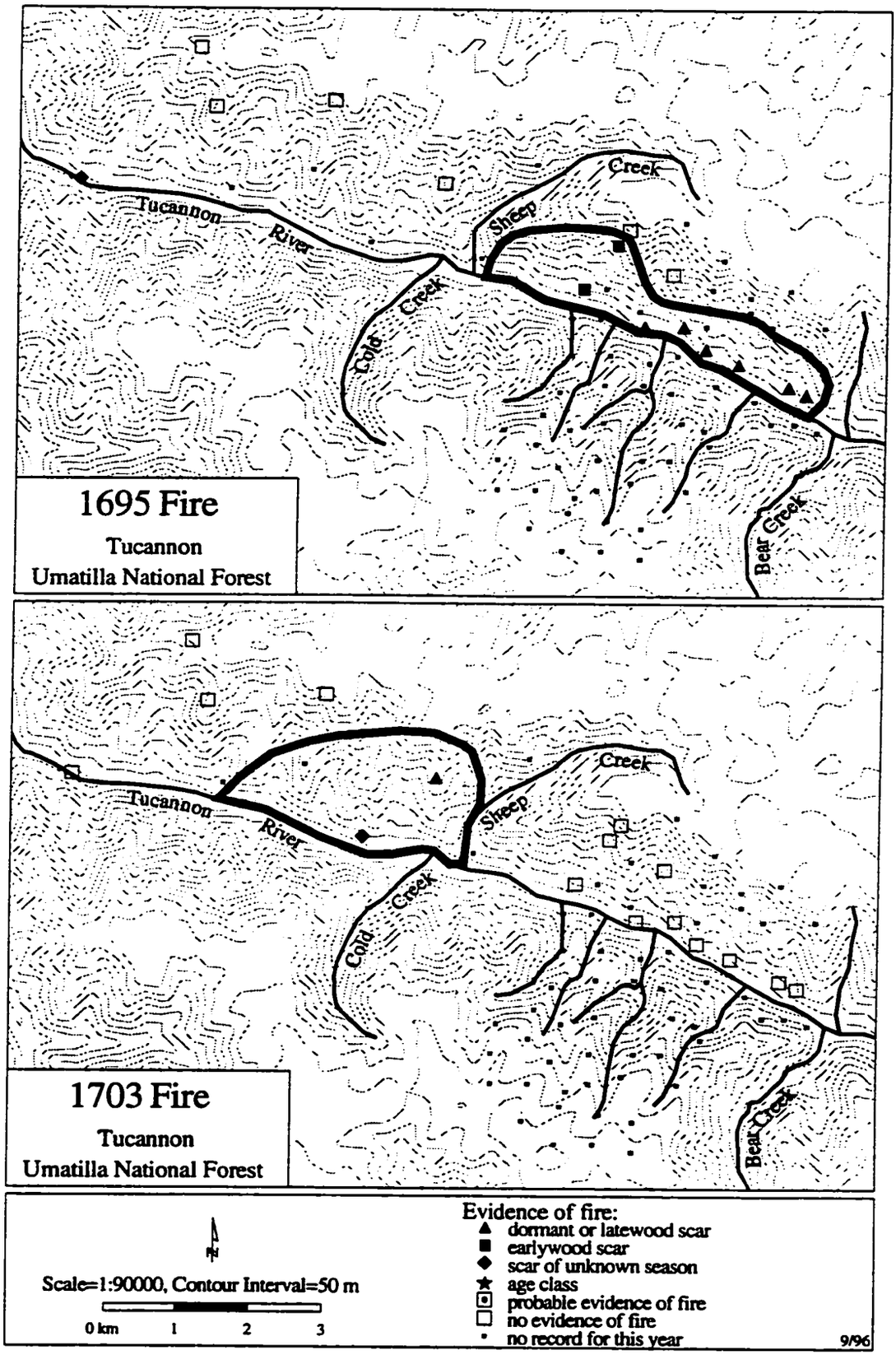


Figure 32. Tucannon fire maps for 1695 (top) and 1703 (bottom).

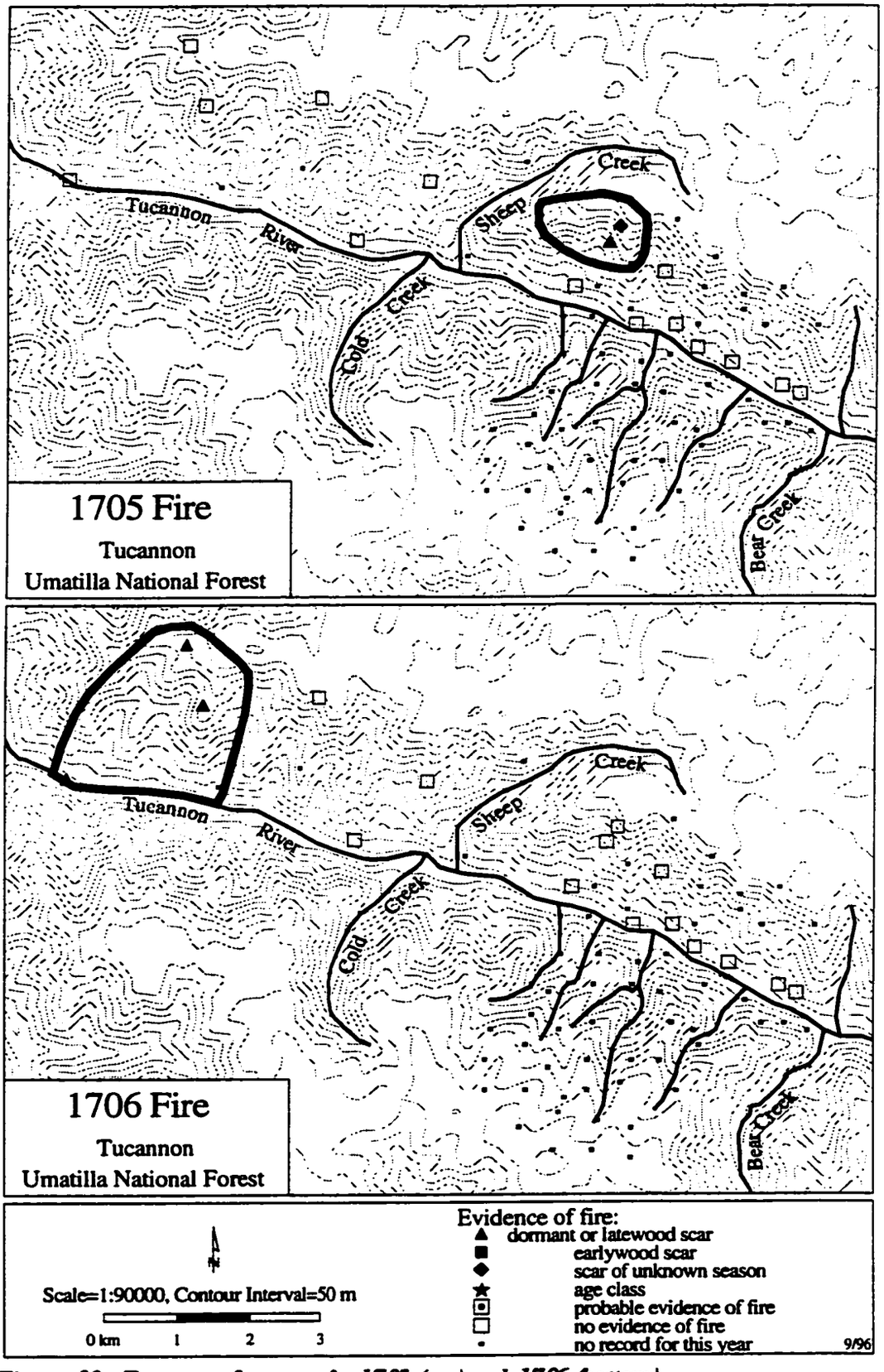


Figure 33. Tucannon fire maps for 1705 (top) and 1706 (bottom).

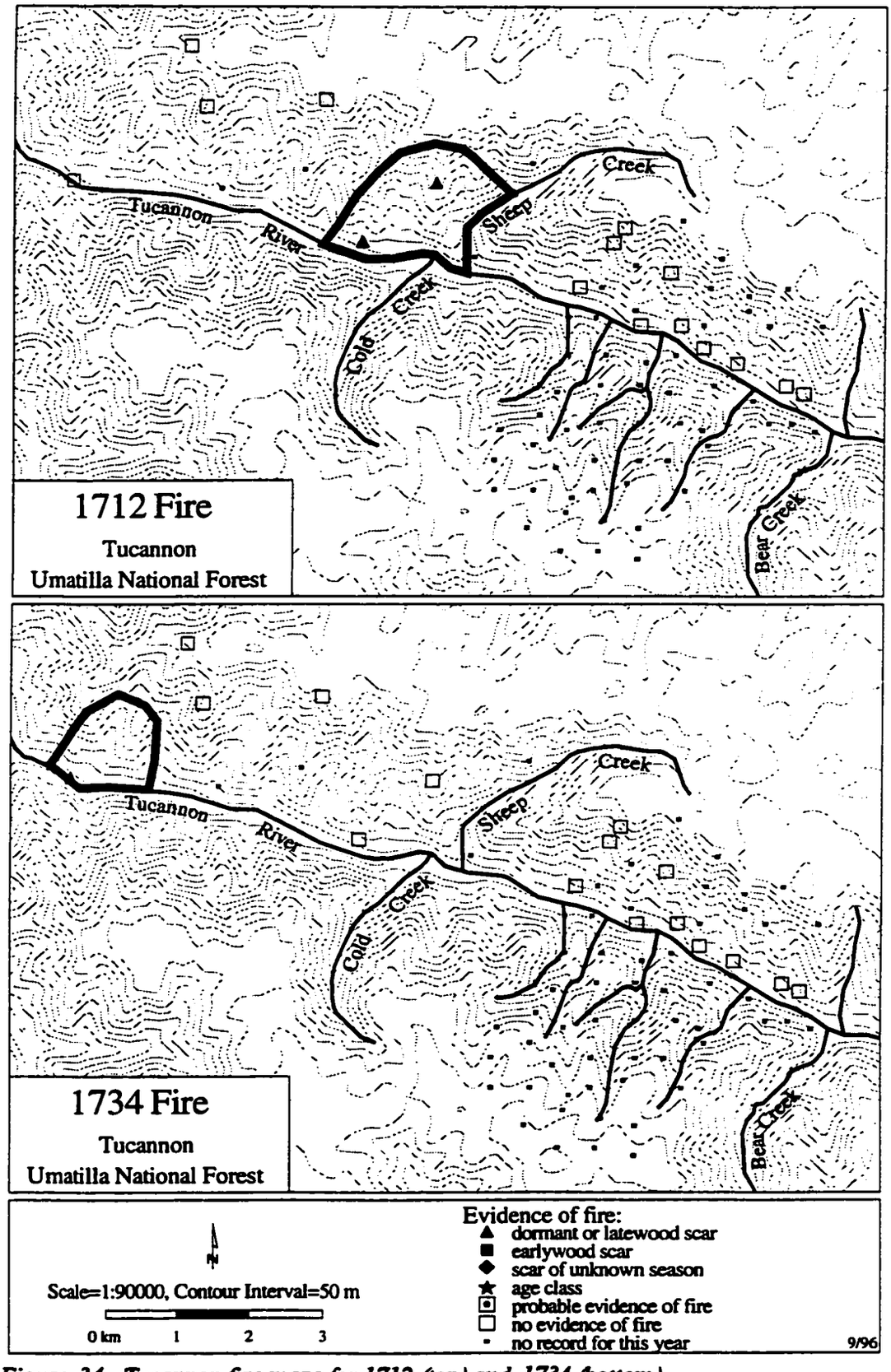


Figure 34. Tucannon fire maps for 1712 (top) and 1734 (bottom).

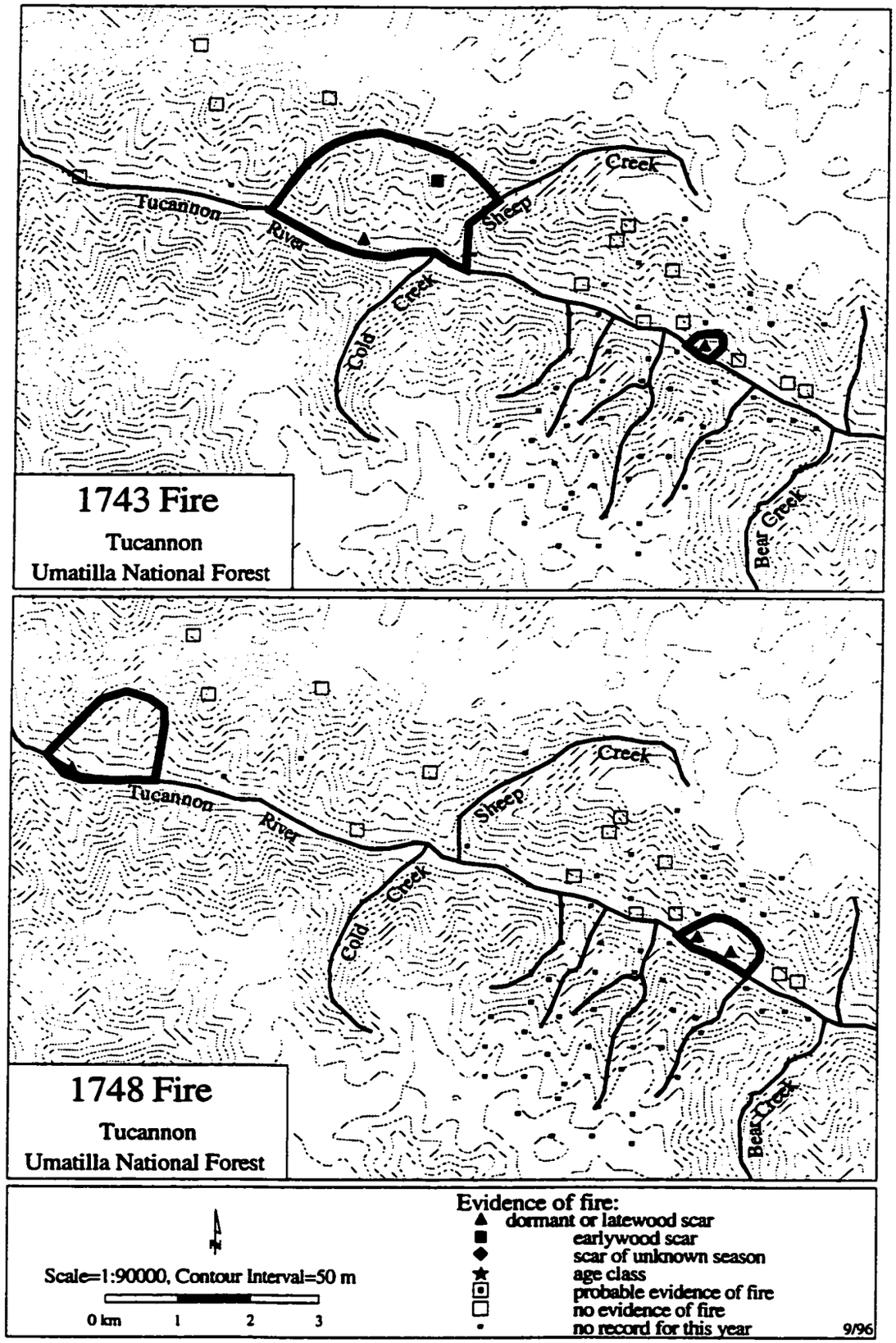


Figure 35. Tucannon fire maps for 1743 (top) and 1748 (bottom).

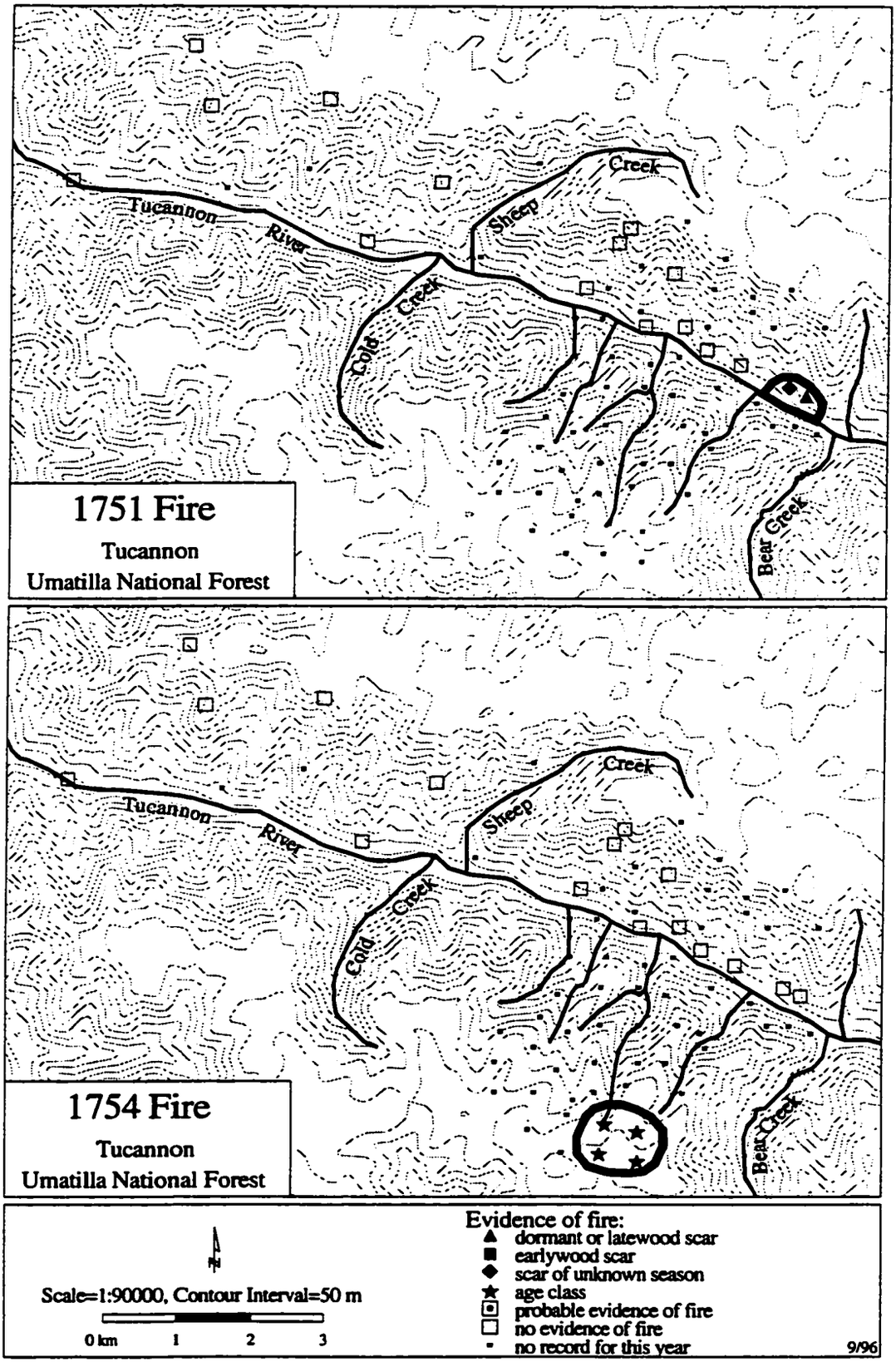


Figure 36. Tucannon fire maps for 1751 (top) and 1754 (bottom).

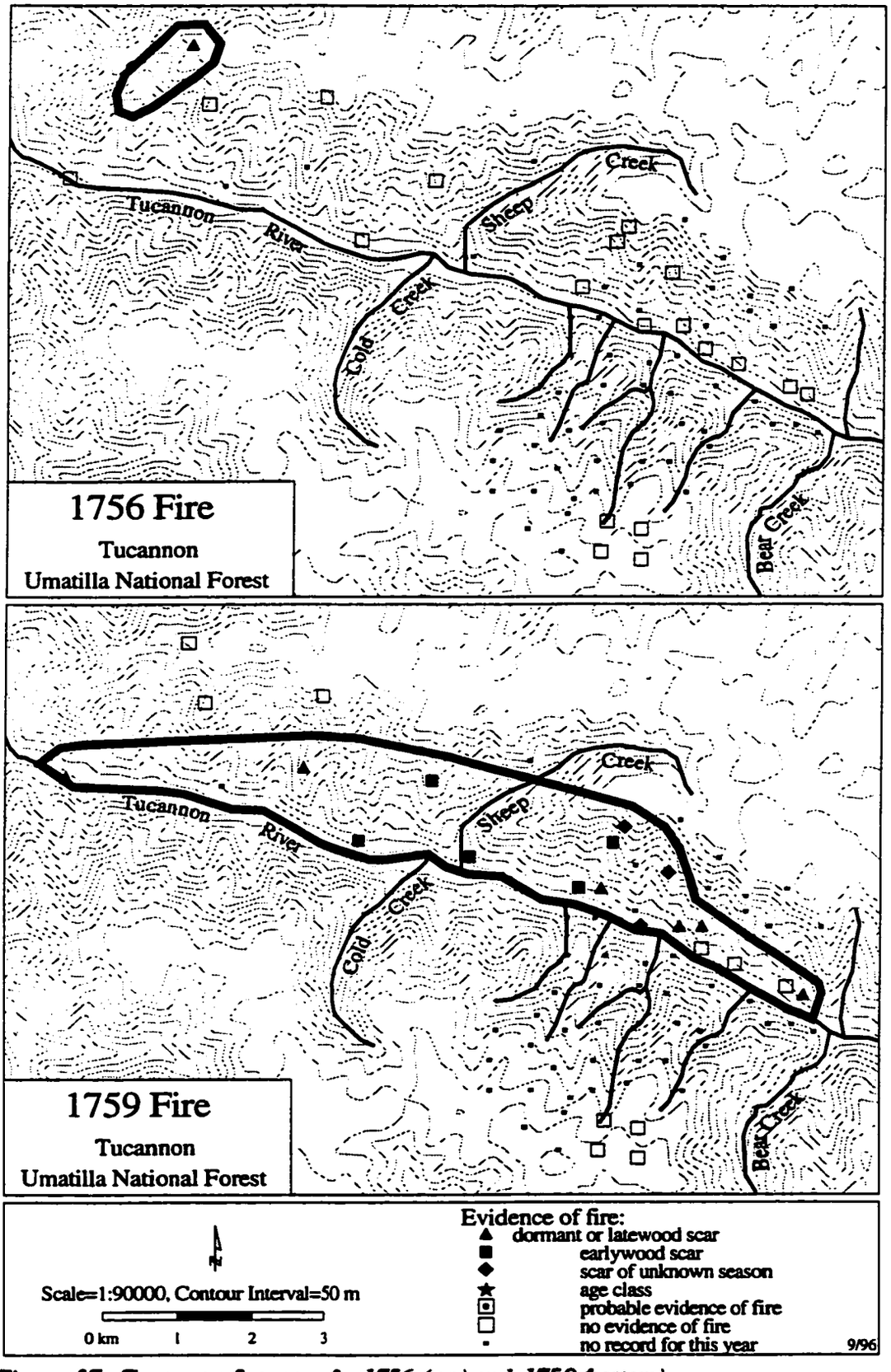


Figure 37. Tucannon fire maps for 1756 (top) and 1759 (bottom).

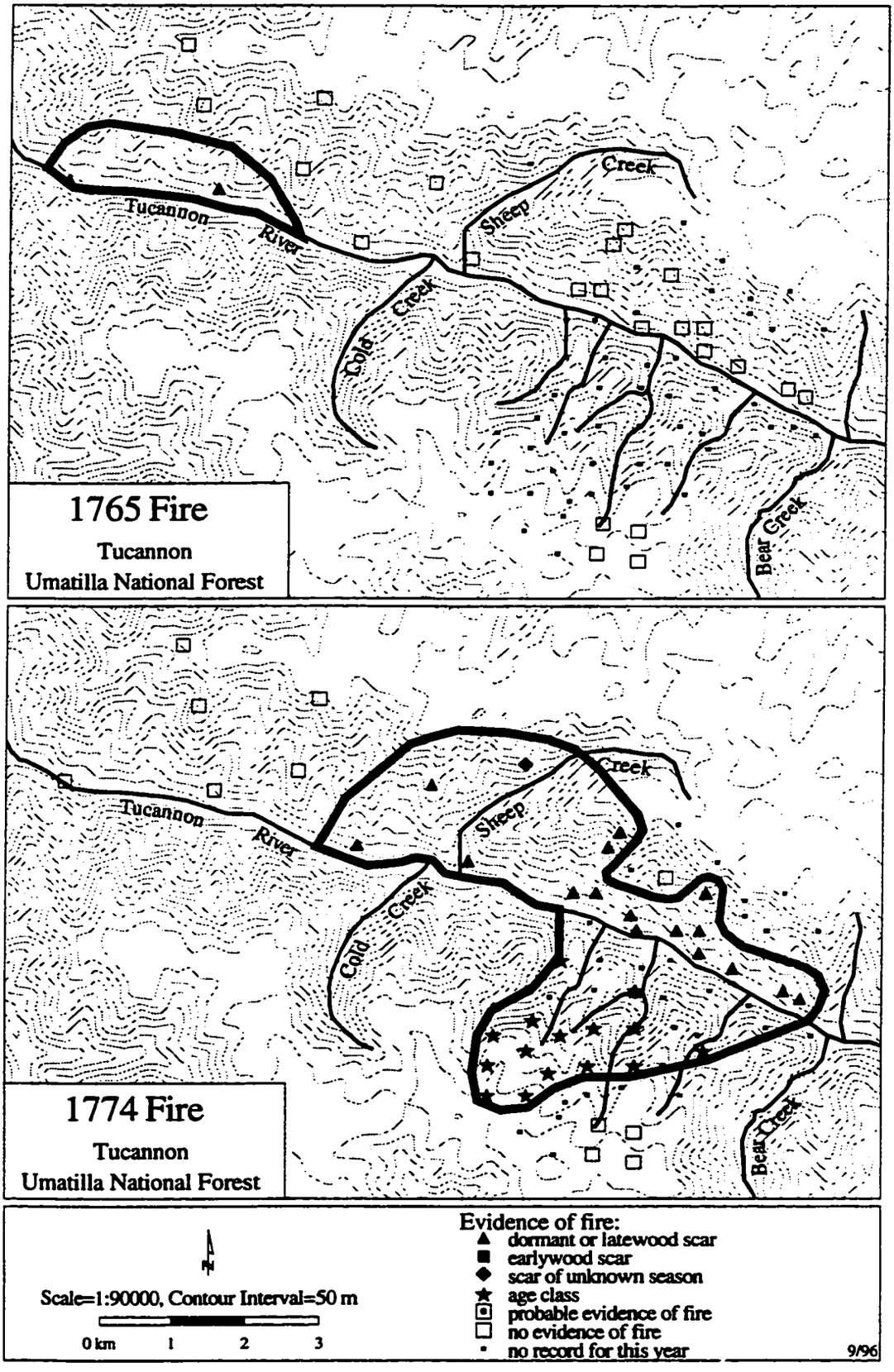


Figure 38. Tucannon fire maps for 1765 (top) and 1774 (bottom).

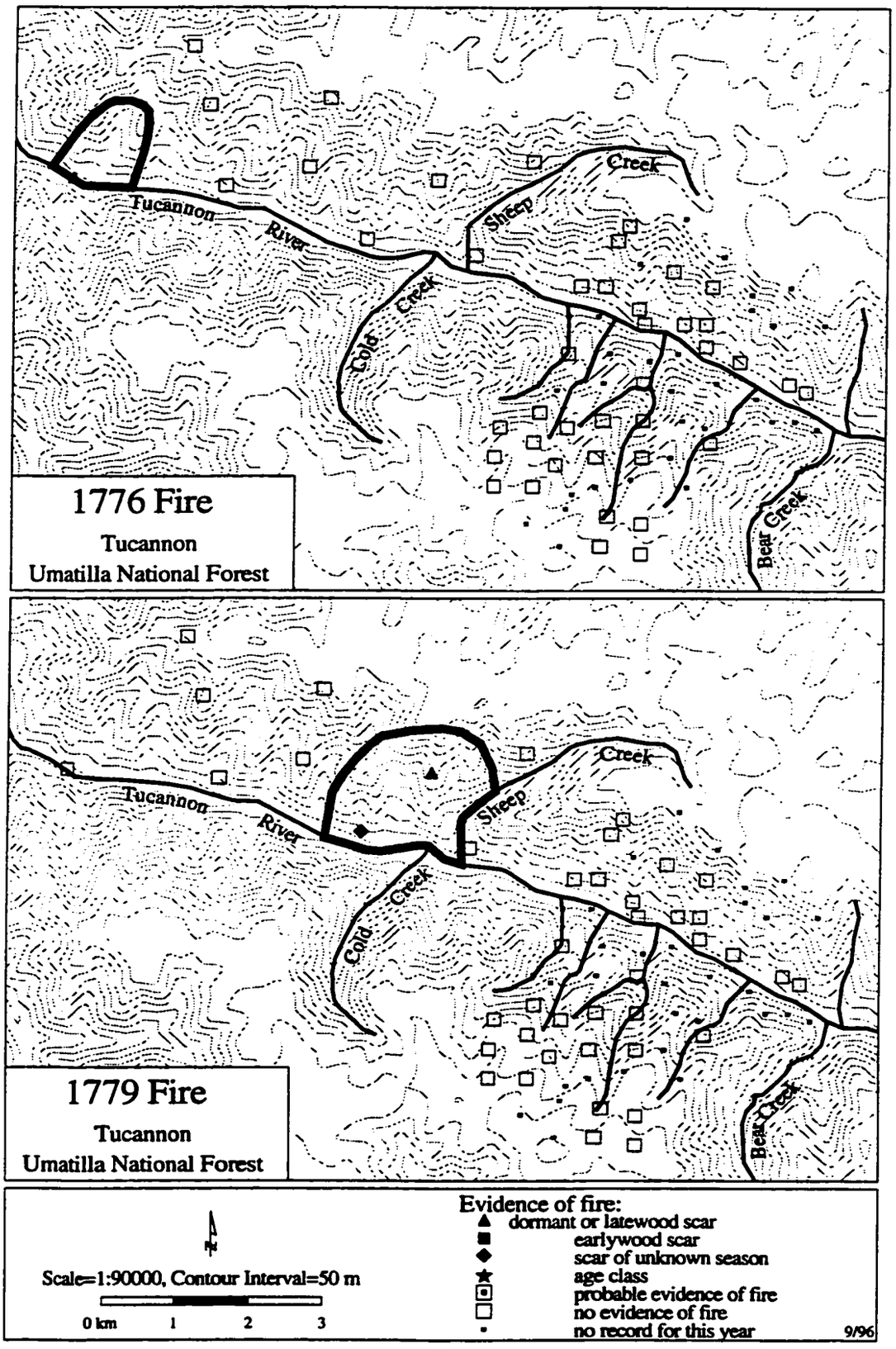


Figure 39. Tucannon fire maps for 1776 (top) and 1779 (bottom).

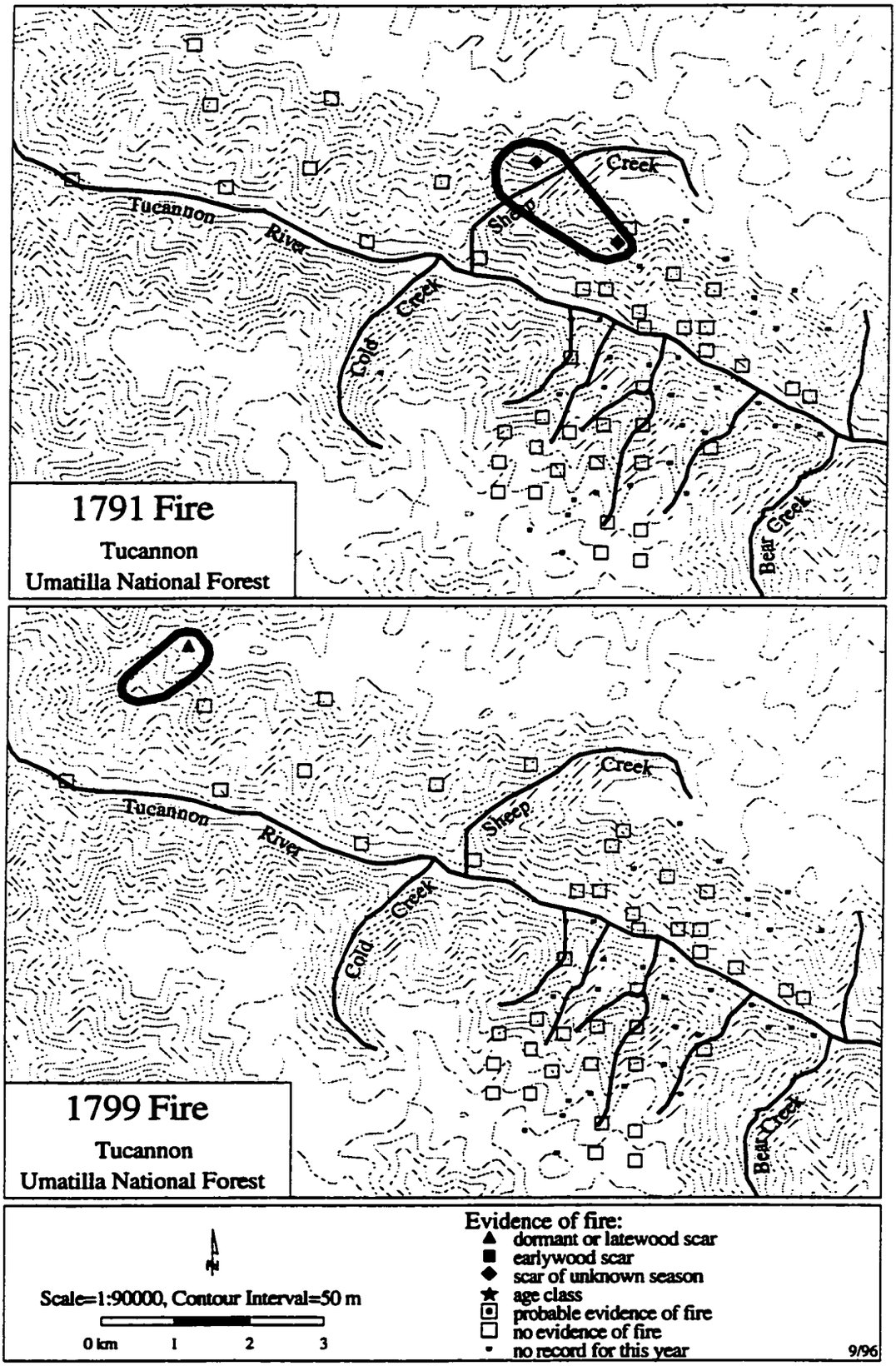


Figure 40. Tucannon fire maps for 1791 (top) and 1799 (bottom).

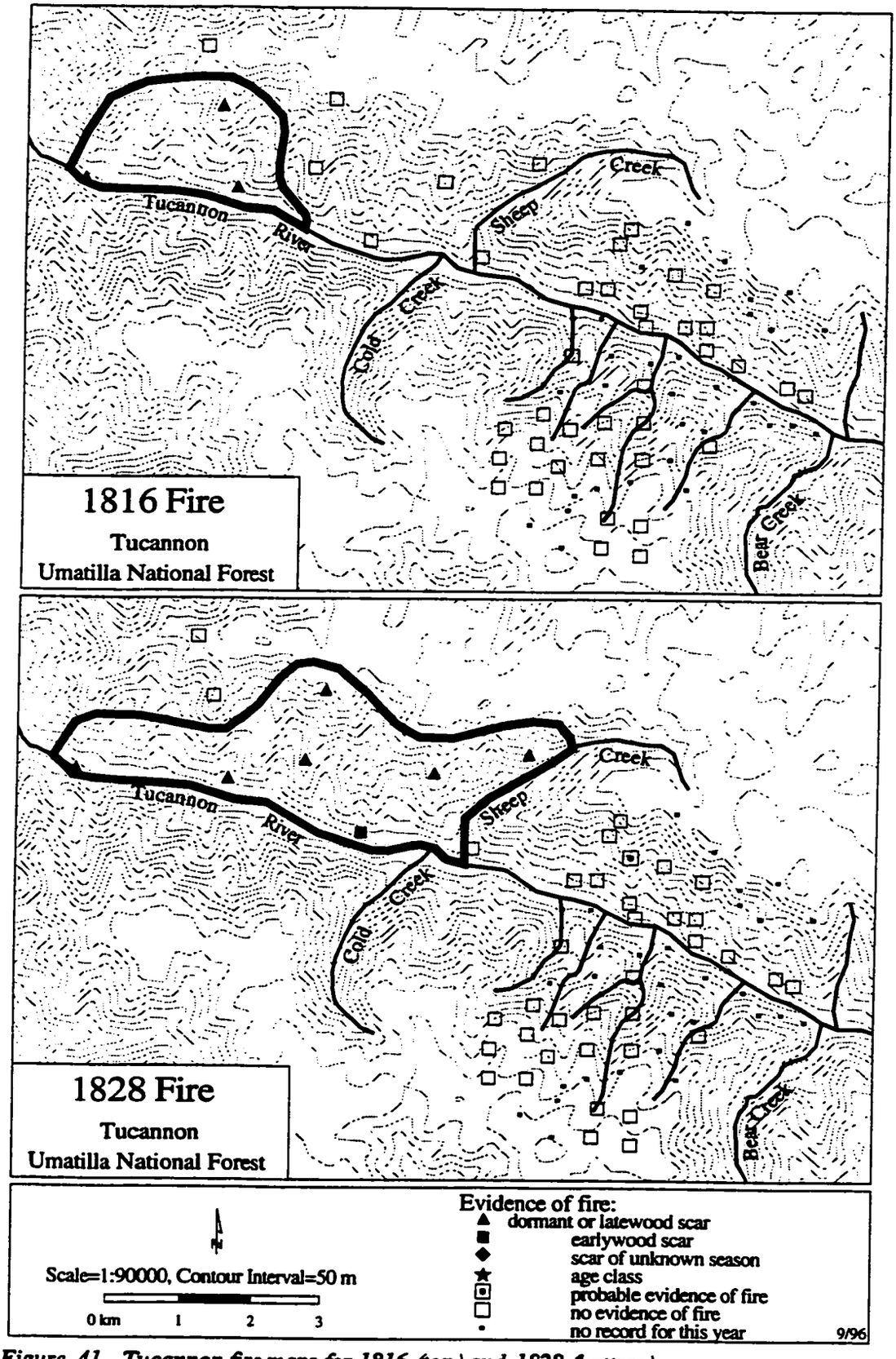


Figure 41. Tucannon fire maps for 1816 (top) and 1828 (bottom).

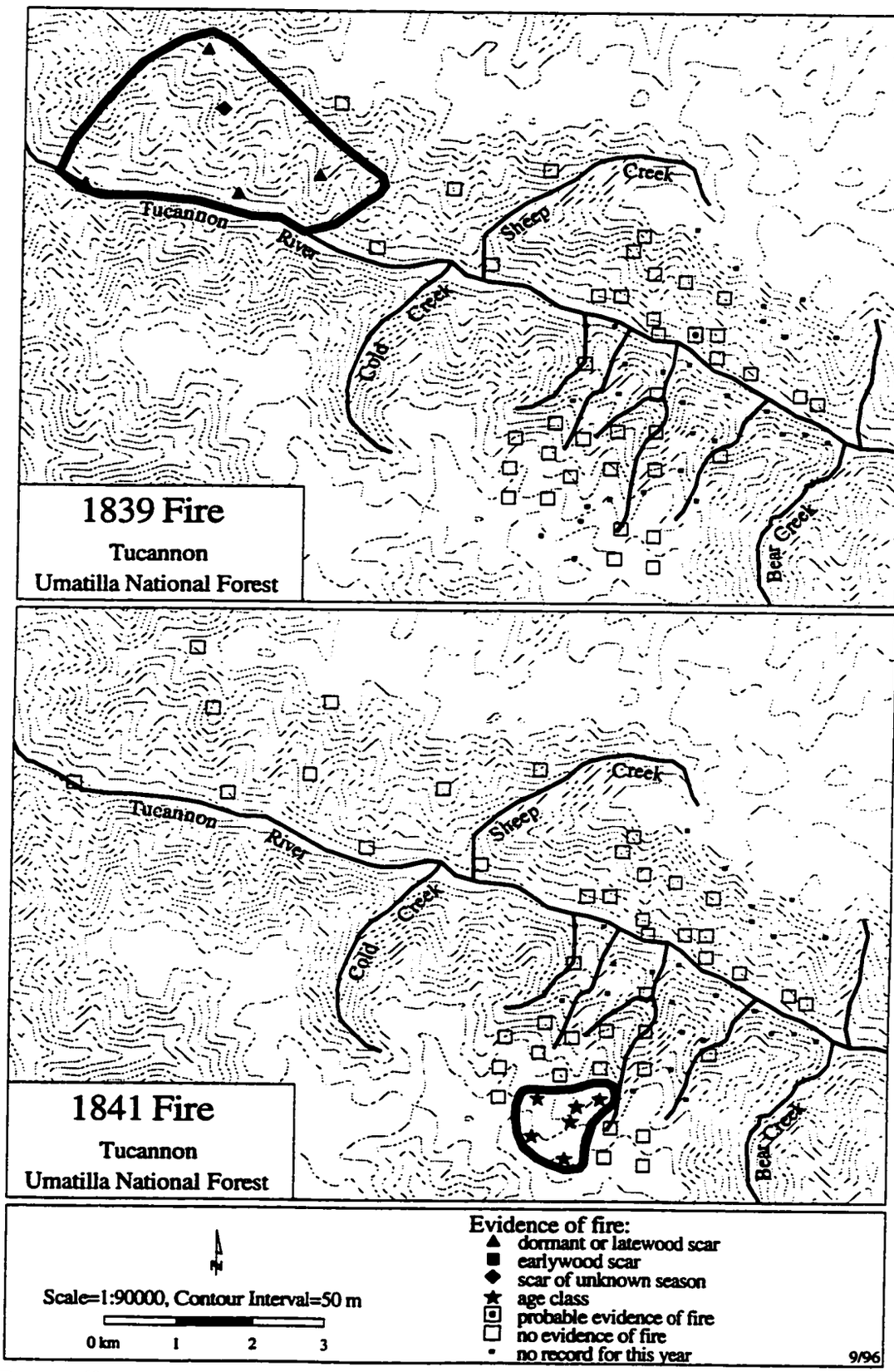


Figure 42. Tucannon fire maps for 1839 (top) and 1841 (bottom).

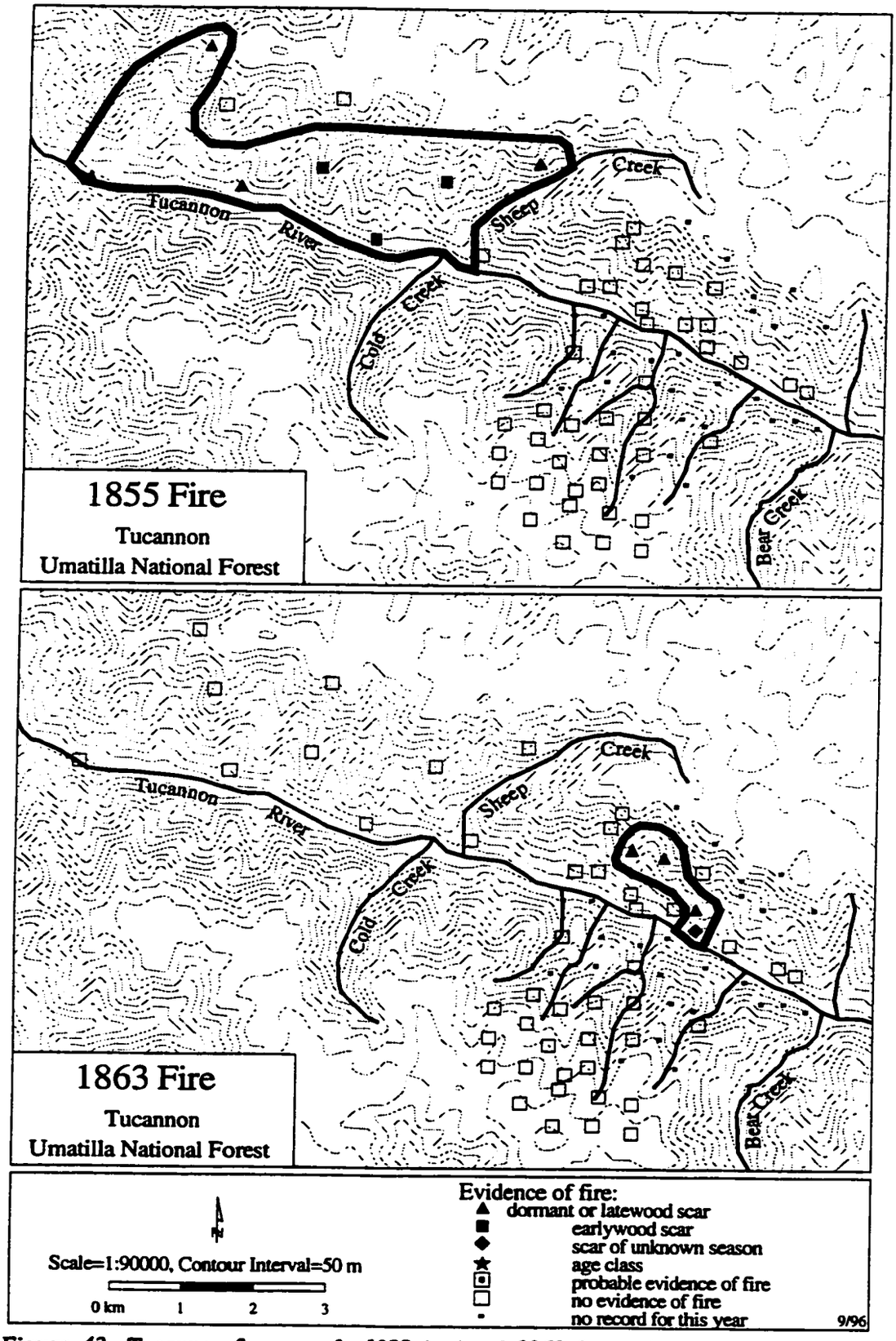


Figure 43. Tucannon fire maps for 1855 (top) and 1863 (bottom).

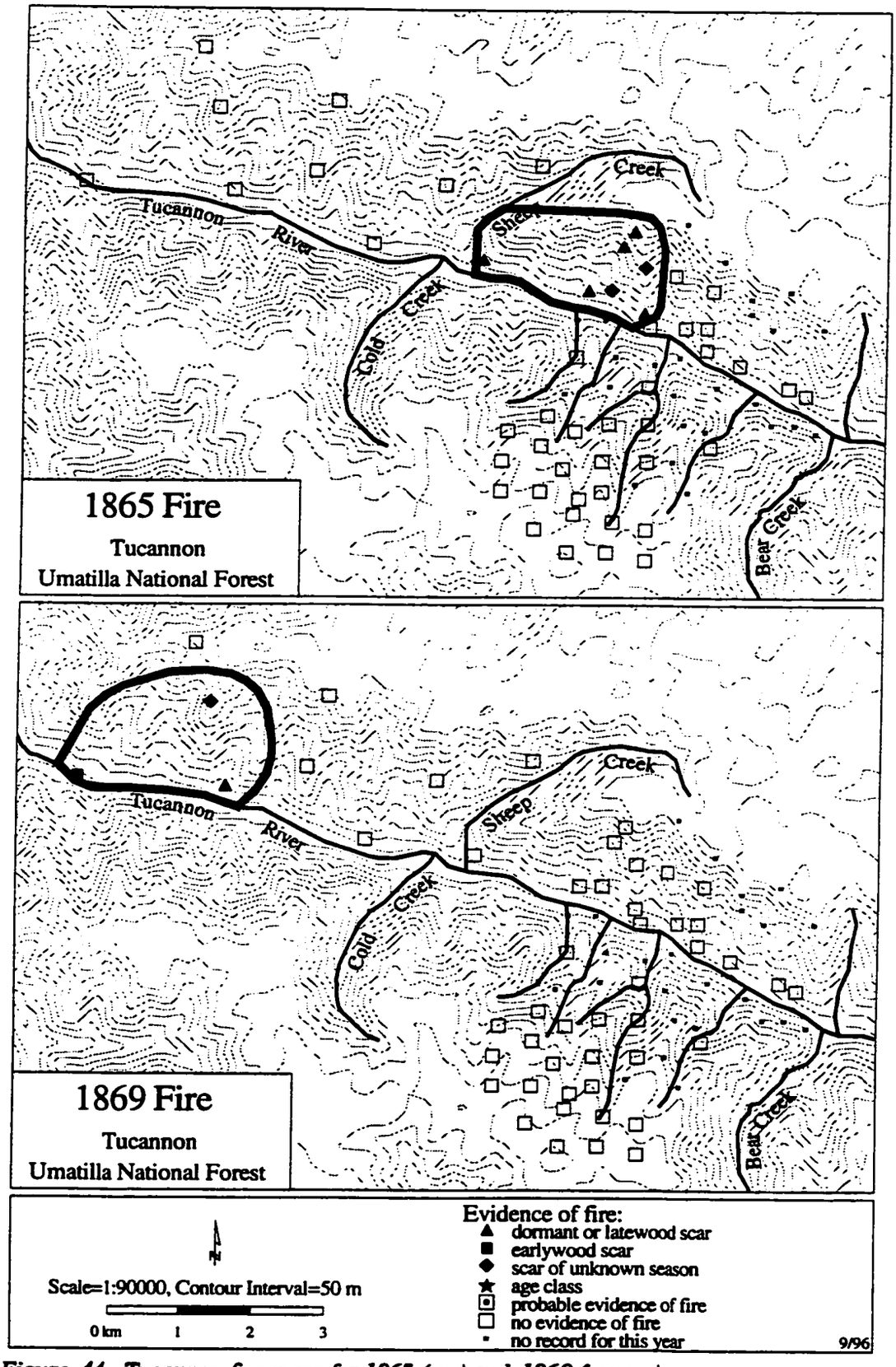


Figure 44. Tucannon fire maps for 1865 (top) and 1869 (bottom).

