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Agee, J.K. 1993
Fire Ecology of Pacific Northwest forests
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CHAPTER 4

METHODS FOR FIRE HISTORY

EARLY ATTEMPTS TO EXPLAIN the ecological effects of fire were hampered by a lack of both ecological data and description of the fire regime. Although experiments that varied the frequency and season of burning extend back to the early part of the century (Schiff 1962), the first ecology textbook describing fire as an ecological factor was published only in 1947 (Daubenmire 1947). One of the first major reviews of fire effects (Ahlgren and Ahlgren 1960) described effects of presence or absence of fire with little detail concerning effects of multiple events over time. Today, it is possible to describe fire regimes in more detail, but the details can be confusing and sometimes misleading.

Defining a particular fire frequency can be likened to describing a cord of wood. There is a precise volumetric definition of a cord of wood, but each person stacking a cord may use different amounts of firewood to produce the stacked volume. Sometimes a short cord results! Johnson and Van Wagner (1985) suggest that clear thinking about fire history is difficult, and that mathematical models are necessary to avoid a storytelling tradition of fire history. However, mathematical models, which usually have rigid assumptions about the nature of the system, can be just another form of storytelling if they are not carefully interpreted.

This chapter reviews the common methods of determining fire history in order to provide an understanding of what the techniques are, where they are best applied, and how they should be interpreted in an ecological context. It does not provide an exhaustive review of fire history studies. The regional studies will be summarized in later chapters dealing with specific forest types, and broader reviews are also available (Alexander 1979, 1980, Mastrogiuseppe et al. 1983). This chapter emphasizes methods to determine fire frequency and predictability, but the application of techniques will depend on past fire severity as well.

FIRE FREQUENCY DEFINITIONS

The terminology used in fire history work is gradually becoming standardized. A review of terminology at a fire history workshop (Romme 1980) reached consensus on several terms. The literature published since 1980, however, has not closely reflected that consensus in usage. The phrases defined here and used in this chapter are adapted in part from Romme (1980). Preferred phrases are followed by commonly used synonyms in parentheses:

Fire frequency: a general term referring to the recurrence of fire in a given area over time.

Fire event (fire occurrence, fire incidence): a single fire or series of fires within an area at a particular time.

Fire interval (fire-free interval or fire-return interval): the number of years between two successive fire events in a given area.

Mean fire-return interval (mean fire interval): arithmetic average of all fire intervals in a given area over a given time period.

Fire rotation (natural fire rotation): the length of time necessary for an area equal in size to the study area to burn.

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Fire cycle: the average stand age of a forest whose age distribution fits a mathematical distribution (negative exponential or Weibull).

The terms *fire event* and *fire interval* are simply descriptive of the presence of one or two fires on a landscape. Their interpretation is relatively unambiguous. Other terms are either derived or interpreted in several ways that make comparison between studies quite difficult. The *mean fire-return interval* is typically applied in fire regimes of low to moderate severity, using data from multiple fires in the same stand. In practice, data are often pooled over different-sized areas, which confounds ecological interpretation unless the area factor is clearly integrated into the interpretation. *Fire rotation* and *fire cycle* are terms used in fire regimes of moderate to high severity. The extent of individual past fires or present age classes across the landscape are pooled to derive an average rotation or cycle. This value may be derived from a large area containing different fire regimes, which again may confound ecological interpretation.

CREATING A FIRE HISTORY DATABASE

The first evidence to establish in creating a fire history database is fire occurrence—whether fire has been present on the landscape. This may be established from fire scars on trees, from plants that appear to have germinated after fire, or from charcoal. The most consistent indication of fire occurrence is charcoal, since the other two indicators become less reliable over time. Charcoal may be found in the surface soil, often in contact with the roots of the current stand.

Charcoal has been recovered in lake sediment cores and used to interpret fire and vegetation history. Swain (1973) used relative increases in charcoal presence and varve (annually laminated sediment) thickness to reconstruct past fire history in Minnesota. Charcoal peaks within sediment deposits in a small lake in the North Cascades (Cwynar 1987) were used to infer the relative importance of fire over the last 12,000 years. Techniques for analyzing thin sections of lake varve continue to improve. Charcoal in thin sections of lake varve can produce a local (i.e., catchment) record of fire frequency (Clark 1988, Clark 1990).