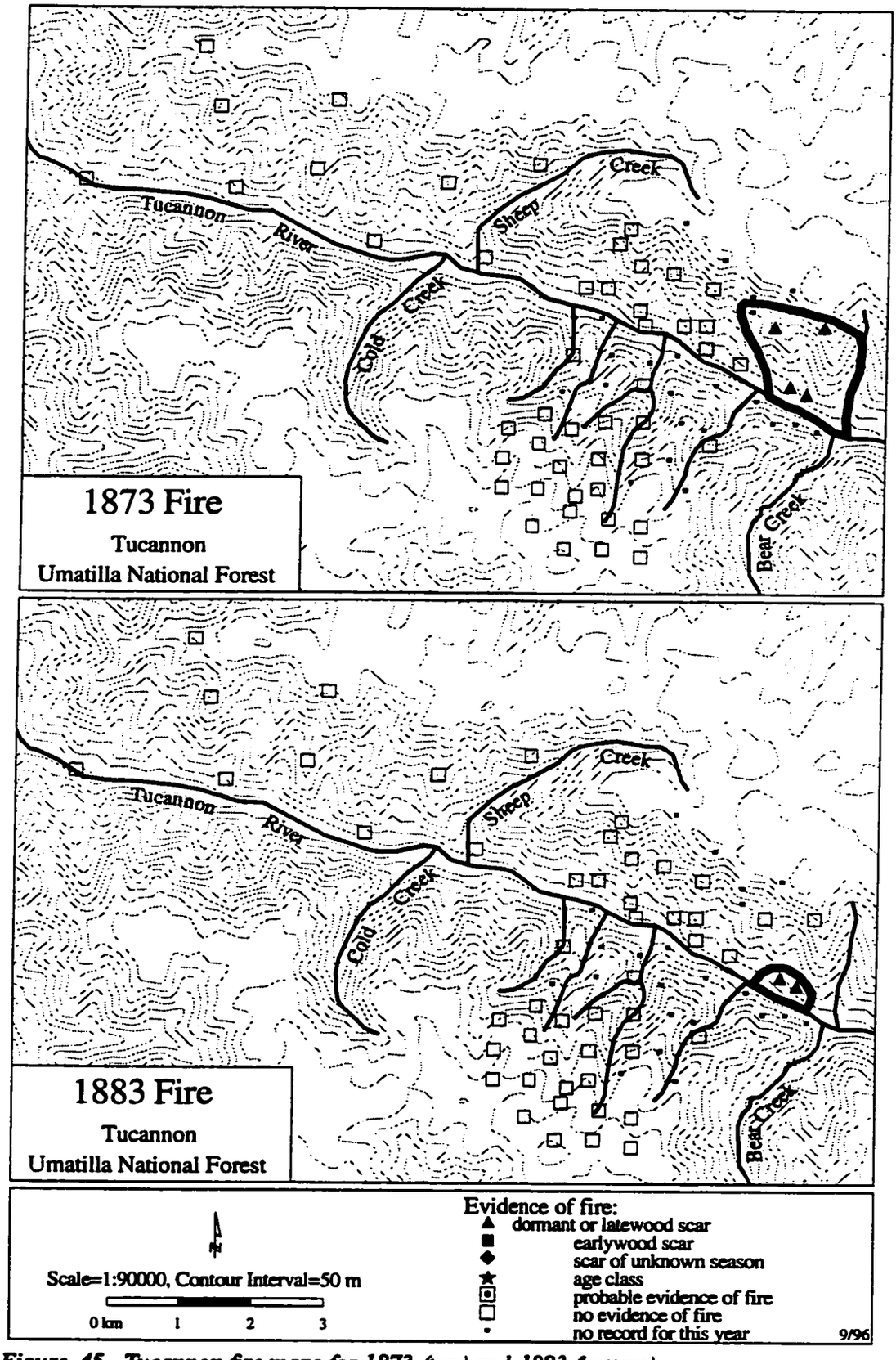


Figure 45. Tucannon fire maps for 1873 (top) and 1883 (bottom).

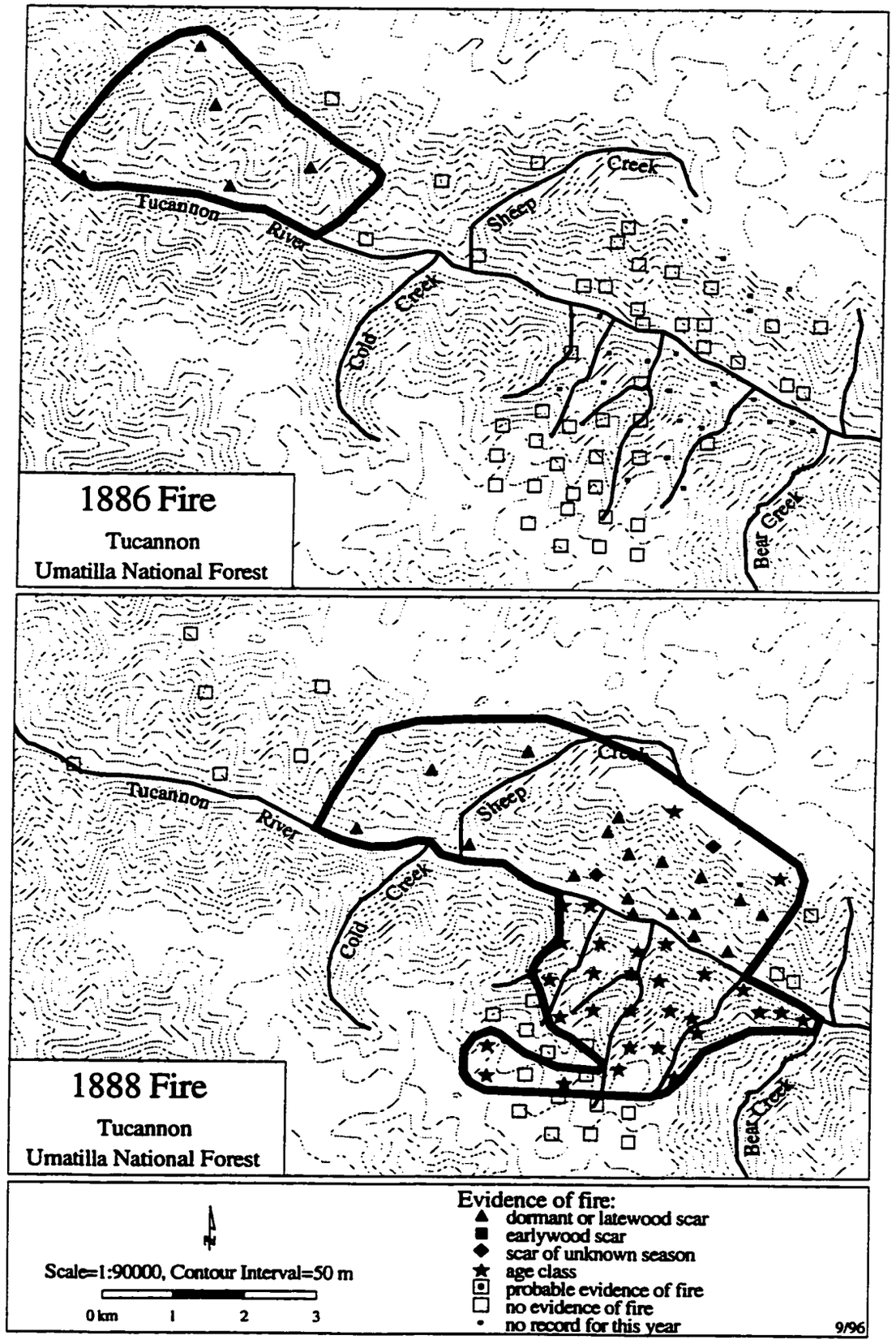


Figure 46. Tucannon fire maps for 1886 (top) and 1888 (bottom).

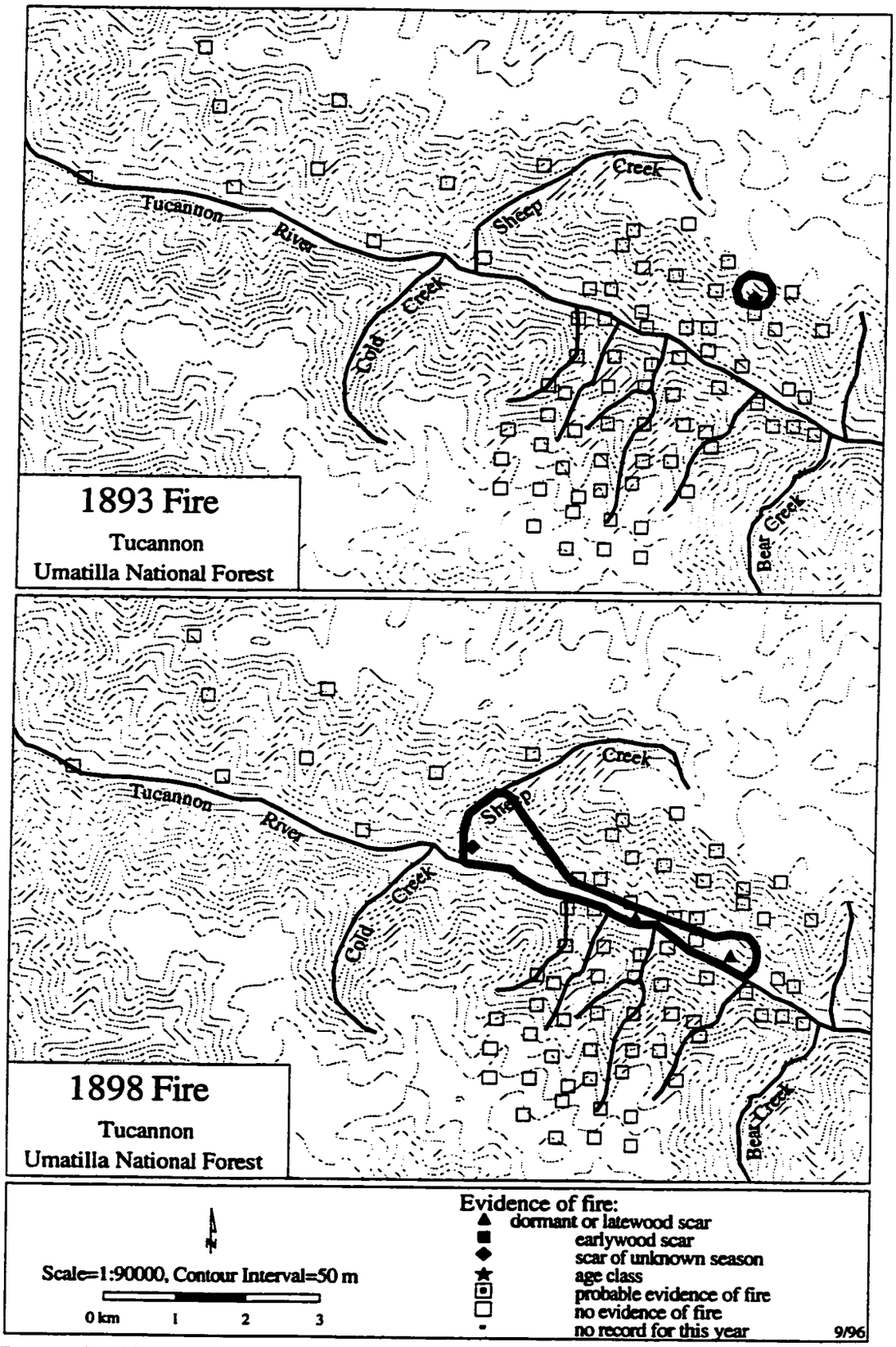


Figure 47. Tucannon fire maps for 1893 (top) and 1898 (bottom).

APPENDIX E: IMNAHA FIRE MAPS

Evidence of fire was mapped at Imnaha for every year in dry forests that had at least two scars and for every fire event identified in mesic forests. Symbols indicate whether the evidence of fire was cohorts or scars. If the later, the intra-annular position of the scar is also indicated. Plots indicating as having probable evidence of fire are those for which the only evidence was an abrupt increase or decrease in ring width. Plots having no evidence of fire in a given year include plots at which no sampled trees were alive during that year as well as plots with trees that were less susceptible to scarring (i.e., the fire year occurred before the first scar). Plots indicated as having no record for a given year are plots that were sampled but had no trees recording during that year. Fire boundaries are shown as a heavy line.

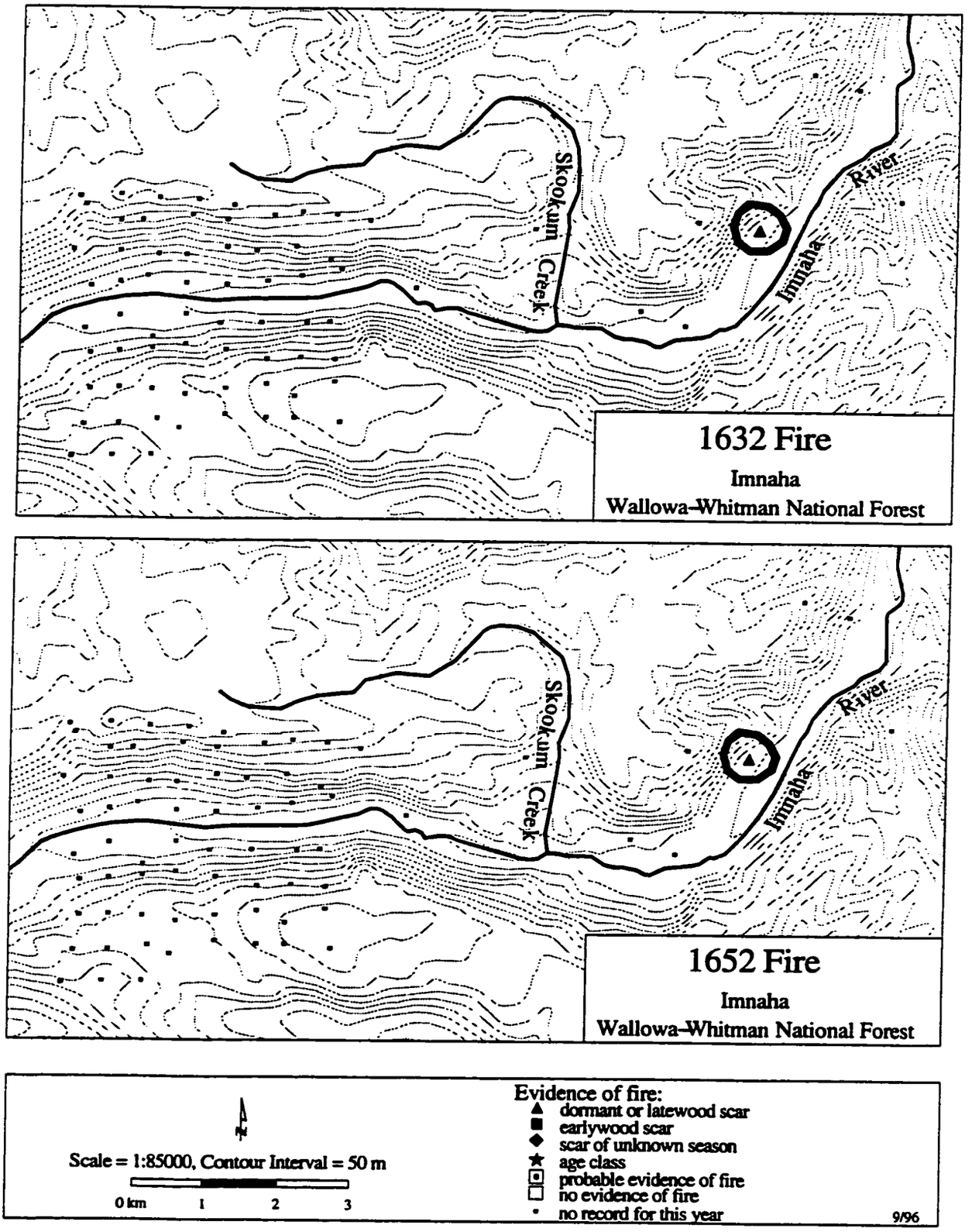


Figure 48. Imnaha fire maps for 1632 (top) and 1652 (bottom) fires.

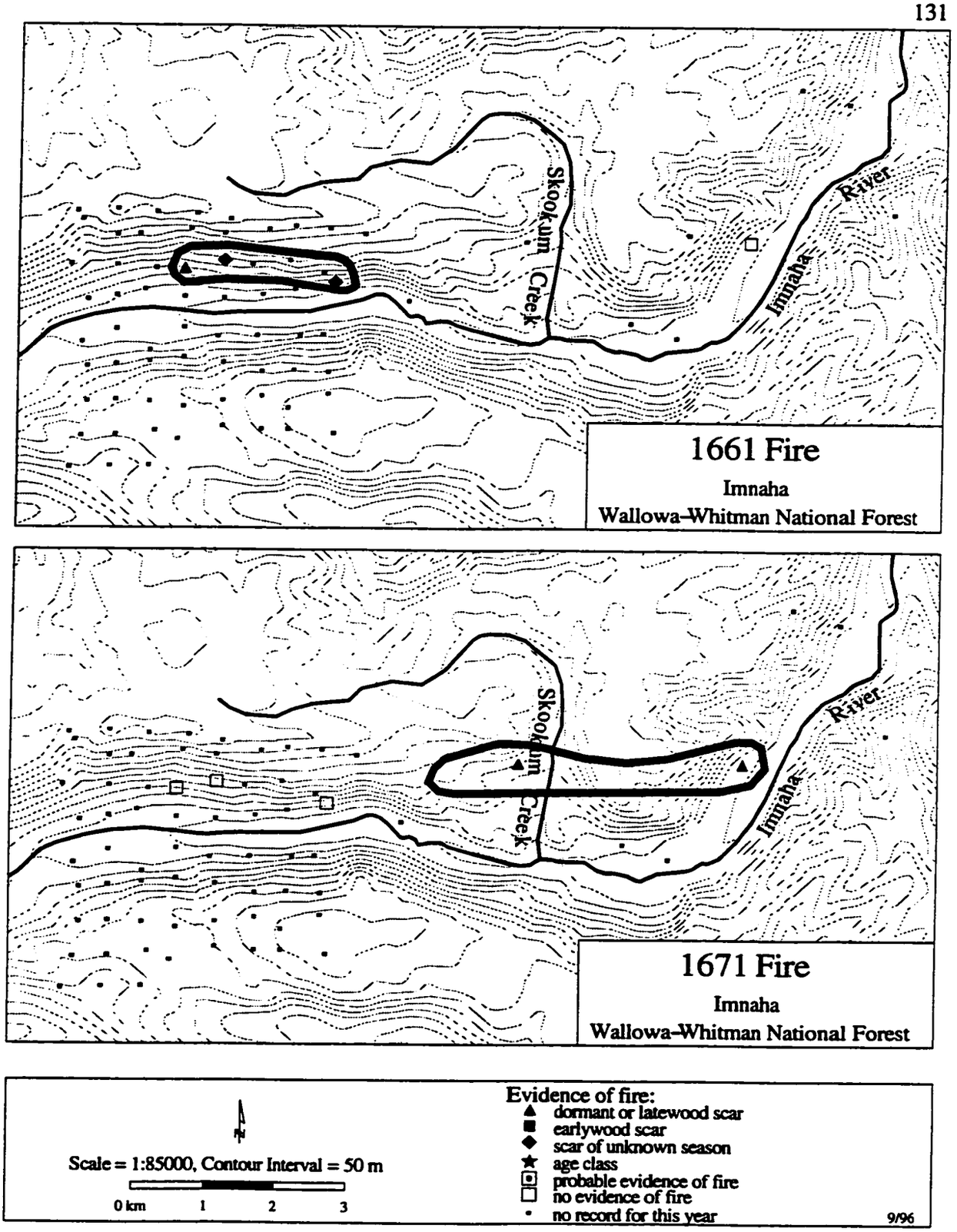


Figure 49. Imnaha fire maps for 1661 (top) and 1671 (bottom) fires.

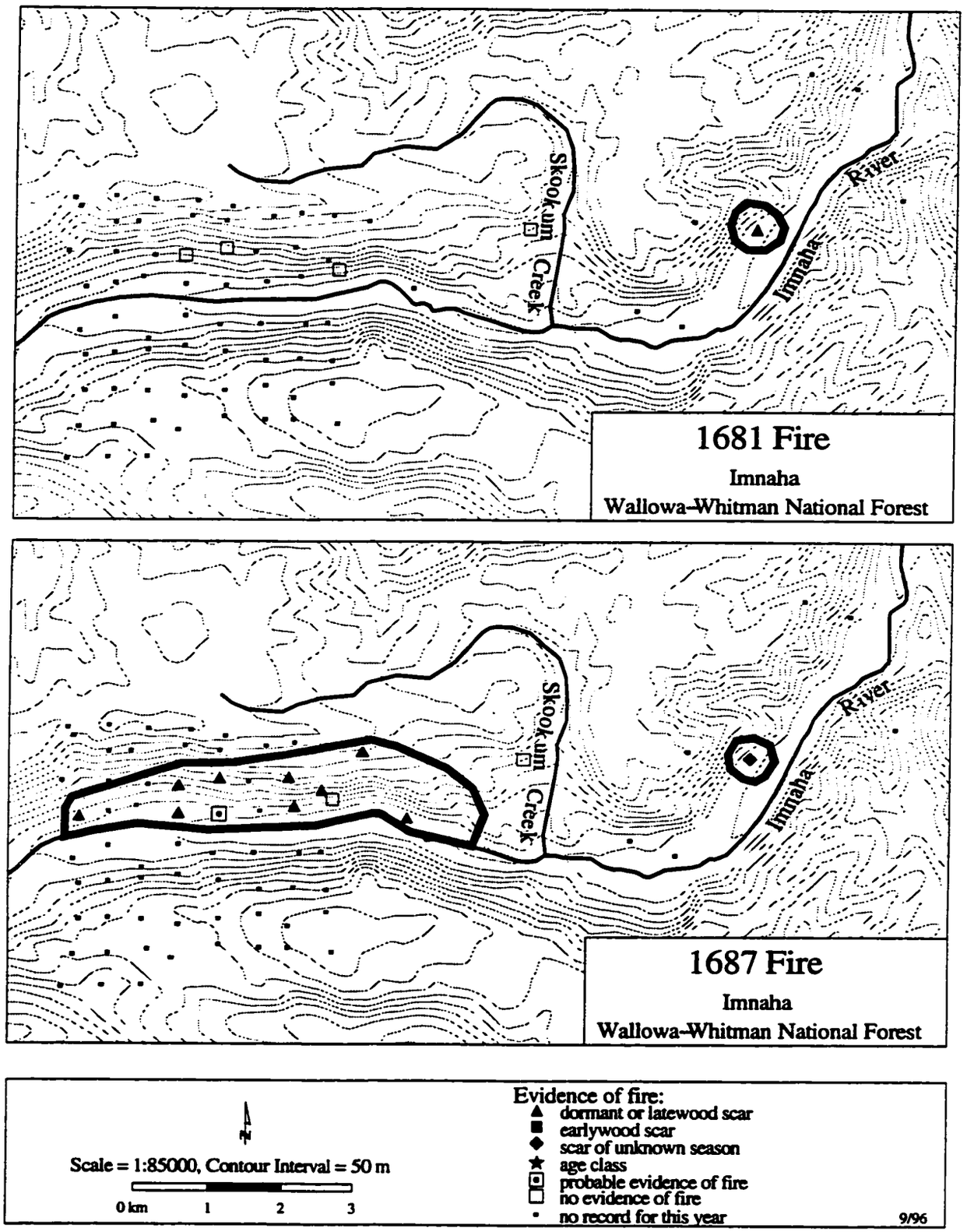


Figure 50. Imnaha fire maps for 1681 (top) and 1687 (bottom) fires.

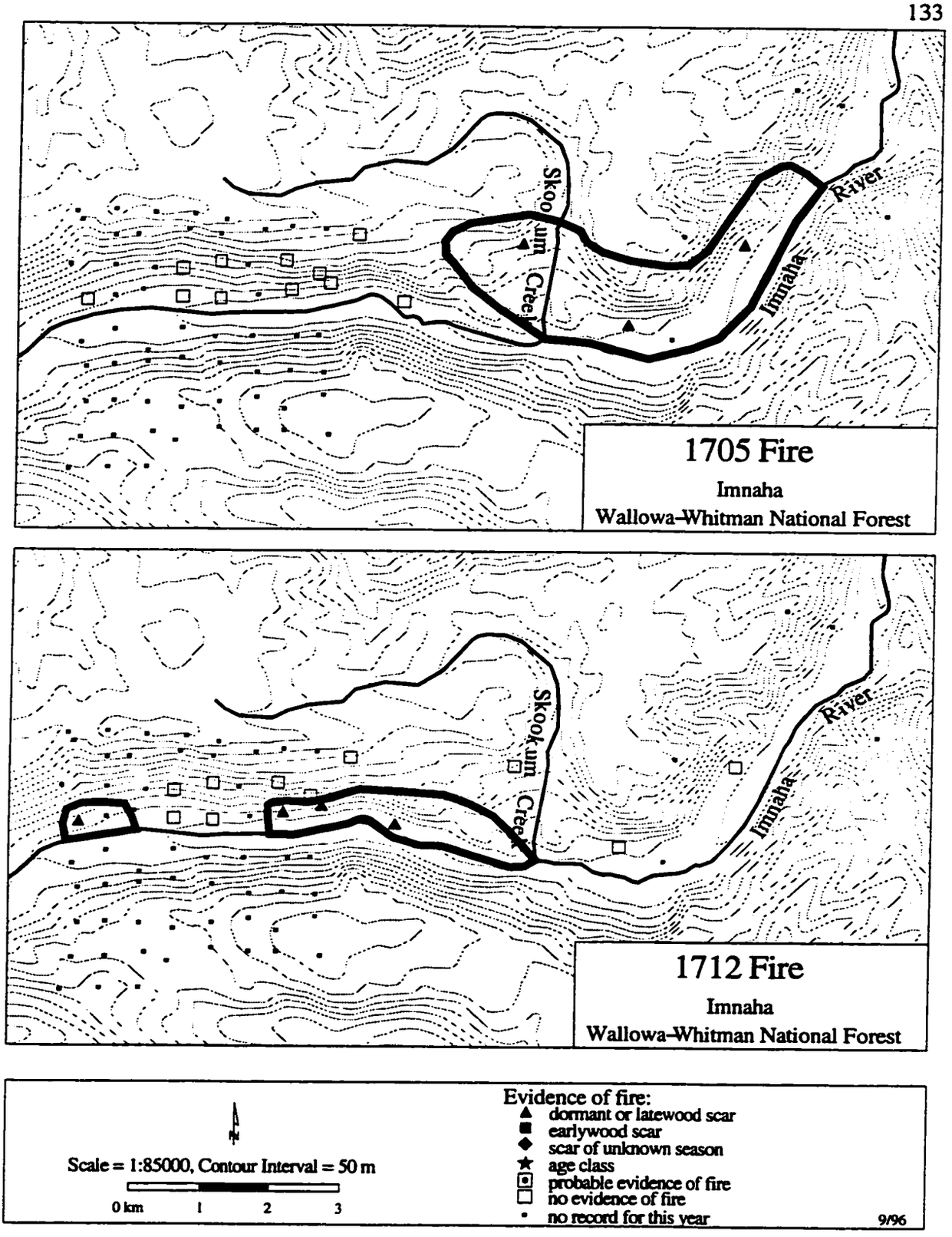


Figure 51. Imnaha fire maps for 1705 (top) and 1712 (bottom) fires.

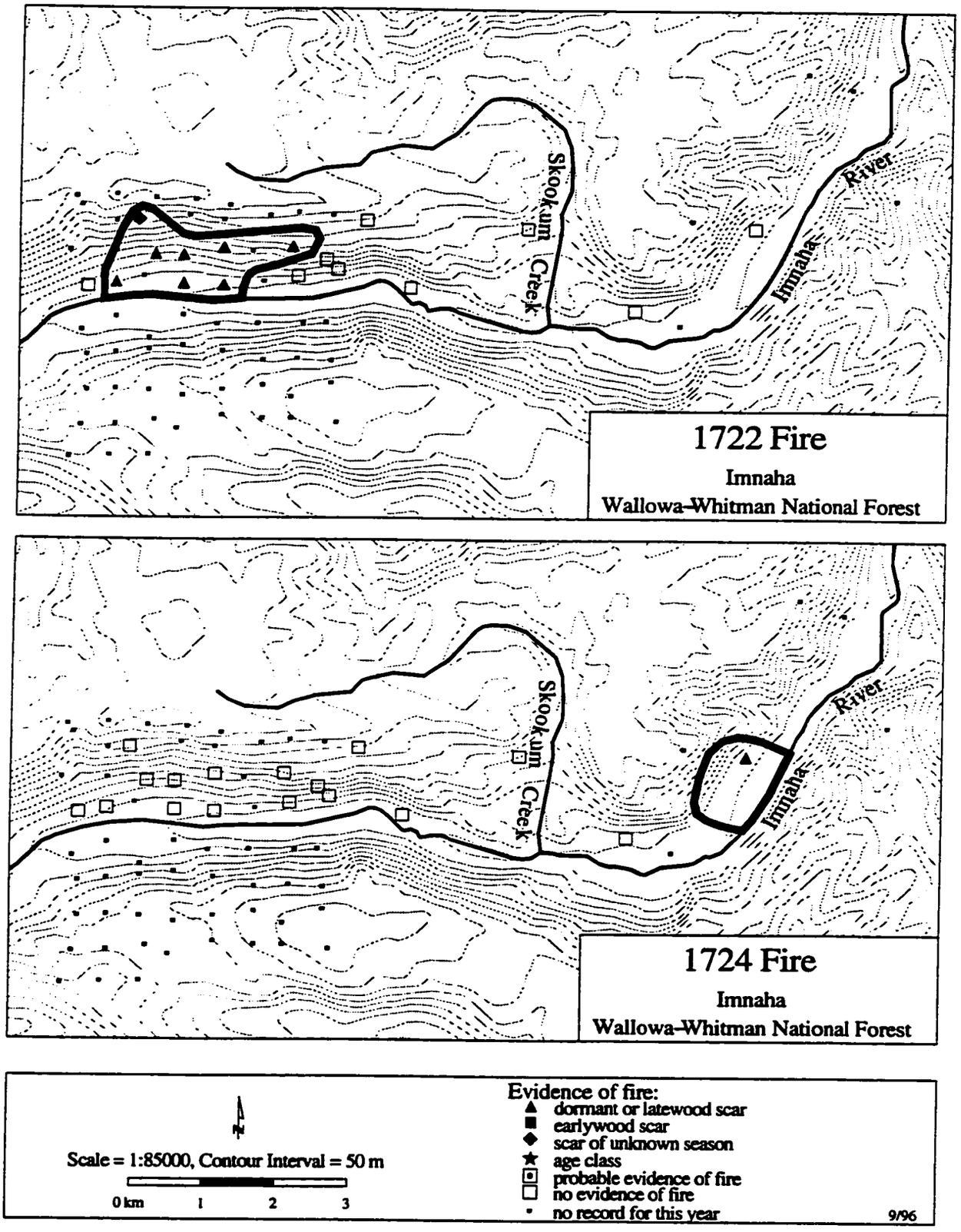


Figure 52. Imnaha fire maps for 1722 (top) and 1724 (bottom) fires.

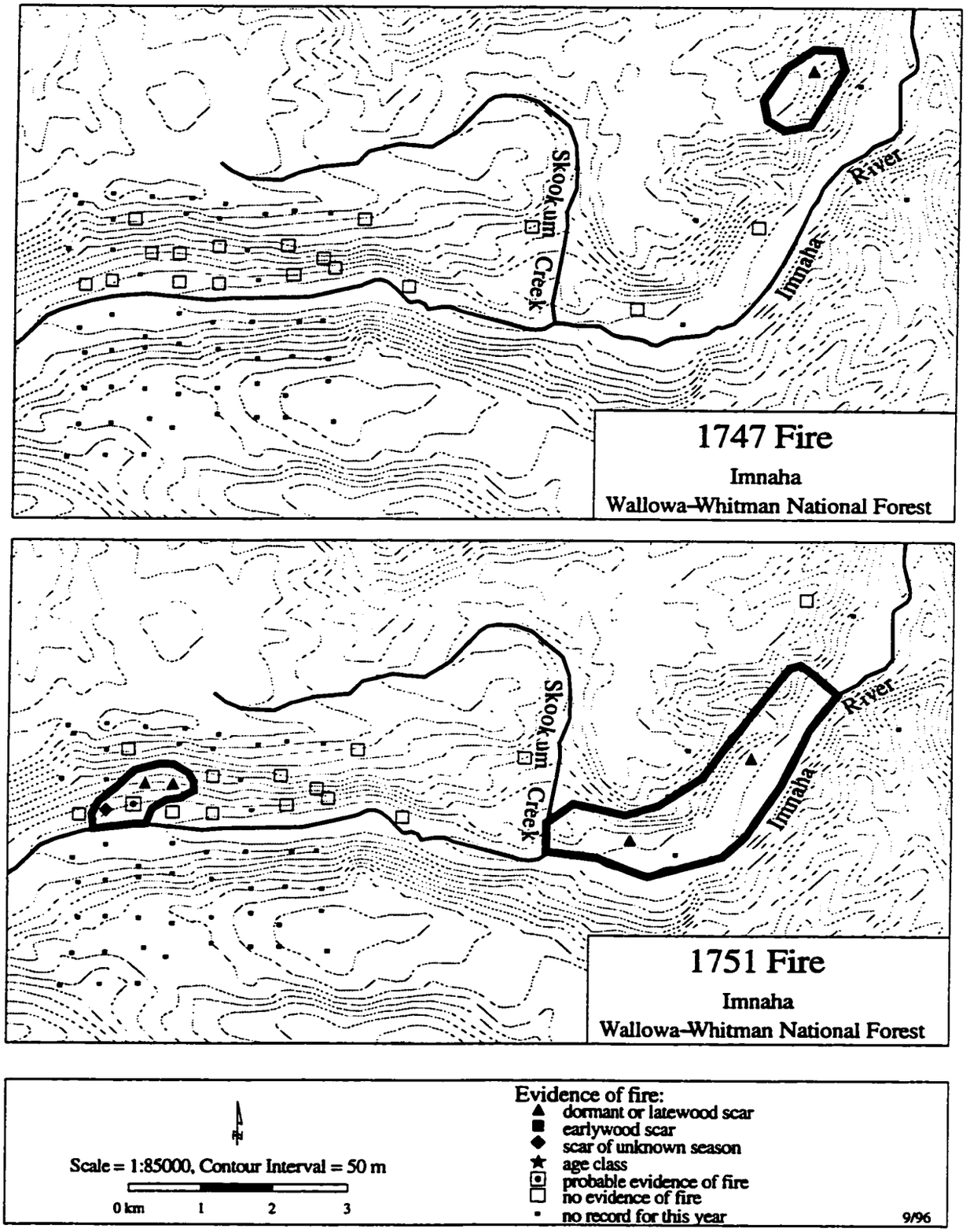


Figure 53. Imnaha fire maps for 1747 (top) and 1751 (bottom) fires.

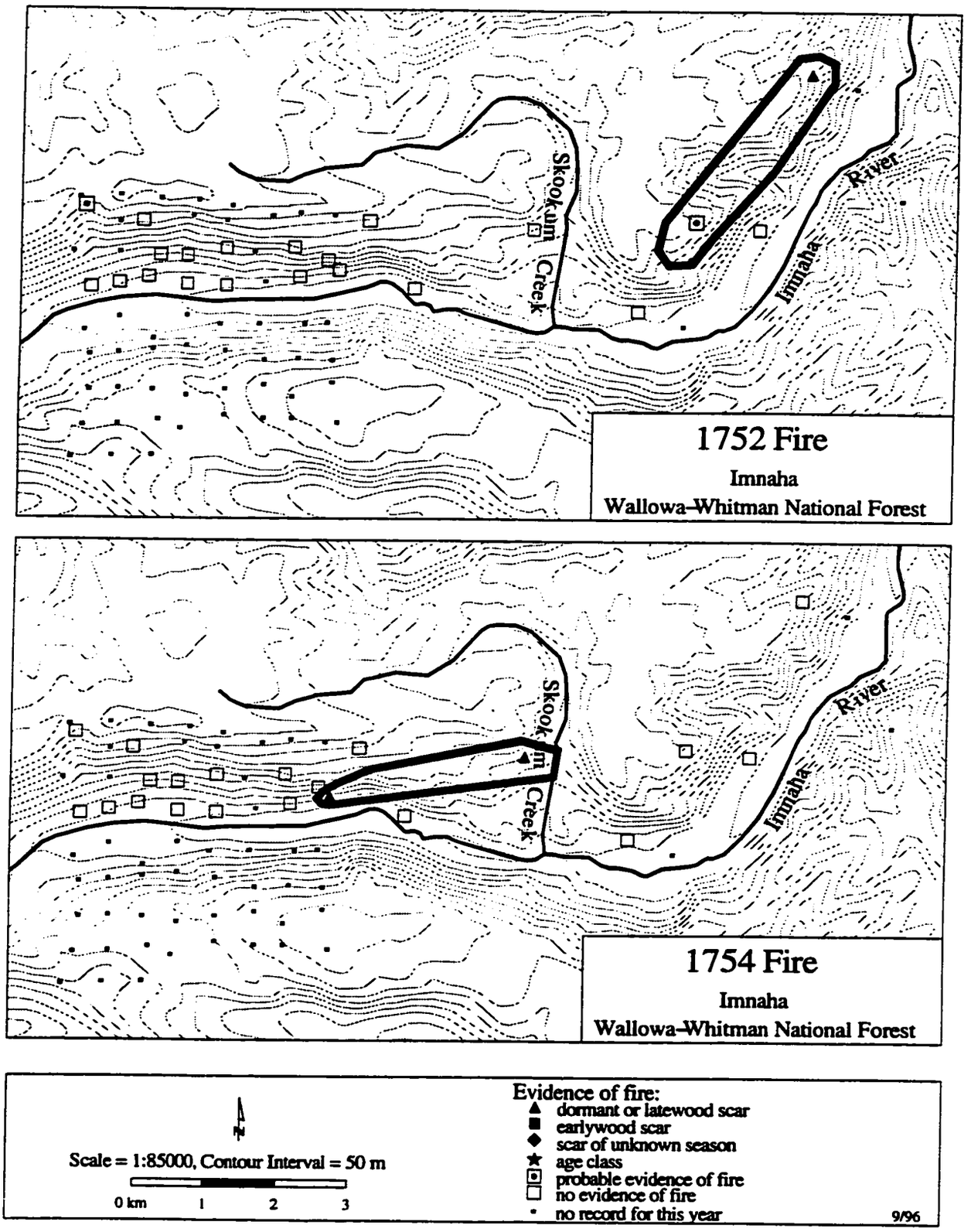


Figure 54. Imnaha fire maps for 1752 (top) and 1754 (bottom) fires.

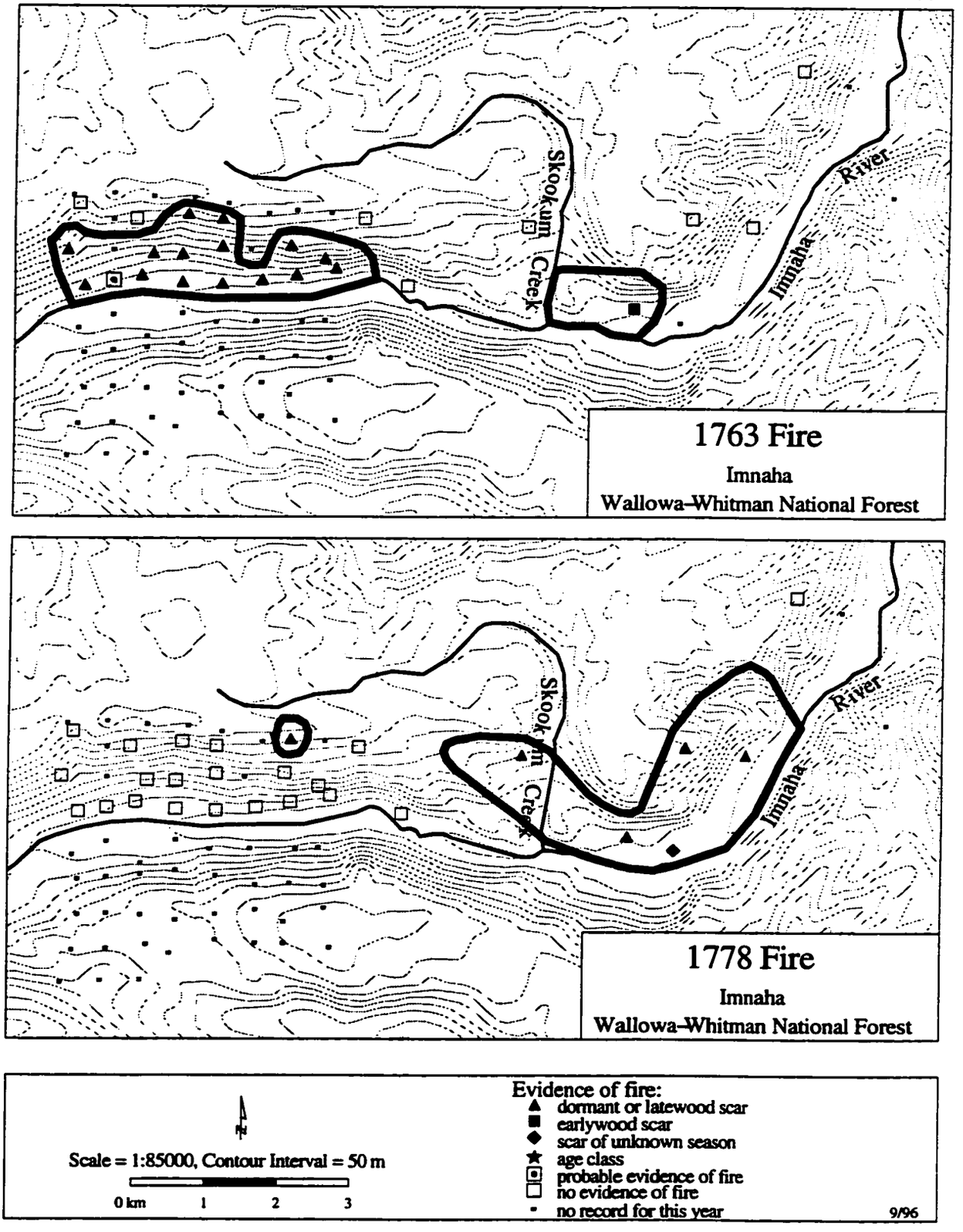


Figure 55. Imnaha fire maps for 1763 (top) and 1778 (bottom) fires.

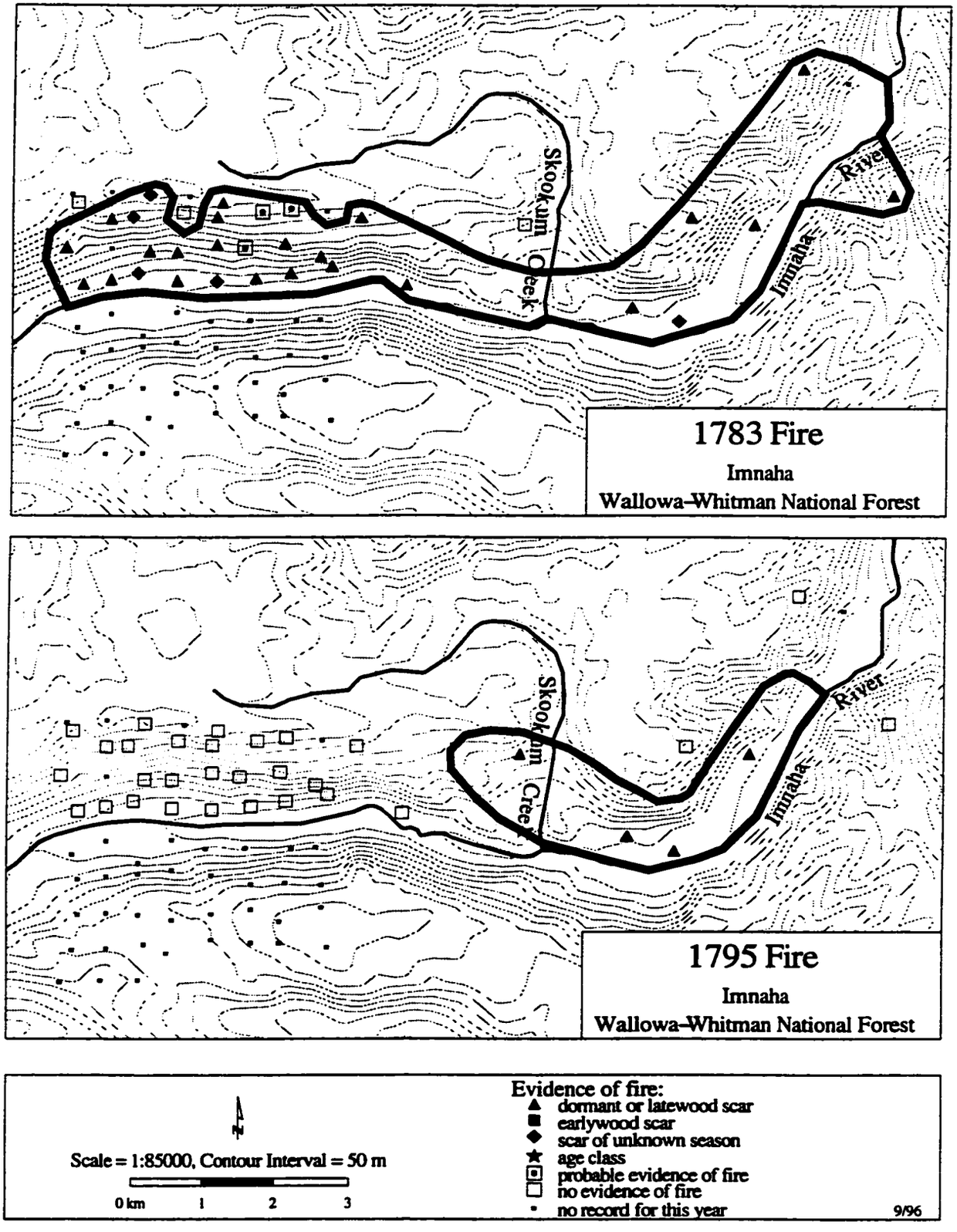


Figure 56. Imnaha fire maps for 1783 (top) and 1795 (bottom) fires.

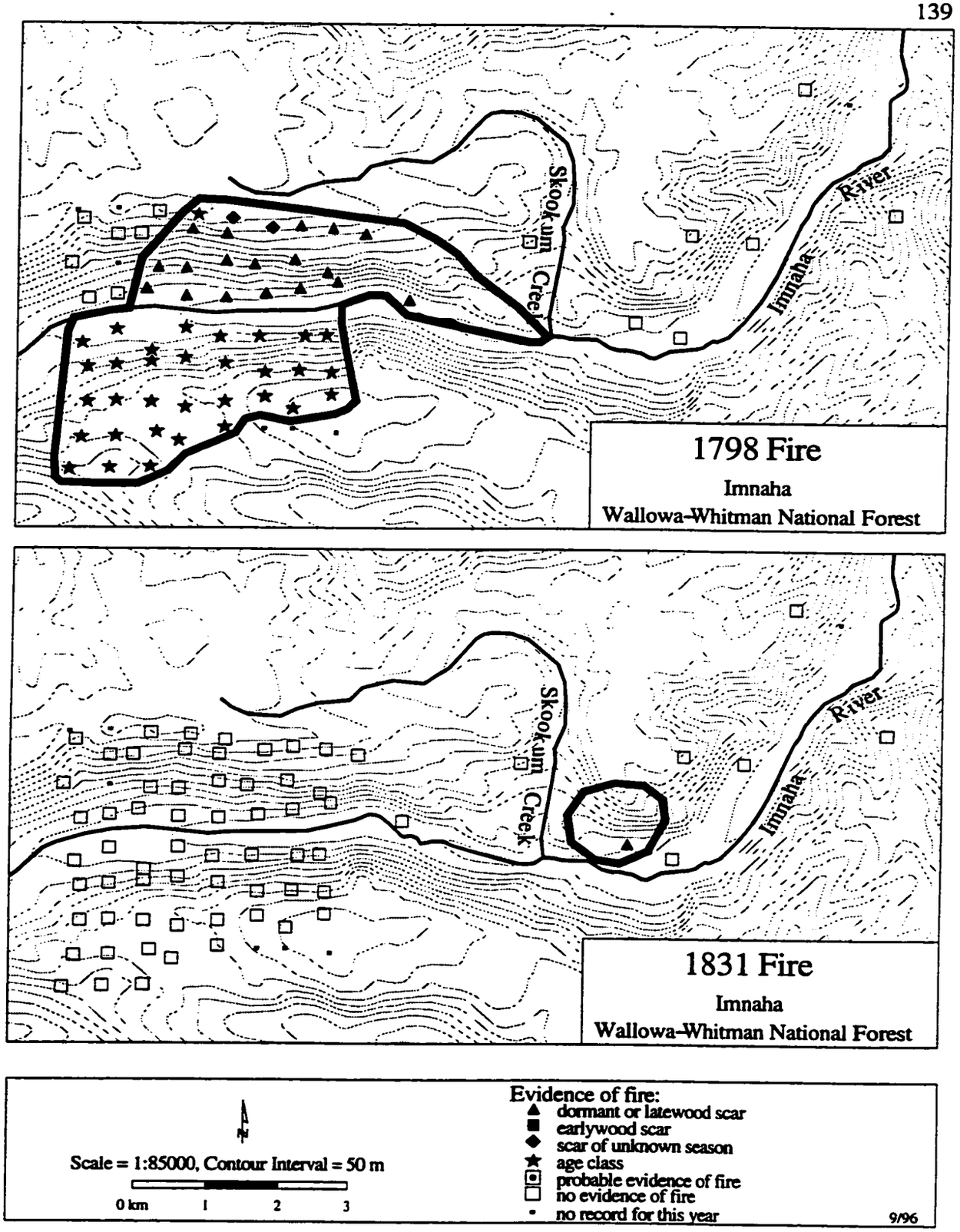


Figure 57. Imnaha fire maps for 1798 (top) and 1831 (bottom) fires.

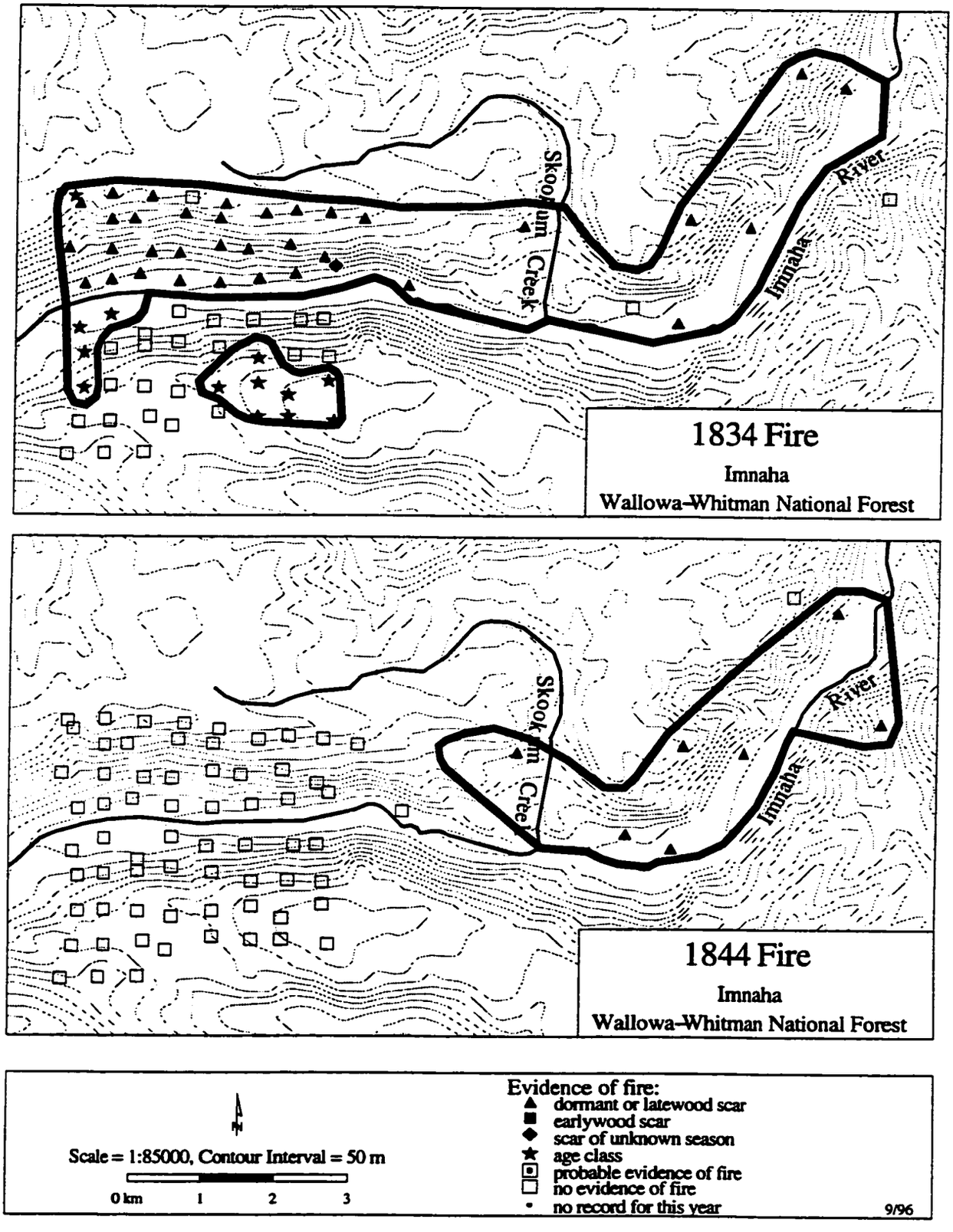


Figure 58. Imnaha fire maps for 1834 (top) and 1844 (bottom) fires.

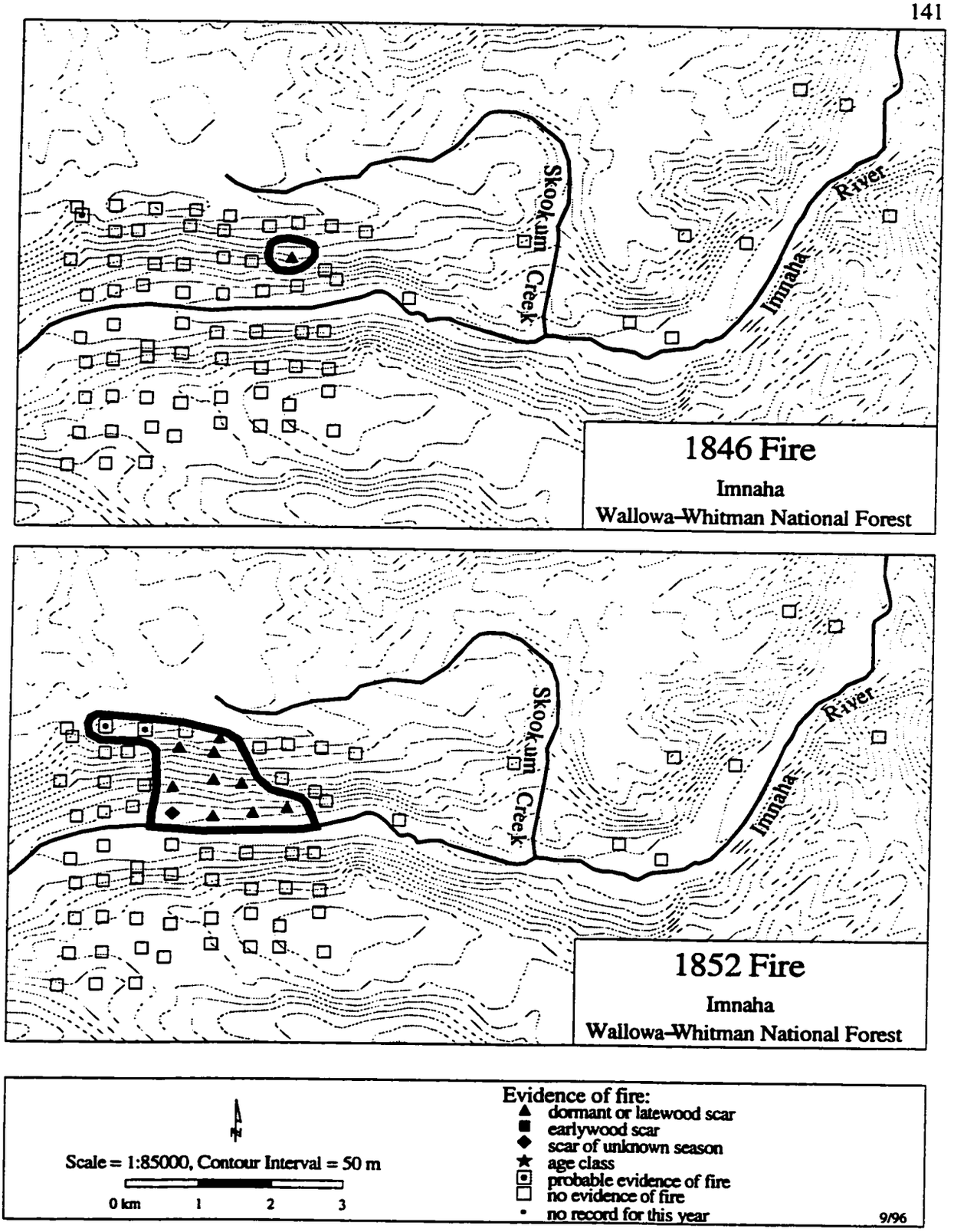


Figure 59. Imnaha fire maps for 1846 (top) and 1852 (bottom) fires.

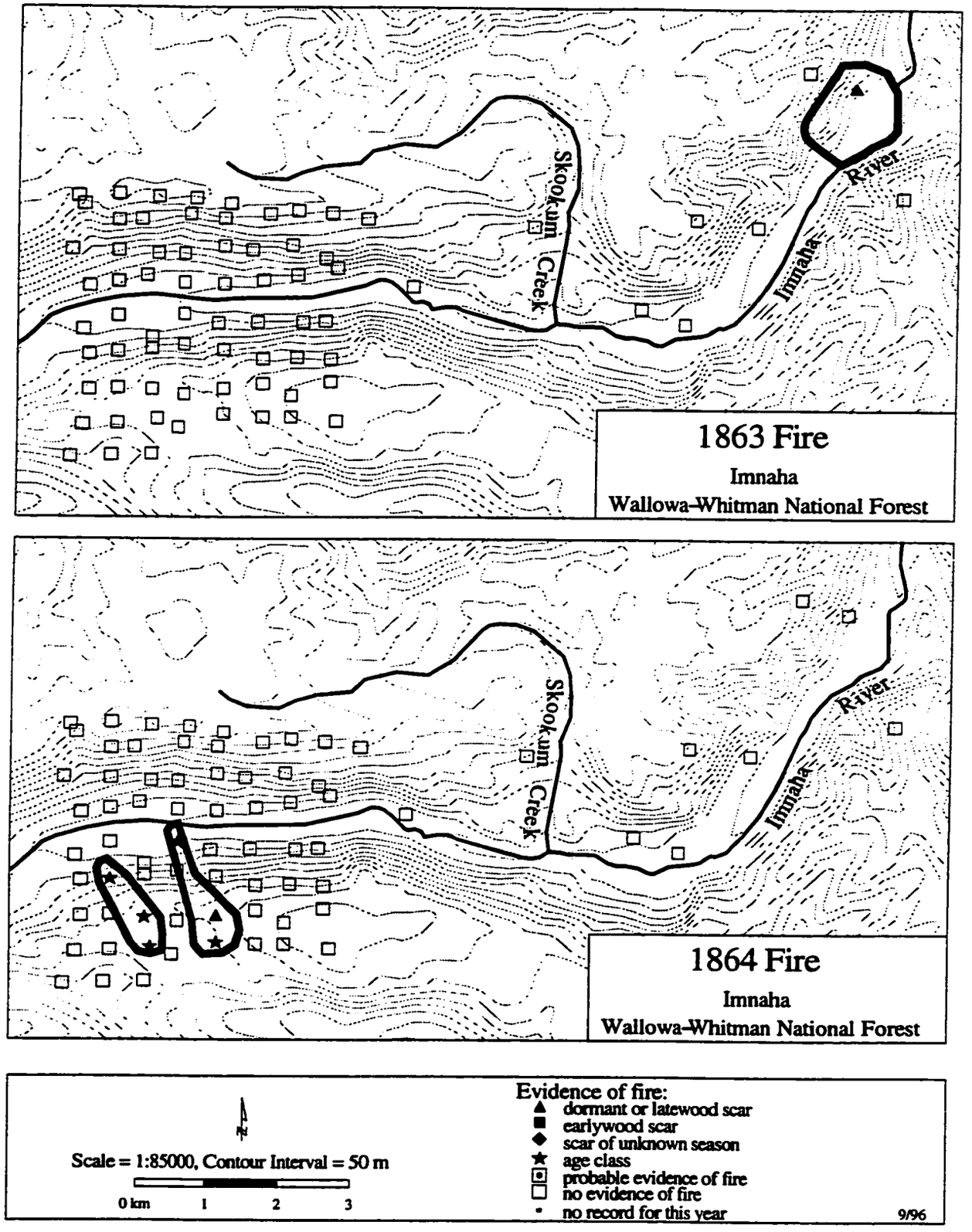


Figure 60. Imnaha fire maps for 1863 (top) and 1864 (bottom) fires.

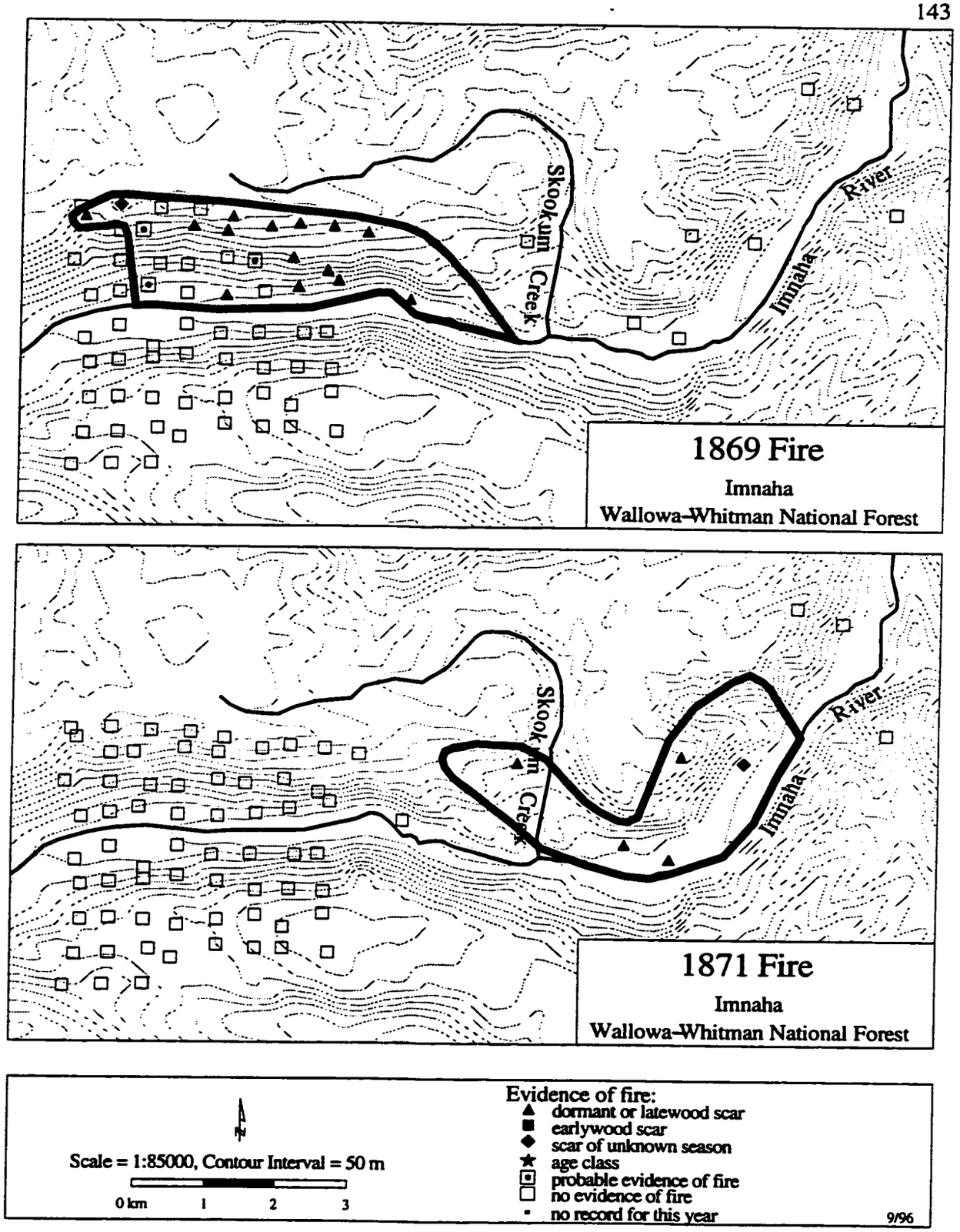


Figure 61. Imnaha fire maps for 1869 (top) and 1871 (bottom) fires.

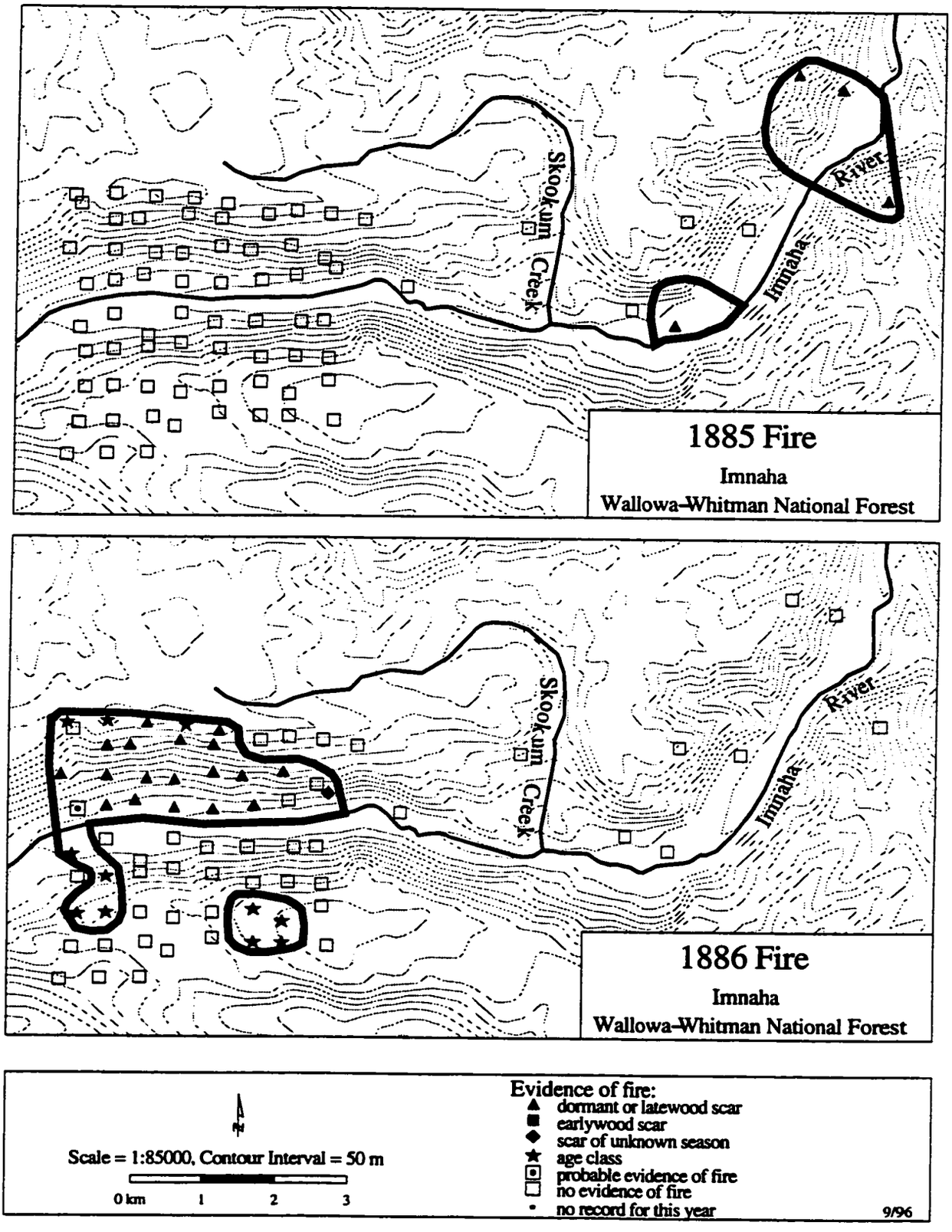


Figure 62. Imnaha fire maps for 1885 (top) and 1886 (bottom) fires.

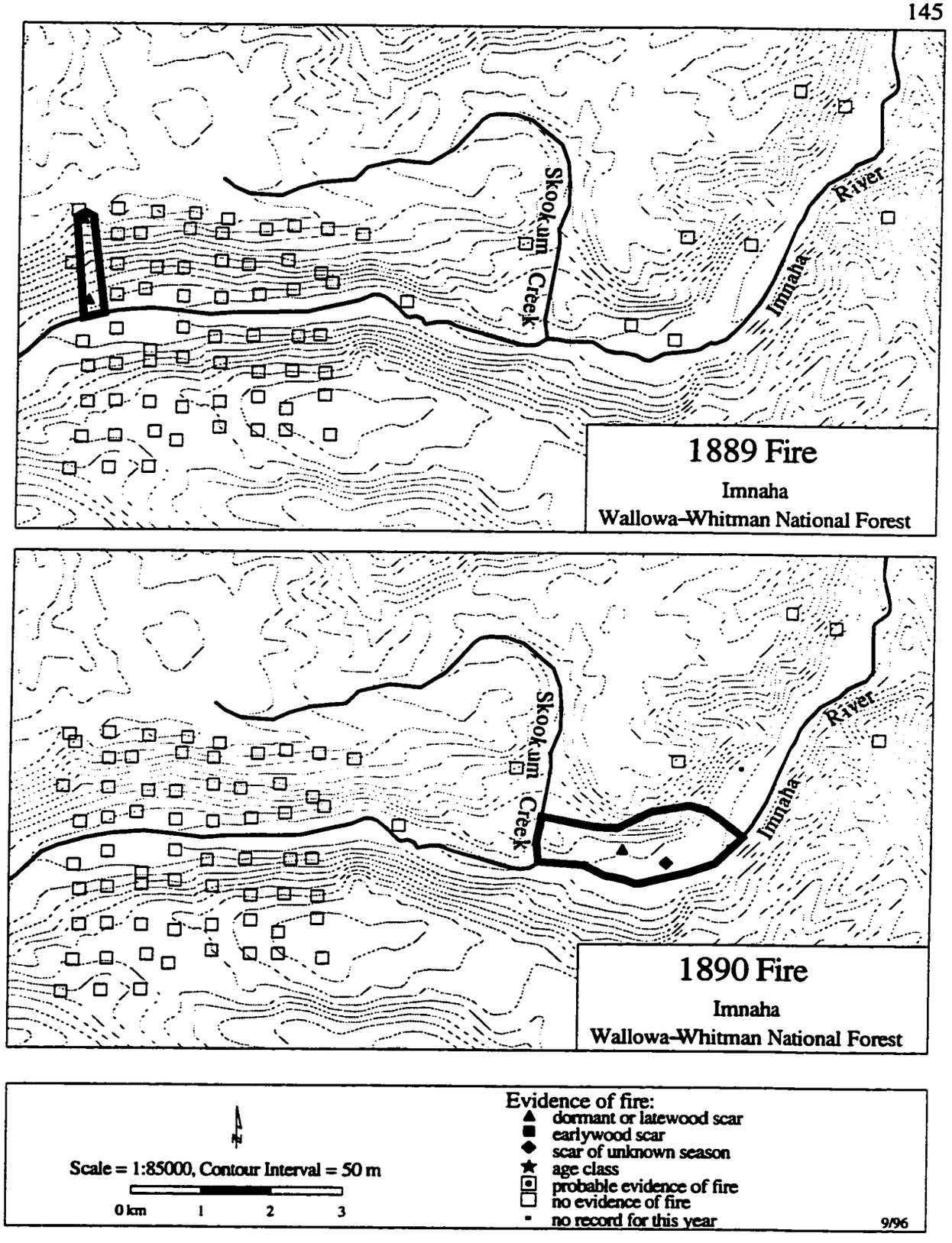


Figure 63. Imnaha fire maps for 1889 (top) and 1890 (bottom) fires.

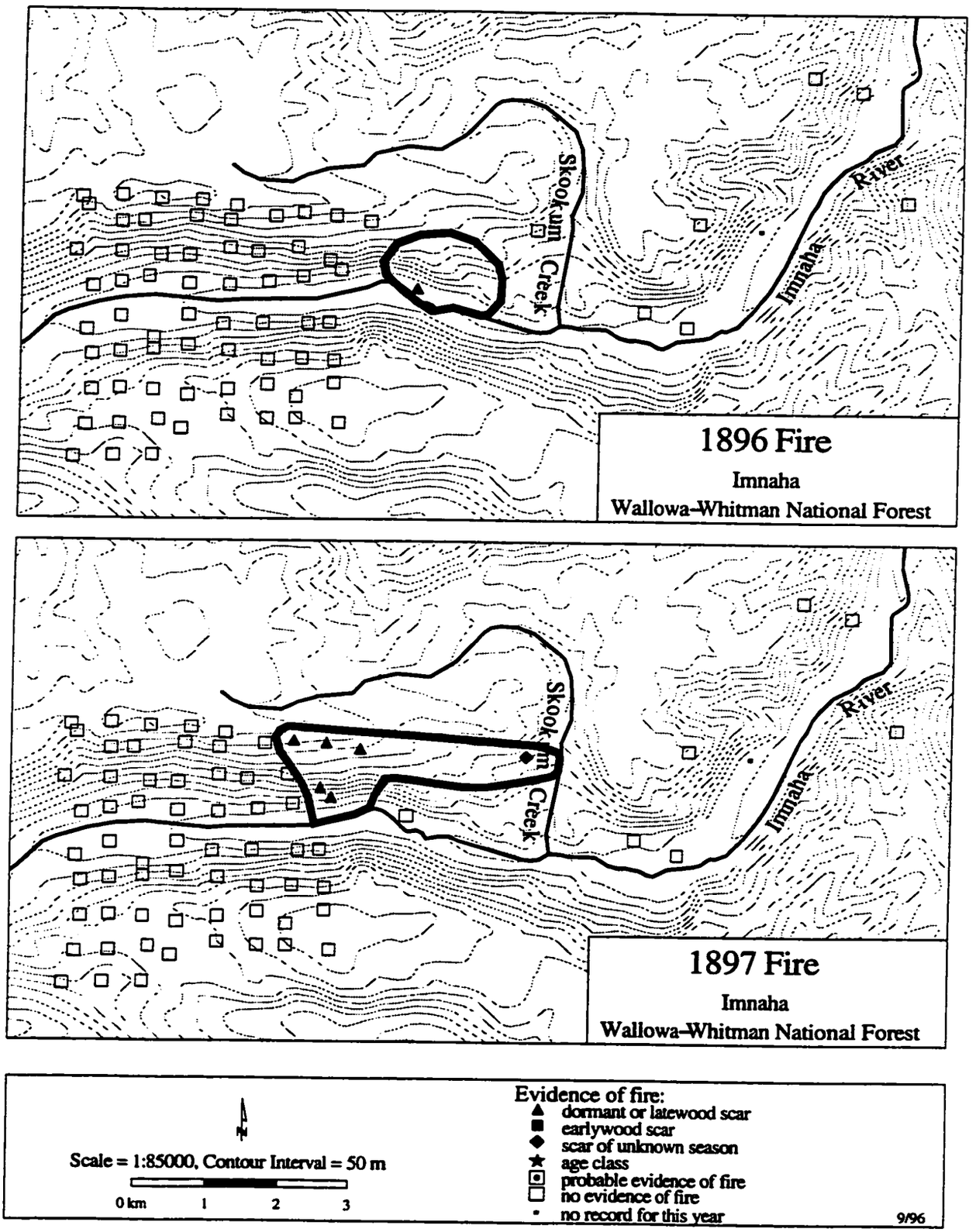
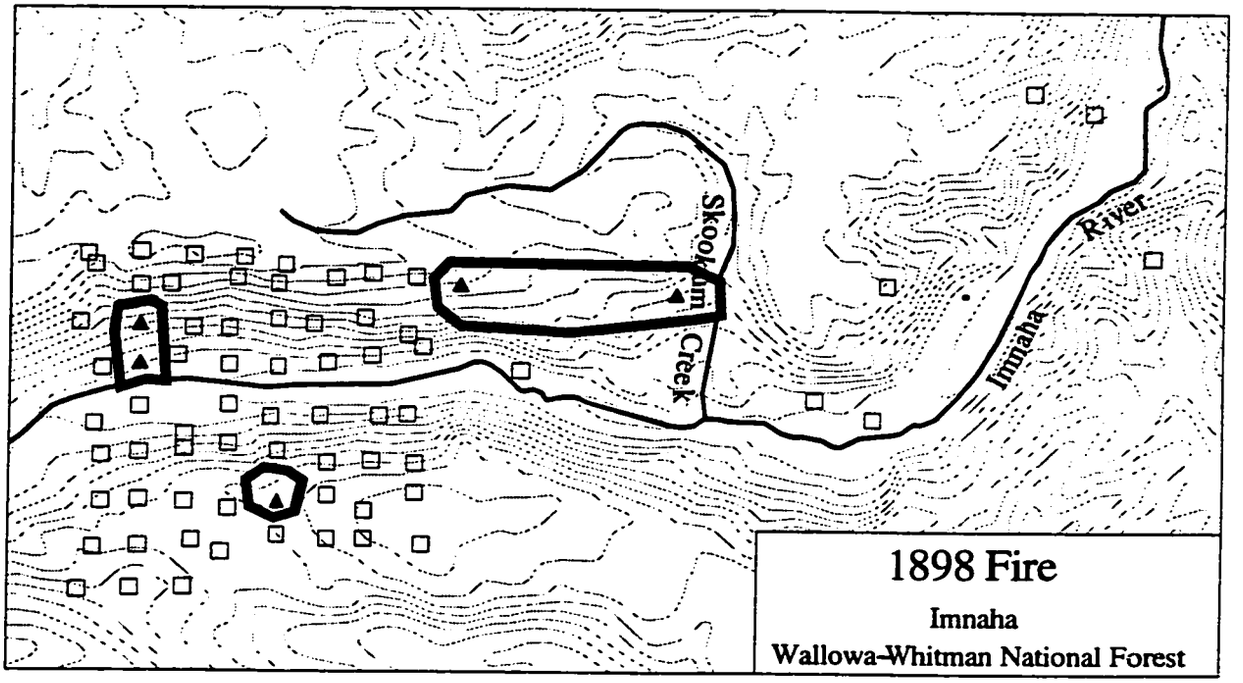


Figure 64. Imnaha fire maps for 1896 (top) and 1897 (bottom) fires.



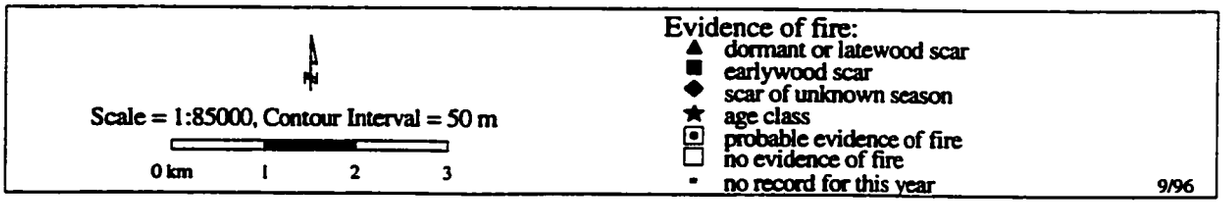


Figure 65. Imnaha fire map for 1898 fire.

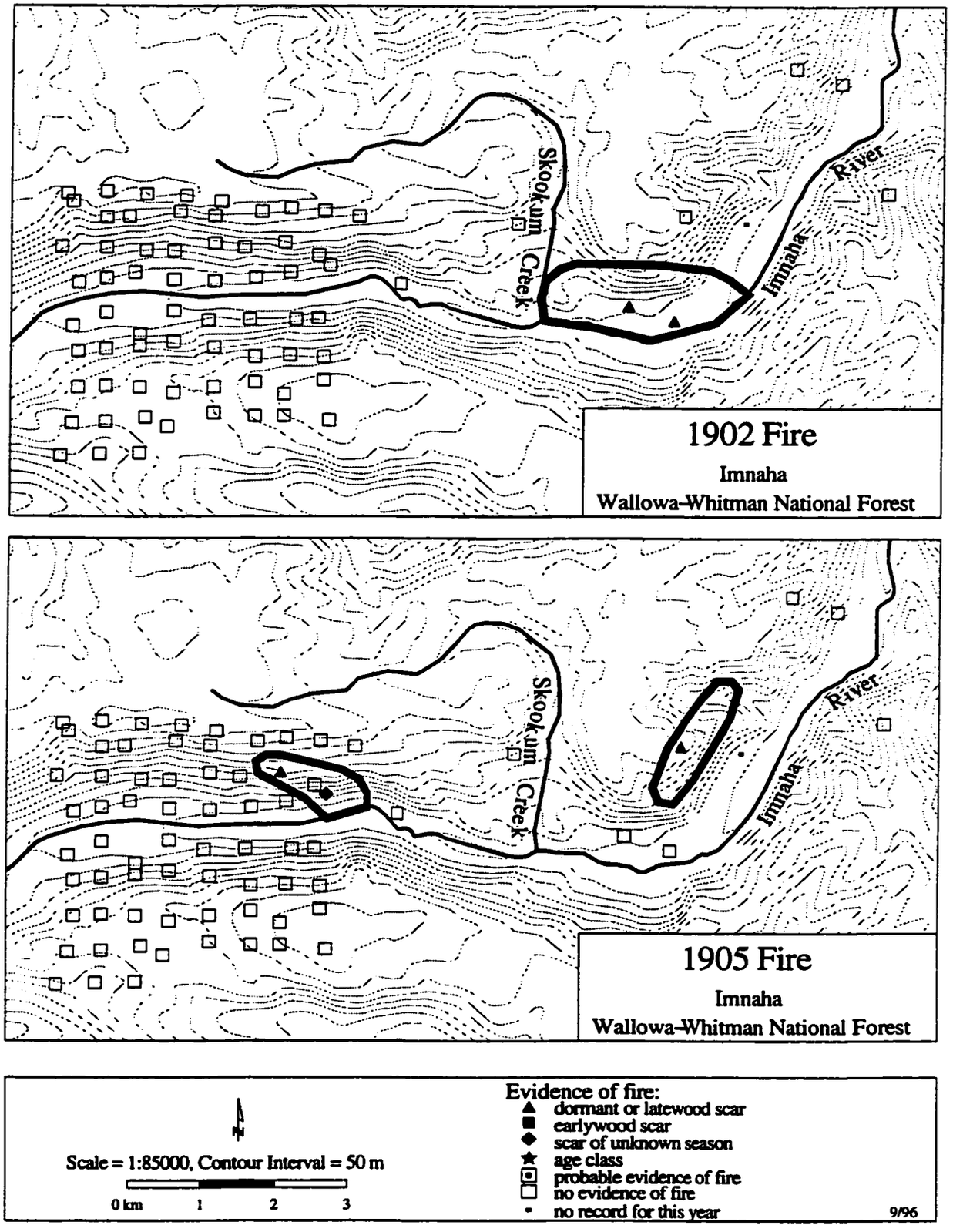


Figure 66. Imnaha fire maps for 1902 (top) and 1905 (bottom) fires.

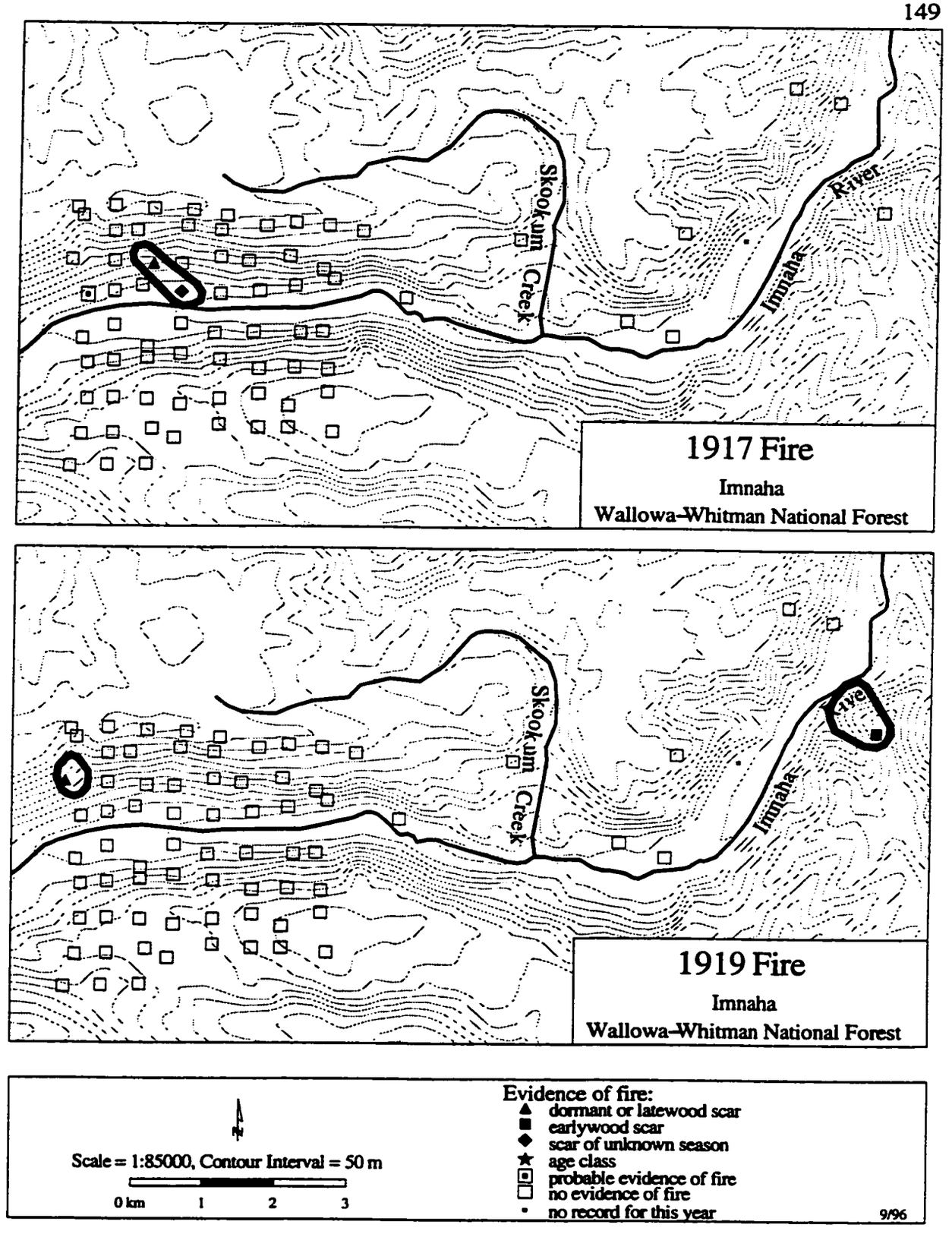


Figure 67. Imnaha fire maps for 1917 (top) and 1919 (bottom) fires.

APPENDIX F: BAKER FIRE MAPS

Evidence of fire was mapped at Baker for every year in dry forests that had at least two scars and for every fire event identified in mesic forests. Symbols indicate whether the evidence of fire was cohorts or scars. If the later, the intra-annular position of the scar is also indicated. Plots indicating as having probable evidence of fire are those for which the only evidence was an abrupt increase or decrease in ring width. Plots having no evidence of fire in a given year include plots at which no sampled trees were alive during that year as well as plots with trees that were less susceptible to scarring (i.e., the fire year occurred before the first scar). Plots indicated as having no record for a given year are plots that were sampled but had no trees recording during that year. Fire boundaries are shown as a heavy line. Individual fires could not be resolved in the mesic forests at this watershed.

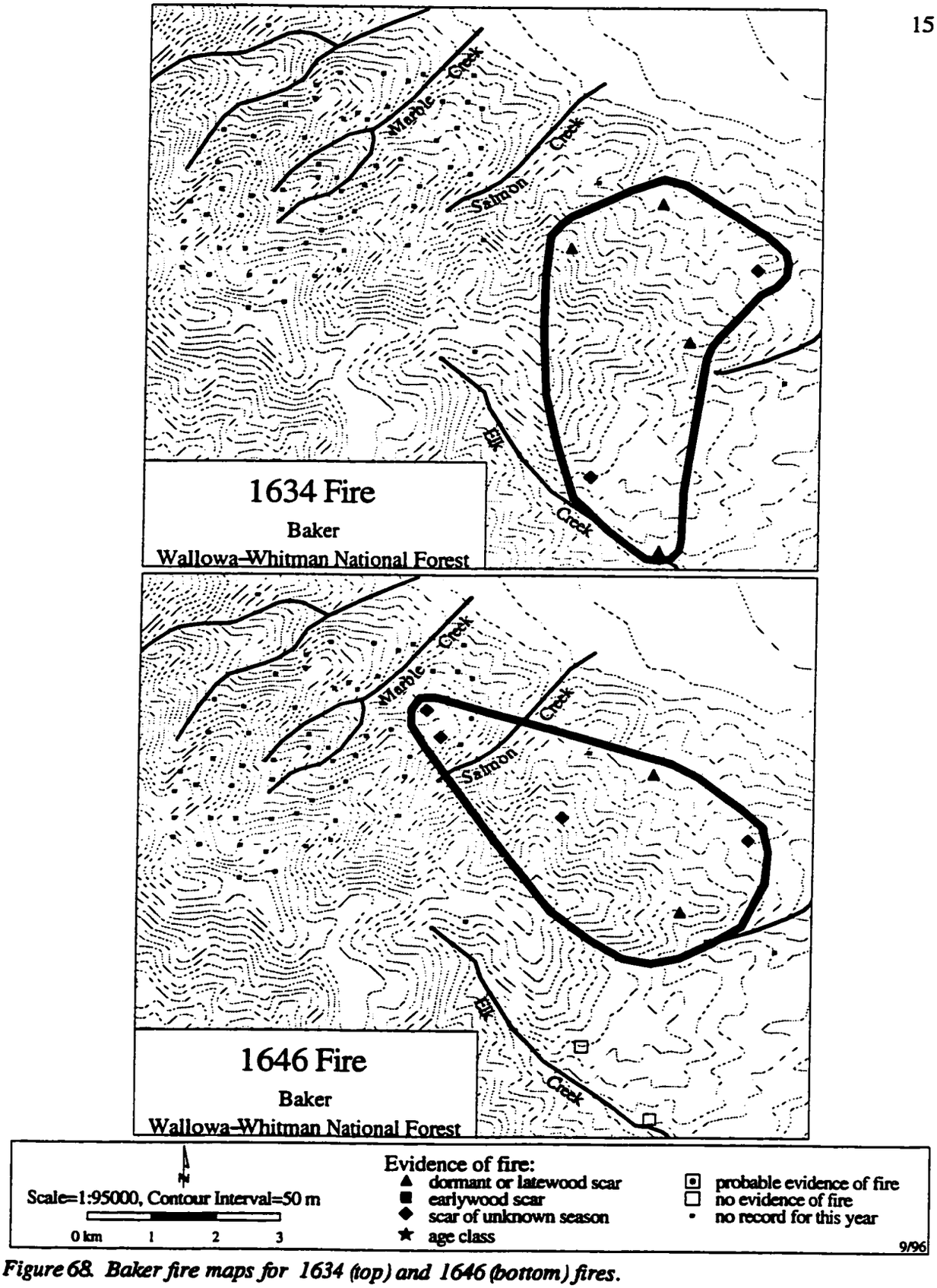


Figure 68. Baker fire maps for 1634 (top) and 1646 (bottom) fires.

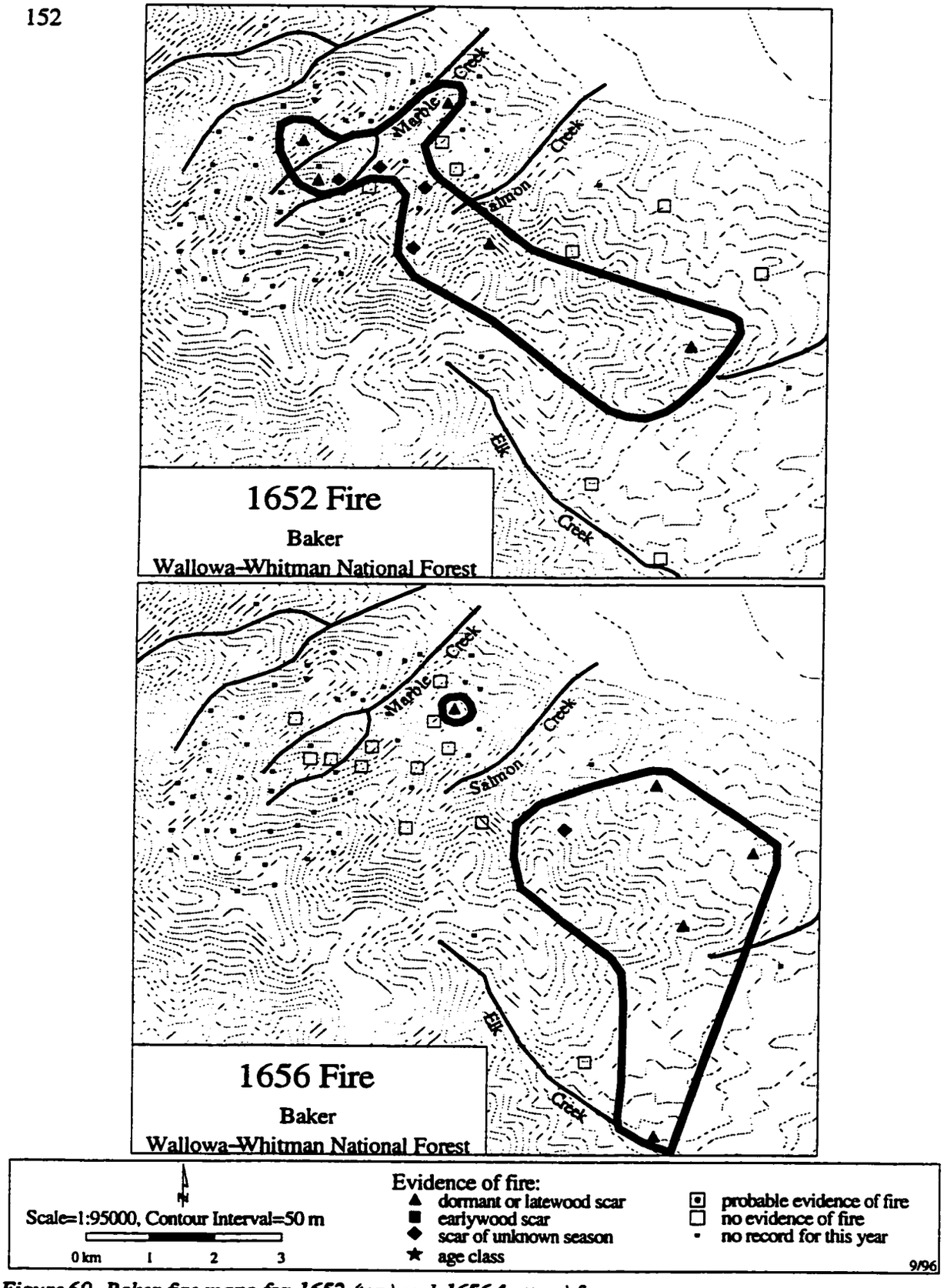


Figure 69. Baker fire maps for 1652 (top) and 1656 (bottom) fires.

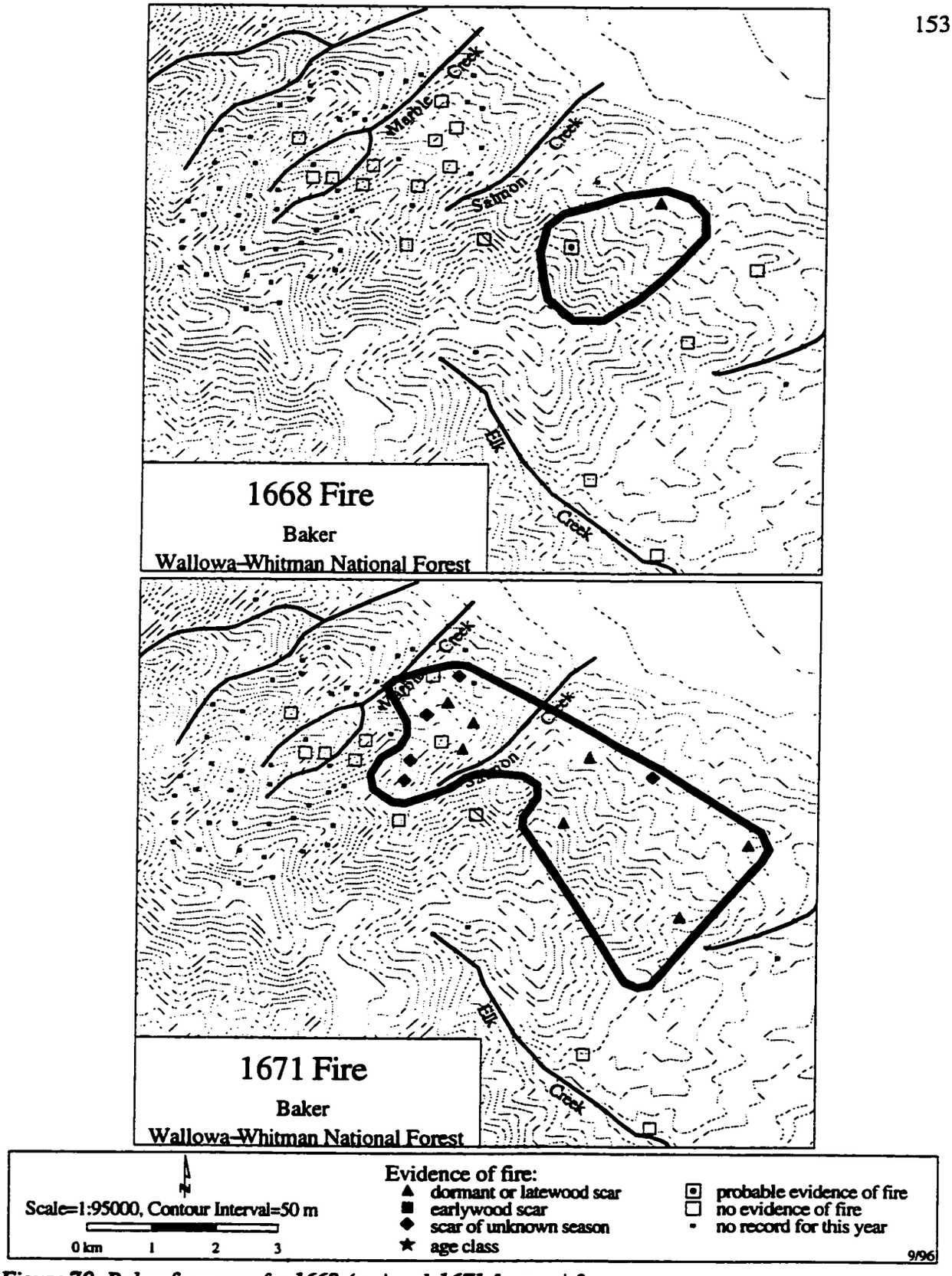


Figure 70 Baker fire maps for 1668 (top) and 1671 (bottom) fires.

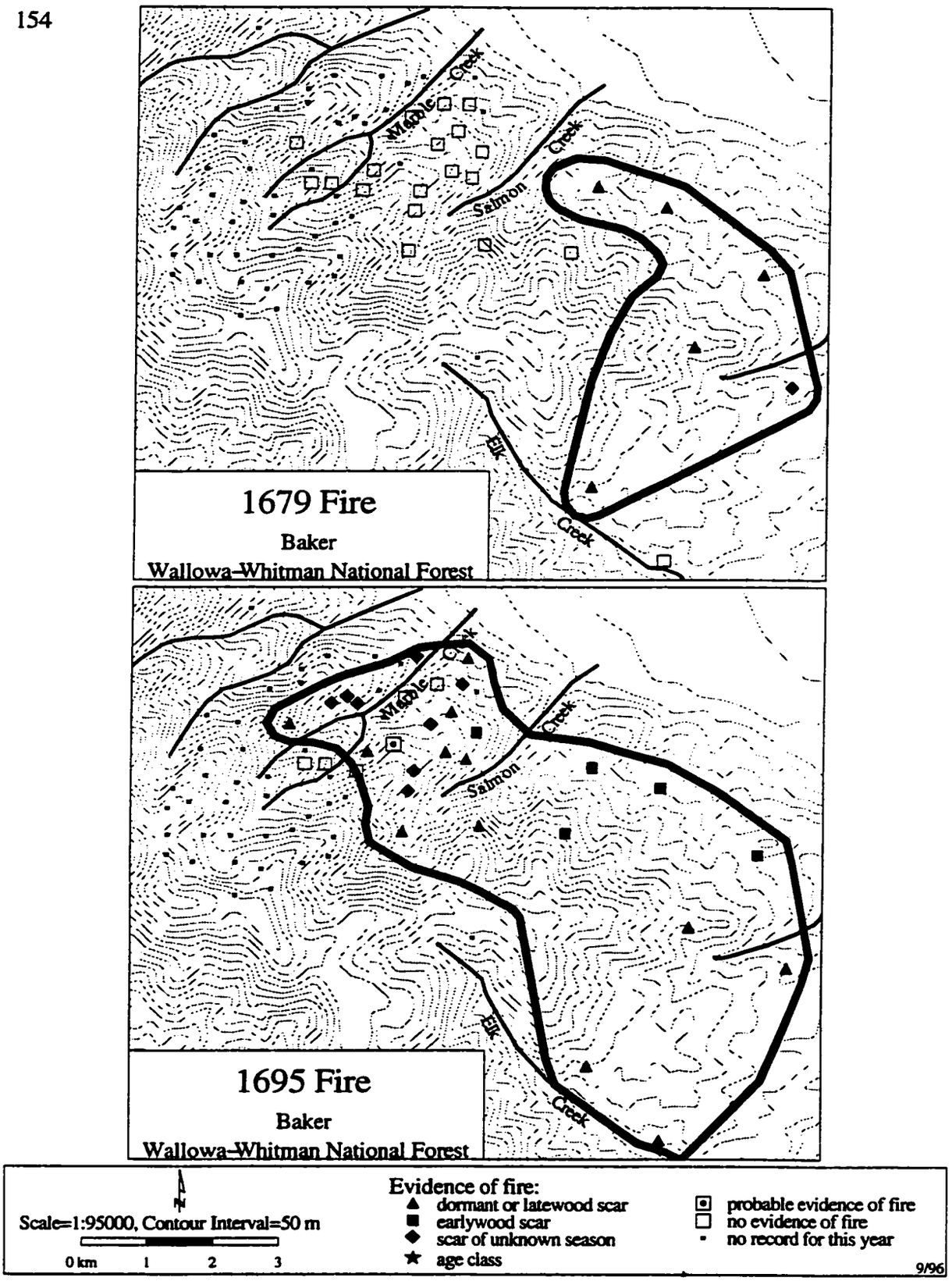


Figure 71. Baker fire maps for 1679 (top) and 1695 (bottom) fires.