Inferences of fire occurrence may also be made from charcoal on the bark of currently living trees. The bark of coastal Douglas-fir will retain its char for centuries, based on evidence from stands in the Olympic Mountains. Two-hundred-year-old stands have occasional residual trees with substantial charcoal on the bark left by the fire that created the stand. In young stands that burn, charred residual trees will eventually appear to have a candy-stripe pattern as the tree increases in diameter: charred strips will be separated by newer bark produced since the fire. Other species retain charcoal on the bark for shorter periods of time. Ponderosa pine, for example, may shed most of its charred bark plates within several years if the tree is vigorous, so that fire evidence must be established by finding the blackened, jigsaw-shaped bark plates on the forest floor. In Okanogan County, Washington, bark char on the boles of ponderosa pine has been observed to last at least 50 years, so its presence on the bole of ponderosa pine is not necessarily evidence of a very recent fire.

Fire Scar and Age-Class Evidence

Fire scars are an excellent source of fire frequency data, because they can be used to establish precise years of past fire events. Techniques for reconstruction of fire dates from fire scars are discussed later in this chapter. It is important to make sure that the scar was caused by fire. Many other disturbance processes can also create bole scars.

A fire scar is caused when heat from a fire persists around the tree bole long enough to allow a temperature pulse to penetrate the bark and kill part of the cambium. Mechanisms of fire scar formation are discussed in chapter 5. Each succeeding year after the fire injury, the adjacent live cambium expands slowly over the surface of the scarred area and may eventually enclose it (Figs. 4.1, 4.2). Once a scar has been created, another fire is likely to rescar the same area. This happens because often a pitch or resin deposit ignites in the vicinity of the wound, the bark is thinnest at this part of the bole circumference (even if the scar has healed over), and dead, dry

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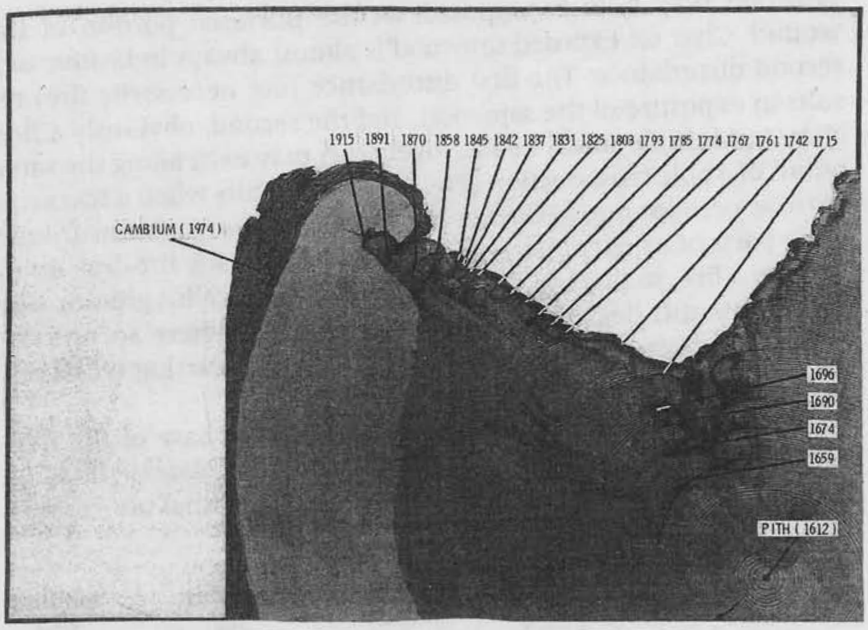

FIG. 4.1. *Cross-section of ponderosa pine with multiple fire scars in the catface.* (USDA Forest Service photo, courtesy S. F. Arno)