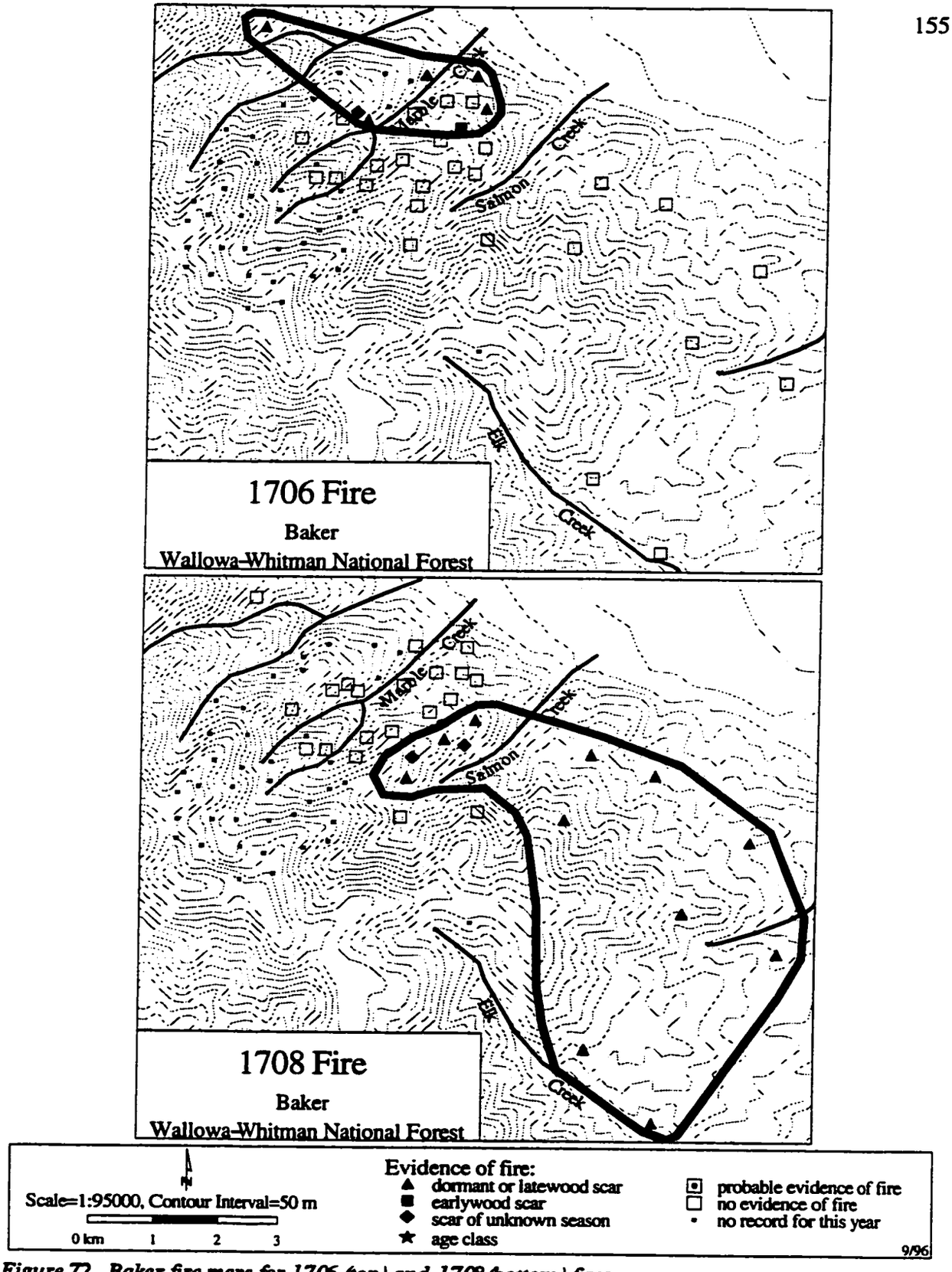


Figure 72. Baker fire maps for 1706 (top) and 1708 (bottom) fires.

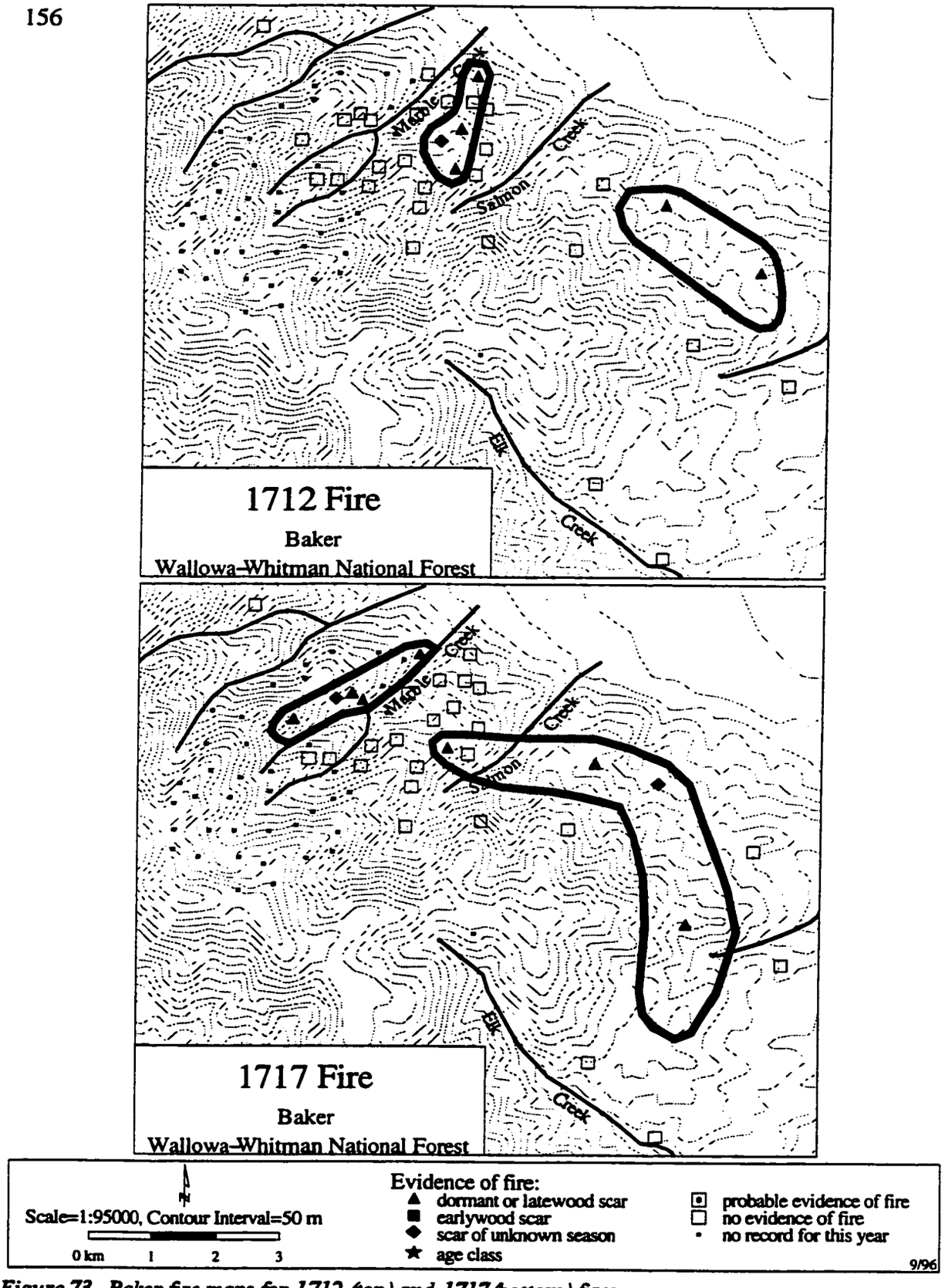


Figure 73. Baker fire maps for 1712 (top) and 1717 (bottom) fires.

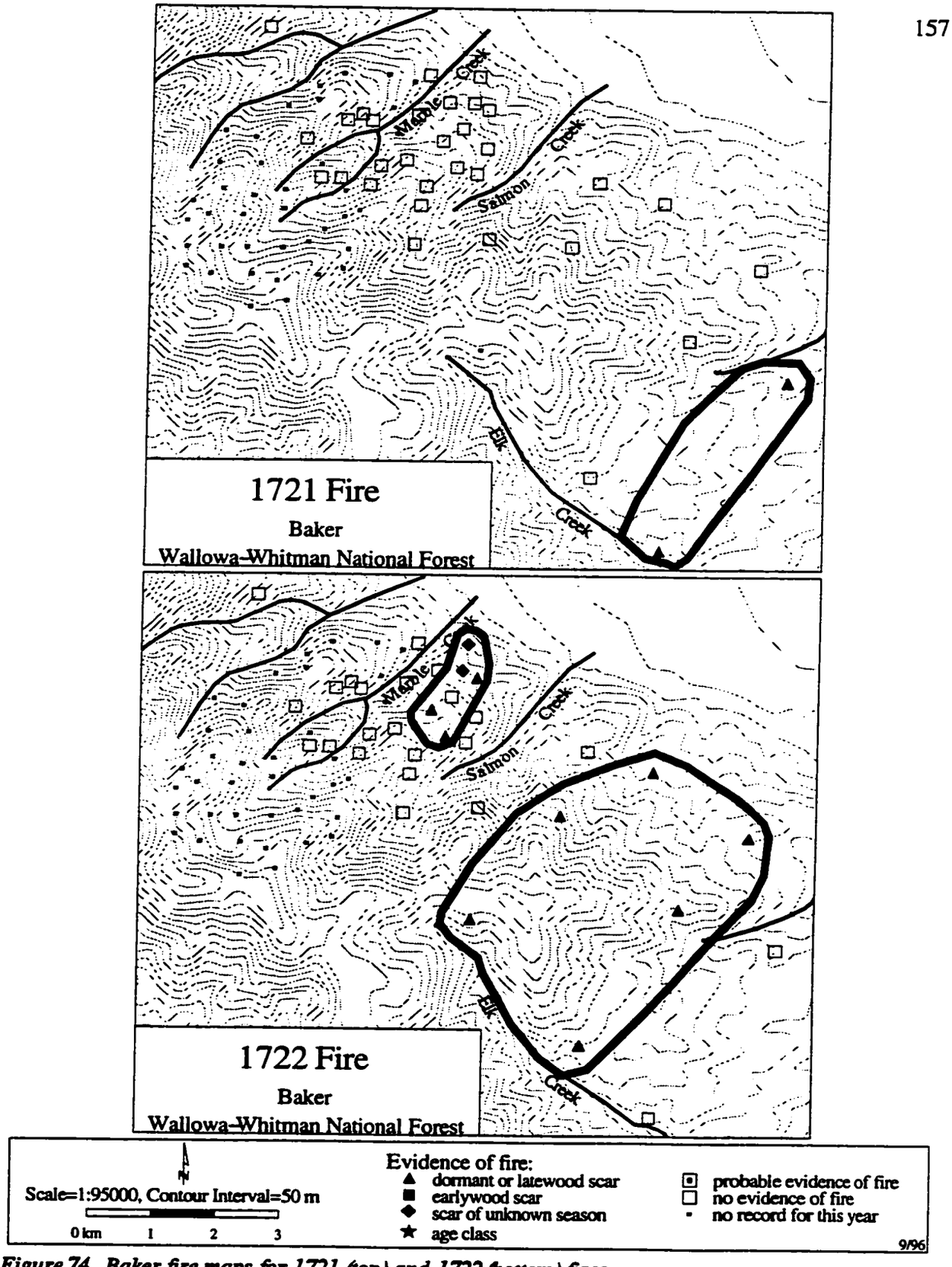


Figure 74. Baker fire maps for 1721 (top) and 1722 (bottom) fires.

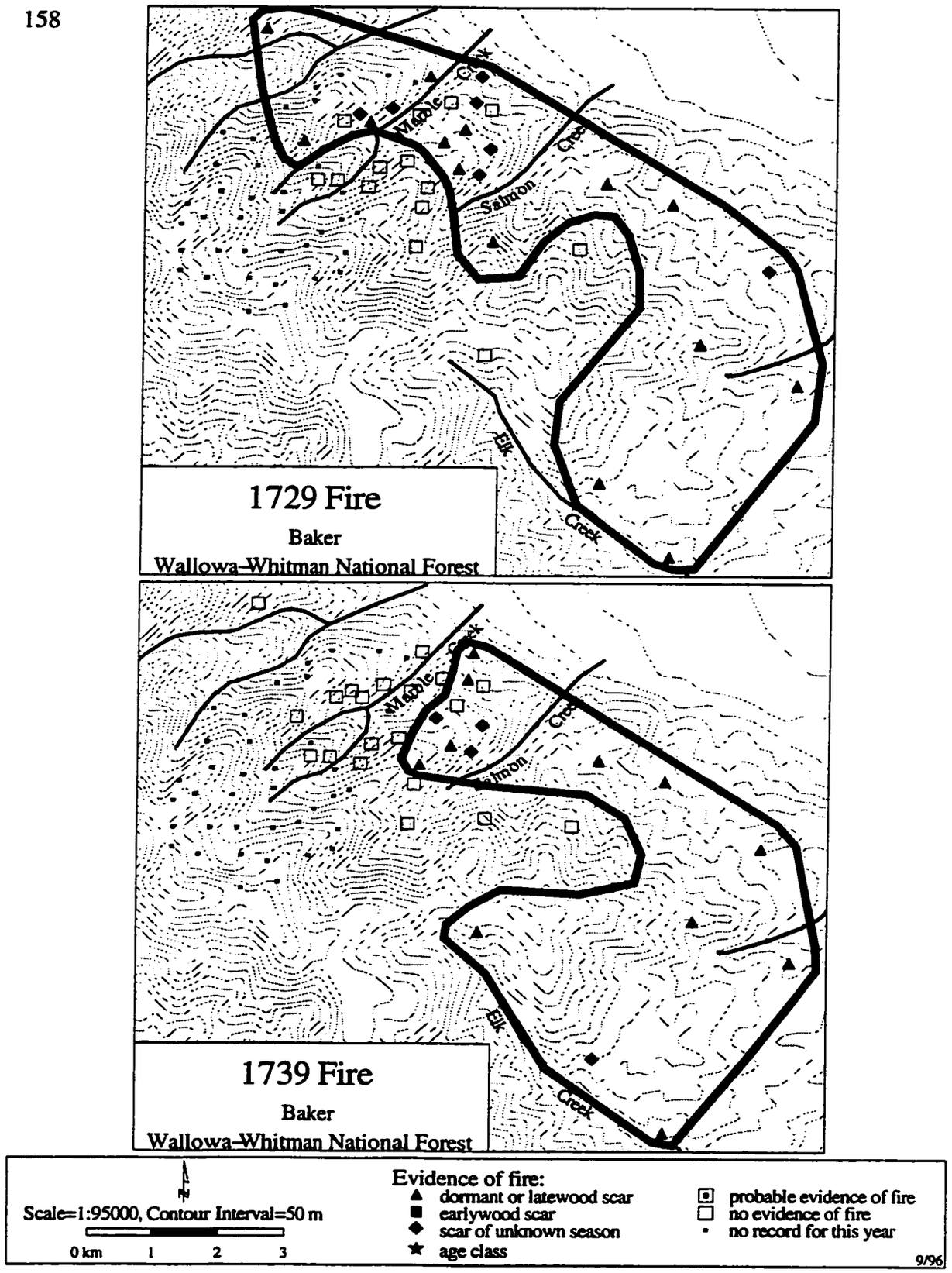


Figure 75. Baker fire maps for 1729 (top) and 1739 (bottom) fires.

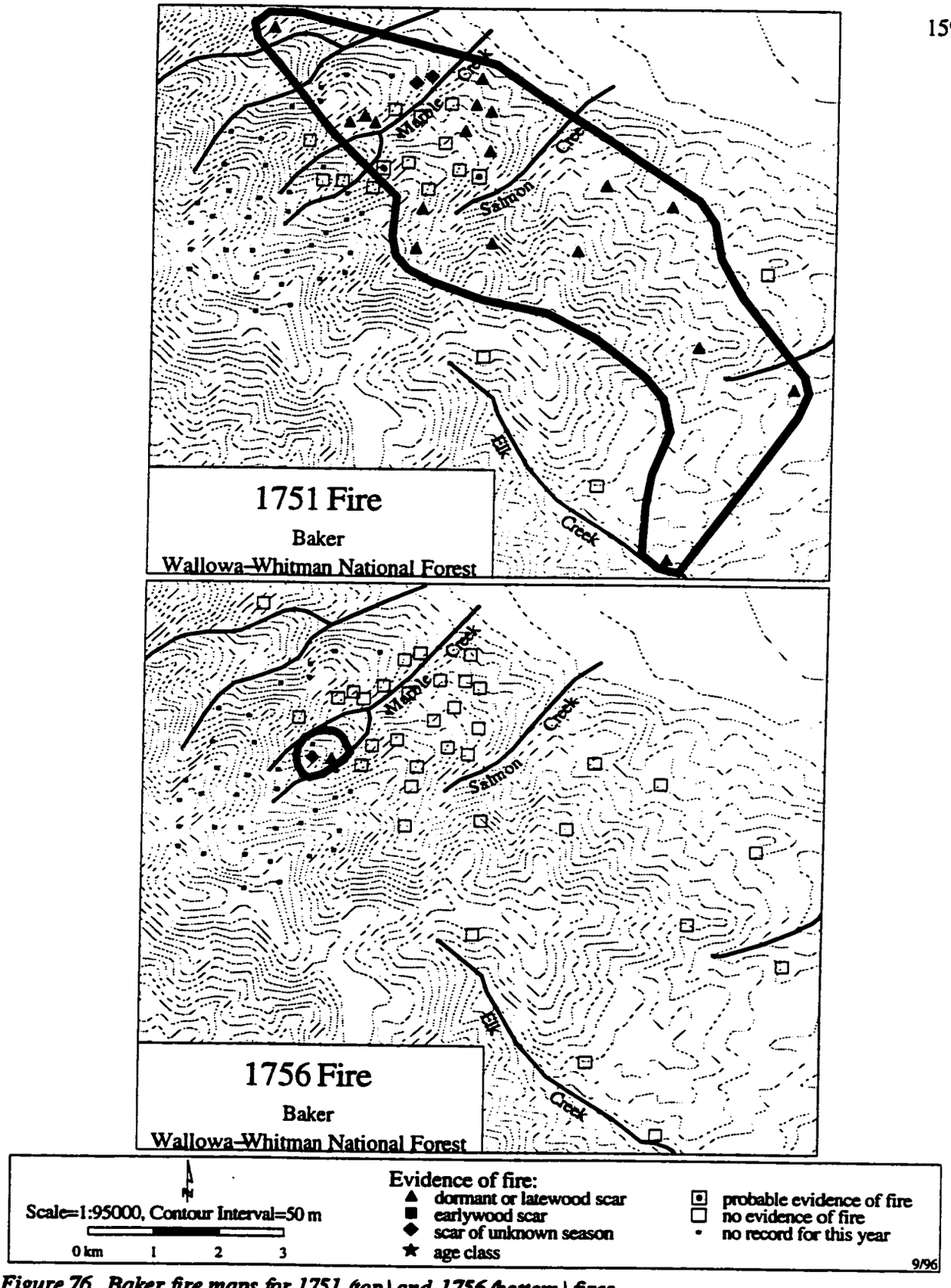


Figure 76. Baker fire maps for 1751 (top) and 1756 (bottom) fires.

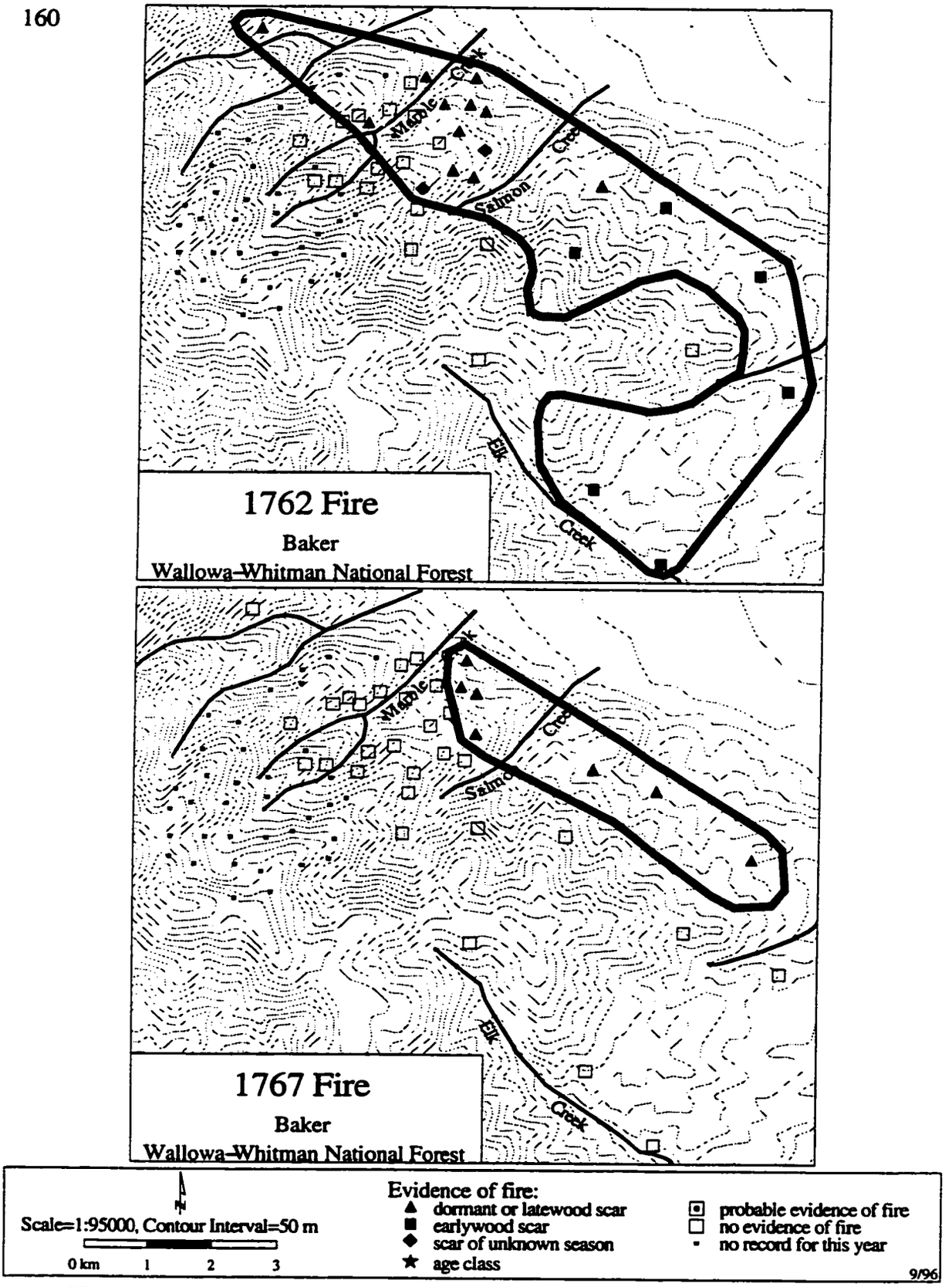


Figure 77. Baker fire maps for 1762 (top) and 1767 (bottom) fires.

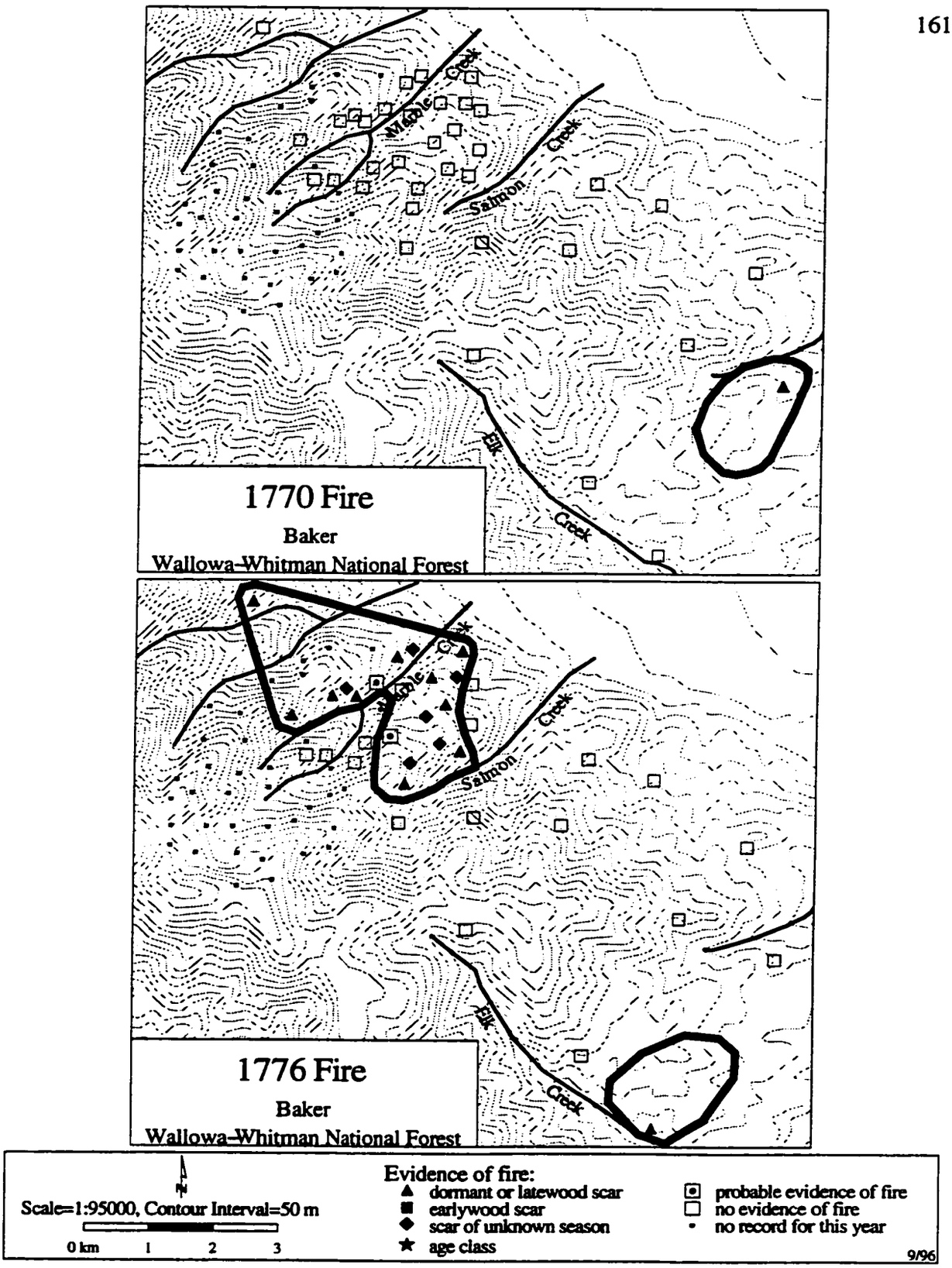


Figure 78. Baker fire maps for 1770 (top) and 1776 (bottom) fires.

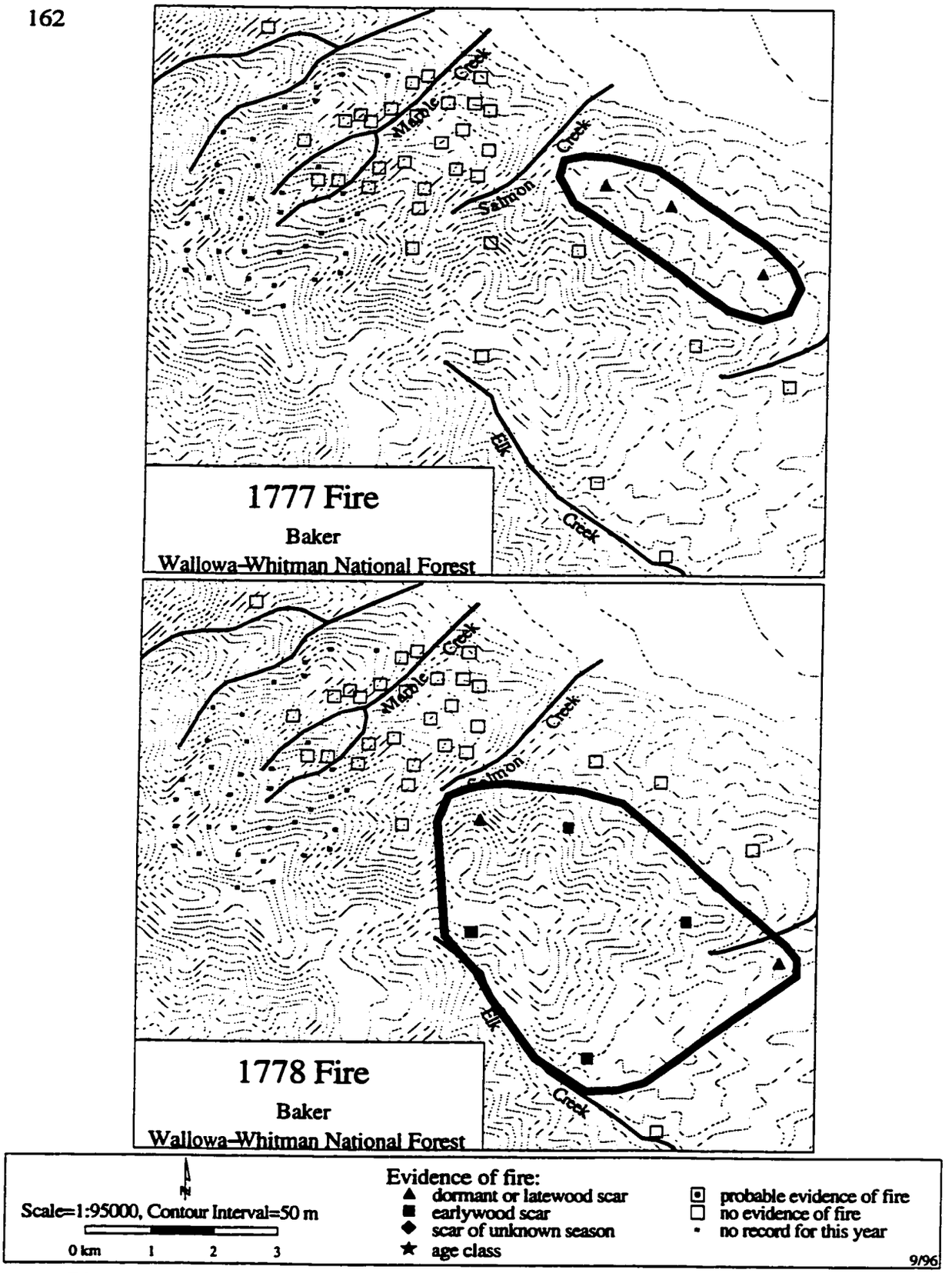


Figure 79. Baker fire maps for 1777 (top) and 1778 (bottom) fires.

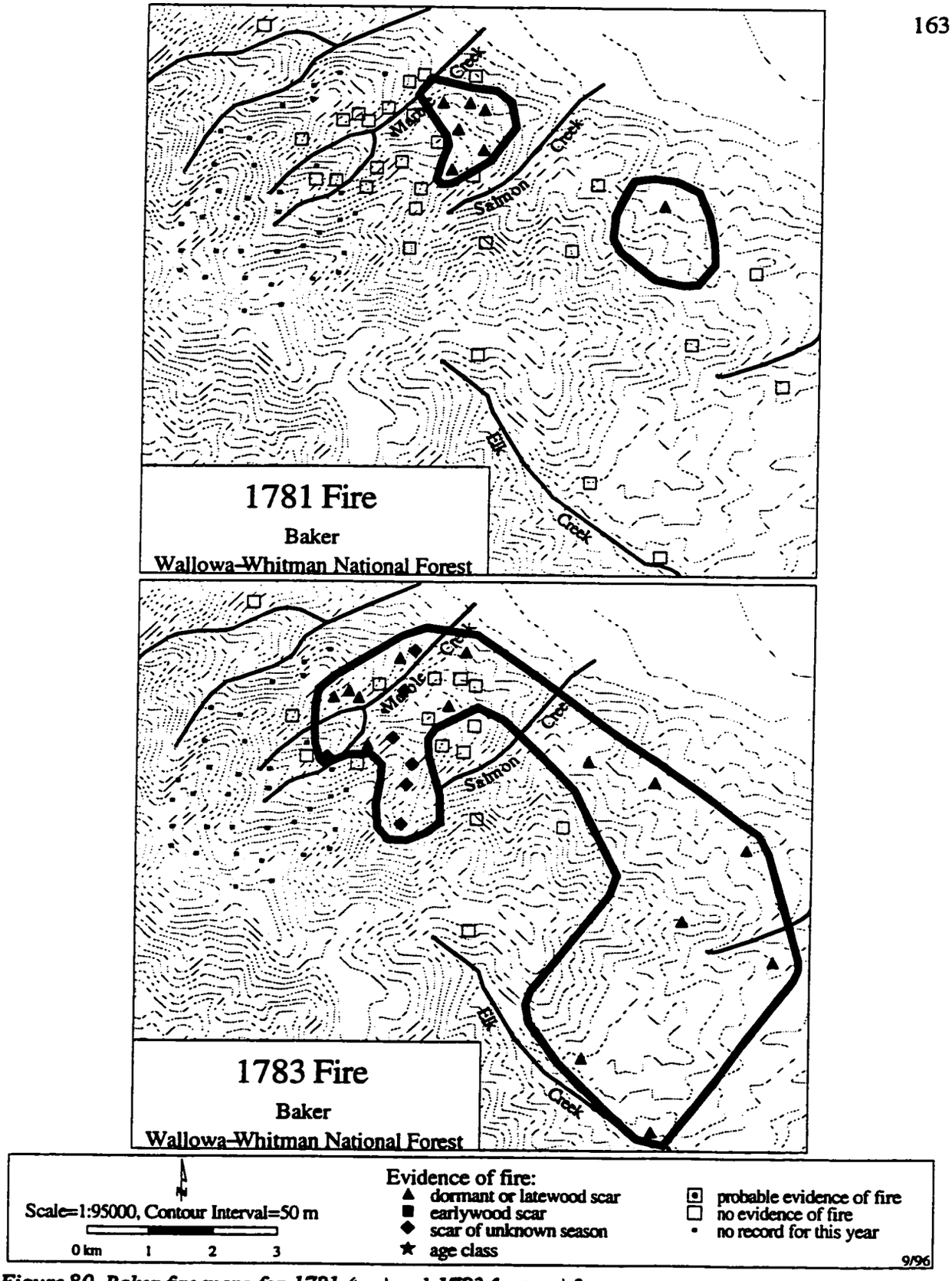


Figure 80. Baker fire maps for 1781 (top) and 1783 (bottom) fires.

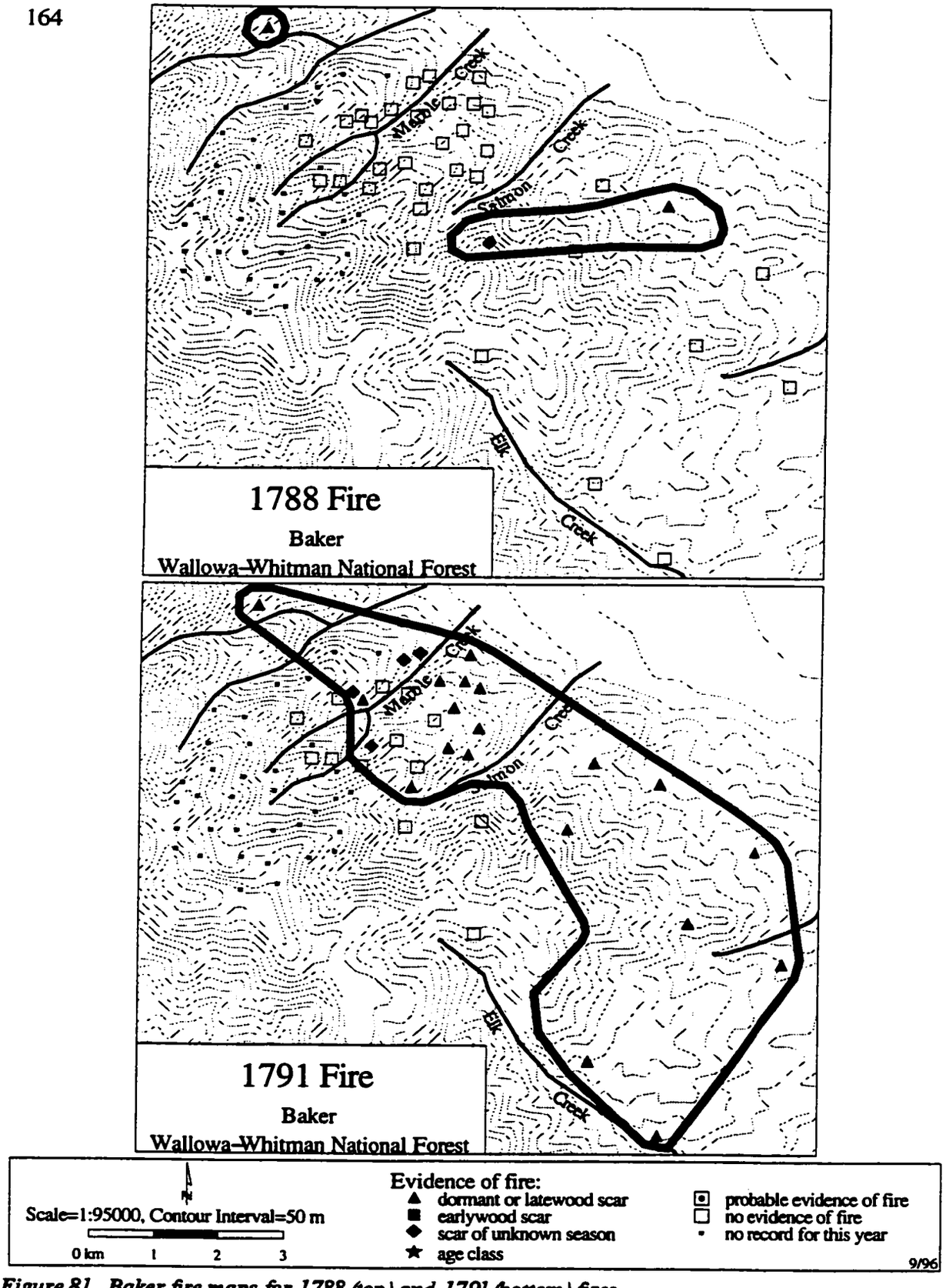


Figure 81. Baker fire maps for 1788 (top) and 1791 (bottom) fires.

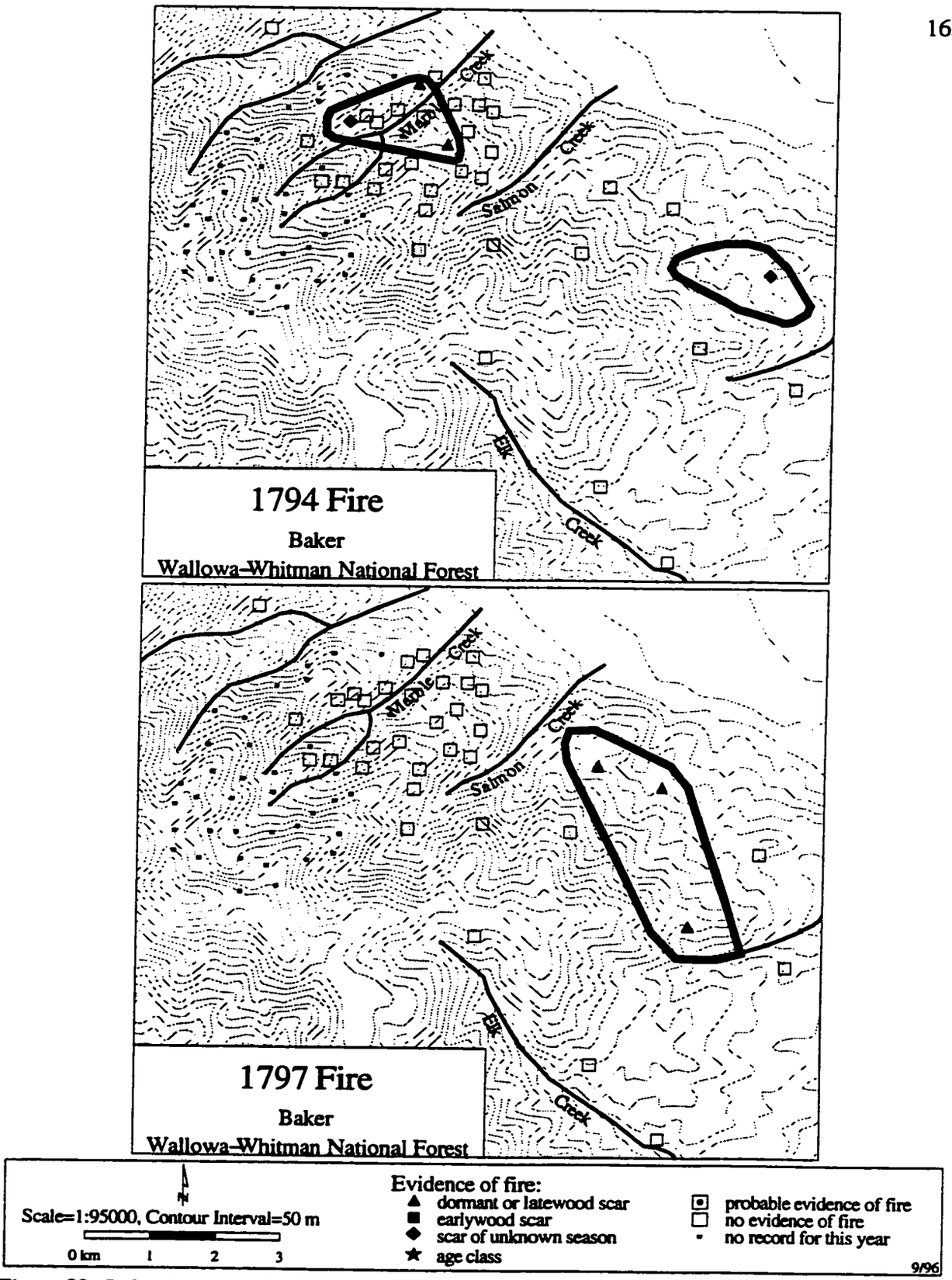


Figure 82. Baker fire maps for 1794 (top) and 1797 (bottom) fires.

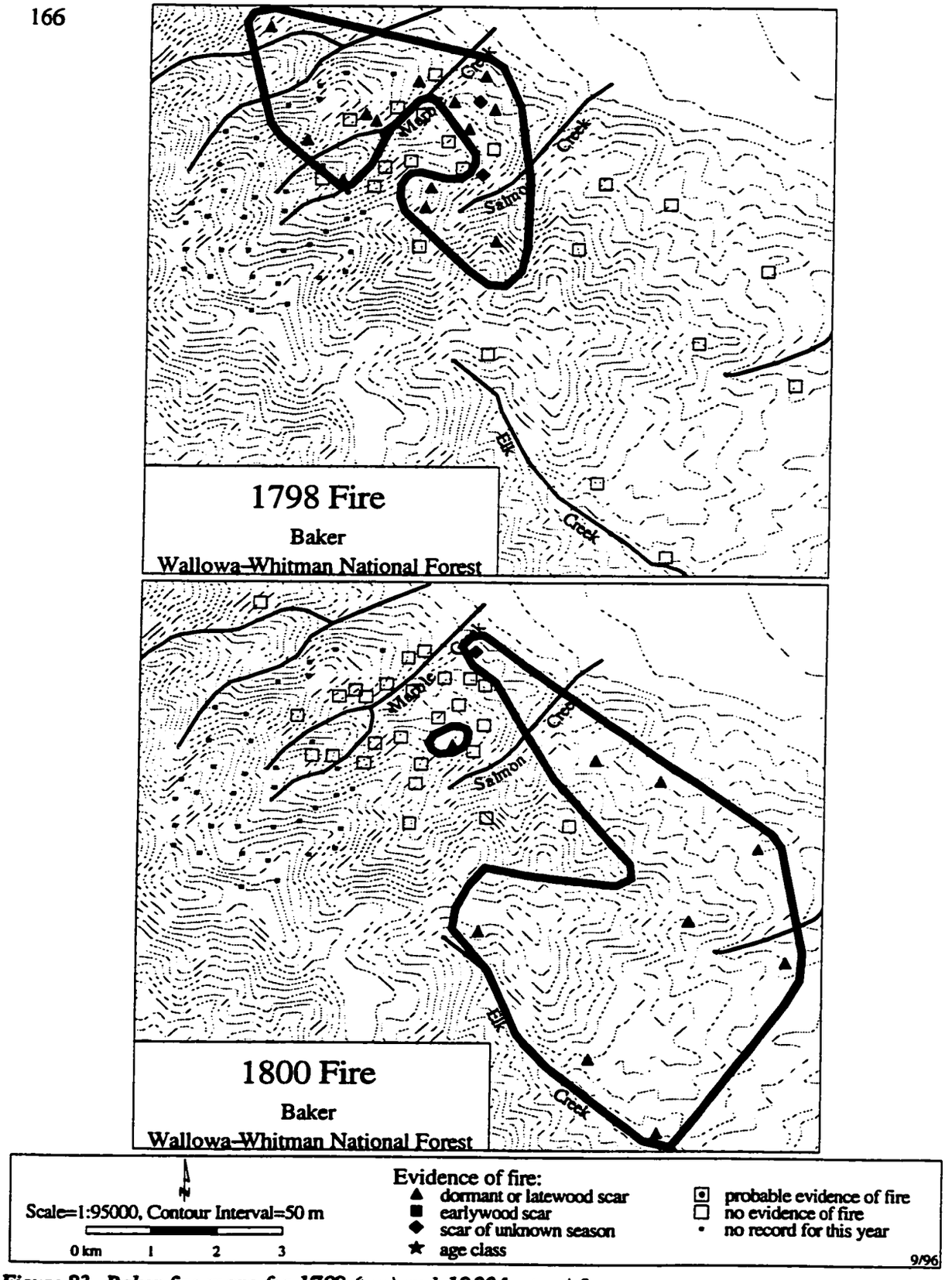


Figure 83. Baker fire maps for 1798 (top) and 1800(bottom) fires.

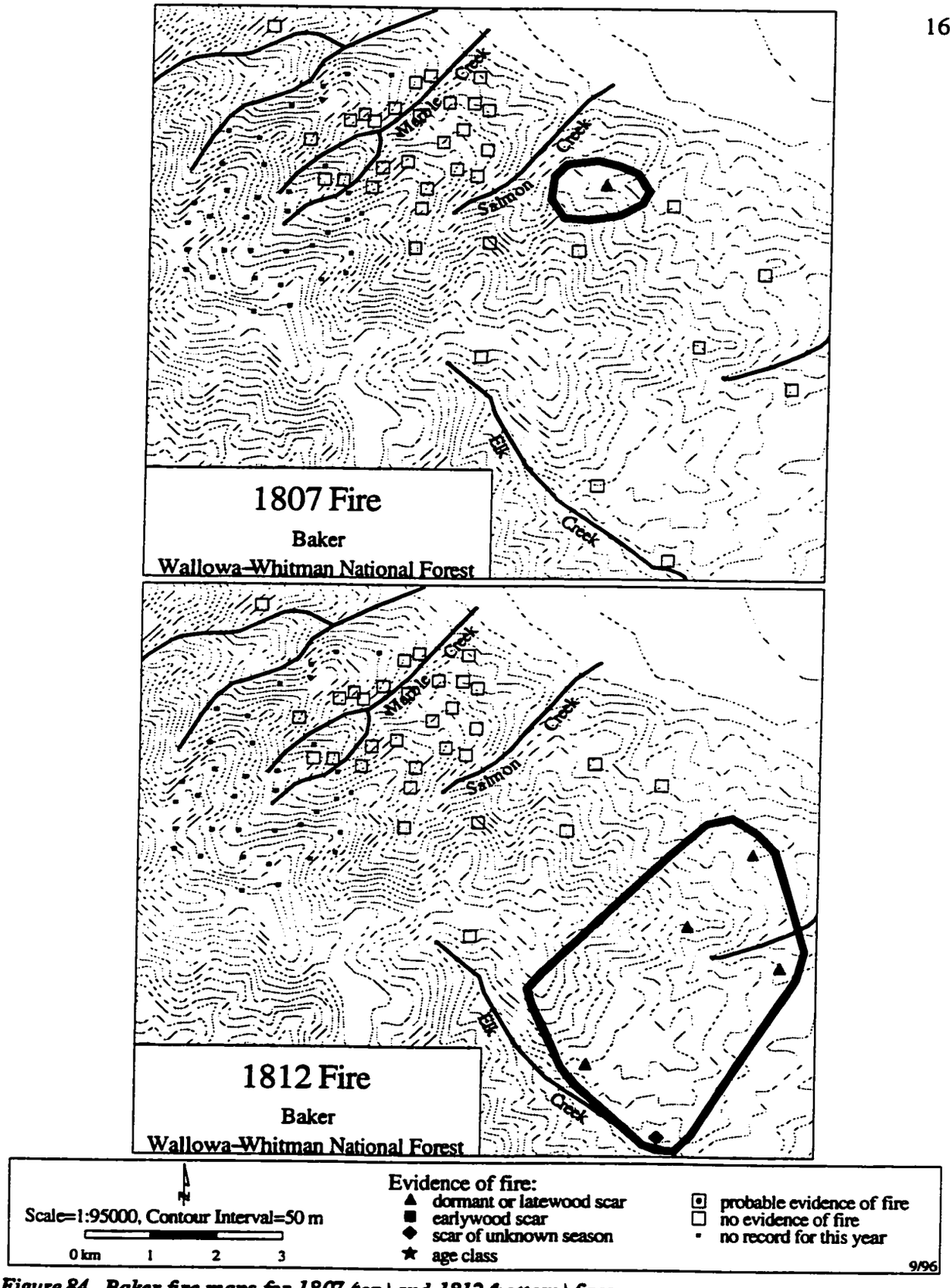


Figure 84. Baker fire maps for 1807 (top) and 1812 (bottom) fires.