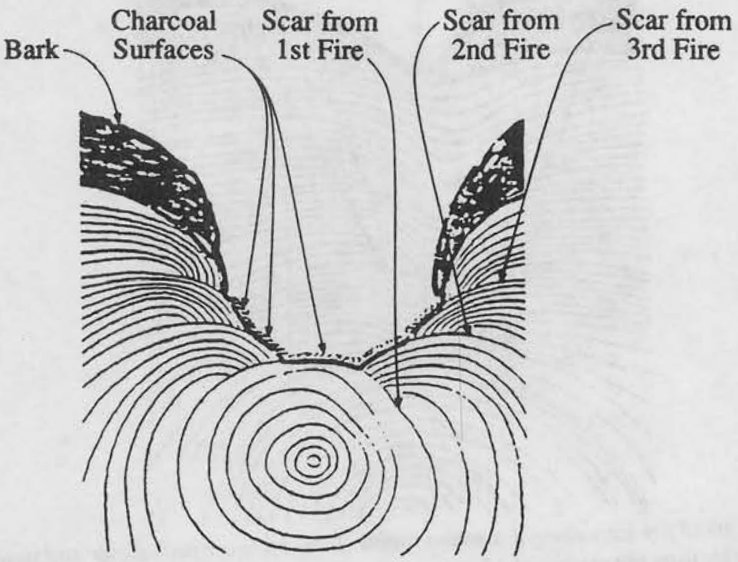

FIG. 4.2. *Characteristics of fire scars, such as the one shown in Figure 4.1.* (From Morrison and Swanson 1990)

sapwood may now be exposed on the unclosed portion of the wound. Char on exposed sapwood is almost always indicative of a second disturbance: The first disturbance (not necessarily fire) results in exposure of the sapwood, and the second, obviously a fire, chars it. Multiple small, healed-over scars may exist along the same radius of a bole cross-section (Fig. 4.3). This occurs when a scar arc is narrow, perhaps due to thicker bark shielding the cambium around other parts of its circumference, or because of a long fire-free interval after a fire, so that the scar is enclosed by later callus growth. The bark across this healed area is thinner than elsewhere around the tree and is therefore more susceptible to repeat scarring when another fire occurs.

Fire scars are usually triangular, extend to the base of the tree, occur on adjacent trees of the same age and species, date to the same year, and are associated with the presence of charcoal on exposed

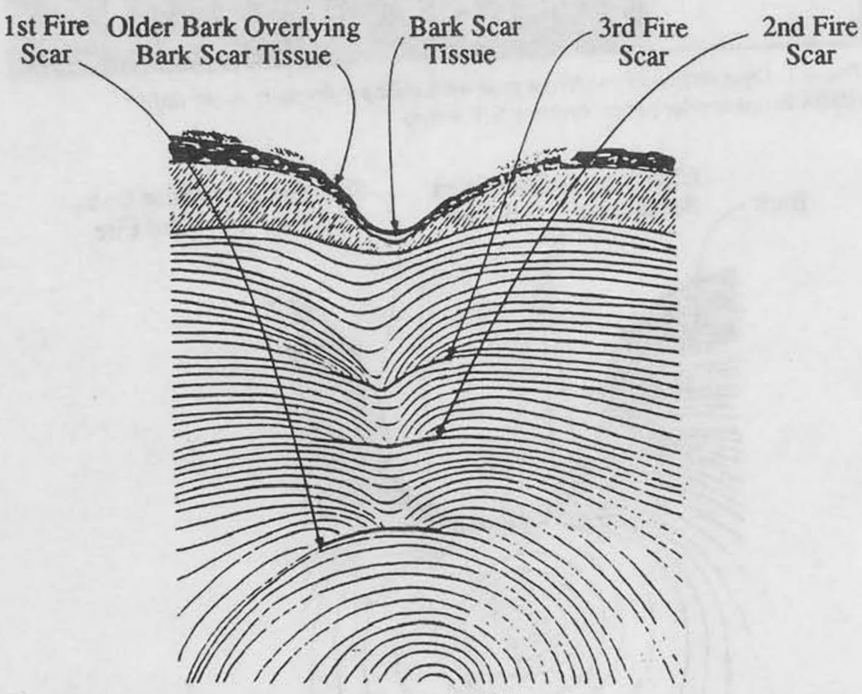

FIG. 4.3. *Small fire scars along a common radius. These often are healed over and would not be visible from the exterior of a live tree.*
(From Morrison and Swanson 1990)

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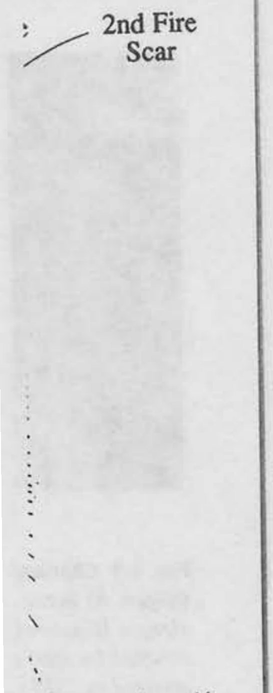

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sapwood or bark. Other agents may also be responsible for bole scars on trees, so that unless properly identified such scars may cause researchers to exaggerate the occurrence of fire at the site. Scars can be created by humans, other animals, physical processes, and diseases.

Humans have scarred trees for boundary or trail markers throughout the West for more than a century. Typically such scars are well above the base of the tree and may have characteristic shapes. Native Americans are known to have stripped bark off ponderosa pine to eat the live phloem tissue (Swetnam 1984). Such scars are oval to rectangular, may have tool marks on the upper and lower edge, and begin above the base of the tree and in some cases extend to a height of 3 m. Similar human-caused scars are noted on Alaska yellow-cedar in southeast Alaska (Hennon et al. 1990).

A common scarring agent in young stands is the black bear (*Ursus americanus*). Bears strip the bark off trees in spring to eat the phloem or lick the sap (Molnar and McMinn 1960). Sapwood claw marks may be present (Fritz 1951). After 30–50 years, bear scars may appear very similar to fire scars (Fig. 4.4), except that when dated

FIG. 4.4. A: *Recent bear damage on subalpine fir in Olympic Mountains.* B: *Older bear damage on Pacific silver fir in Olympic Mountains.*

they may reflect a period of 2–5 years of stripping rather than a common date of a fire event.

Red squirrels (*Tamiasciurus hudsonicus*) have been observed to create scars on most of the conifers of the northern Rocky Mountains (Stillinger 1944). Usually no tooth marks are evident (Sullivan and Sullivan 1982). Hares (*Lepus americanus*) and porcupines (*Erithrizon dorsatum*) also strip bark but leave tooth marks on the tree; hares will generally leave a shaggy sapwood with their tooth marks, while porcupines will leave broad, prominent vertical and diagonal incisor marks (Sullivan and Sullivan 1982). Voles (*Microtus* spp.) chew the bark on small trees right at the base, and deer (*Odocoileus* spp.) scrape their antlers on stiff young trees, creating scars about 1 m above the ground.

Partially successful insect attacks may also cause scars. The fir engraver beetle (*Scolytus ventralis*) has been observed to kill patches on the north side of small white fir trees (Furniss and Carolin 1977, Thomas and Agee 1986). The female beetle and the larvae etch a clearly discernible pattern in the sapwood, and the scar is usually not basal. Basal scars may be caused by attacks of the red turpentine beetle (*Dendroctonus valens*), which usually are not fatal. Such scars may be patchy and circular to rectangular, representing the larval gallery pattern.

A classic example of confusion of beetle scars with fire scars occurs in the lodgepole pine forests of the pumice plateau in south-central Oregon (Fig. 4.5). Stuart et al. (1983) found that beetle scars were caused by cambial kill on only one side of the bole (usually the north side) and superficially resembled fire scars (e.g., Gara et al. 1986). The beetle scars could be differentiated from fire scars by the presence of some or all of the following characteristics: pitch tubes, beetle emergence holes, blue stain, larval galleries, retained bark on the scar face, a lack of char, and an orange or red discoloration around healthy sapwood. After 50–100 years, however, the blue stain fades and beetle galleries on the exposed sapwood erode, making differentiation of the scar source more difficult.

Several physical disturbance agents may also cause bole scars. Windthrown trees occasionally slide down and scrape the boles of standing trees, removing the bark along one side of the tree. The sapwood may be damaged, and this damage is visible even decades later. Broken branches may also be evident on the same side of the