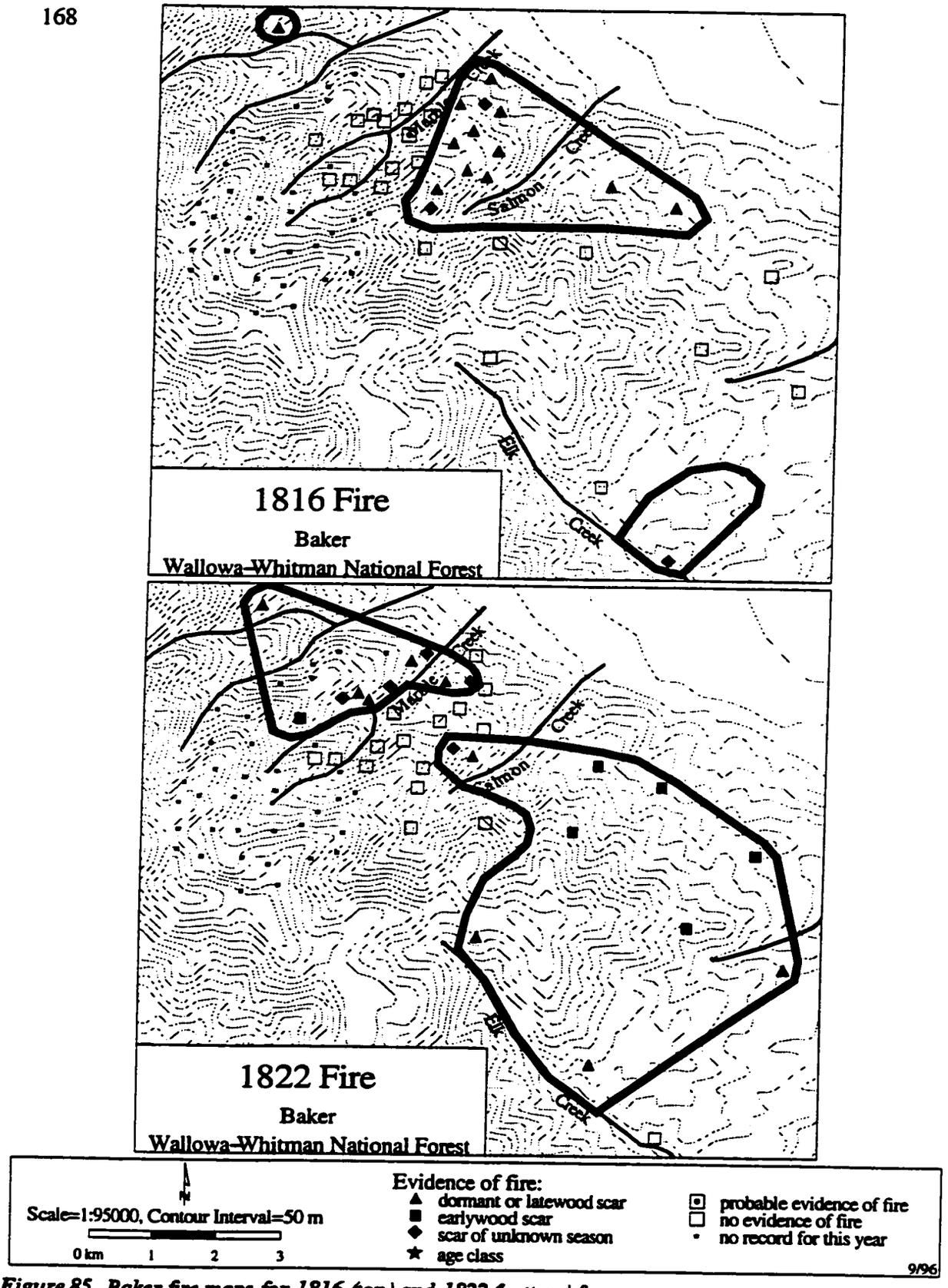


Figure 85. Baker fire maps for 1816 (top) and 1822 (bottom) fires.

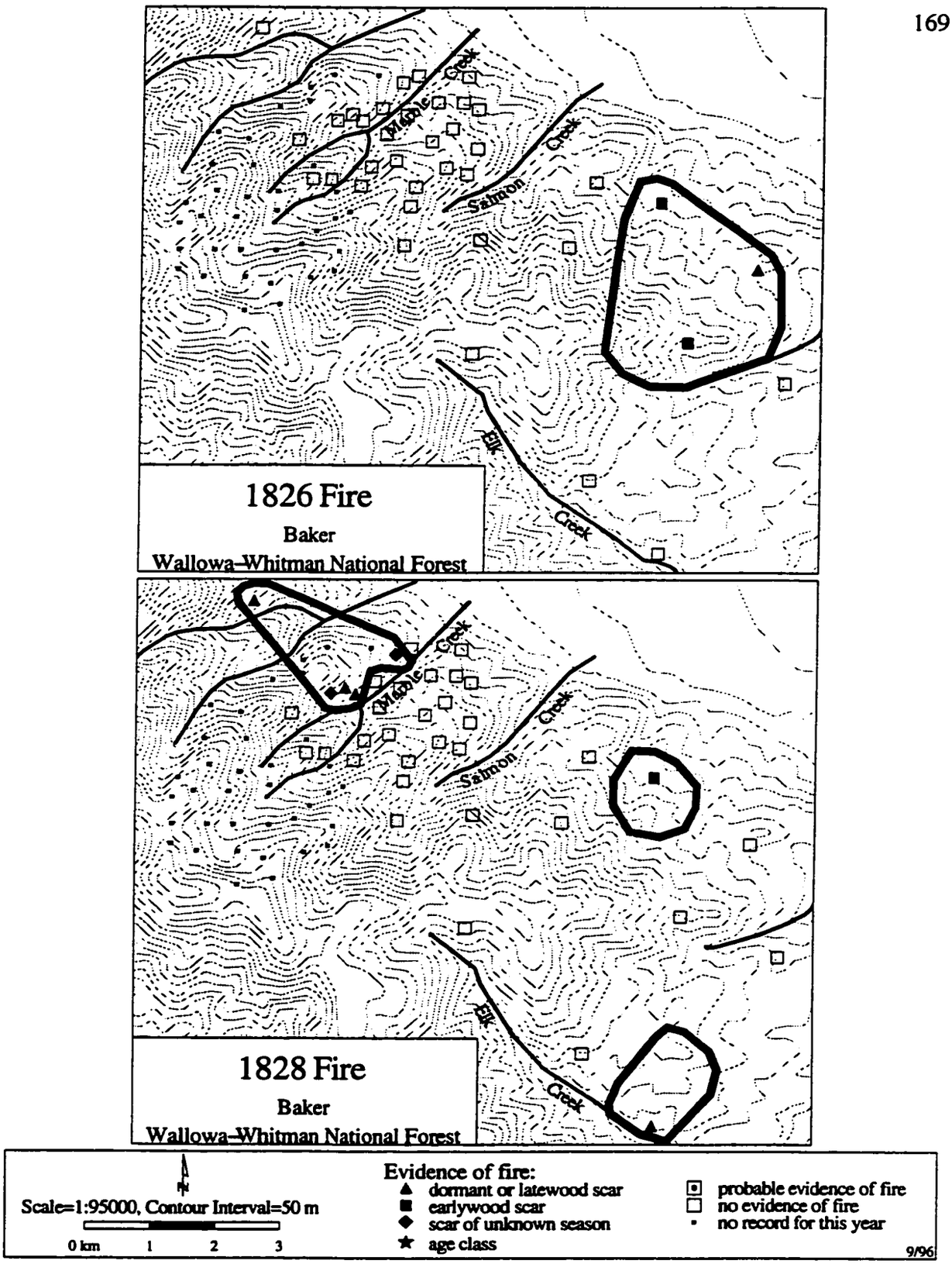


Figure 86. Baker fire maps for 1826 (top) and 1828 (bottom) fires.

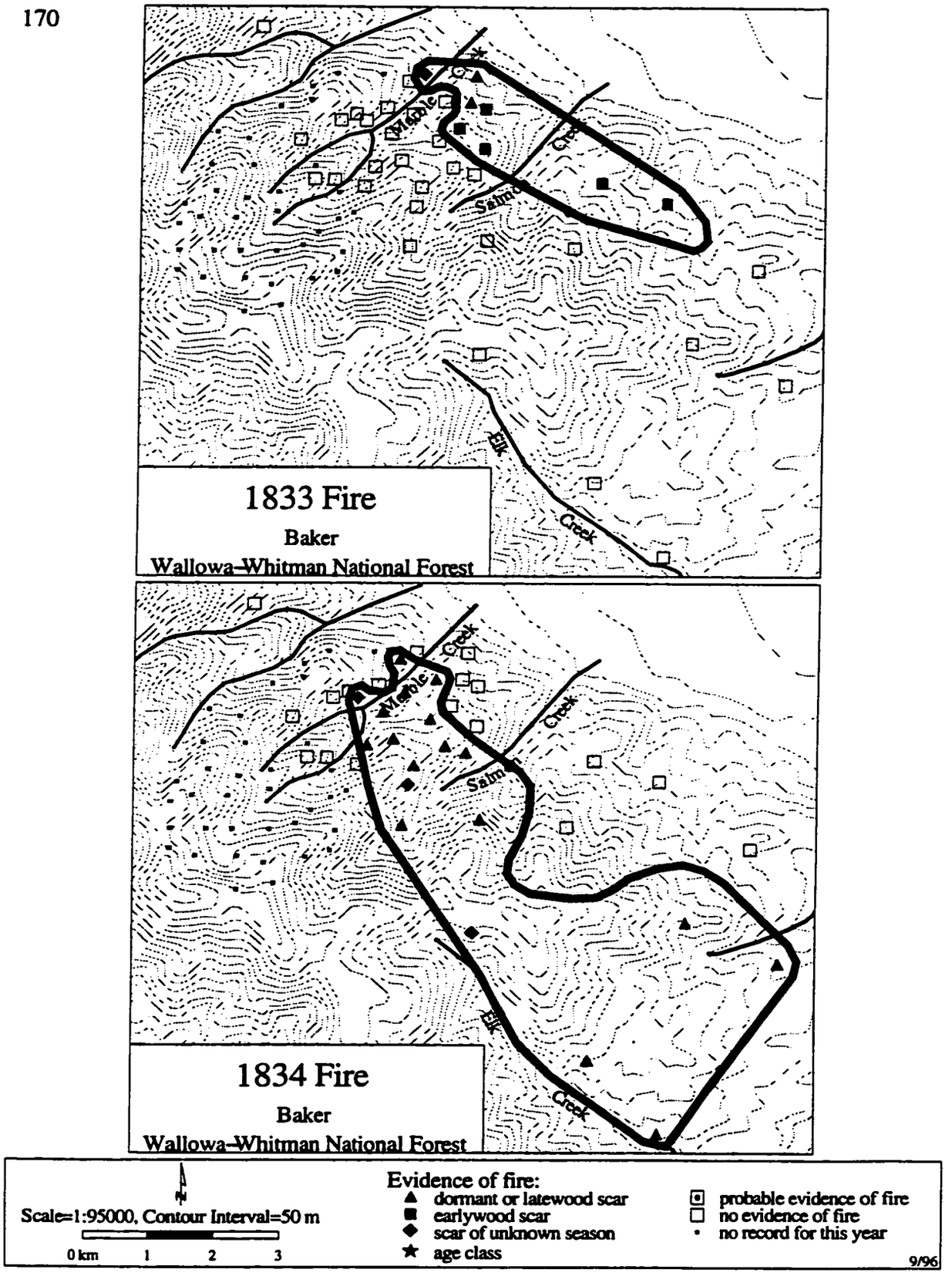


Figure 87. Baker fire maps for 1833 (top) and 1834 (bottom) fires.

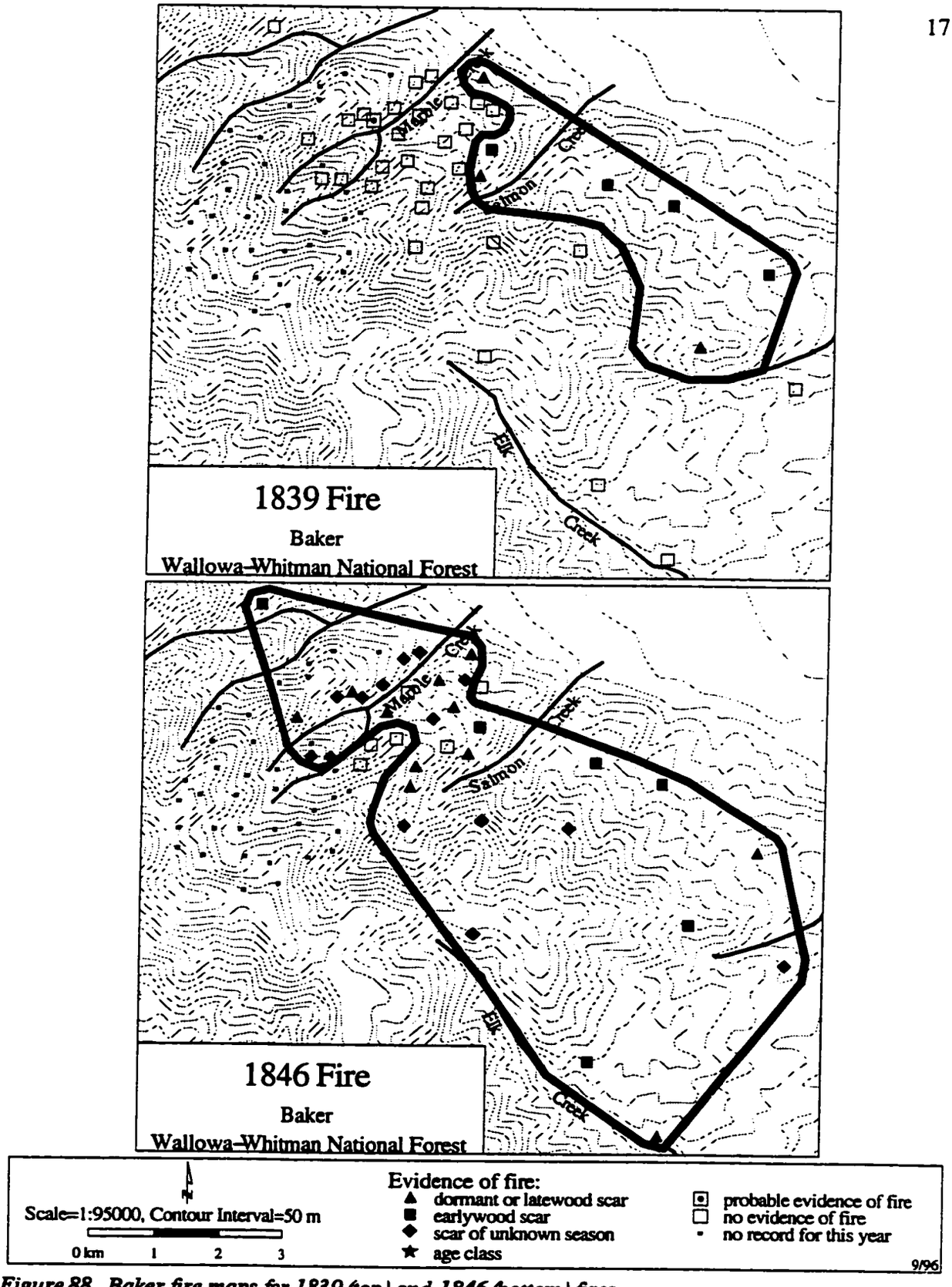


Figure 88. Baker fire maps for 1839 (top) and 1846 (bottom) fires.

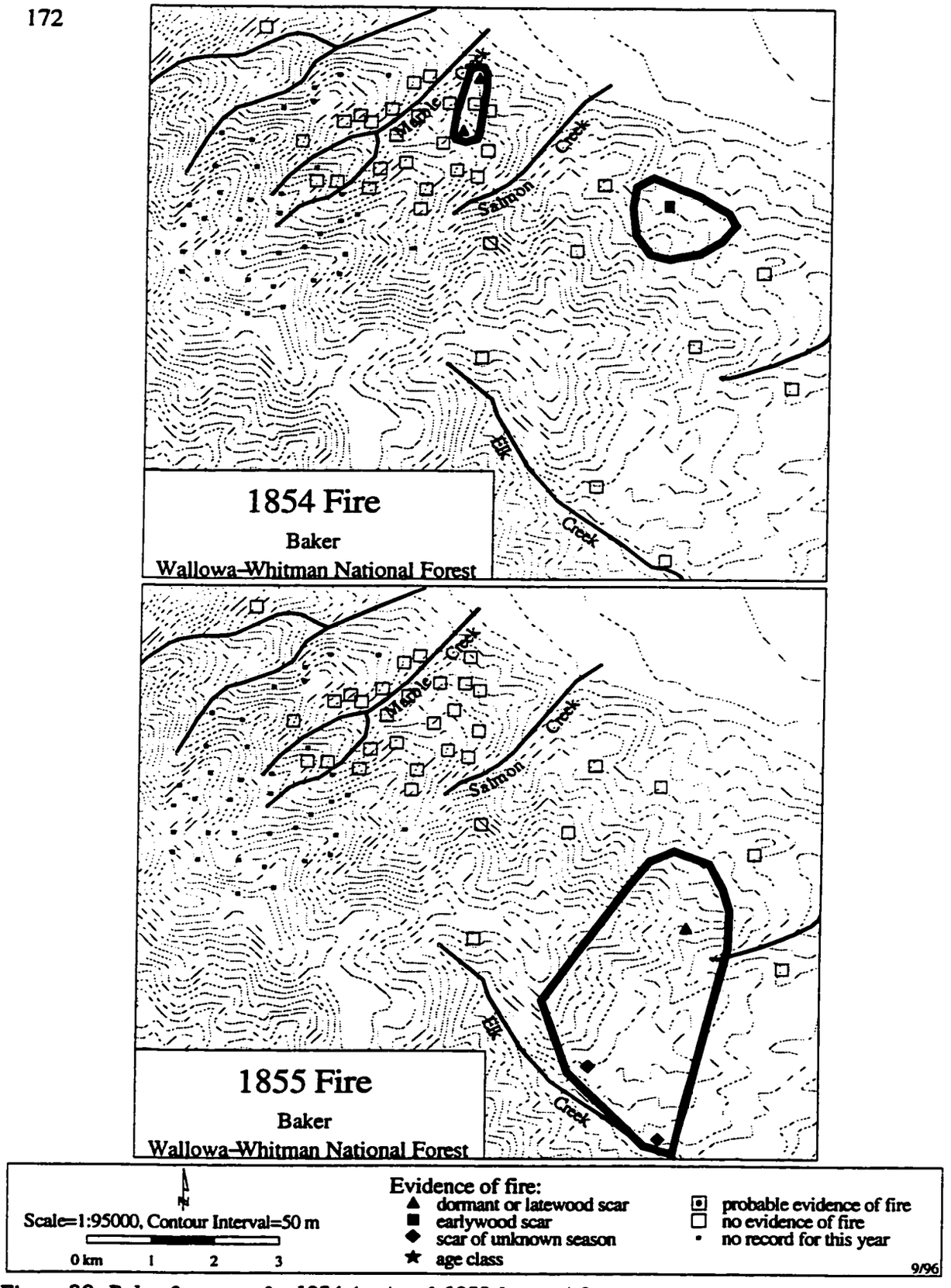


Figure 89. Baker fire maps for 1854 (top) and 1855 (bottom) fires.

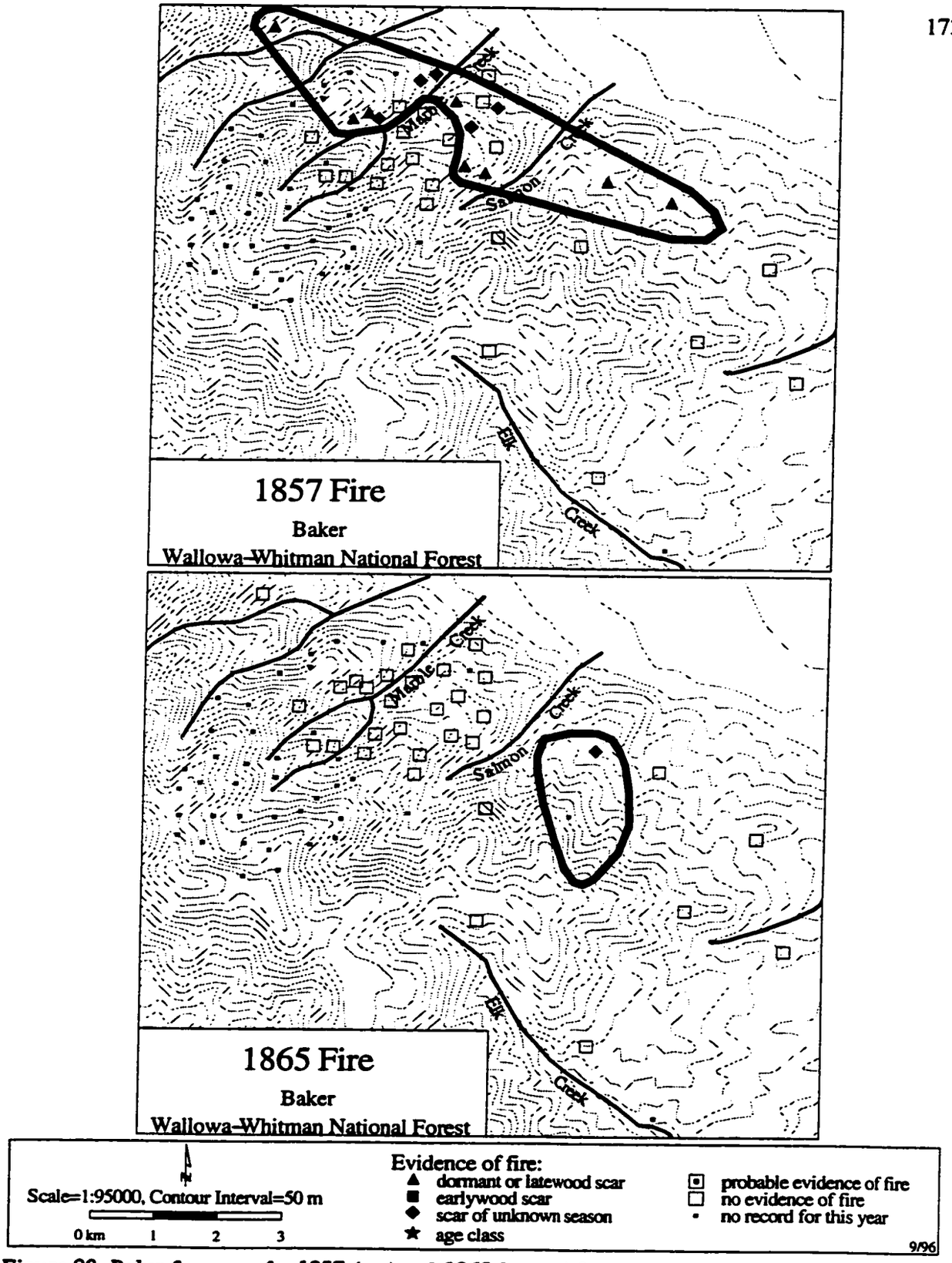


Figure 90. Baker fire maps for 1857 (top) and 1865 (bottom) fires.

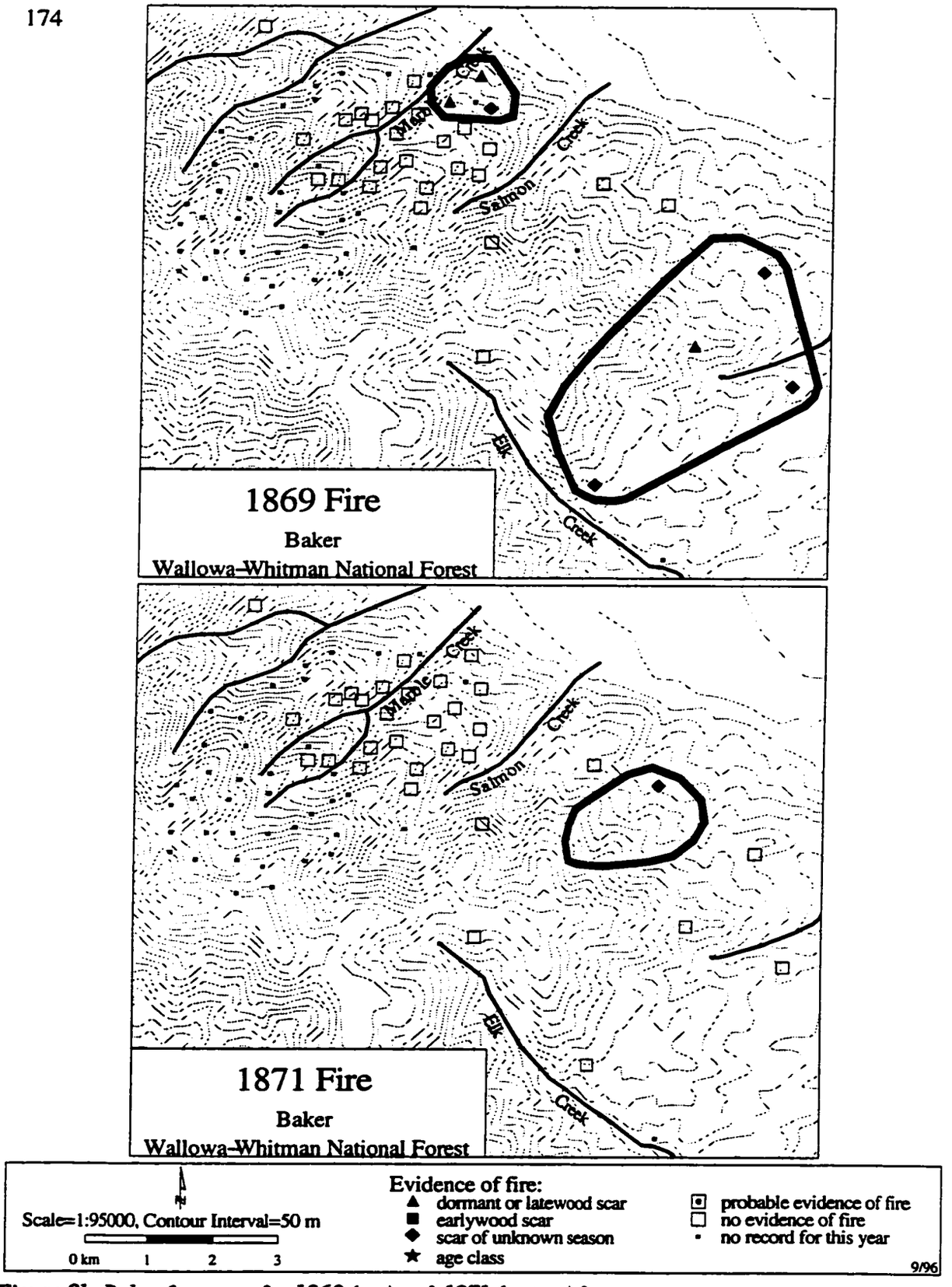


Figure 91. Baker fire maps for 1869 (top) and 1871 (bottom) fires.

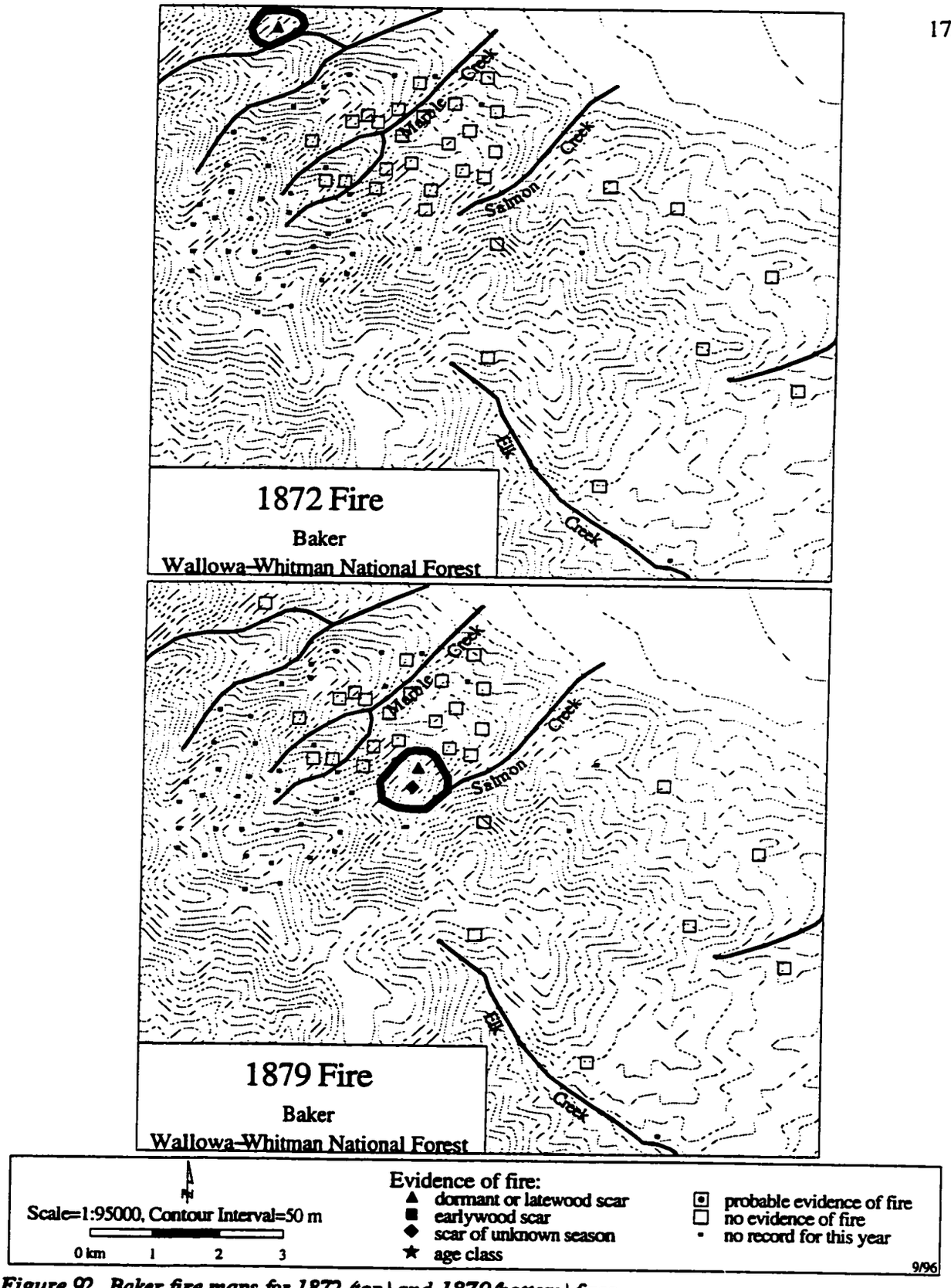


Figure 92. Baker fire maps for 1872 (top) and 1879 (bottom) fires.

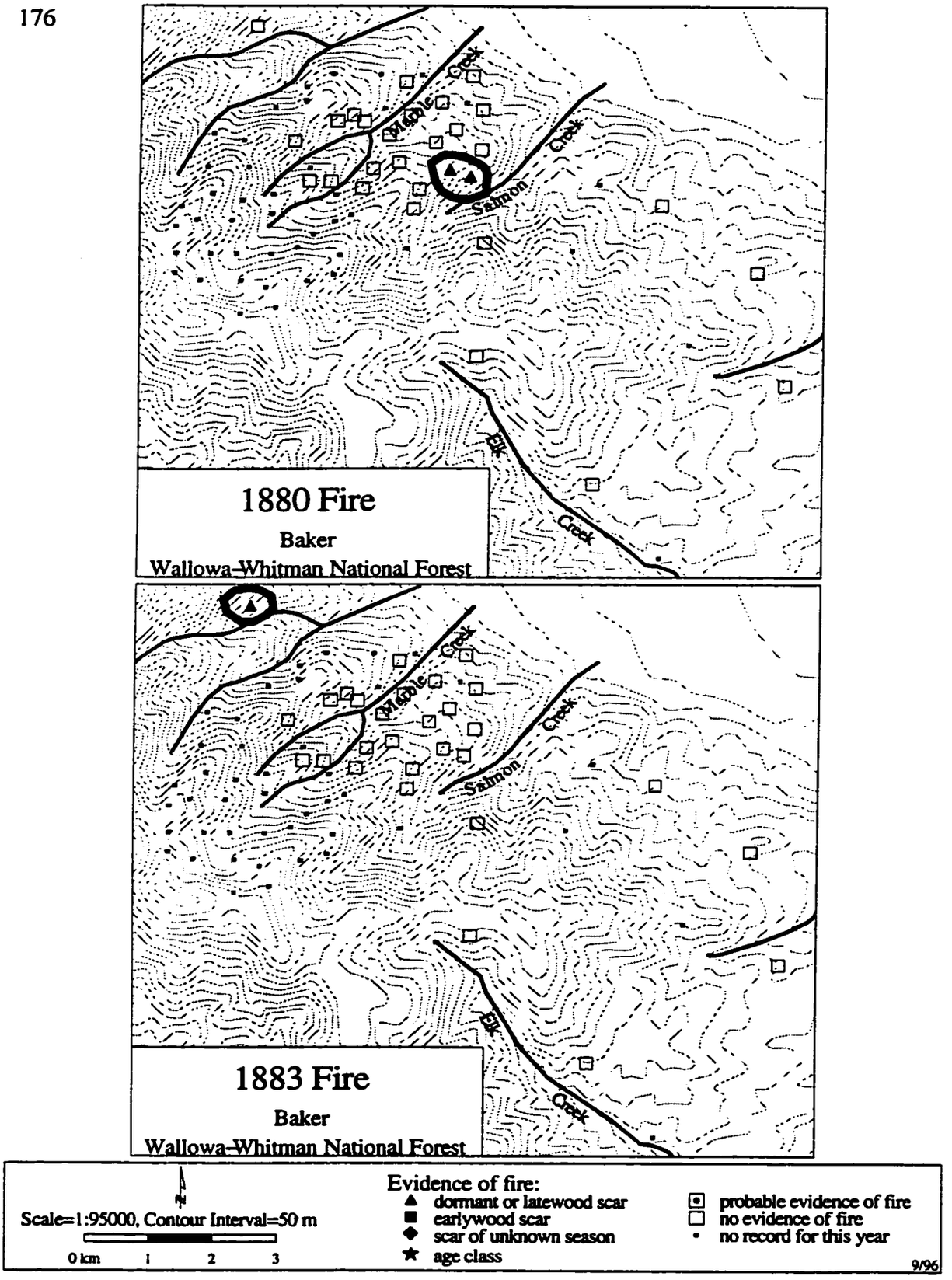


Figure 93. Baker fire maps for 1880 (top) and 1883 (bottom) fires.

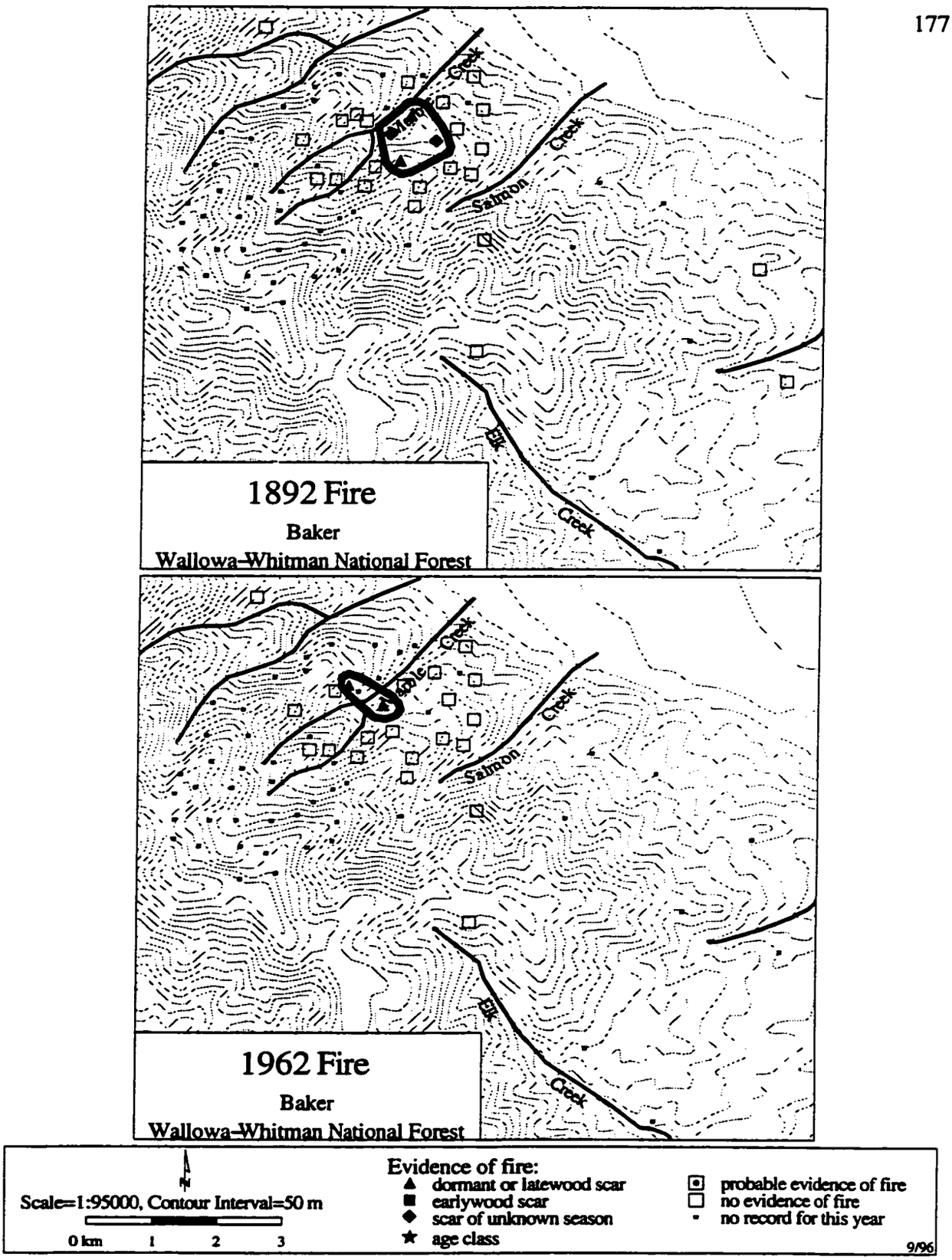


Figure 94. Baker fire maps for 1892 (top) and 1962 (bottom) fires.

APPENDIX G: DUGOUT FIRE MAPS

Evidence of fire was mapped at Dugout for every year in dry forests that had at least two scars. There are no mesic forests at this watershed. The maps show the intra-annular position of the scar is also indicated. Plots indicating as having probable evidence of fire are those for which the only evidence was an abrupt increase or decrease in ring width. Plots having no evidence of fire in a given year had recording trees for that year but did not have scars for that year. Plots indicated as having no record for a given year are plots that were sampled but had no trees recording during that year. Fire boundaries are shown as a heavy line.

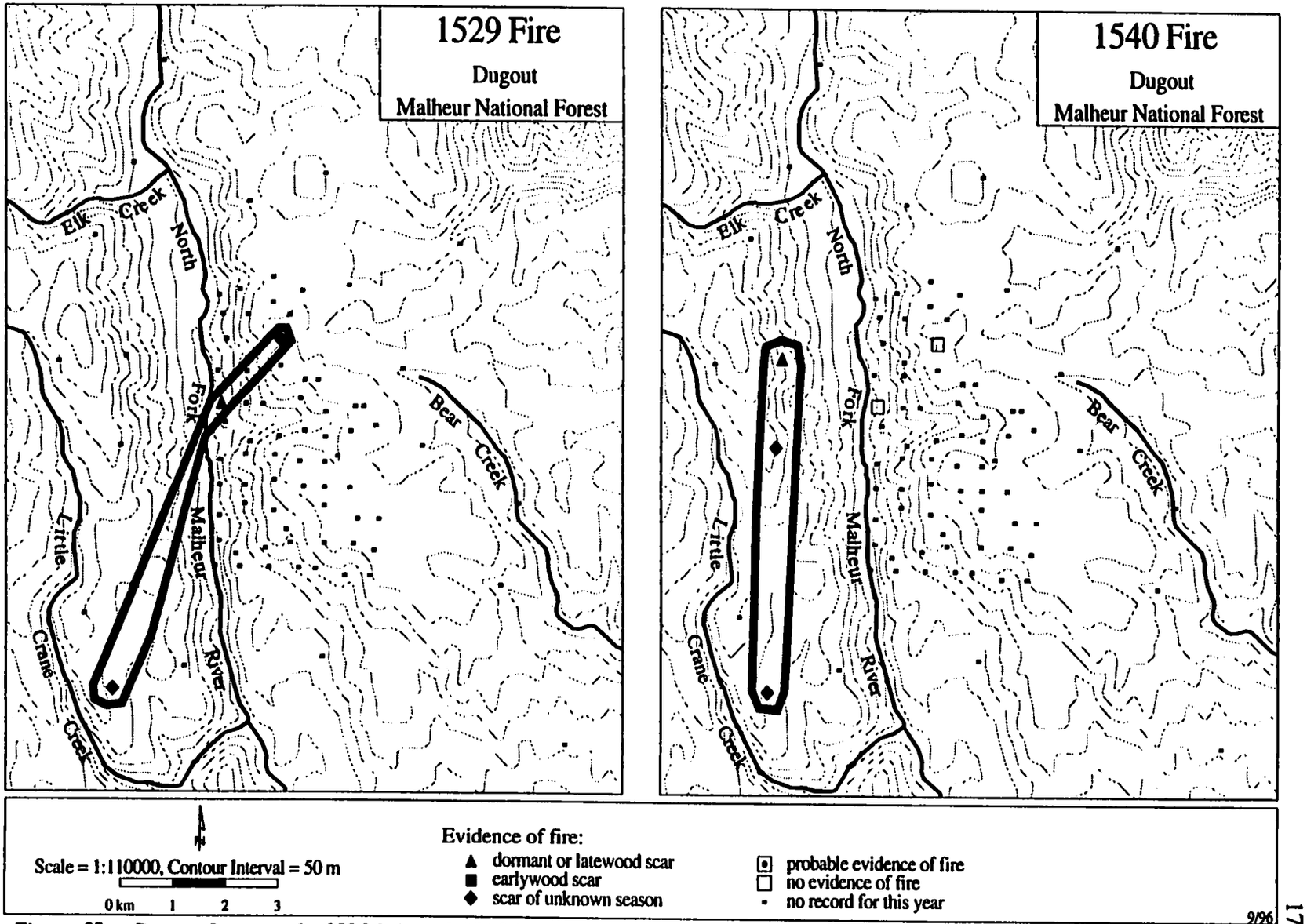


Figure 95 . Dugout fire maps for 1529(left) and 1540(right) fires.

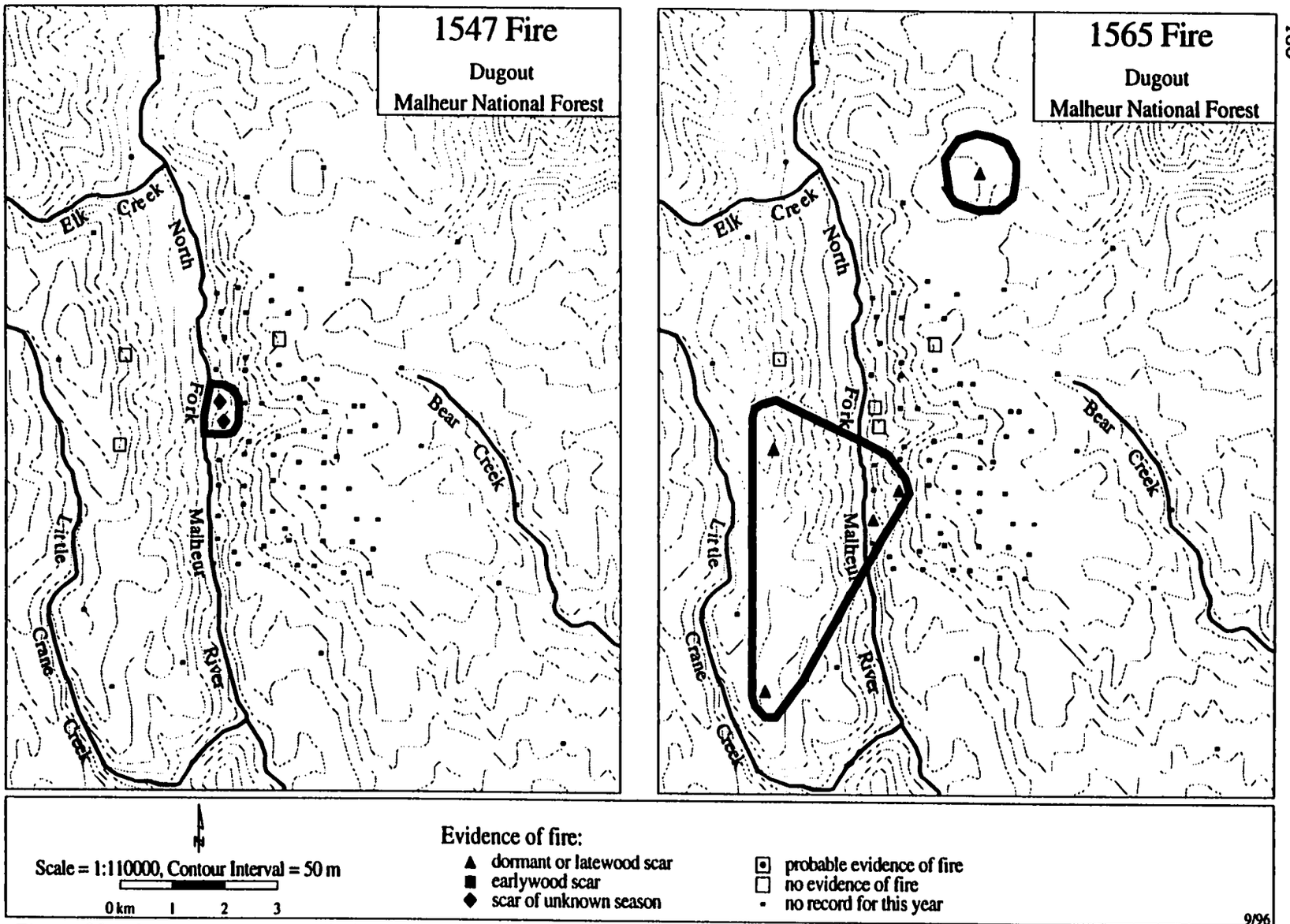


Figure 96 . Dugout fire maps for 1547 (left) and 1565 (right) fires.

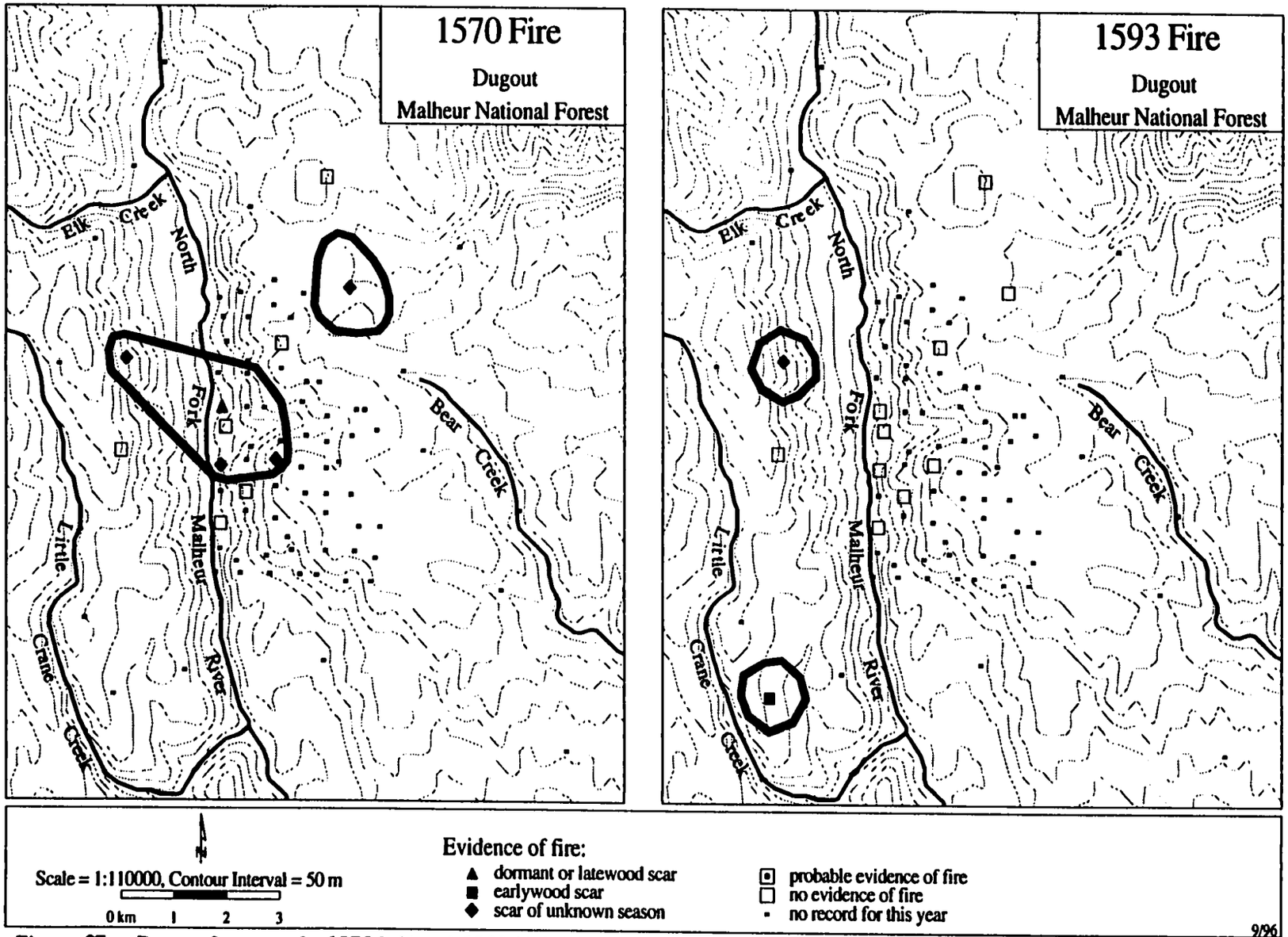


Figure 97 . Dugout fire maps for 1570(left) and 1593 (right) fires.

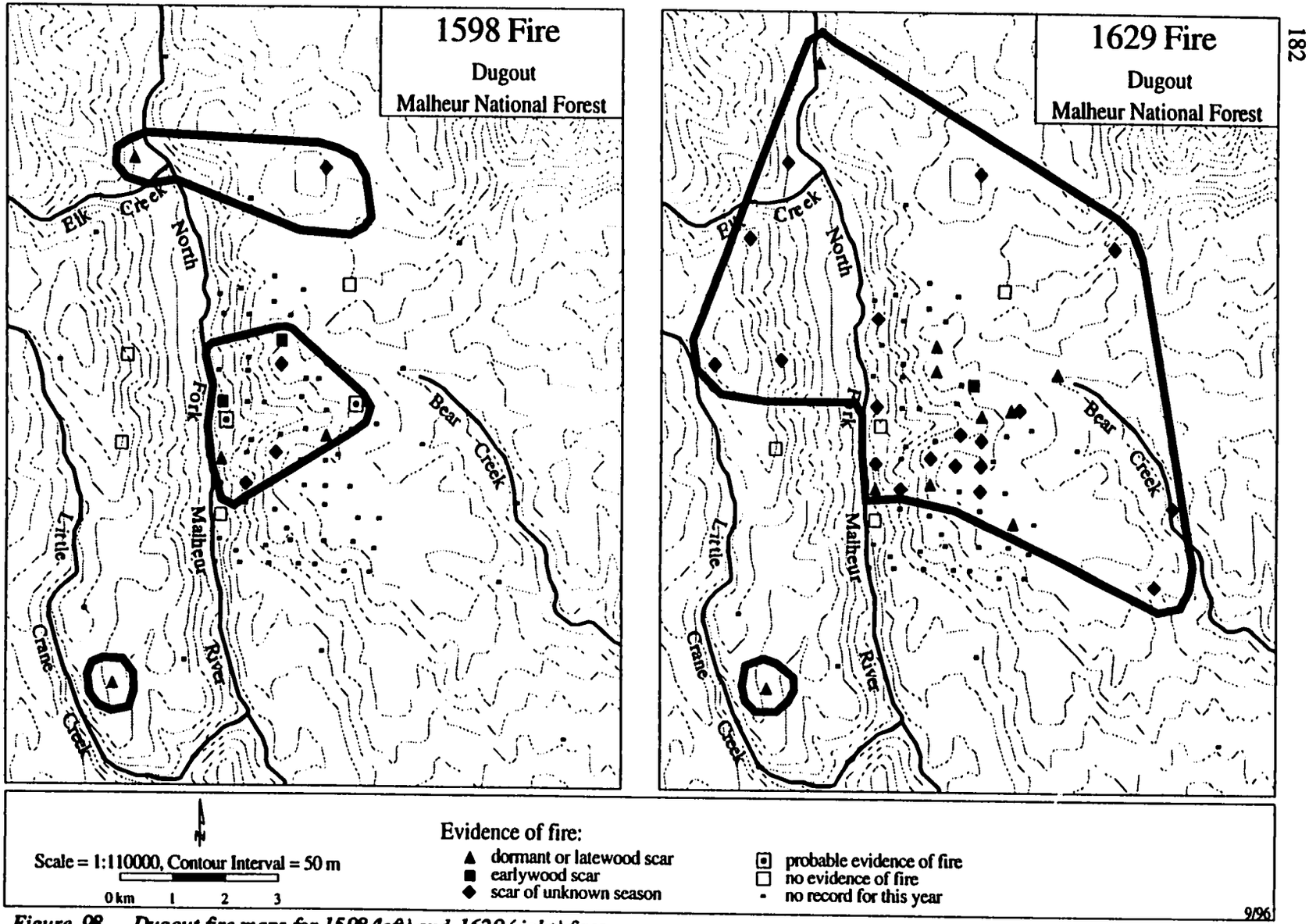


Figure 98 . Dugout fire maps for 1598 (left) and 1629 (right) fires.