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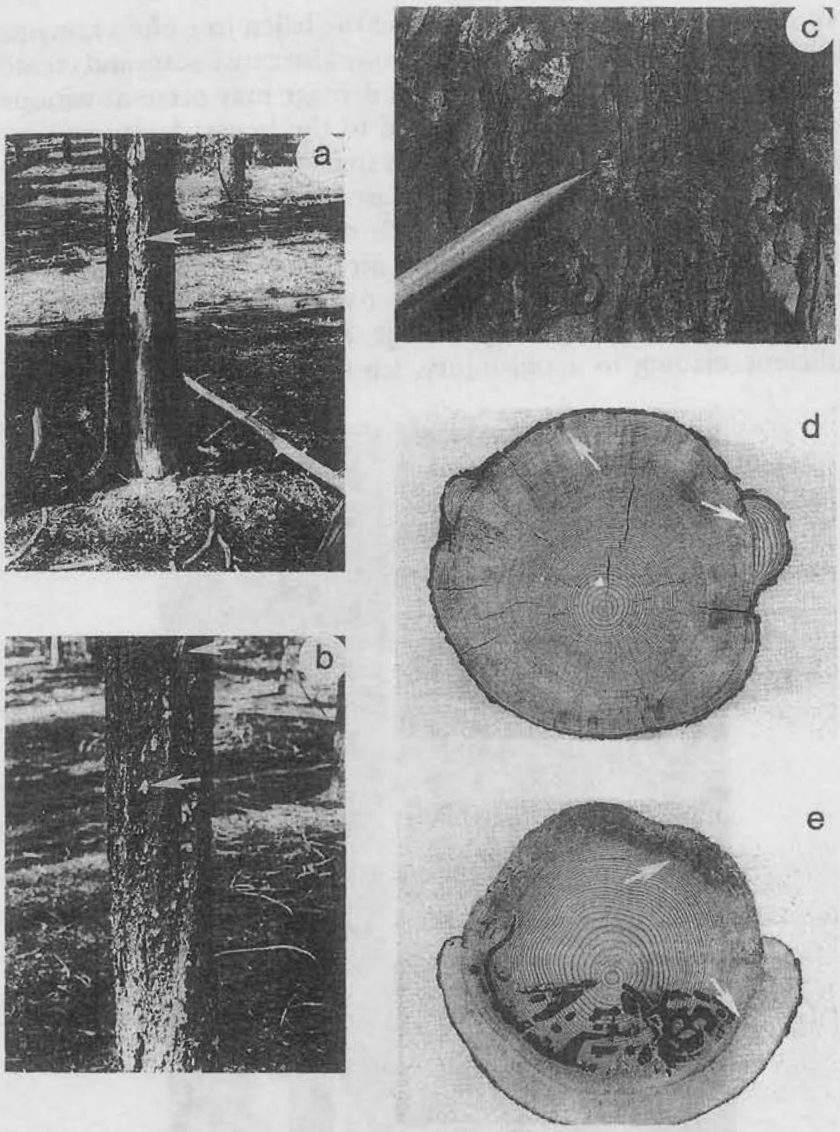

FIG. 4.5. *Characteristics of mountain pine beetle scars on lodgepole pine in south-central Oregon.* A: *Beetle scar with retained bark in scar (arrow).* B: *Pitch tubes and callus tissue along a 10-year-old beetle scar.* C: *Emergence hole of a beetle.* D: *Cross-section of a tree attacked 10 years earlier (arrows denote blue-stained sapwood).* E: *Cross-section of tree attacked in 1925 (arrow at top right denotes zone of blue stain, arrow at bottom right denotes ring of discolored wood coincident with healthy sapwood). Excavations in heartwood are from insects of Cerambycidae family.*
(From Stuart et al. 1983)

tree (Molnar and McMinn 1960), and the fallen tree often remains at the base of the scarred tree. Frost may also cause scars and create damaged annual rings in trees. Frost damage may occur at various elevated places on the bole exposed to the lowest temperatures. Another physical disturbance agent is sunscald (Fig. 4.6). If a disturbance opens a stand to greatly increased light intensity, unshaded portions of the bole on the south side of the tree may experience lethal temperatures. Sunscald scars are usually fusiform and are found at intermediate heights; lower portions of the bole have sufficently thick bark to avoid damage, and upper portions receive sufficient shading to avoid injury. Ice flow in riparian areas can