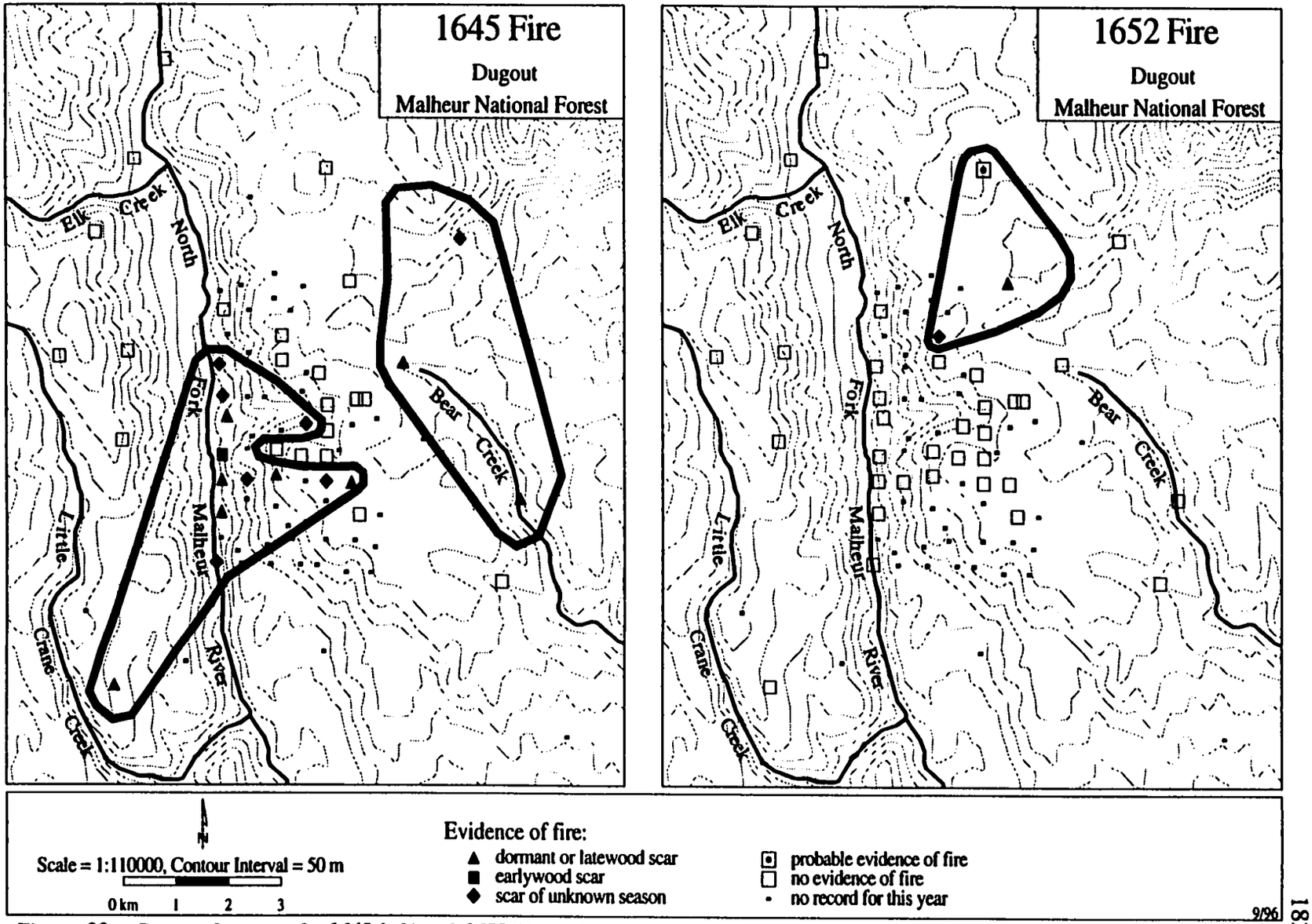


Figure 99 . Dugout fire maps for 1645 (left) and 1652 (right) fires.

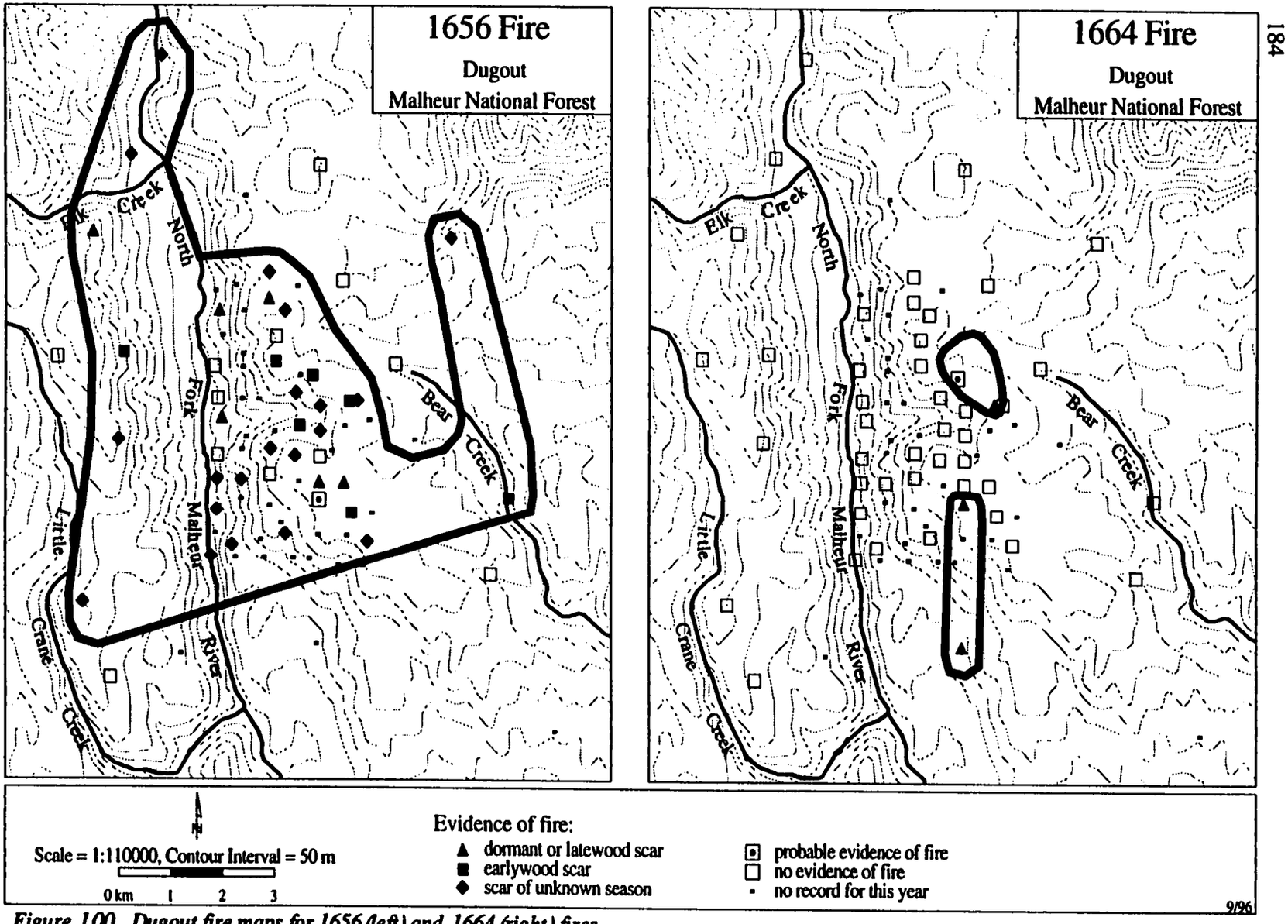


Figure 100. Dugout fire maps for 1656 (left) and 1664 (right) fires.

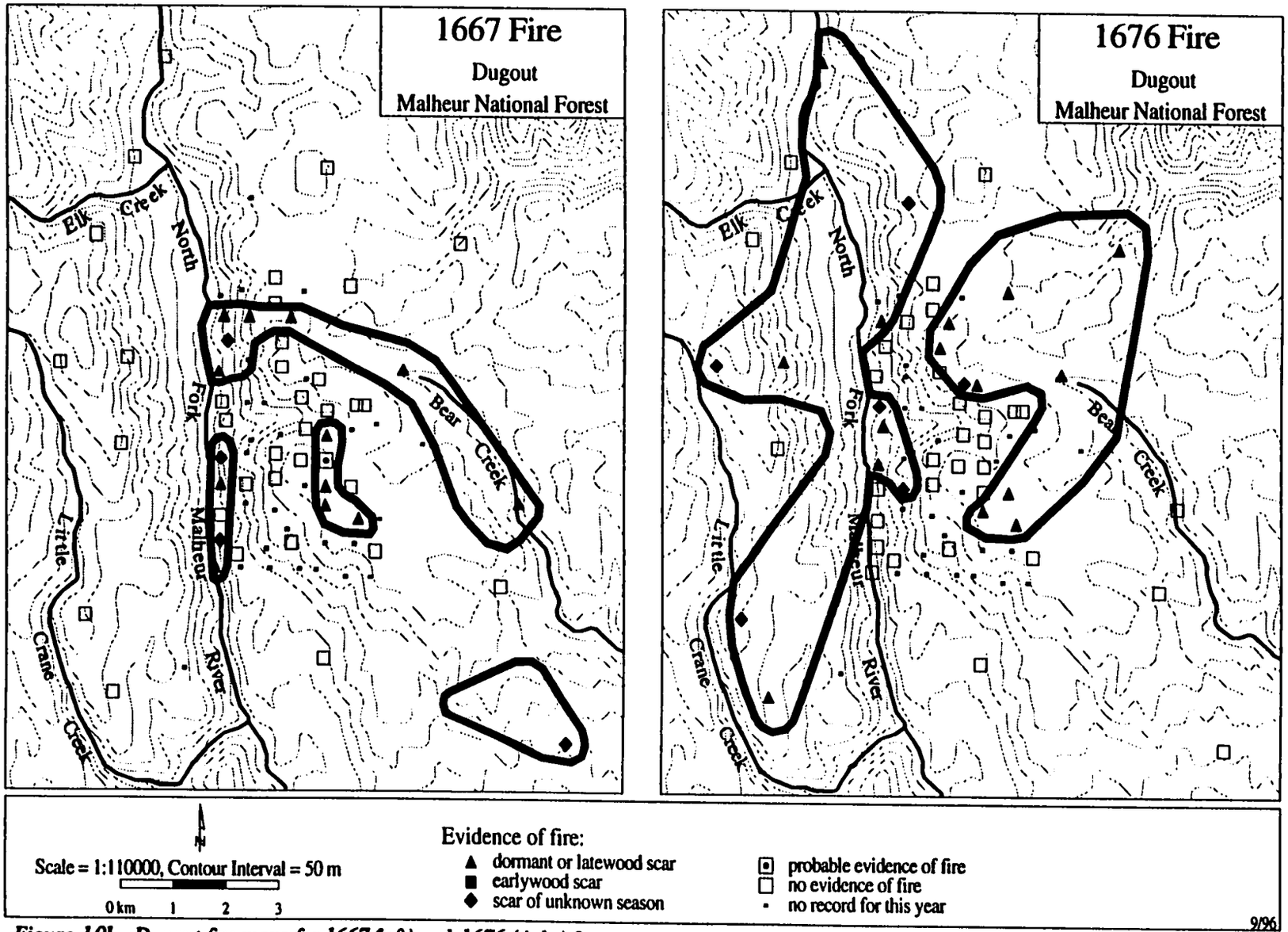


Figure 101. Dugout fire maps for 1667 (left) and 1676 (right) fires.

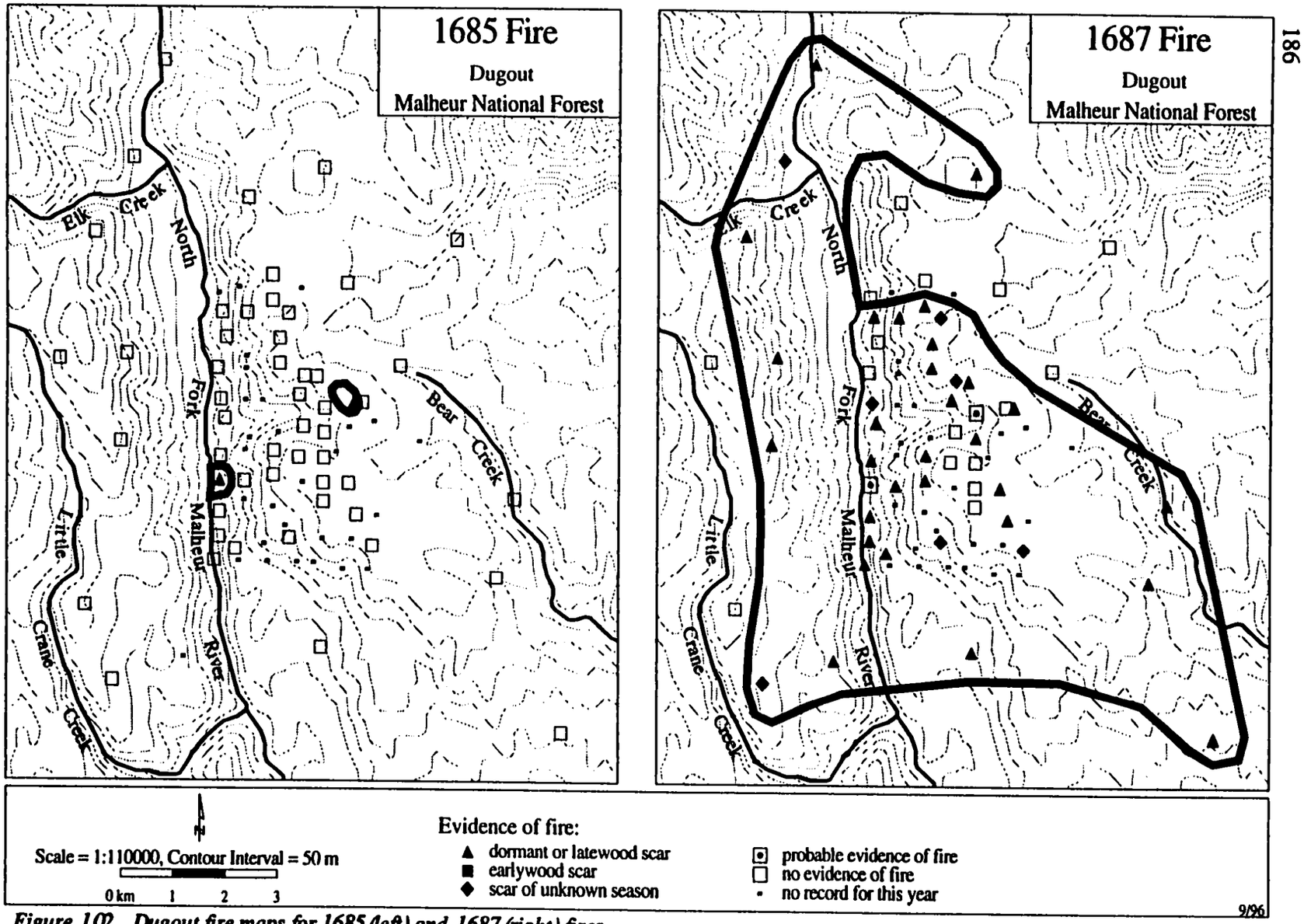


Figure 102. Dugout fire maps for 1685 (left) and 1687 (right) fires.

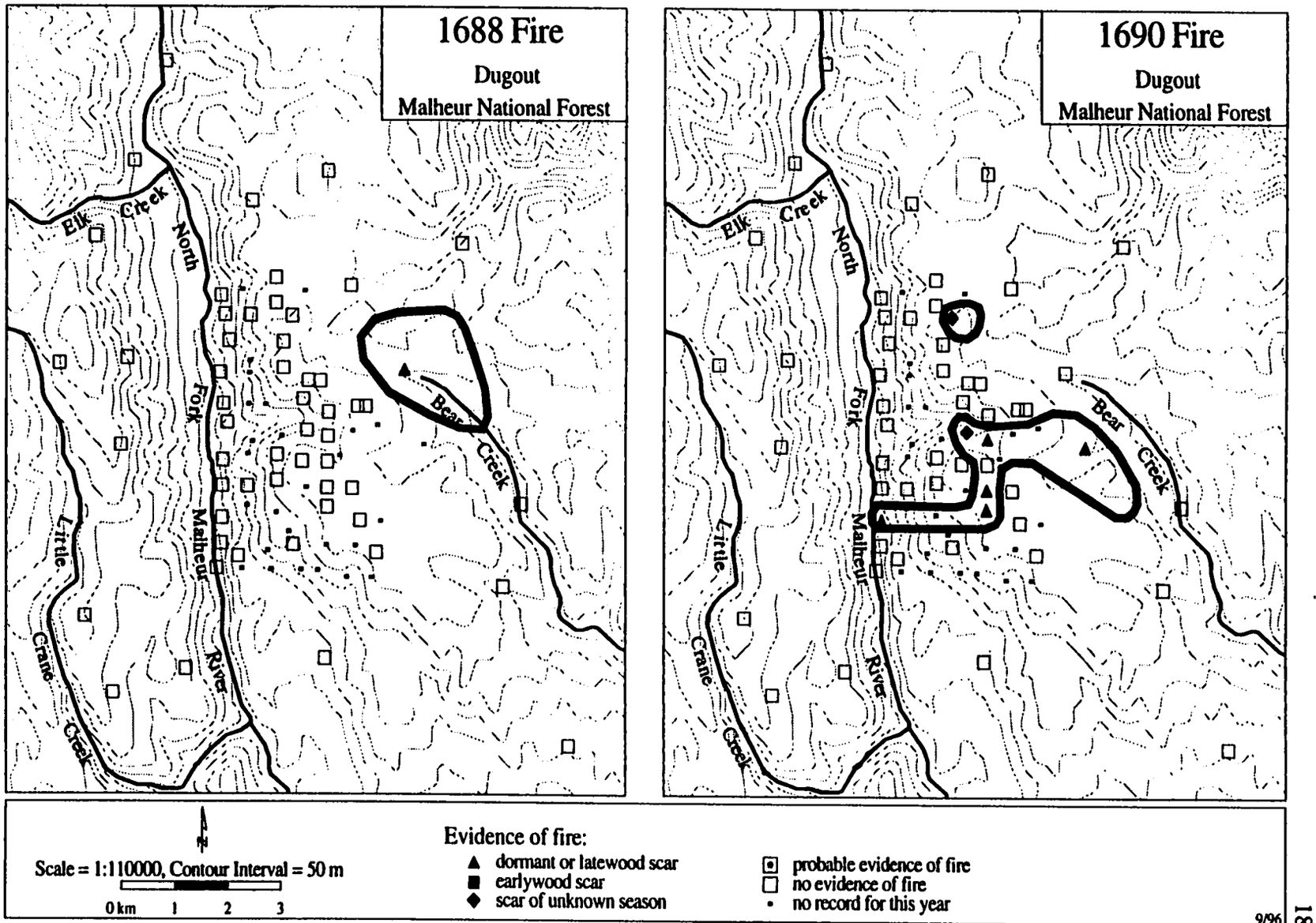


Figure 103. Dugout fire maps for 1688 (left) and 1690 (right) fires.

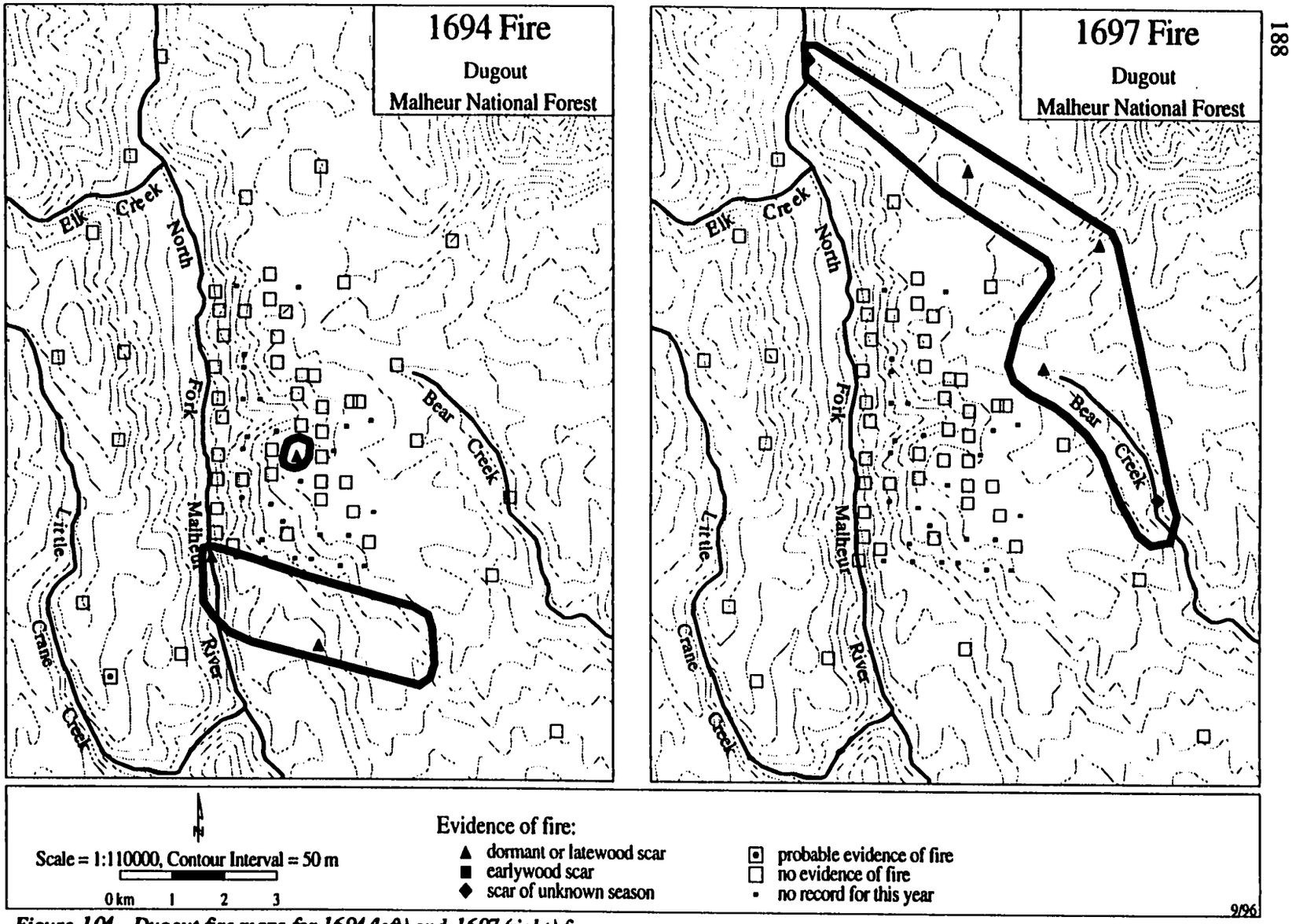


Figure 104. Dugout fire maps for 1694 (left) and 1697 (right) fires.

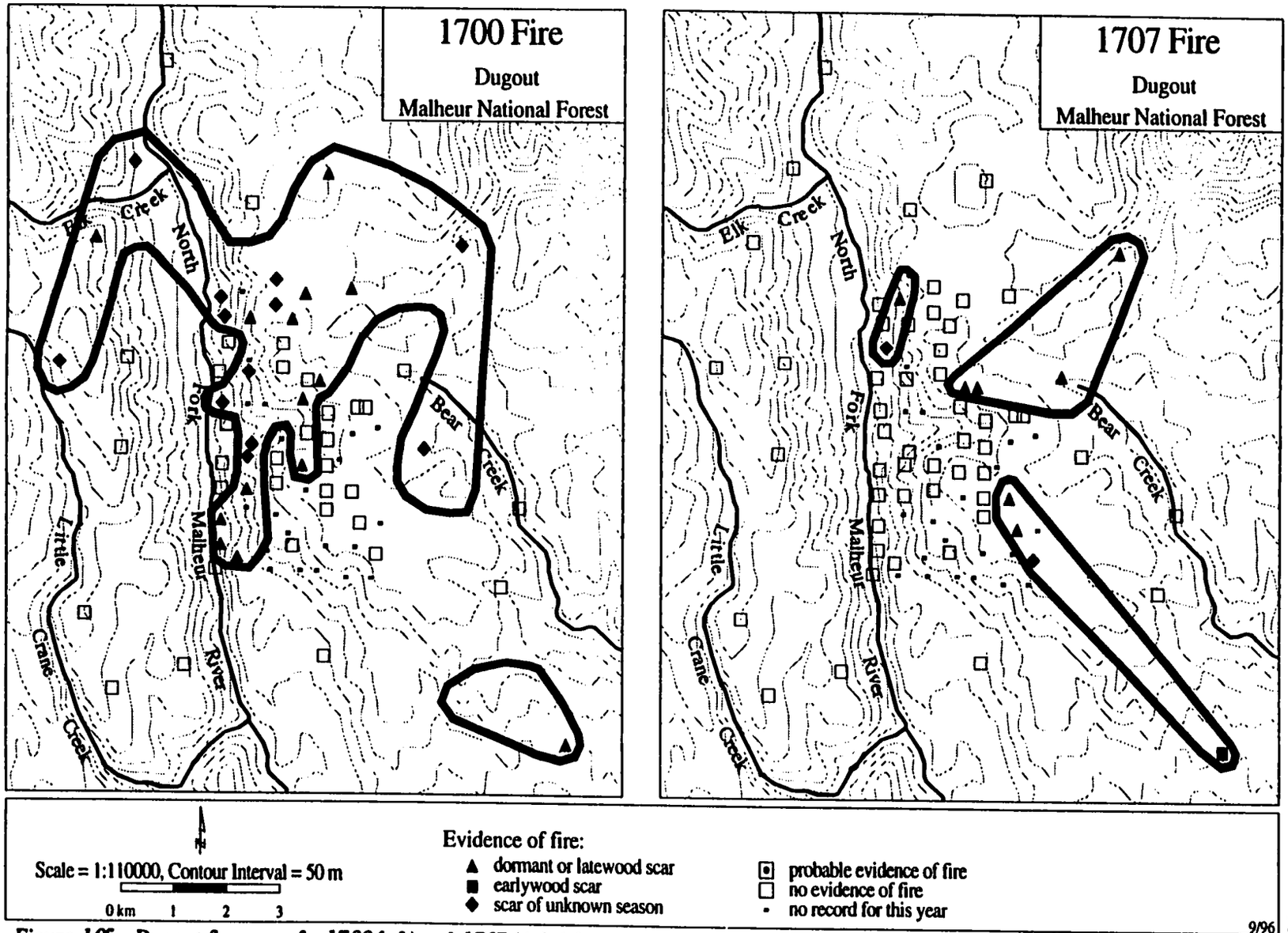


Figure 105. Dugout fire maps for 1700(left) and 1707 (right) fires.

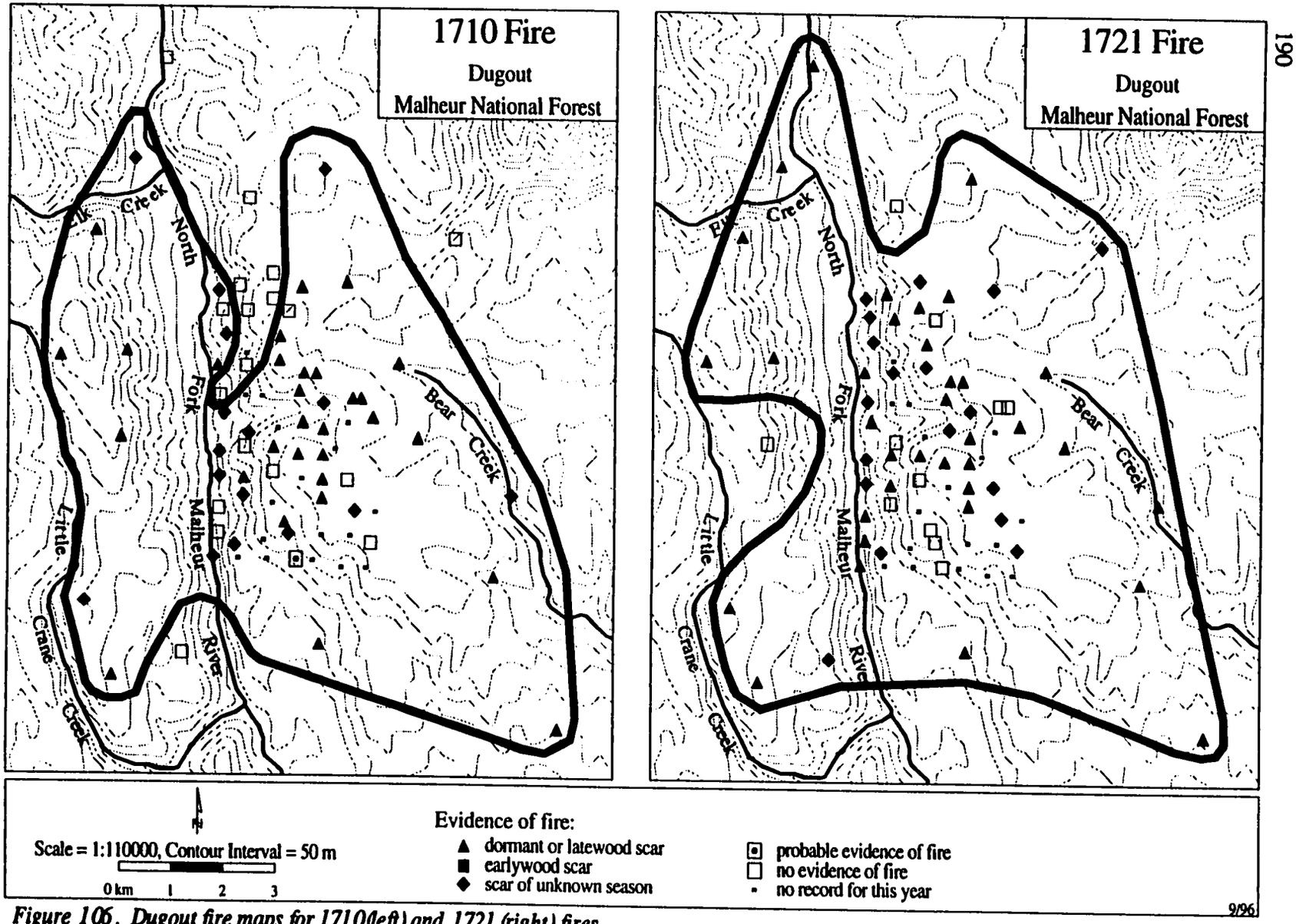


Figure 106. Dugout fire maps for 1710 (left) and 1721 (right) fires.

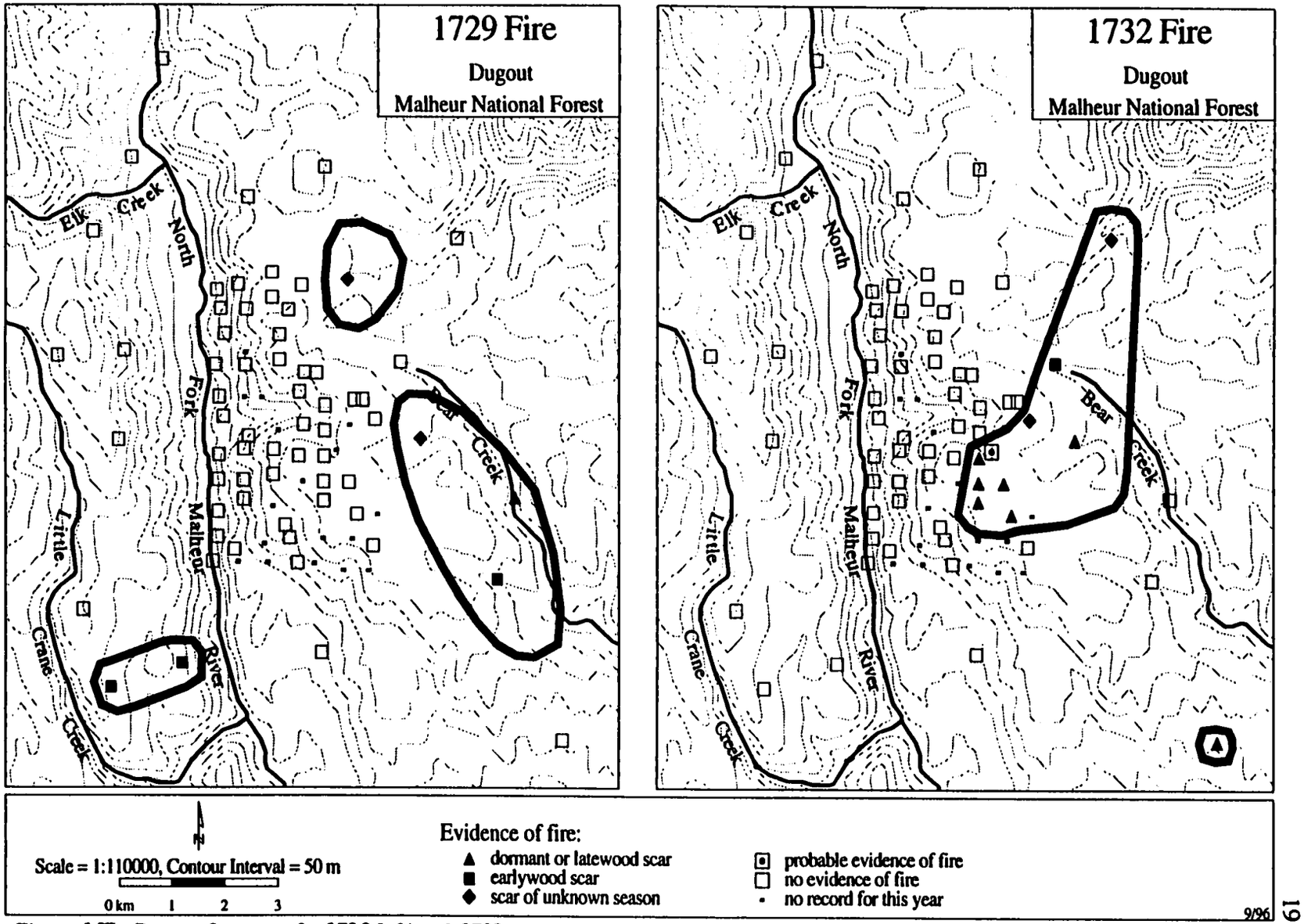


Figure 107. Dugout fire maps for 1729 (left) and 1732 (right) fires.

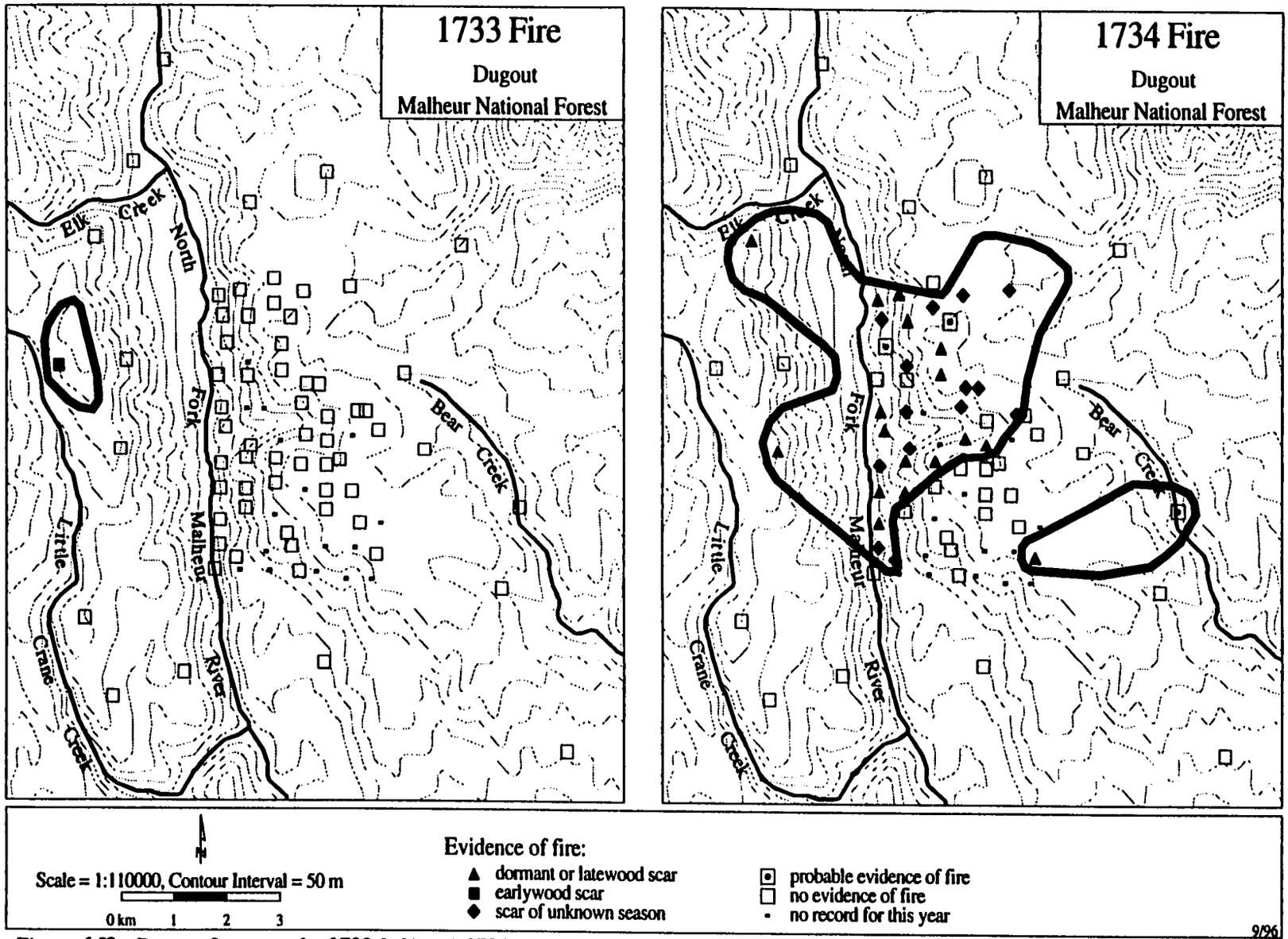


Figure 108. Dugout fire maps for 1733 (left) and 1734 (right) fires.

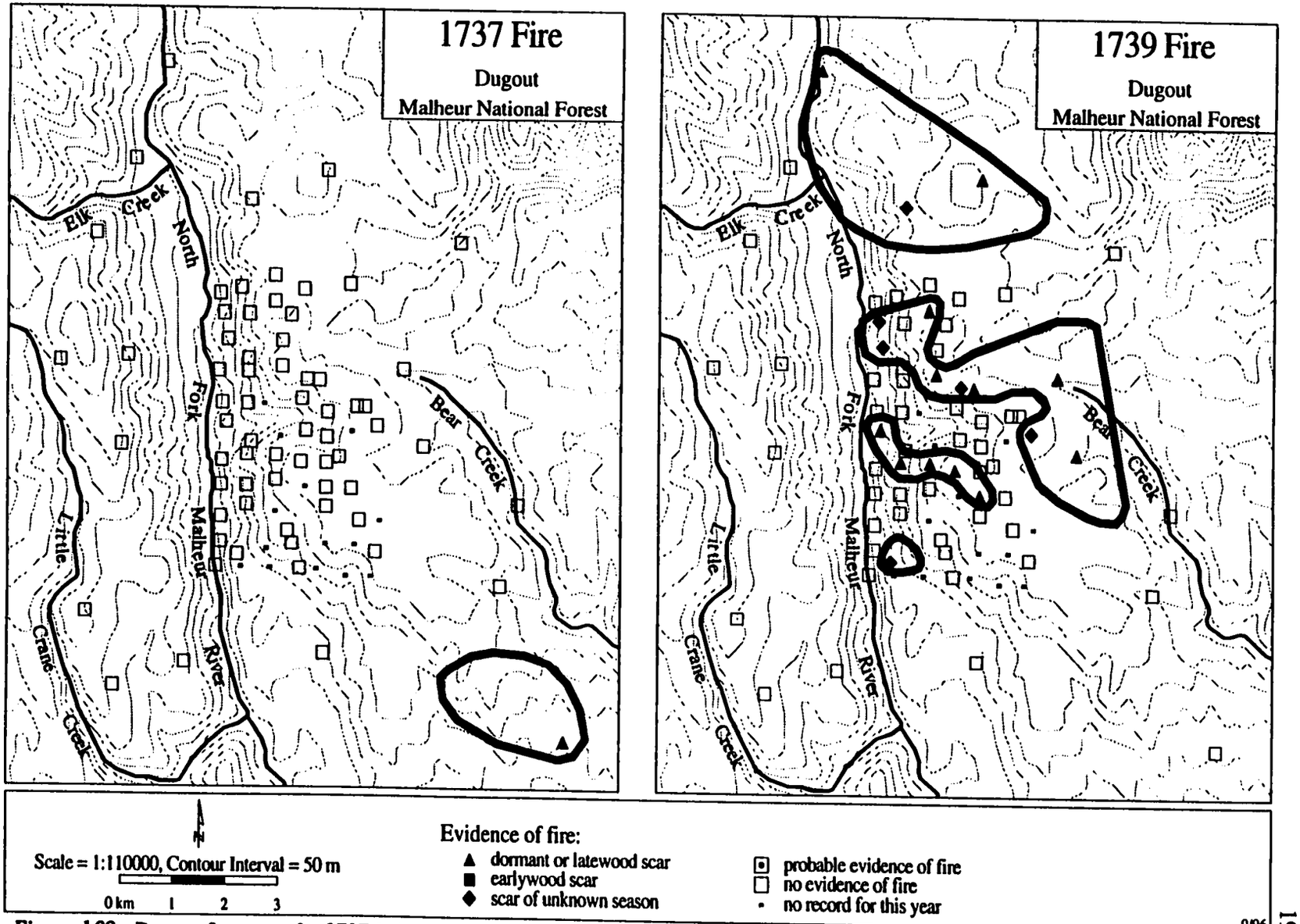


Figure 109. Dugout fire maps for 1737 (left) and 1739 (right) fires.

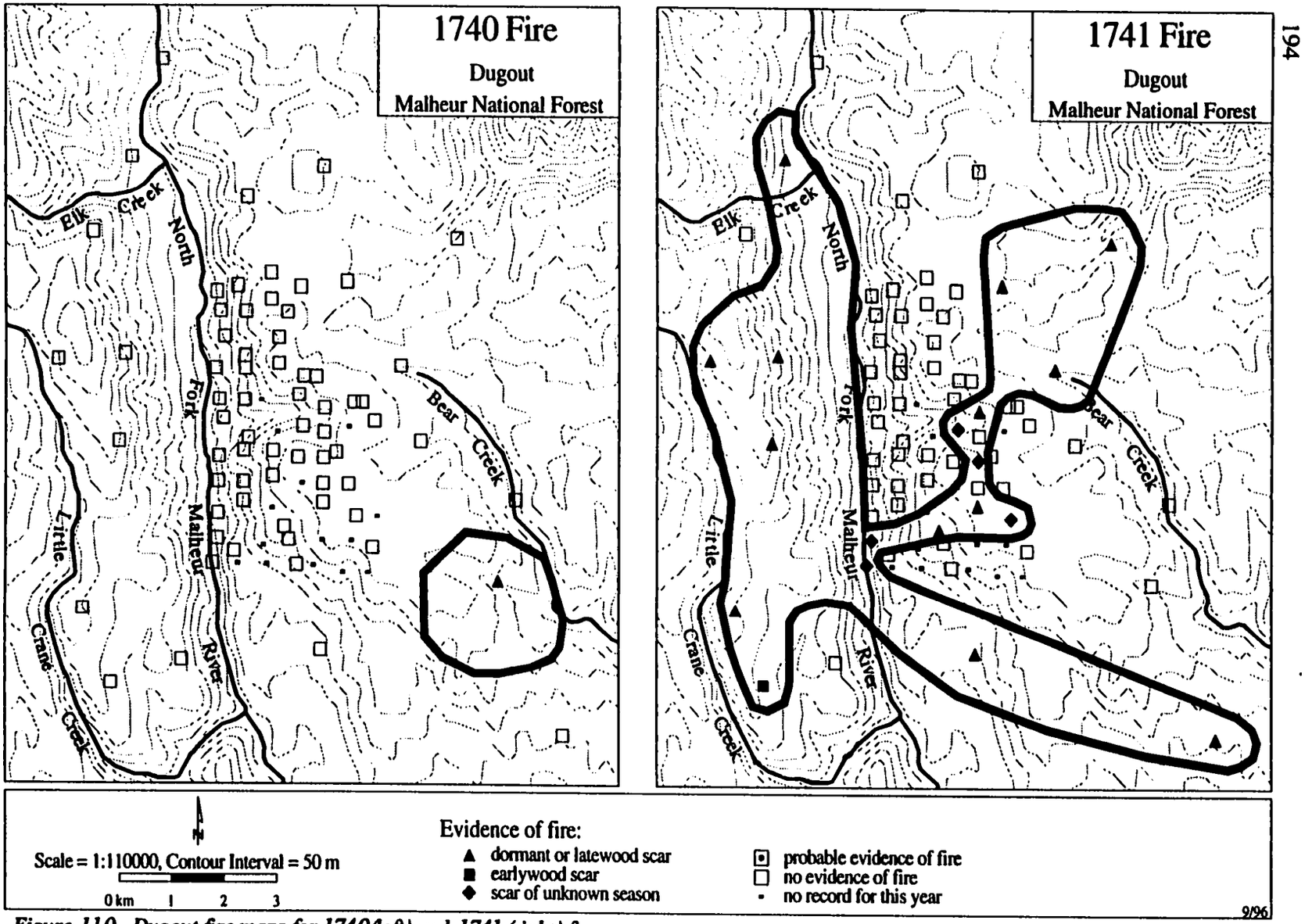


Figure 110. Dugout fire maps for 1740(left) and 1741 (right) fires.

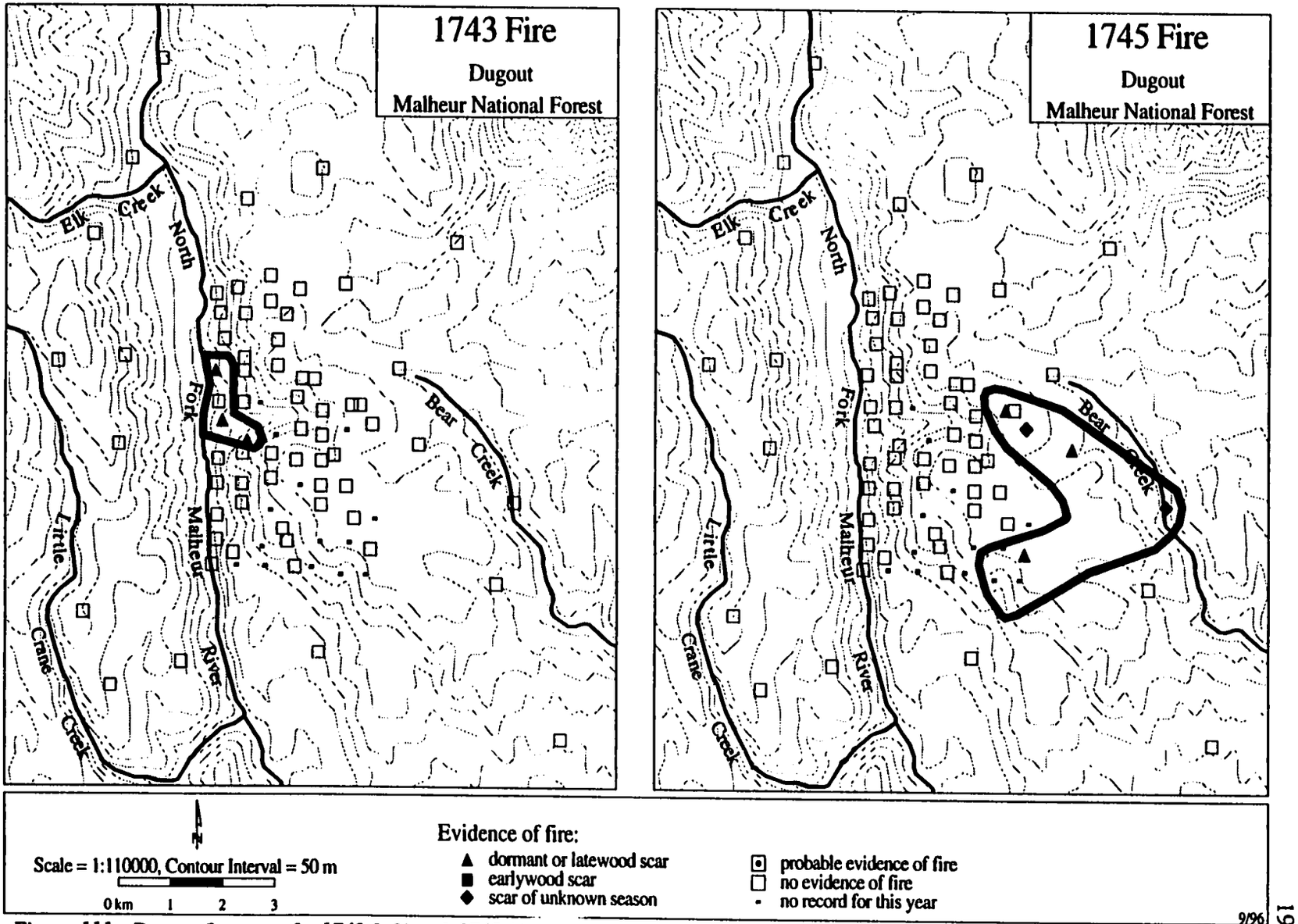


Figure 111. Dugout fire maps for 1743 (left) and 1745 (right) fires.