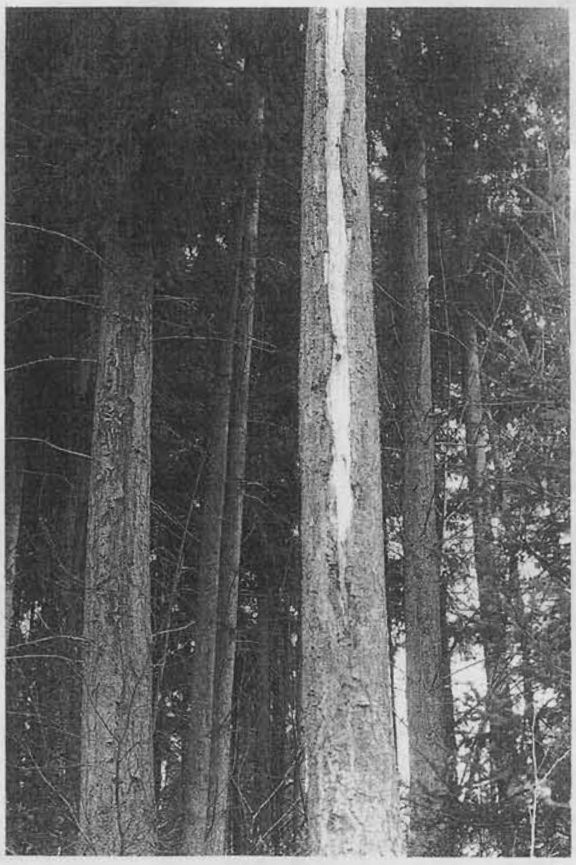

FIG. 4.6. *Sunscald damage (12 years old) to Douglas-fir created by tree removal to the south, exposing the stem.*

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Basal scars can be caused by diseases, particularly *Armillaria mellea*. In cedar-hemlock forests, *Armillaria* is found near the base of the tree, commonly on root buttresses (Arno and Davis 1980). The scarring on root buttresses can be traced to disintegrated roots, and such scars can occasionally be found as high as 1 m on the bole, although most are lower. Arrested *Armillaria* infections were found on 18–73-year-old western white pine and Douglas-fir (Molnar and McMinn 1960). Pole blight is a disease of western white pine on dry sites, which can cause stem lesions (Molnar and McMinn 1960) that can be mistaken for thin, extended fire scars. The blight is usually associated with pines on dry sites (Bega 1978).

Fire scars are a good means of establishing fire history, but they are not commonly present in all fire regimes. In high severity fire regimes, the only evidences of fire besides charcoal may be different age classes of forest across the landscape. Occasional residual trees may occur in protected areas, such as riparian zones or fuel-limited talus slopes. If the age classes can accurately establish the dates of past fires, then they can be used to determine some form of area frequency. Stand establishment dates are estimated by selecting the largest specimens of early seral tree species in the stand and aging as many of these to the pith near ground line as possible.

If logging operations have occurred in the vicinity, field counts of annual rings on stumps or samples for laboratory analysis can be easily obtained. In nature preserves, cutting of large specimens may not be possible, and age must then be established on the basis of increment borer samples. For age analysis, a core taken near the ground along an upslope-downslope centerline is most likely to hit the pith of the tree (Agee and Huff 1986b). If the pith is missed, a geometrically based correction can be applied to estimate pith age of the sample (Liu 1986). Additional years must be added to this pith date to correct for the number of years required for the tree to grow to the height at which it was bored, usually 20–40 cm height. A list of correction factors used for several species and sites is presented in Table 4.1. Such estimates usually have a possible error of at least two years, and unless a good site match is found, a site-specific set of estimates developed as part of the study is the best alternative.

TABLE 4.1. AVERAGE AGE CORRECTION FACTORS FOR CORE HEIGHT TO GROUND LEVEL FOR SEVERAL PACIFIC NORTHWEST CONIFERS

Species	*Site Quality/ Plant Association*	YEARS OF AGE TO ADD AT THESE CORE HEIGHTS (CM ABOVE GROUND)						*Source*
		10	*20*	*30*	*50*	*100*	*150*	
Abies grandis	Abgr/Pamy						12	Cobb (1988)
Abies lasiocarpa	Abla/Xete(10)[b]	5			9	13		Agee et al.
	Abla/Xete(50)	17			25	38		(1986)
Larix occidentalis	Abgr/Pamy					6		Cobb (1988)
Pinus contorta	Abgr/Pamy					5		Cobb (1988)
	Abgr/Hodi	1	2		4	5		Agee et al.
	"high elev."	2	3	4	6			(1986)
Pseudotsuga menziesii	Abgr/Hodi	5		8	10	12		Agee and Dunwiddie (1984)
	Abgr/Pamy						9	Cobb (1988)
	Site I			3		5	7	McArdle and
	Site III			3		7	9	Meyer
	Site V			5		9	11	(1930)
Tsuga mertensiana	"dry"	6	8	11	16			Agee et al. (1986)

[a] Abgr/Pamy = *Abies grandis/Pachistima myrsinites.*
Abgr/Hodi = *Abies grandis/Holodiscus discolor.*
Abla/Xete = *Abies lasiocarpa/Xerophyllum tenax.*
Site = average height of dominant and codominant trees at age 100 (Site I = 200; Site III = 140; Site V = 80).