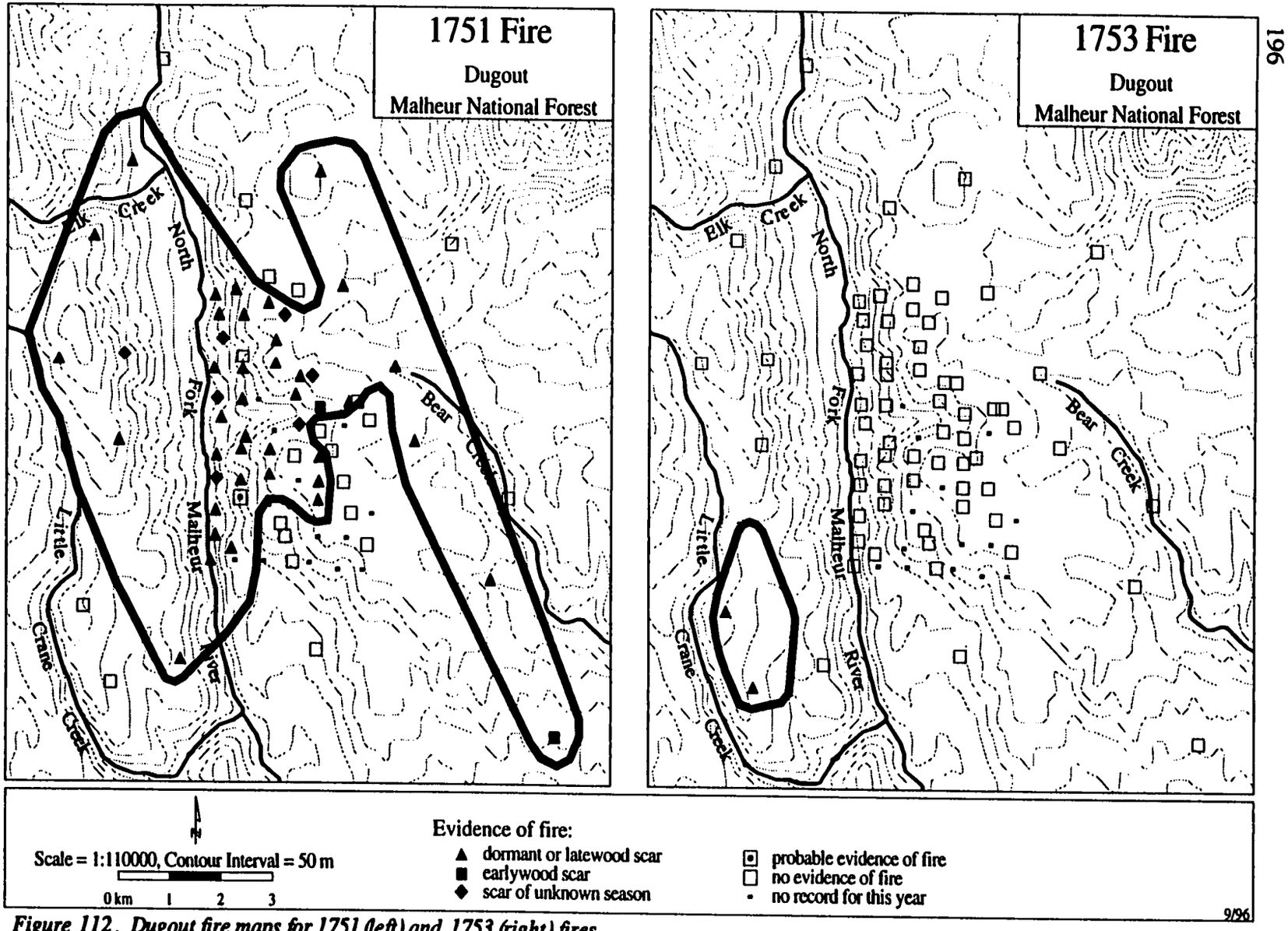


Figure 112. Dugout fire maps for 1751 (left) and 1753 (right) fires.

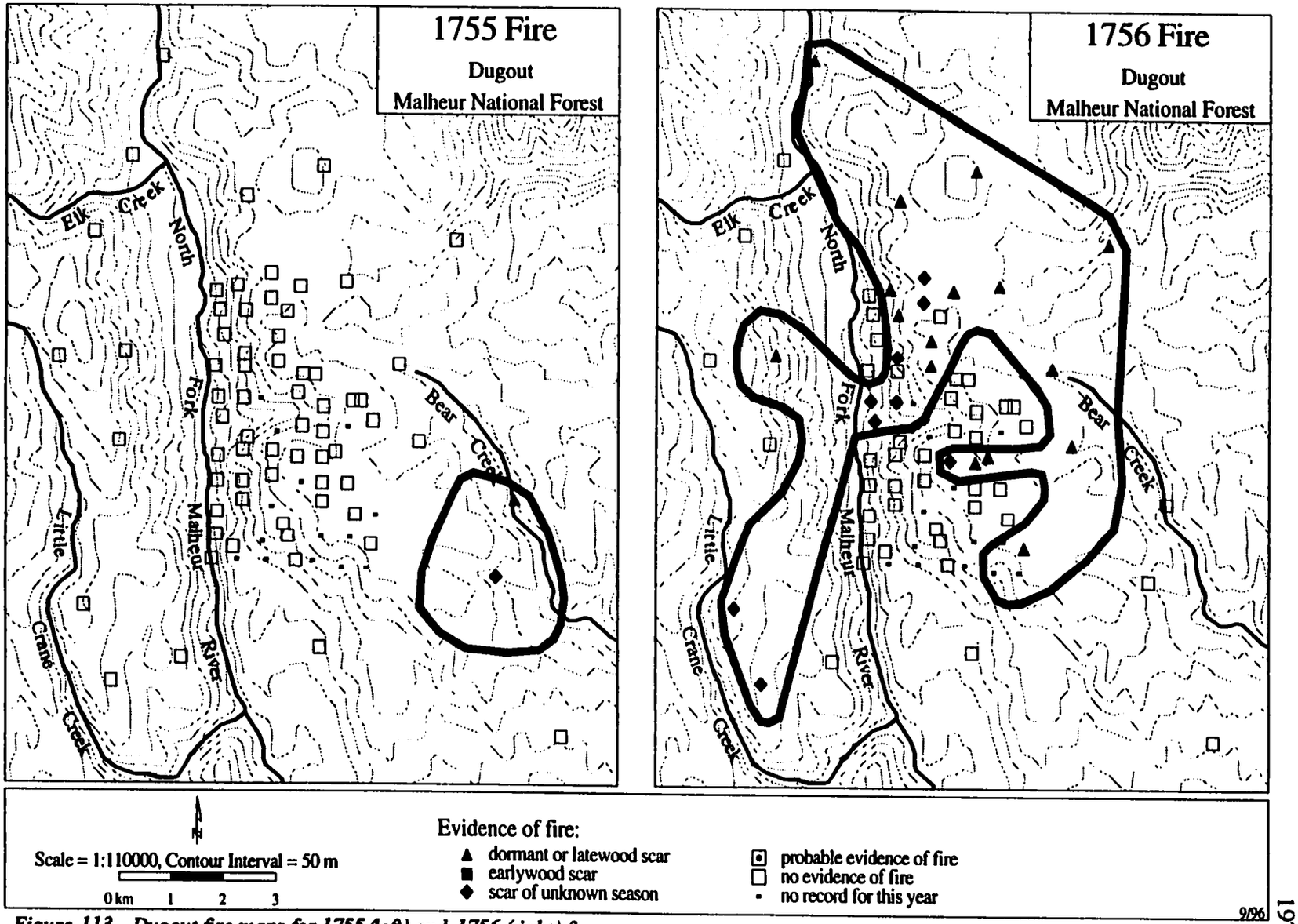


Figure 113. Dugout fire maps for 1755 (left) and 1756 (right) fires.

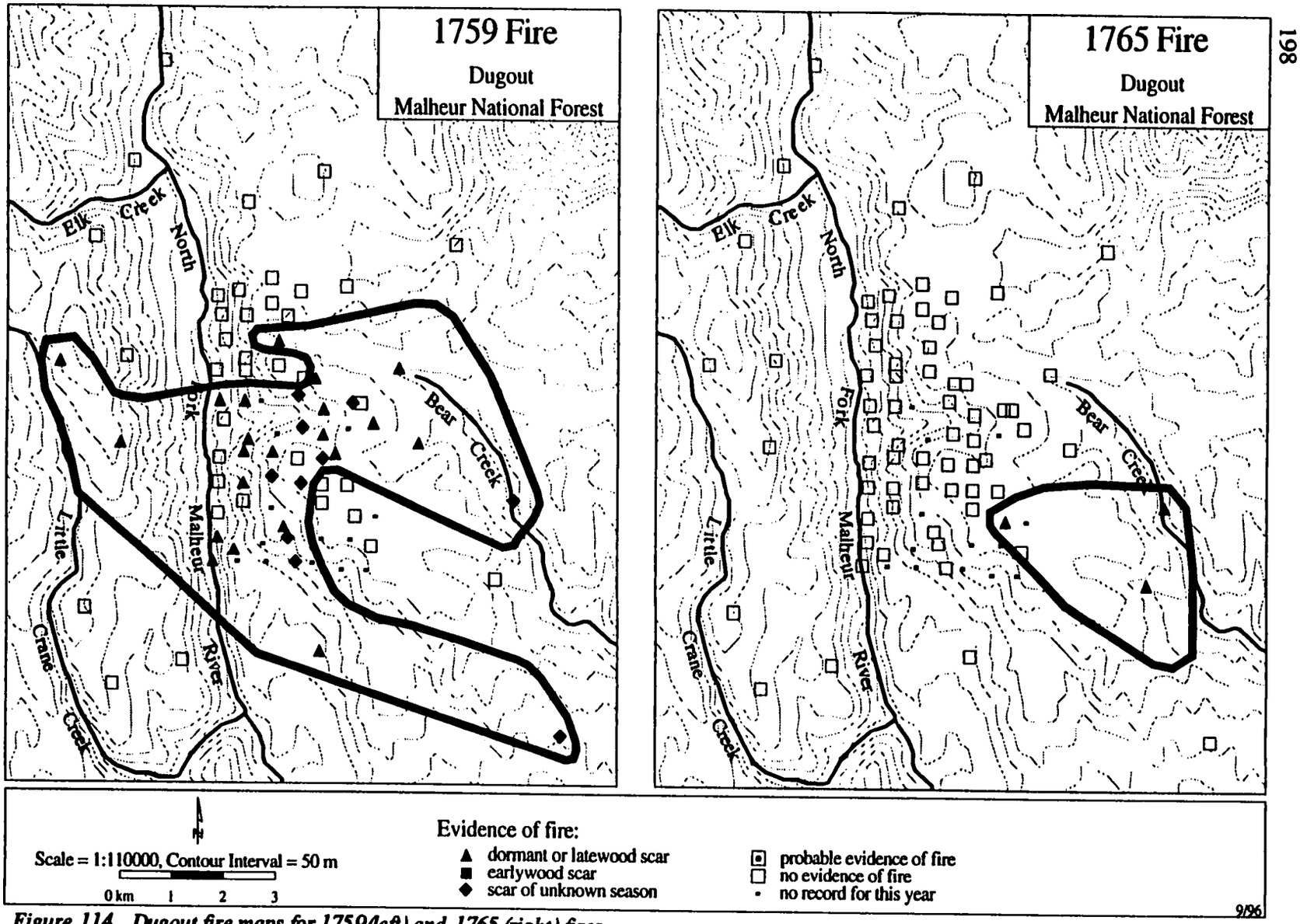


Figure 114. Dugout fire maps for 1759 (left) and 1765 (right) fires.

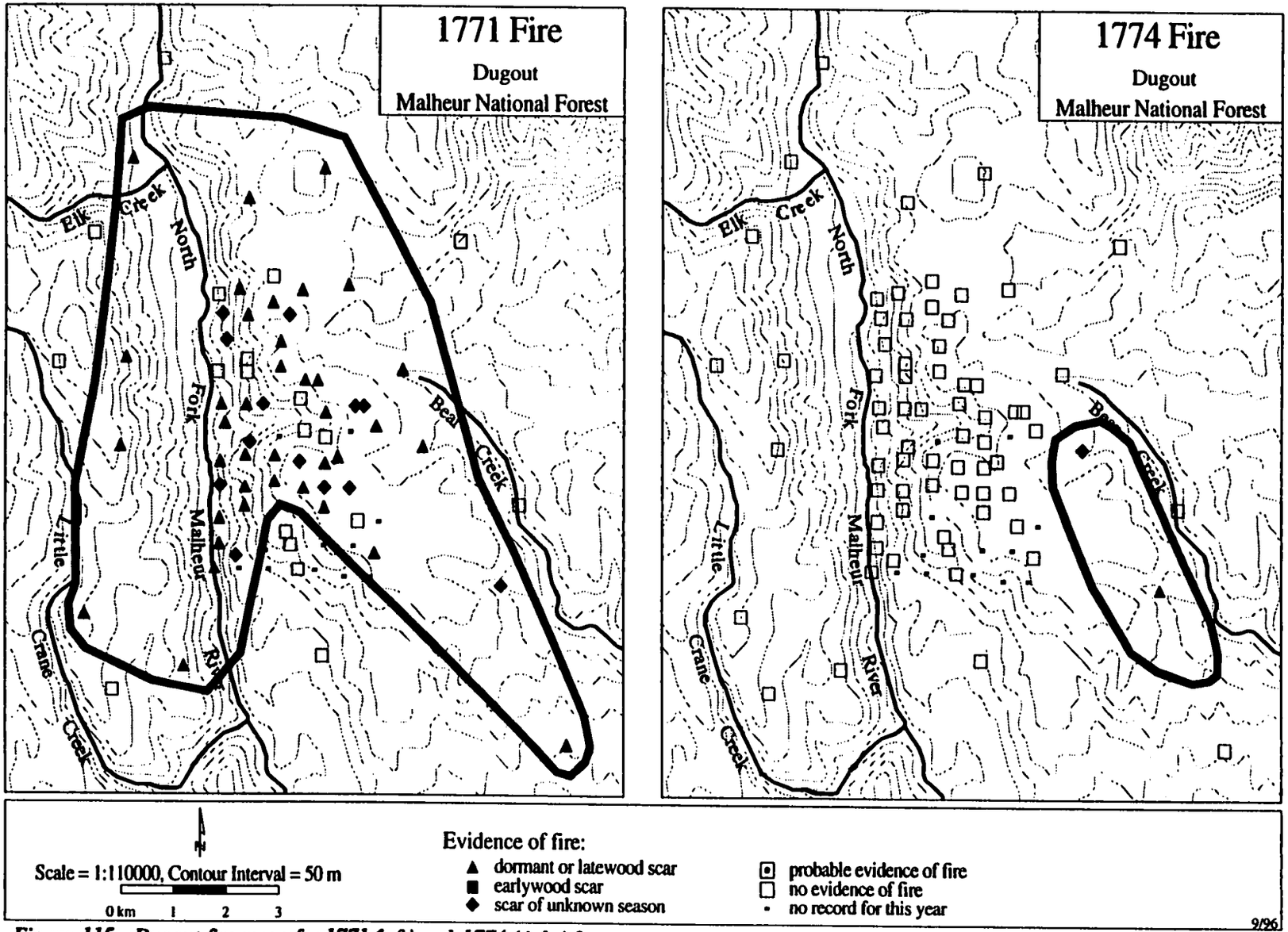


Figure 115. Dugout fire maps for 1771 (left) and 1774 (right) fires.

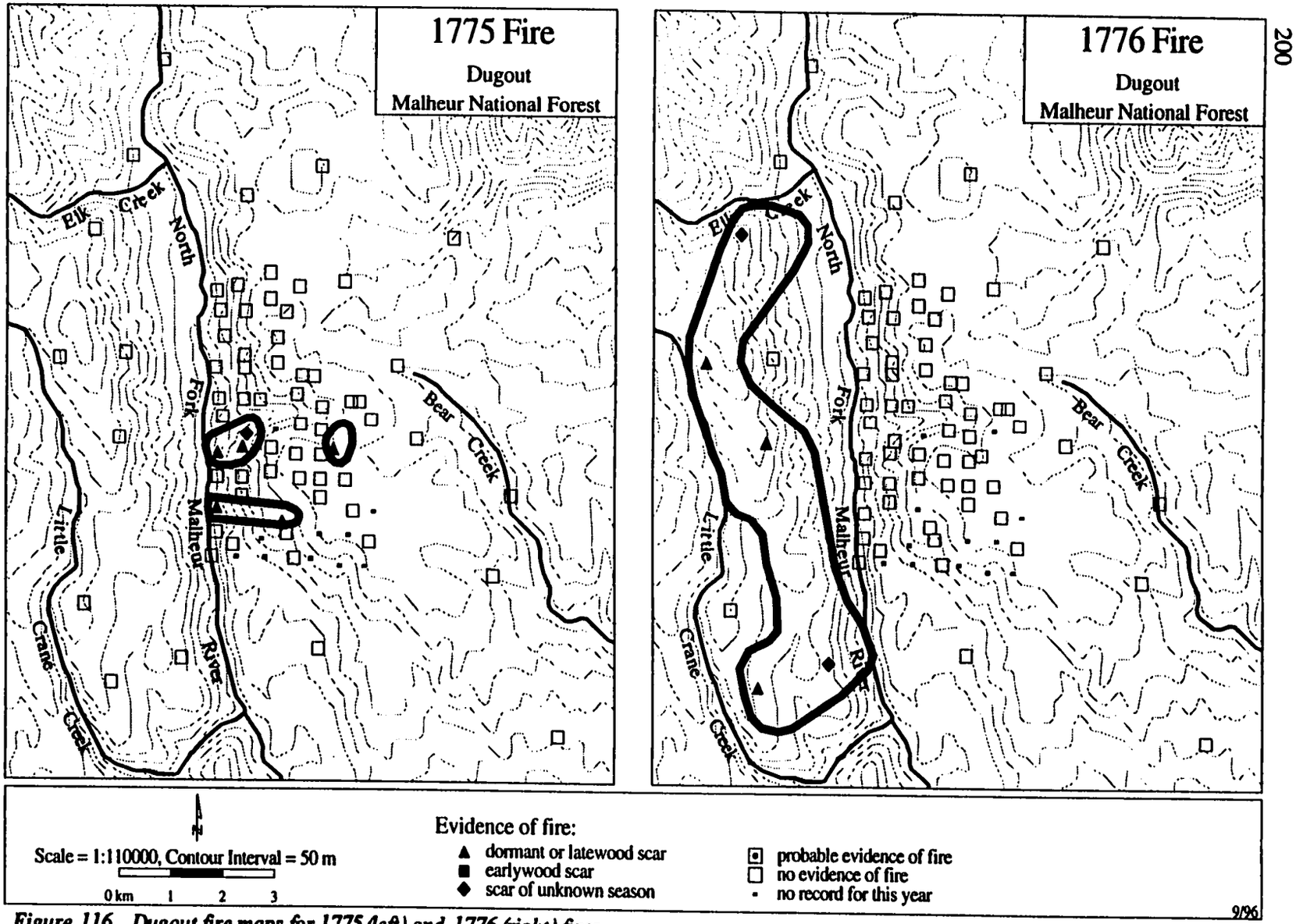


Figure 116. Dugout fire maps for 1775 (left) and 1776 (right) fires.

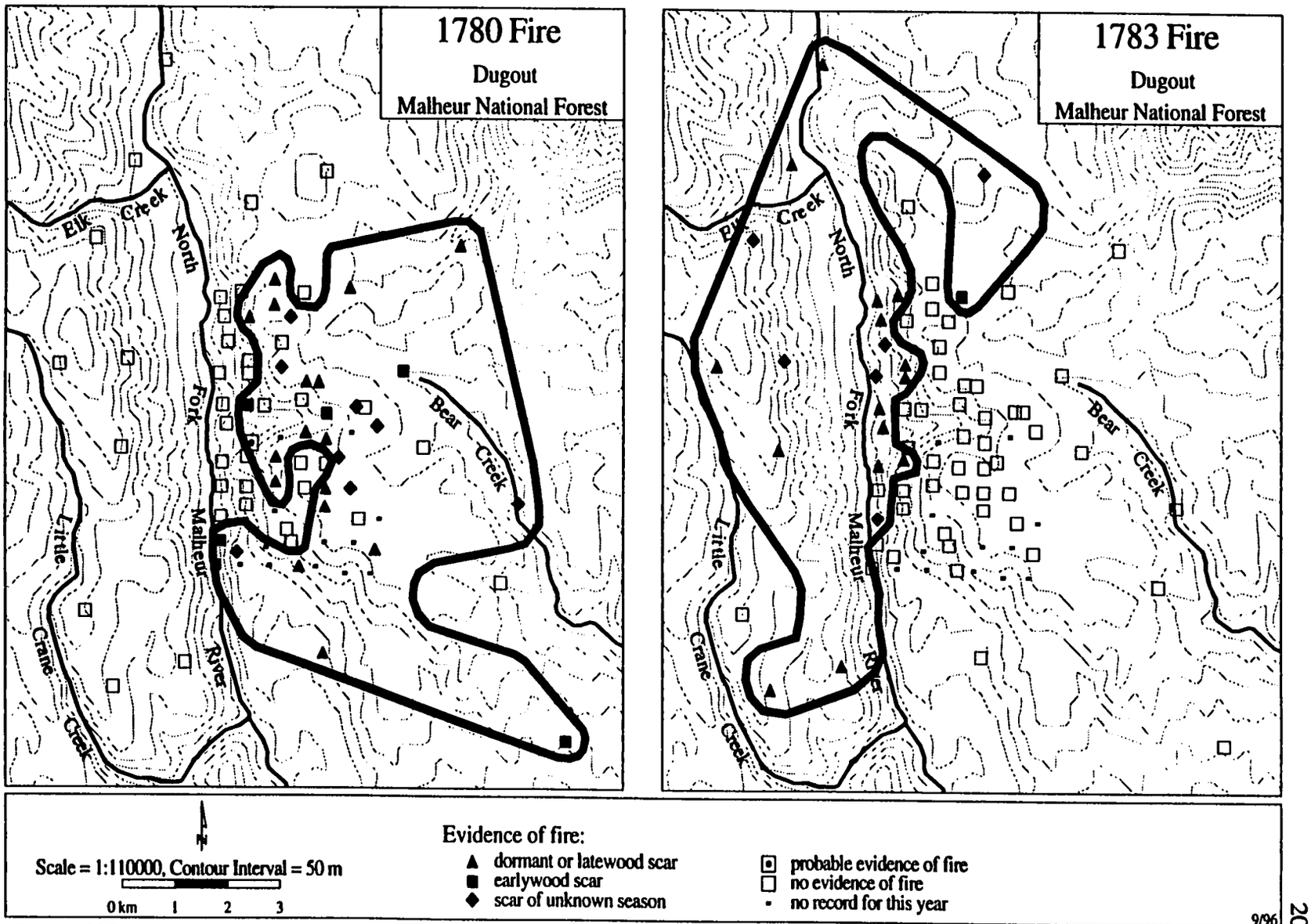


Figure 117. Dugout fire maps for 1780(left) and 1783 (right) fires.

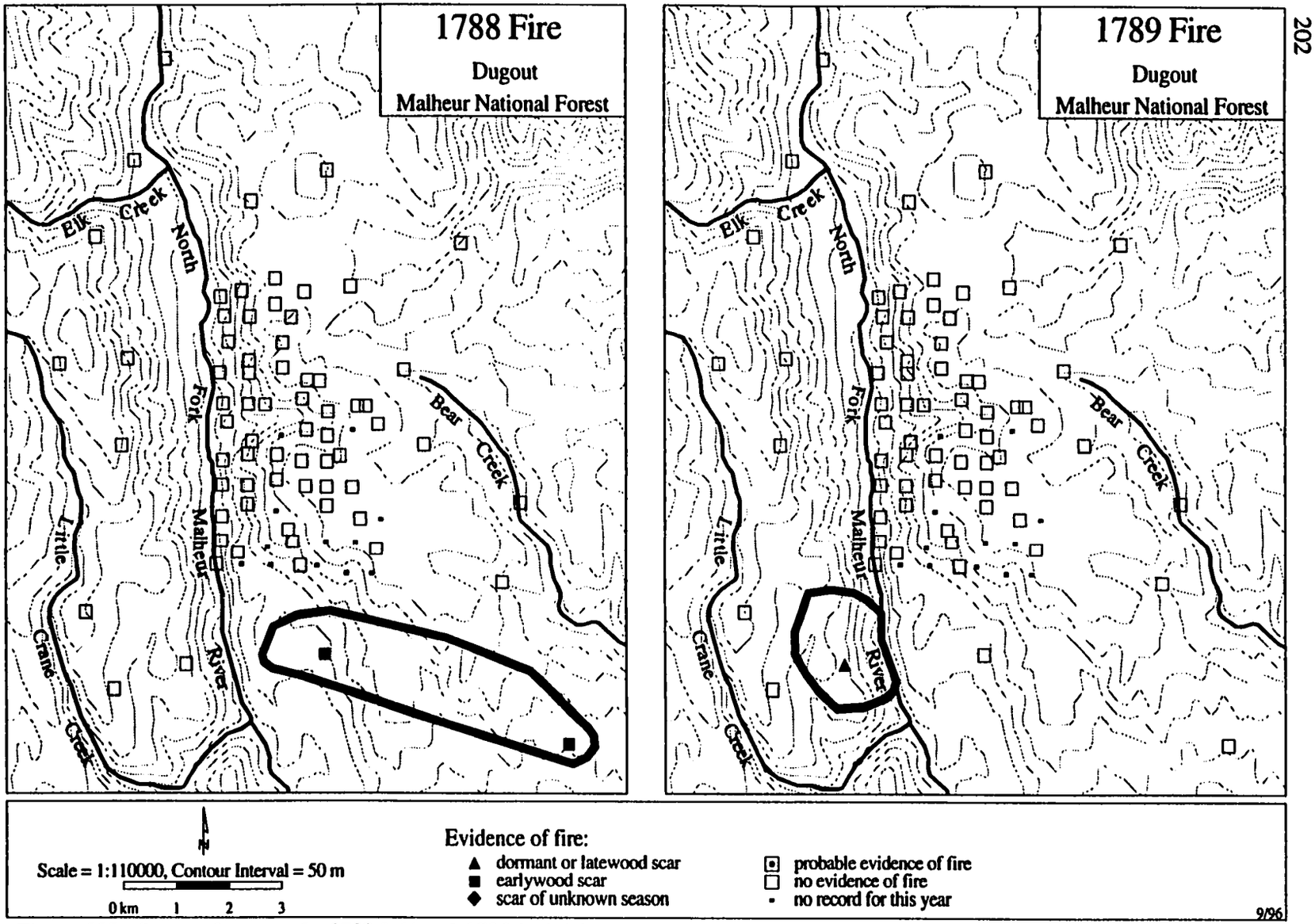


Figure 118. Dugout fire maps for 1788 (left) and 1789 (right) fires.

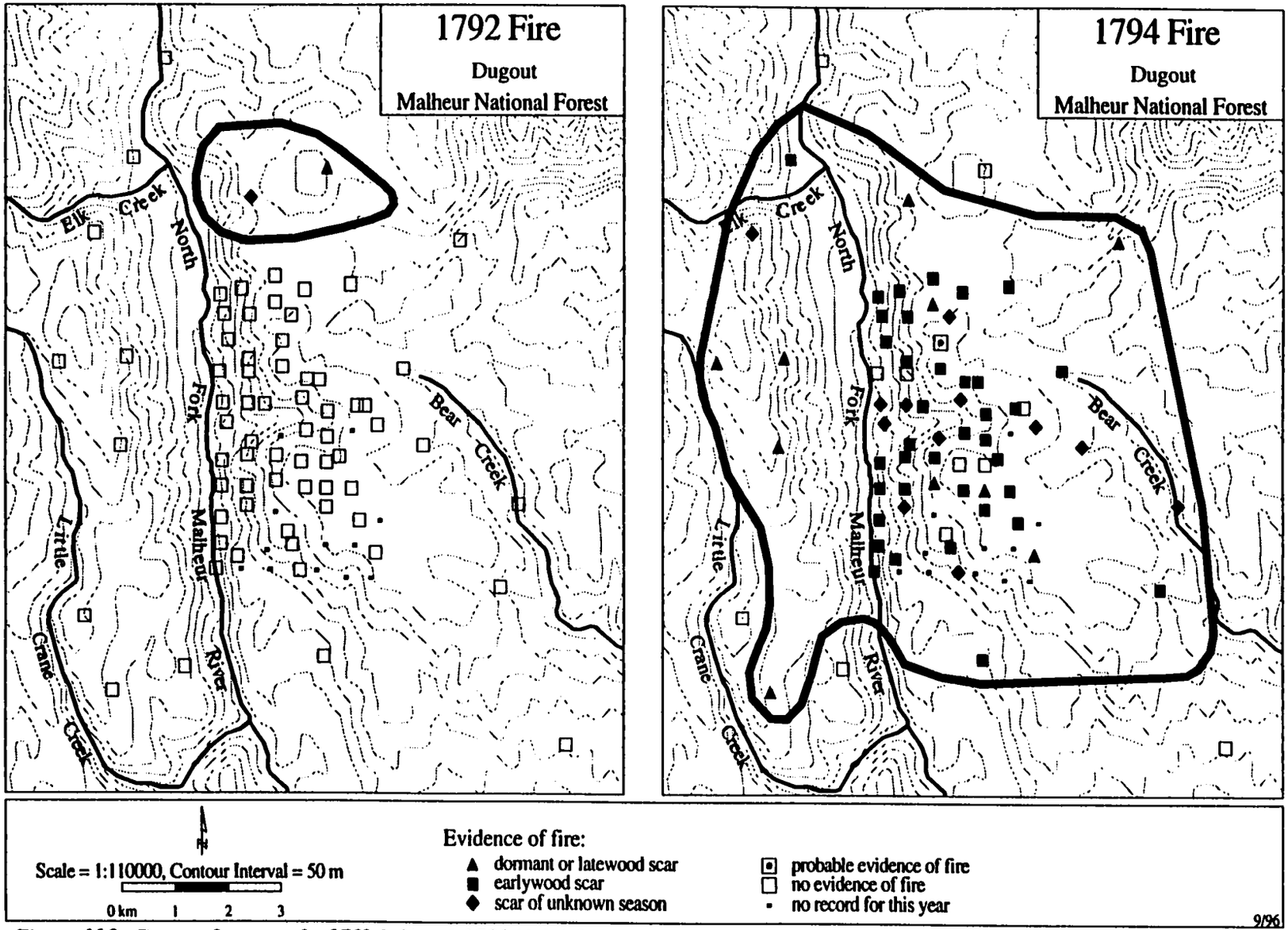


Figure 119. Dugout fire maps for 1792 (left) and 1794 (right) fires.

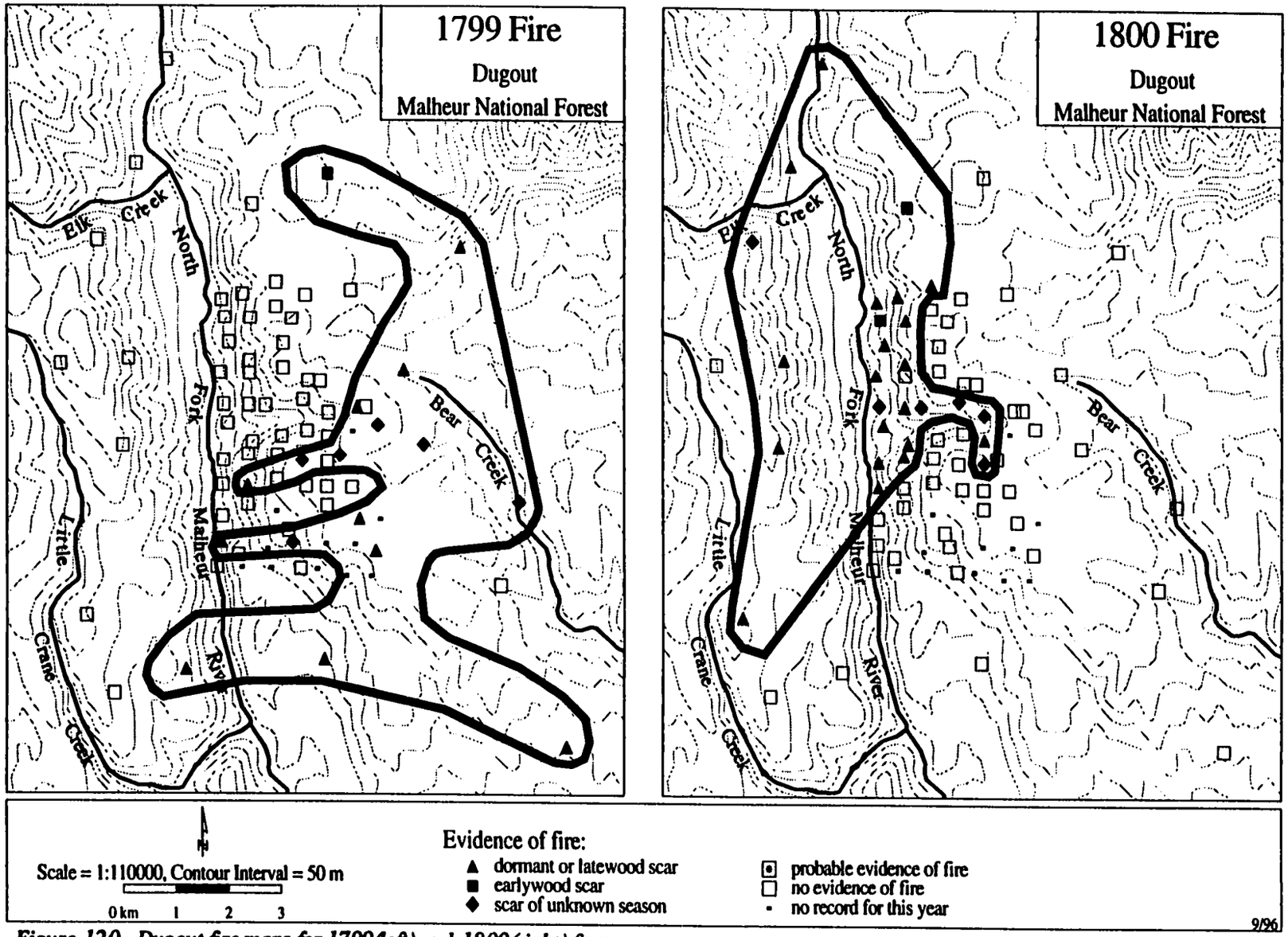


Figure 120. Dugout fire maps for 1799 (left) and 1800 (right) fires.

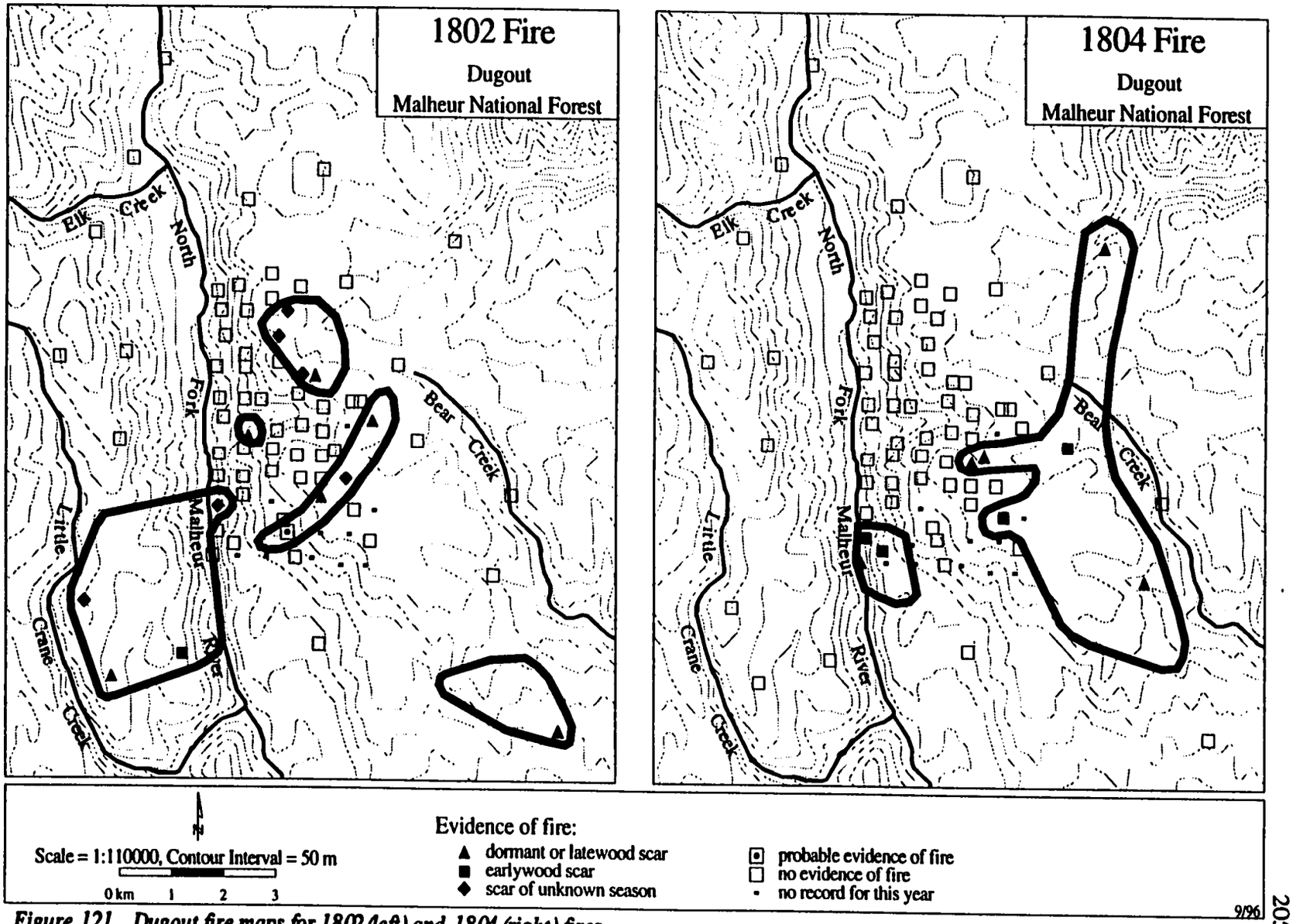


Figure 121. Dugout fire maps for 1802 (left) and 1804 (right) fires.

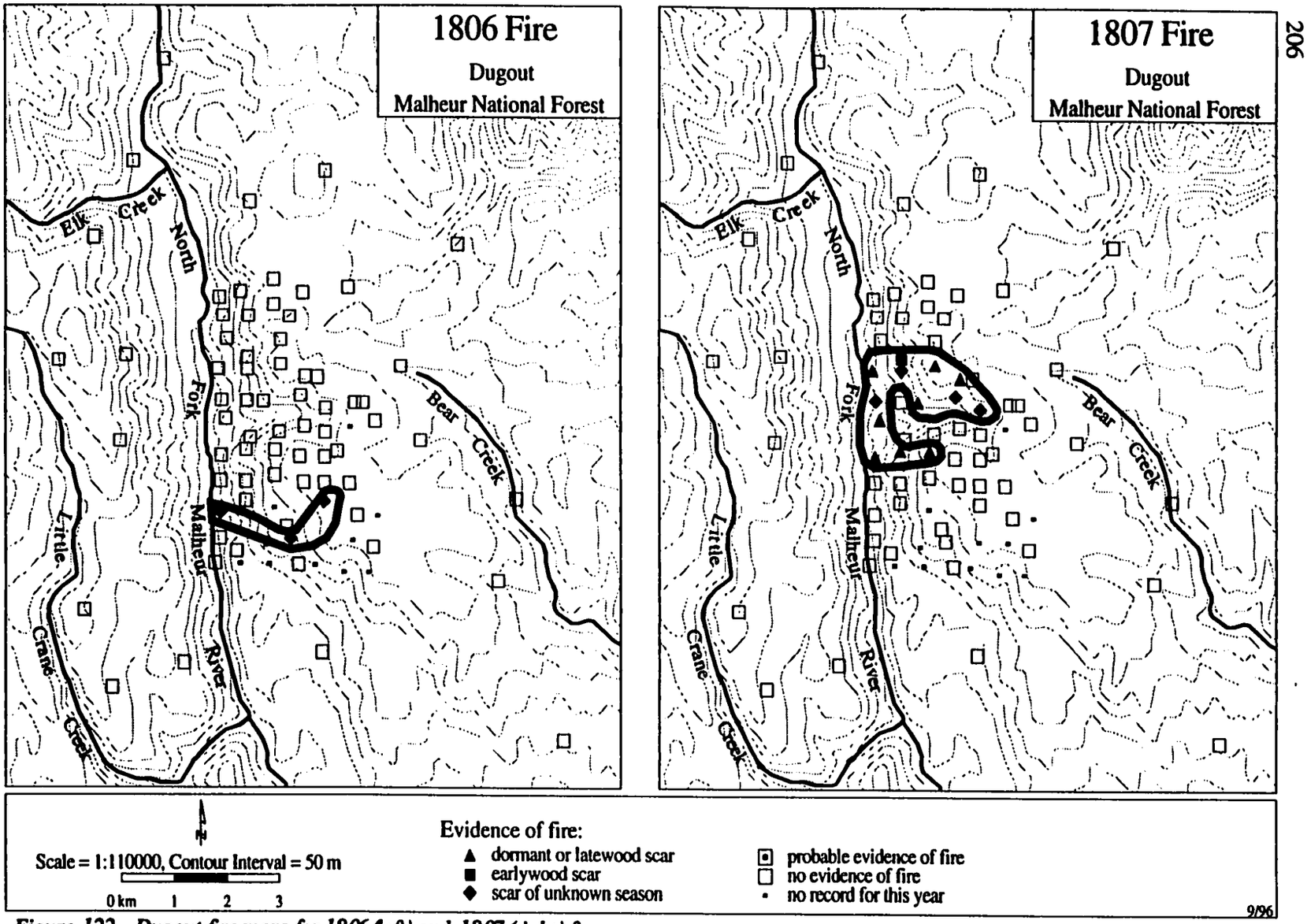


Figure 122. Dugout fire maps for 1806 (left) and 1807 (right) fires.

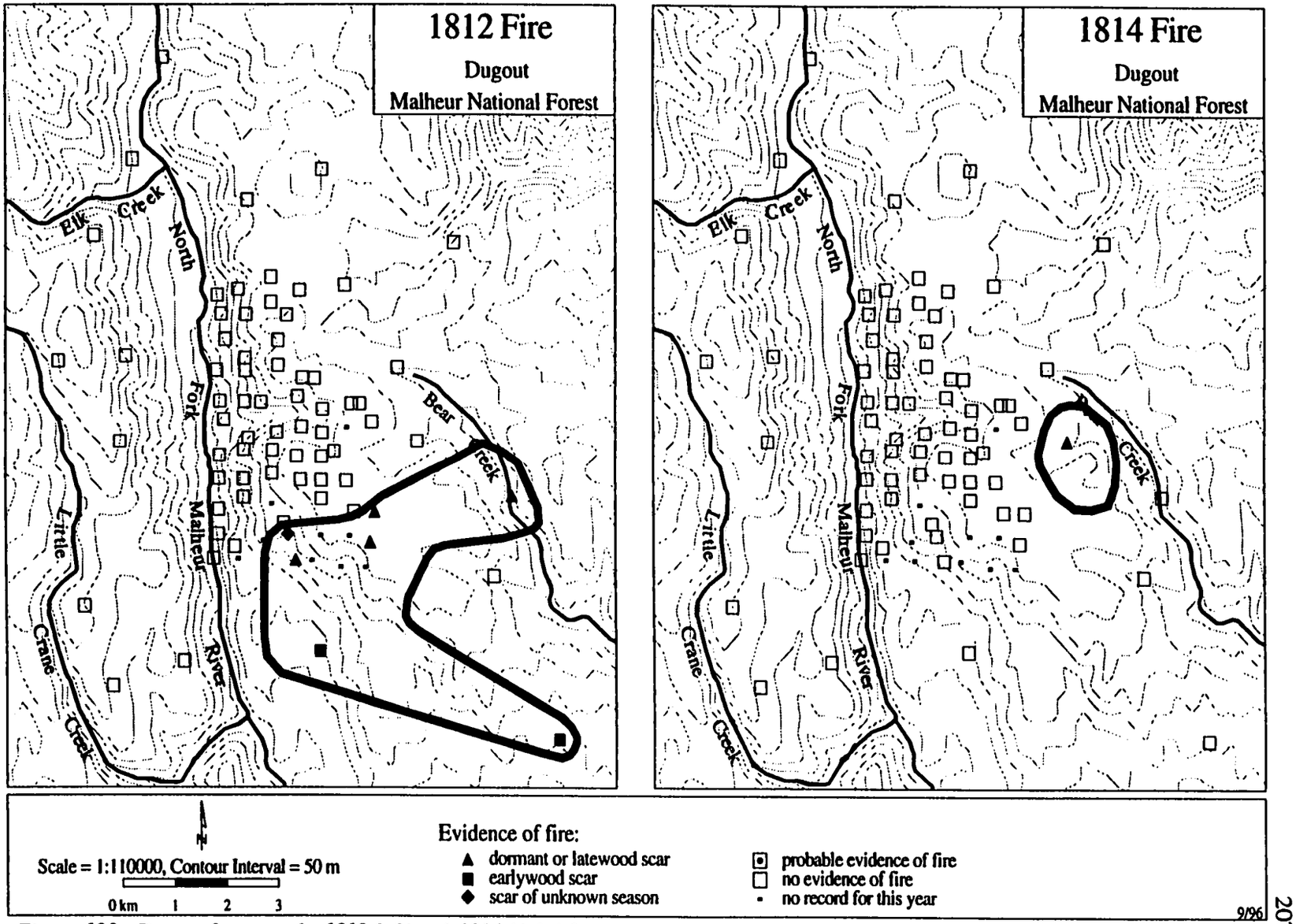


Figure 123. Dugout fire maps for 1812 (left) and 1814 (right) fires.

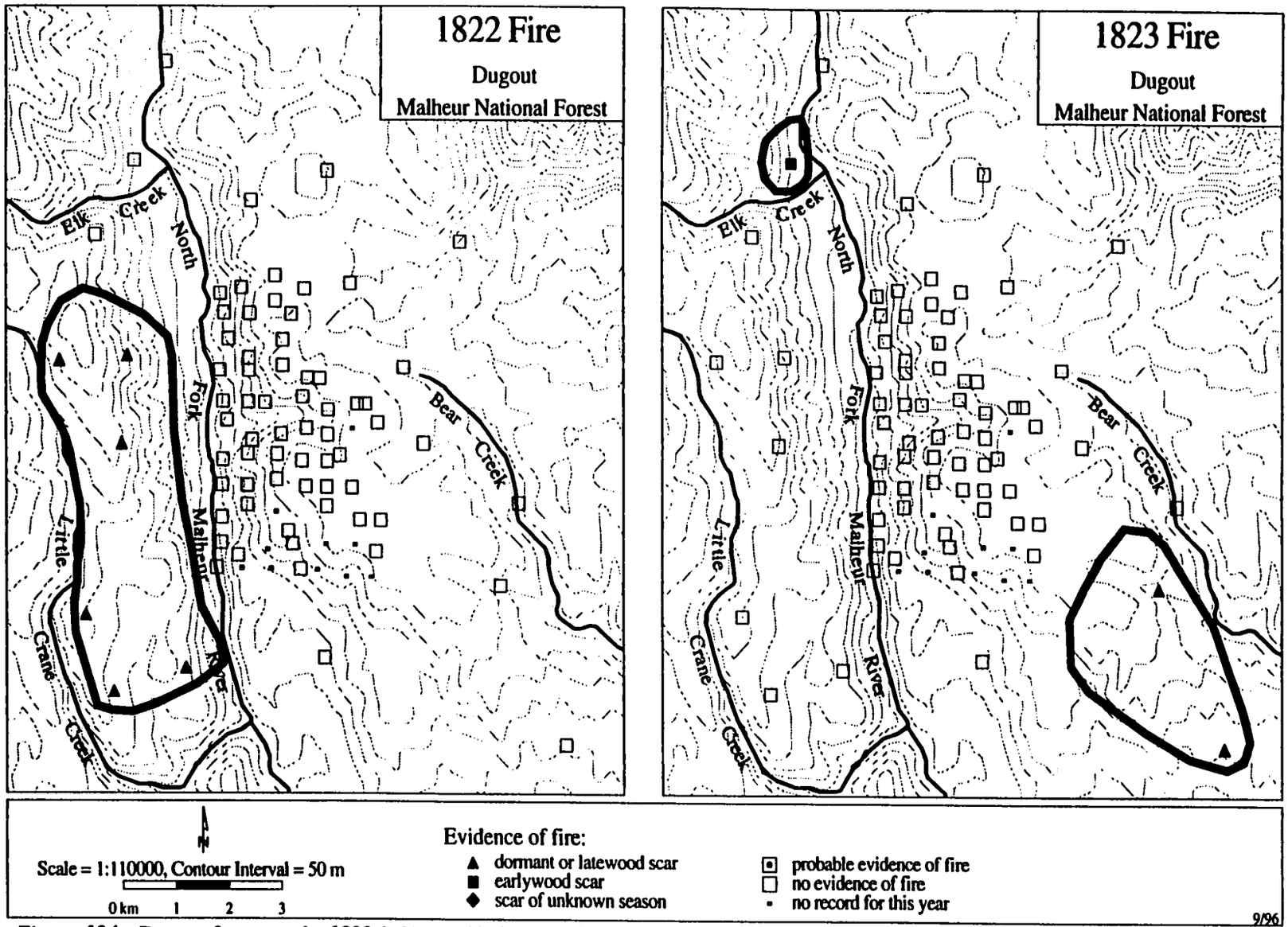


Figure 124. Dugout fire maps for 1822 (left) and 1823 (right) fires.

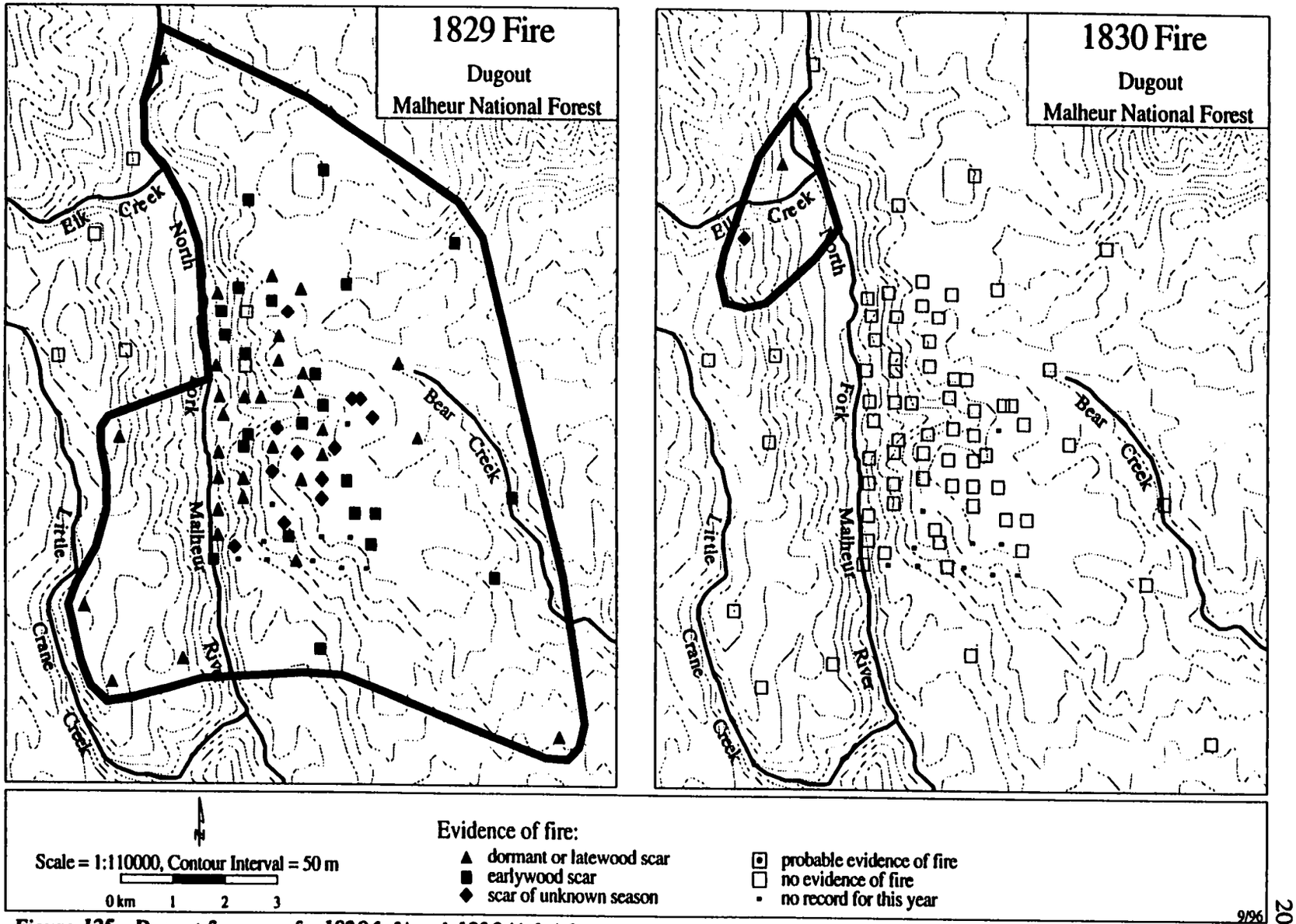


Figure 125. Dugout fire maps for 1829(left) and 1830(right) fires.

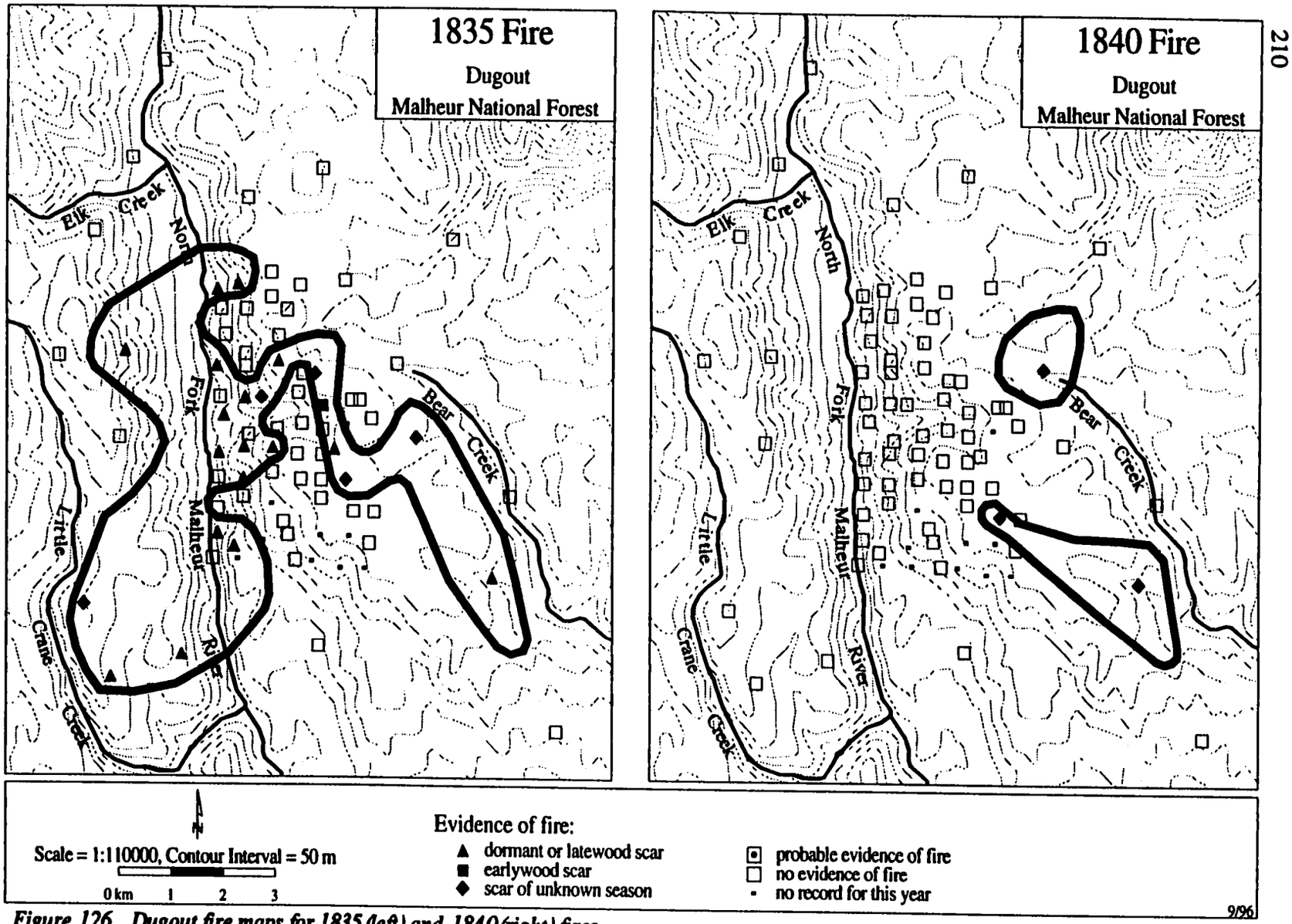


Figure 126. Dugout fire maps for 1835 (left) and 1840 (right) fires.

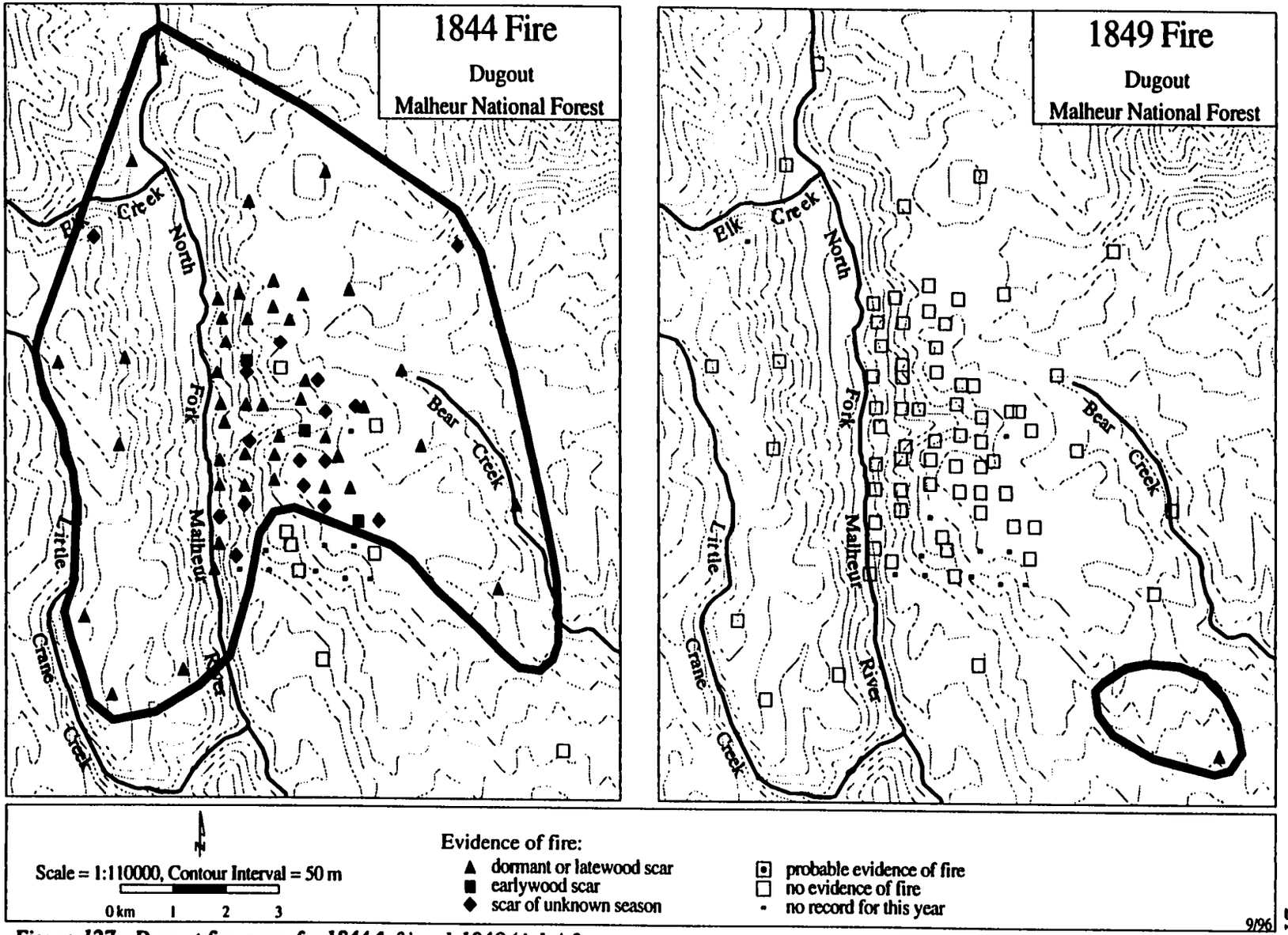


Figure 127. Dugout fire maps for 1844 (left) and 1849 (right) fires.

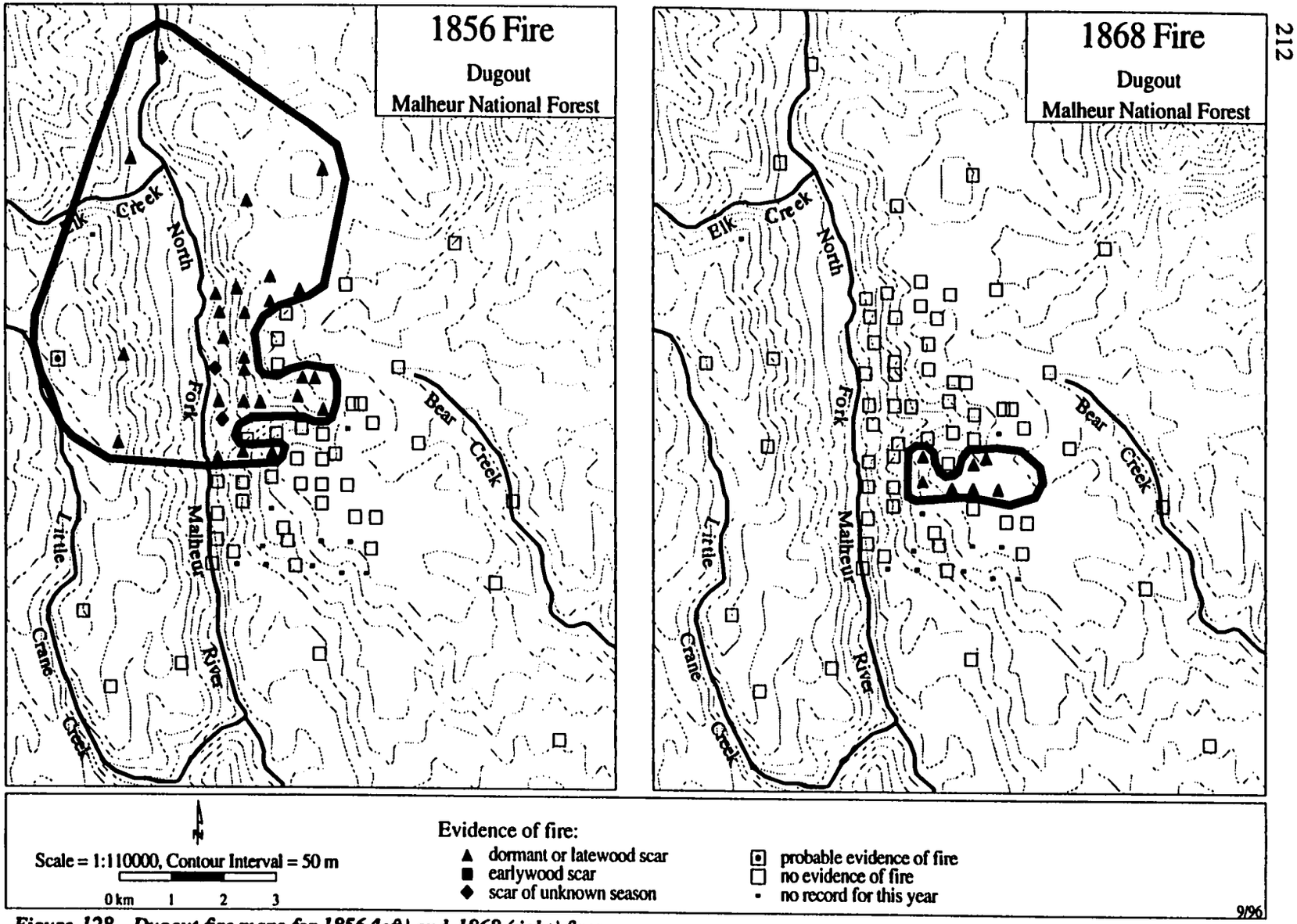


Figure 128. Dugout fire maps for 1856 (left) and 1868 (right) fires.

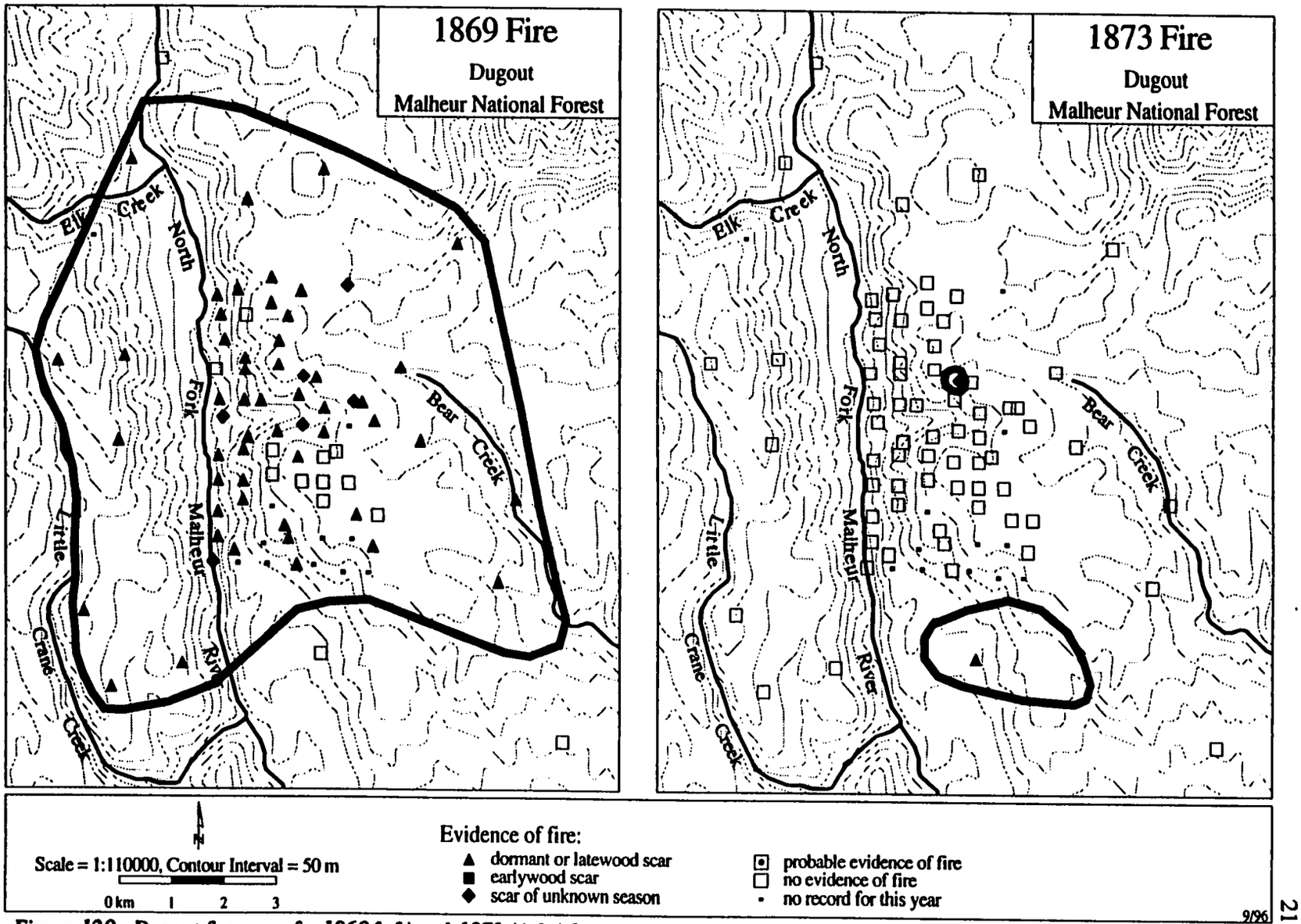


Figure 129. Dugout fire maps for 1869(left) and 1873 (right) fires.

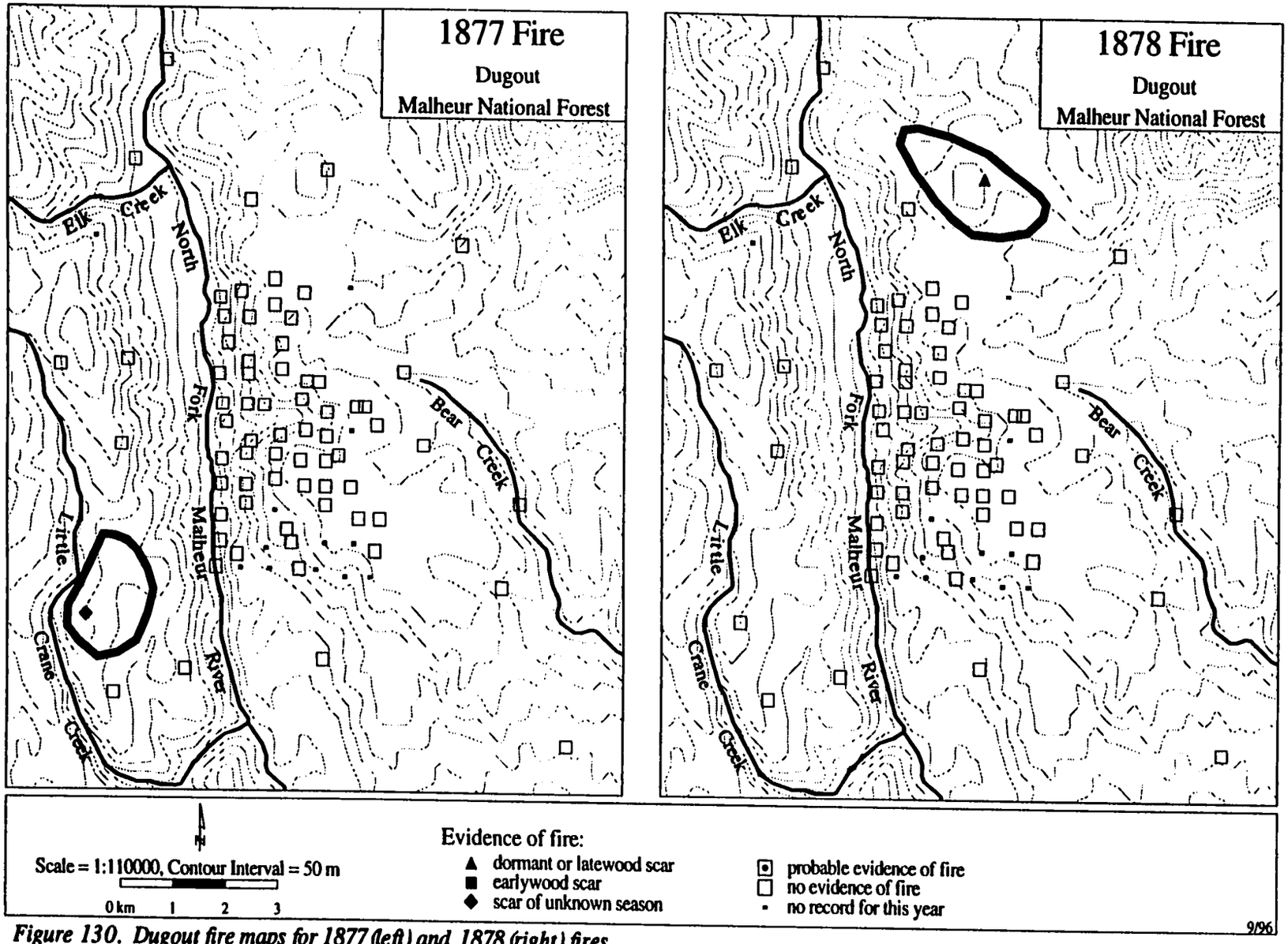


Figure 130. Dugout fire maps for 1877 (left) and 1878 (right) fires.

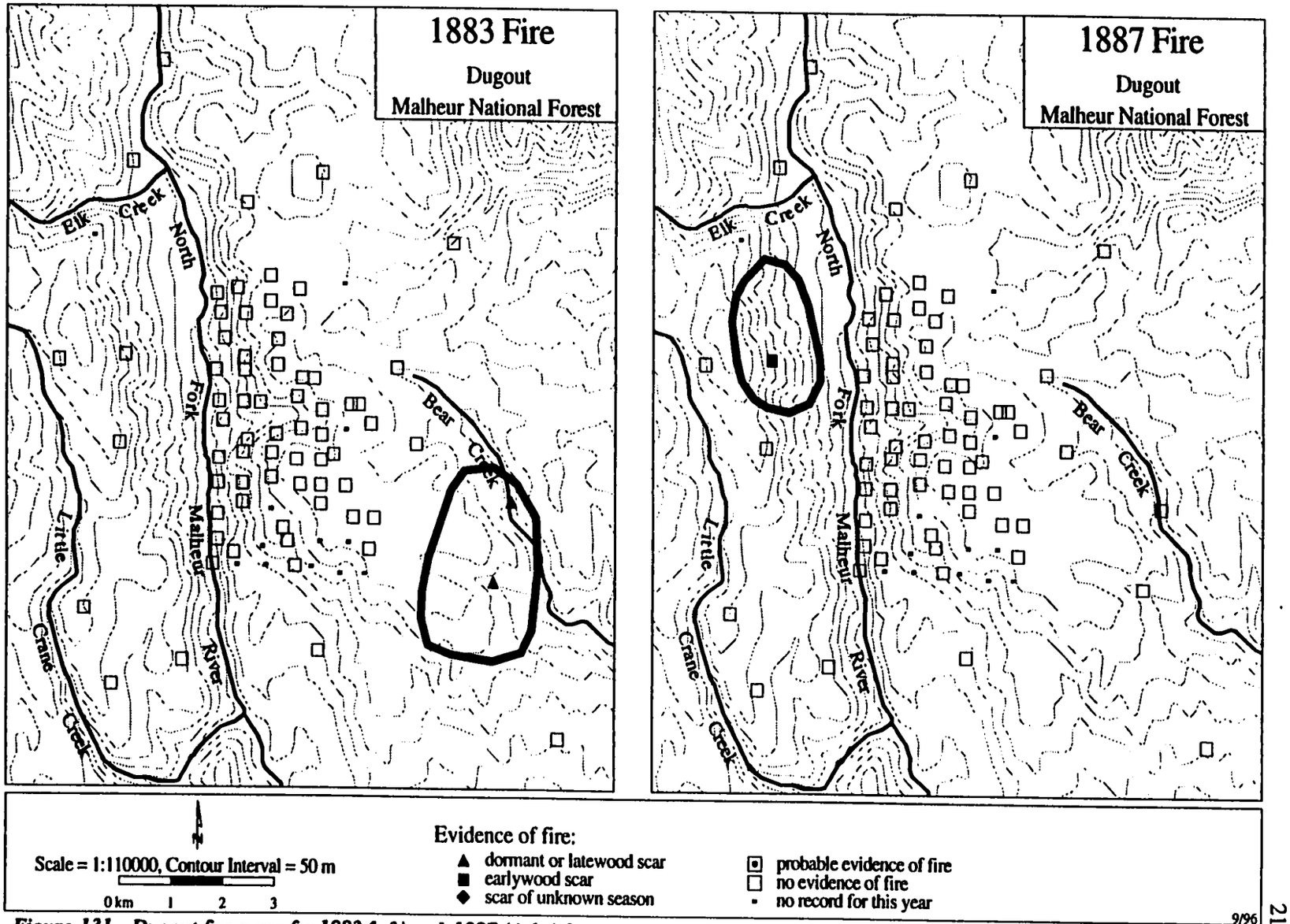


Figure 131. Dugout fire maps for 1883 (left) and 1887 (right) fires.

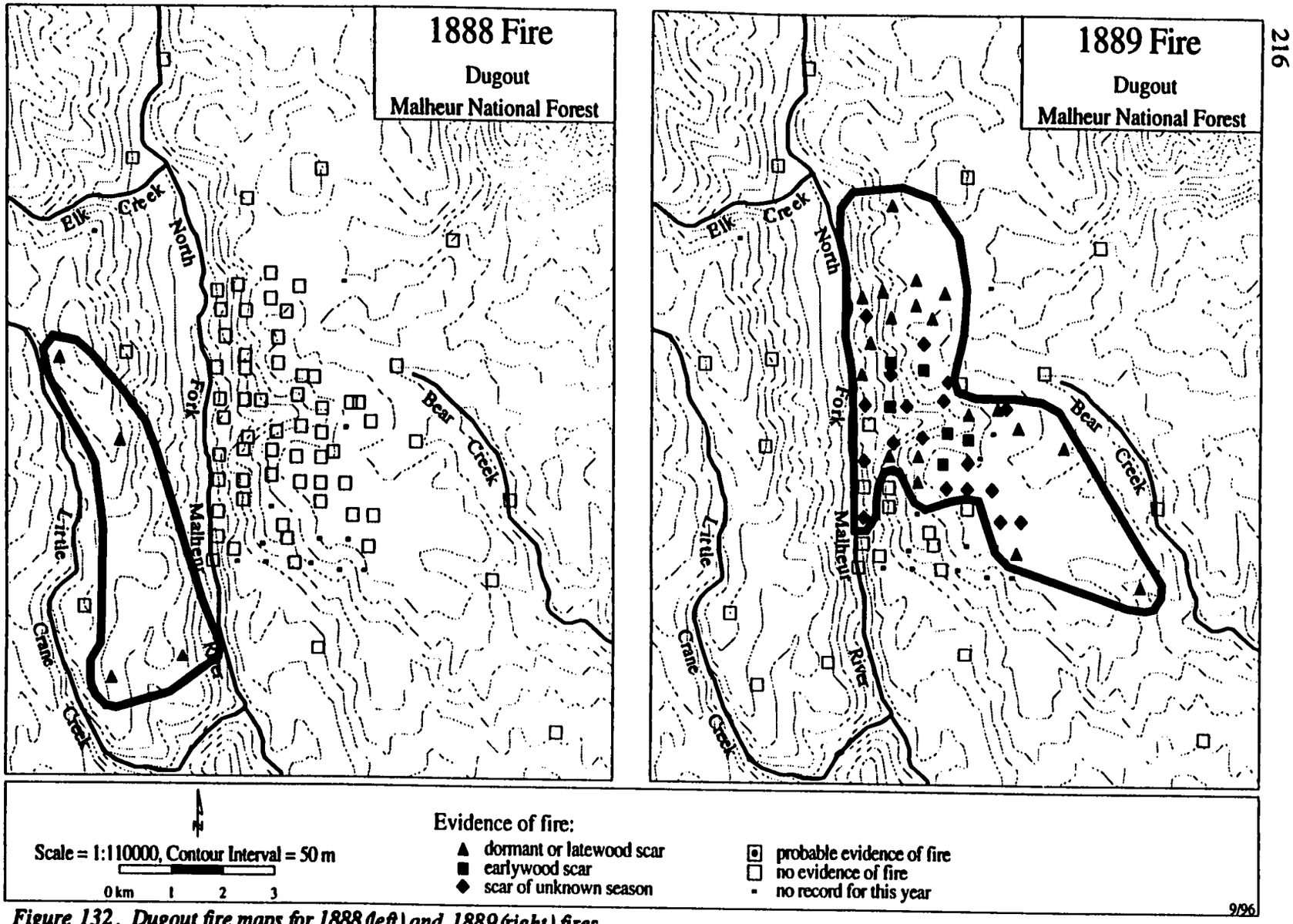


Figure 132. Dugout fire maps for 1888 (left) and 1889 (right) fires.

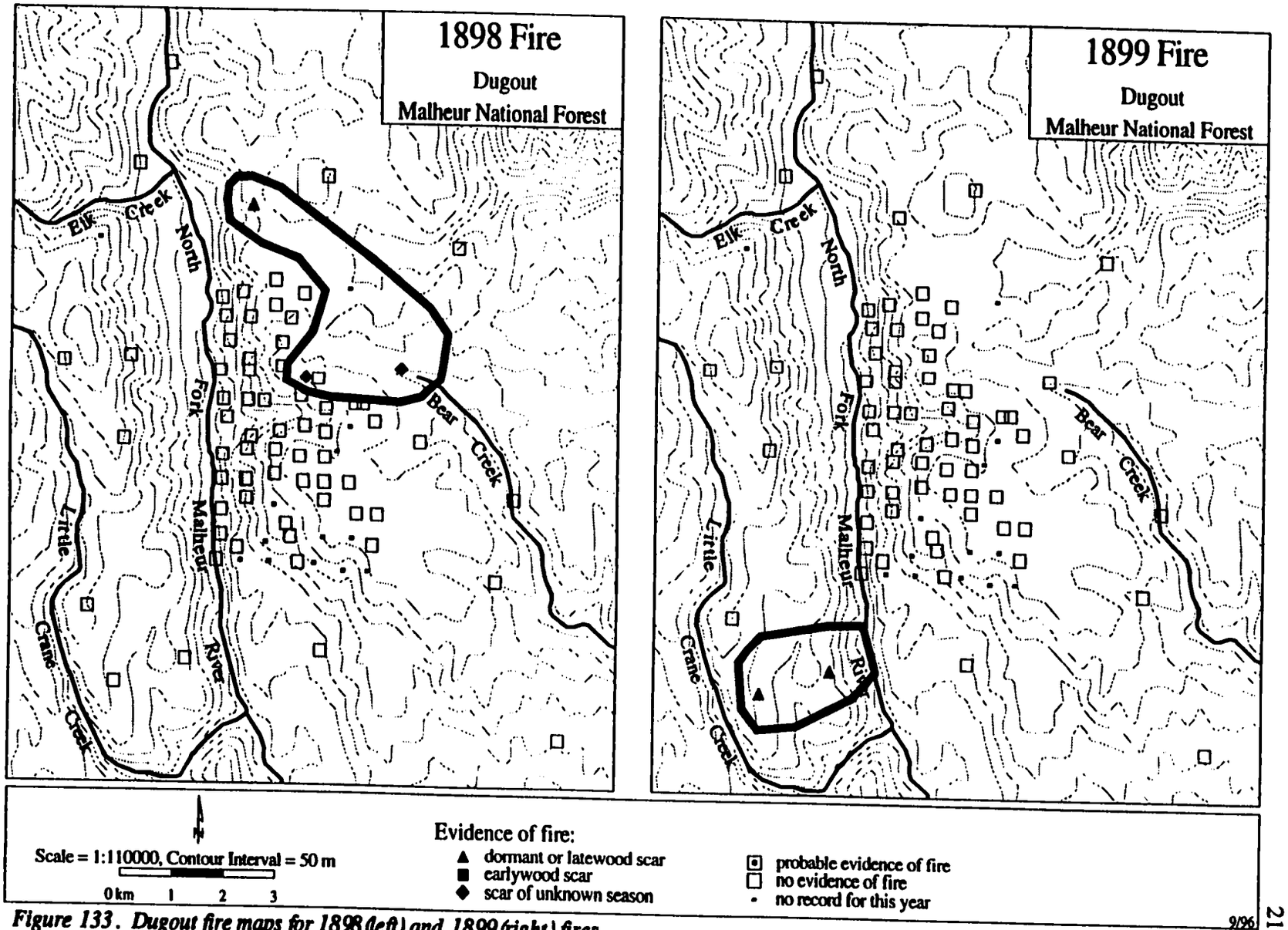


Figure 133. Dugout fire maps for 1898 (left) and 1899 (right) fires.

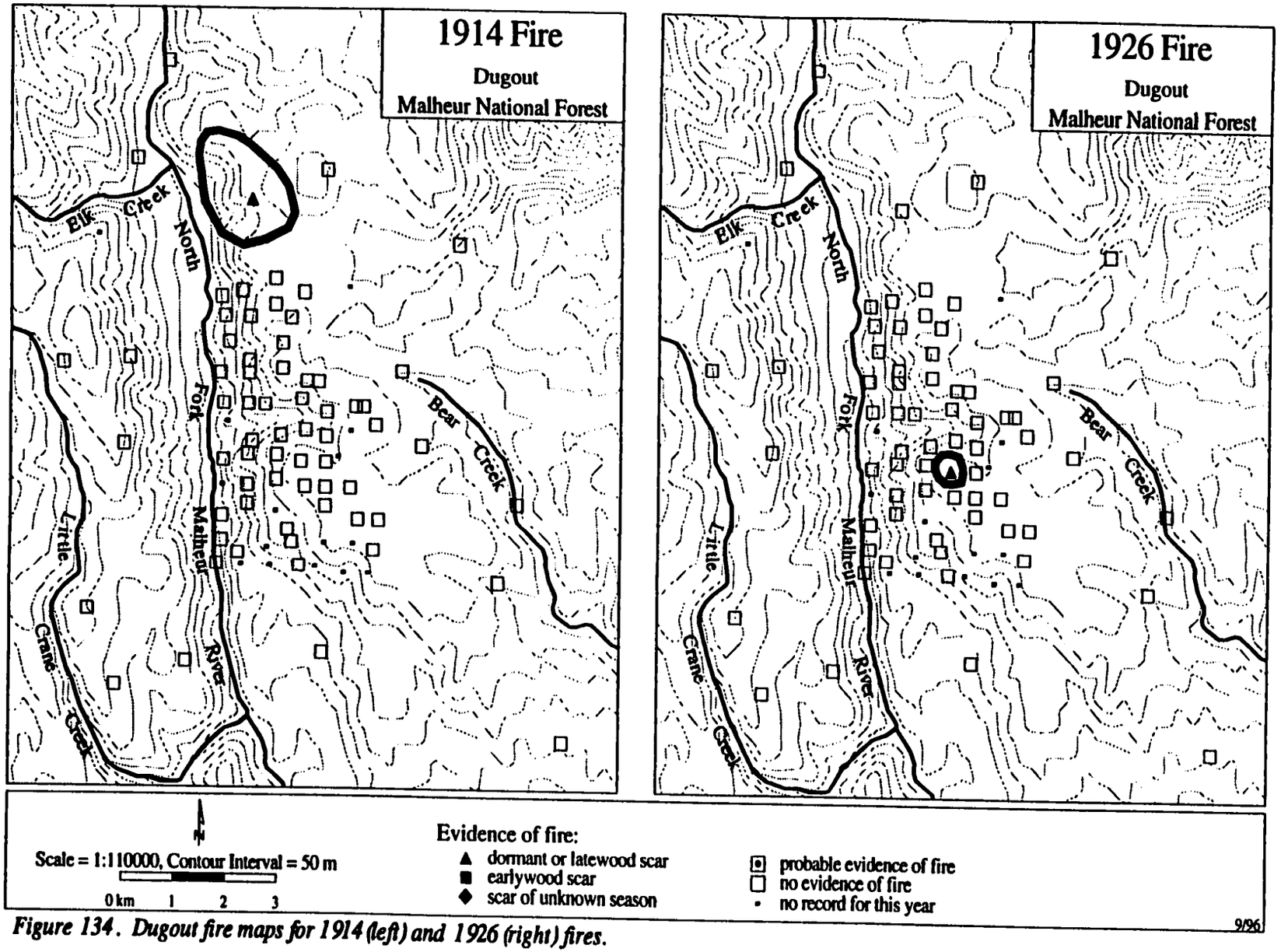


Figure 134. Dugout fire maps for 1914 (left) and 1926 (right) fires.

APPENDIX H: STATISTICS OF FIRE INTERVAL DISTRIBUTIONS AT DRY FOREST PLOTS

This appendix includes additional statistics of the fire interval distributions in dry forest plots at the four watersheds. Included are the mean, median, minimum, maximum, standard deviation, coefficient of variation, skewness, kurtosis and number of intervals for the distribution at each plot. In addition, the distribution of intervals at each plot was fit with a Weibull distribution (Grissino-Mayer 1995). The distribution of intervals at every plot was well-fit with the Weibull distribution (Kolmogorov-Smirnov goodness-of-fit *d*-statistic not significant at level α=0.05) so some variables of the Weibull distribution fit to the interval data at each plot are also included. The Weibull median probability interval (WMPI) indicates the interval length exceeded by half of the fire intervals at a plot while the 5% and 95% exceedance probabilities (5EI and 95EI) are those fire intervals that are exceptionally long or short, respectively, given the distribution of the intervals at that plot.

Table 15. Statistics of fire interval distributions in dry forest plots at ***Tucannon.*** *See page 219 for explanation of abbreviations.*

Plot	Interval							Standard	Coeff.	Skew-	Kurt-	No. of
ID	Mean	Median	Min.	Max.	WMPI	95EI	5EI	deviation	of var.	ness	osis	intervals
1.5	37	23	6	91	29	7	72	34	0.93	0.8	-1.2	5
2.4	32	20	10	74	28	9	59	26	0.80	0.7	-1.3	6
2.5	14	17	2	23	12	3	26	11	0.77	-0.4	-2.0	3
3.3	32	31	15	55	32	17	47	14	.44.	0.4	-1.1	6
3.4	43	23	15	91	36	10	82	42	0.97	0.6	-2.0	3
3.5	38	23	13	78	32	10	71	35	0.92	0.5	-2.0	3
4.5	51	40	10	114	39	9	101	49	0.96	0.4	-1.8	4
4.6	64	64	15	114	56	19	114	50	0.77	0.0	-2.0	3
4.7	43	25	15	89	36	11	81	40	0.93	0.5	-2.0	3
5.7	32	26	5	89	24	5	65	31	0.97	0.9	-0.6	6
5.8	51	40	10	114	41	11	97	46	0.90	0.6	-1.5	4
6.9	47	40	10	99	39	12	88	40	0.84	0.4	-1.7	4
6.10	38	15	8	99	27	6	77	40	1.05	0.7	-1.4	5
1	35	19	10	91	27	6	69	38	1.09	0.9	-1.3	4
2	23	22	5	49	21	8	39	15	0.63	0.4	-1.1	8
3	20	15	11	51	18	7	36	15	0.76	1.6	0.4	6
4	16	13	6	40	15	6	26	9	0.58	1.6	1.6	12
5	36	40	16	50	36	23	49	13	0.36	-0.6	-1.3	5
7	23	22	5	49	21	8	39	15	0.63	0.4	-1.1	8
8	36	30	17	69	34	16	58	20	0.57	0.8	-1.1	5
9	23	17	12	37	22	11	35	11	0.50	0.3	-2.0	5
10	32	24	11	69	28	9	58	26	0.83	0.7	-1.5	4

Table 16. Statistics of fire interval distributions in dry forest plots at ***Imnaha.*** *See page 219* *for explanation of abbreviations.*

Plot	Interval							Standard	Coeff.	Skew-	Kurt-	No. of
ID	Mean	Median	Min.	Max.	WMPI	95EI	5EI	deviation	of var.	ness	osis	intervals
1.4	29	17	17	54	27	11	50	21	0.73	0.6	-2.0	3
1.5	21	17	15	36	20	11	30	9	0.42	1.3	-0.5	5
2.3	55	52	51	61	55	48	60	6	0.10	0.6	-2.0	3
2.4	25	18	17	36	25	14	35	10	0.41	0.4	-2.1	5
2.5	21	18	15	36	20	12	30	8	0.38	1.5	0.2	6
2.7	30	32	20	36	30	23	37	7	0.25	-0.5	-1.8	4
2.8	33	35	28	36	34	30	37	4	0.13	-0.5	-2.0	3
3.1	41	51	20	52	41	25	57	18	0.44	-0.6	-2.0	3
3.3	27	25	12	52	26	12	44	15	0.55	0.6	-1.2	6
3.4	25	25	12	36	25	15	35	10	0.39	-0.1	-1.8	8
3.5	28	34	15	41	29	18	39	10	0.37	-0.2	-1.9	7
3.6	22	18	17	36	22	12	32	9	0.42	1.0	-1.3	4
3.7	25	22	12	41	25	13	37	11	0.44	0.3	-1.7	8
3.8	30	26	10	76	27	10	53	22	0.73	1.3	0.4	7
4.1	34	38	3	52	29	11	58	21	0.61	-0.4	-1.7	6
4.2	29	31	4	52	25	8	53	20	0.70	-0.1	-1.7	6
4.3	23	19	12	36	22	12	34	10	0.46	0.5	-1.7	6
4.4	28	34	15	41	29	18	39	10	0.37	-0.2	-1.9	7
4.5	21	18	12	41	20	10	31	9	0.44	1.5	1.0	8
4.6	24	21	15	36	24	15	34	9	0.36	0.5	-1.7	6
4.7	26	20	15	51	25	12	41	13	0.50	1.0	-0.6	7
4.8	23	19	9	42	22	10	37	13	0.55	0.4	-1.7	8
1	17	19	10	22	17	12	23	6	0.37	-0.4	-2.0	3
2	20	19	5	39	20	9	32	11	0.52	0.2	-1.1	9
3	17	13	5	36	16	7	27	9	0.55	0.7	-0.6	11
4	42	35	15	96	38	14	74	31	0.75	1.1	-0.6	5
5	23	19	5	51	19	5	45	21	0.89	0.5	-1.7	4
6	35	41	5	51	31	11	59	22	0.63	-0.5	-1.7	4
7	30	25	13	71	27	10	52	21	0.69	1.1	-0.2	7
8	28	27	10	49	27	14	42	13	0.47	0.4	-1.1	7
9	15	11	4	39	12	4	27	12	0.85	1.0	-0.5	8
10	29	26	11	61	27	10	51	20	0.68	0.5	-1.4	6

Table 17. Statistics of fire interval distributions in dry forest plots at ***Baker.*** *See page 219 for explanation of abbreviations.*

Plot	Interval							Standard	Coeff.	Skew-	Kurt-	No. of
ID	Mean	Median	Min.	Max.	WMPI	95EI	5EI	deviation	of var.	ness	osis	intervals
2.8	10	7	3	25	9	3	18	8	0.73	1.2	-0.2	11
2.9	14	11	7	31	13	6	21	7	0.49	1.7	1.8	12
2.10	9	8	2	21	9	4	15	4	0.48	1.0	0.7	21
3.6	14	11	6	25	13	6	21	7	0.51	0.6	-1.3	12
3.9	11	12	5	18	11	6	15	4	0.37	0.2	-0.8	10
3.10	10	9	4	27	9	4	17	6	0.60	1.6	1.9	15
3.11	15	14	5	29	14	7	23	7	0.48	0.6	-0.6	11
4.5	22	22	12	34	22	13	30	7	0.34	0.2	-0.9	7
4.6	18	18	6	34	17	8	29	10	0.55	0.2	-1.5	9
4.7	12	11	6	24	11	6	18	5	0.47	1.2	0.4	14
4.9	20	18	7	46	18	7	34	13	0.64	1.1	-0.3	10
4.10	11	11	2	22	10	4	18	6	0.55	0.3	-1.1	15
4.11	13	12	5	25	13	6	20	6	0.45	0.6	-0.6	13
5.6	30	27	15	48	29	15	46	17	0.56	0.3	-2.0	3
5.7	46	43	8	88	38	11	88	40	0.87	0.1	-2.0	3
5.9	12	10	4	23	11	5	19	7	0.58	0.7	-0.9	16
5.10	12	11	5	23	11	6	18	5	0.46	0.7	-0.4	16
6.9	18	17	7	33	18	9	28	20	0.45	0.5	-0.9	10
7.8	17	13	6	37	15	6	29	391	0.65	0.7	-0.9	11
8.8	38	42	12	56	36	18	58	26	0.53	0.5	-1.8	4
1	20	22	7	34	19	9	31	33	0.51	0.5	-1.7	9
2	19	15	11	31	19	10	28	8	0.42	0.4	-1.6	8
3	10	10	3	23	8	4	16	5	0.50	0.5	0.9	18
4	9	9	3	13	9	5	12	3	0.32	0.3	-1.0	20
5	7	6	2	16	6	3	11	4	0.57	0.6	-0.4	26
6	9	7	3	23	8	3	14	5	0.57	0.6	1.3	20
7	9	8	3	27	8	3	15	5	0.62	0.6	4.1	20
8	11	10	5	23	11	6	16	5	0.42	0.4	0.8	16
9	9	10	3	14	9	6	13	3	0.33	0.3	-0.7	17
10	21	20	12	39	20	10	32	10	0.49	0.5	-0.5	6
11	10	10	5	23	10	5	15	4	0.41	0.4	3.0	17

Table 18. Statistics of fire interval distributions in dry forest plots at ***Dugout.*** *See page 219* *for explanation of abbreviations.*

Plot	Interval							Standard	Coeff.	Skew-	Kurt-	No. of
ID	Mean	Median	Min.	Max.	WMPI	95EI	5EI	deviation	of var.	ness	osis	intervals
2.1	14	13	6	32	14	6	23	8	0.54	1.2	0.2	14
2.2	13	13	5	29	13	6	20	6	0.48	1.0	0.9	14
2.3	19	17	6	35	18	9	29	9	0.46	0.5	-0.8	10
2.4	16	13	10	35	15	8	24	7	0.45	1.8	2.2	12
3.1	14	13	5	29	14	7	22	6	0.44	0.7	0.1	14
3.2	17	14	5	44	15	6	29	11	0.67	1.3	0.7	12
3.3	14	13	5	35	14	6	23	7	0.52	1.4	1.9	14
3.4	18	15	3	51	16	6	33	13	0.71	1.3	1.1	11
4.1	14	12	3	29	13	7	22	7	0.47	0.6	0.1	13
4.2	16	14	6	27	15	8	23	7	0.45	0.2	-1.3	10
4.3	17	16	3	31	16	7	27	9	0.51	0.0	-1.1	12
5.1	16	12	6	33	15	6	27	10	0.60	0.6	-1.1	11
5.2	24	23	12	37	24	14	33	9	0.38	0.1	-1.4	8
5.3	14	13	5	34	14	6	24	8	0.56	0.9	0.2	14
5.4	12	12	3	22	11	6	18	6	0.48	0.2	-0.9	18
5.5	11	11	3	27	10	5	17	5	0.49	1.5	3.1	17
6.1	13	13	3	22	12	6	19	6	0.44	0.0	-0.9	16
6.2	12	12	3	29	11	5	20	7	0.59	1.0	0.3	13
6.3	13	12	6	23	13	6	21	7	0.53	0.4	-1.6	9
6.4	14	13	6	35	14	6	23	7	0.52	1.5	1.7	14
6.5	12	11	6	22	12	6	18	5	0.43	0.8	-0.7	15
6.6	15	13	5	30	14	6	24	8	0.54	0.5	-1.1	12
6.7	34	24	15	61	32	14	56	20	0.60	0.6	-1.7	6
7.1	11	11	4	23	10	5	17	6	0.52	0.9	0.0	17
7.2	14	11	2	27	12	5	23	8	0.61	0.3	-1.4	14
7.3	24	23	15	35	24	15	33	9	0.36	0.4	-1.6	4
7.4	17	15	7	35	16	8	26	8	0.49	0.9	0.0	12
7.5	17	18	3	29	16	8	26	8	0.47	-0.2	-1.1	12
7.7	14	11	3	40	12	4	25	10	0.74	1.4	1.1	13
8.1	13	12	4	23	12	6	20	6	0.48	0.4	-1.2	16
8.2	11	11	4	22	11	5	18	6	0.50	0.7	-0.6	17
8.3	13	12	5	23	12	7	19	5	0.42	0.7	-0.4	16
8.4	18	17	6	30	17	9	26	8	0.43	0.2	-1.1	11
8.5	14	11	3	29	13	5	23	8	0.61	0.5	-1.2	13
8.6	10	6	3	25	9	3	19	8	0.77	1.0	-0.6	11
9.1	16	16	6	25	16	9	23	6	0.38	-0.1	-1.2	10
9.2	13	12	5	30	12	5	21	7	0.57	1.0	0.0	14
9.3	22	15	8	64	20	7	41	18	0.79	1.5	0.9	9
9.4	22	22	12	35	22	13	30	8	0.37	0.5	-1.0	6
9.5	17	15	7	35	16	8	26	8	0.47	0.9	0.2	12
9.6	17	14	6	39	16	7	28	10	0.58	0.9	-0.1	12

Table 18 (continued). Statistics of fire interval distributions in dry forest plots at ***Dugout.***

Plot	Interval							Standard	Coeff.	Skew-	Kurt-	No. of
ID	Mean	Median	Min.	Max.	WMPI	95EI	5EI	deviation	of var.	ness	osis	intervals
10.1	13	13	3	25	13	6	22	7	0.54	0.0	-1.4	15
10.2	32	25	15	61	30	14	51	18	0.56	0.9	-1.0	5
10.4	32	31	16	54	31	16	49	16	0.50	0.3	-1.6	5
10.5	14	11	4	23	13	7	21	6	0.45	0.3	-1.3	13
10.6	14	11	3	29	13	5	25	9	0.63	0.2	-1.6	14
10.7	26	17	15	45	24	11	42	17	0.65	0.6	-2.0	3
11.1	12	10	5	25	12	5	20	7	0.55	0.9	-0.5	15
11.2	13	12	5	31	13	6	22	7	0.55	1.3	0.3	16
11.4	24	23	5	49	21	7	42	16	0.68	0.2	-1.5	9
11.7	17	14	5	40	16	7	27	9	0.55	1.4	1.1	14
12.1	15	12	7	30	15	7	23	7	0.45	0.9	-0.5	17
12.4	18	18	12	28	18	12	25	6	0.31	0.6	-0.9	6
1	12	12	3	30	11	5	19	6	0.51	1.4	2.6	16
2	13	14	2	29	12	4	23	8	0.62	0.2	-0.8	12
3	13	10	5	35	12	5	22	8	0.65	1.5	1.3	13
4	13	12	6	30	13	6	20	6	0.48	1.6	2.1	12
5	13	12	5	23	13	7	19	6	0.43	0.4	-0.9	16
6	13	12	5	24	12	6	20	6	0.50	0.6	-1.0	16
7	14	11	7	28	14	7	22	7	0.48	0.7	-1.0	13
8	14	13	3	44	12	4	25	10	0.73	1.7	2.8	15
9	15	12	2	34	13	5	26	10	0.65	0.5	-0.9	15
10	12	11	1	31	11	4	21	8	0.63	0.8	-0.3	22
11	13	10	3	34	12	4	23	9	0.37	0.8	-0.4	16
12	11	9	2	30	9	3	20	8	0.79	1.3	0.6	20
13	9	8	3	25	9	3	16	6	0.64	1.1	0.4	21
14	12	13	4	25	12	6	18	5	0.43	0.5	0.3	16
15	13	0	3	58	11	3	25	12	0.96	2.5	6.2	20
16	11	11	3	31	10	4	18	6	0.59	1.5	2.4	22
17	13	14	3	25	12	5	22	8	0.58	0.4	-1.2	13
18	19	17	10	29	19	11	26	7	0.35	0.3	-1.3	9
19	13	12	6	23	13	7	19	5	0.38	0.7	-0.5	14

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