[b] At core height, 10 or 50 annual rings in first cm from pith.

There is no foolproof way to determine how soon after the disturbance the oldest sampled trees became established. Relying on tree establishment dates produces a minimum rather than a true age of the event. Graphing the estimated tree germination dates over time will show the oldest sampled trees and may show a pronounced establishment pulse for certain early seral species (Fig. 4.7; Larson and Oliver 1981). These pulses may reflect delayed tree establishment. Major pulses of seral subalpine fir establishment after fire have occurred 50 years after the fire (Agee and Smith 1984). In drier subalpine ecosystems, establishment of seral lodgepole pine

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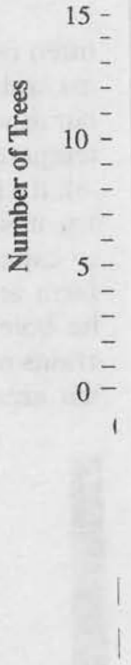

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	7	McArdle and
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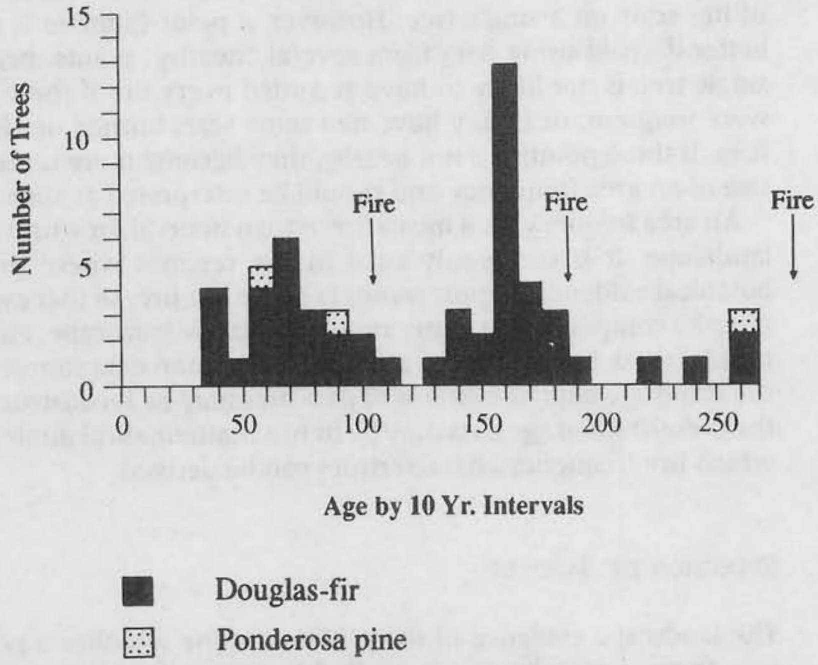

FIG. 4.7. *Pulsed establishment of Douglas-fir in the Stehekin Valley, Washington, after forest fires about 90 years apart. Disturbance opens growing space for new regeneration.*
(From Larson and Oliver 1981)

can usually be used as a disturbance "marker"; in southwestern Oregon, seral knobcone pine is a good indicator, and in moist western hemlock forests, seral Douglas-fir is a good indicator species for disturbance studies.

POINT AND AREA FREQUENCY

The various definitions of fire frequency attempt to describe one of two kinds of frequency: *point* or *area*. A point frequency is the mean fire-return interval at a single point on the landscape. An ecological interpretation derived from such data assumes that fires will burn across this point on the landscape at that mean frequency, usually with considerable variation around the mean. Technically, a point frequency should be derived solely from point data, such as a series of fire scars on a single tree. However, a point estimate is usually better derived using data from several "nearby" points, because a single tree is not likely to have recorded every fire if these events were frequent, or it may have had some scars burned out by later fires. If these points are not nearby, they become more representative of an area frequency and should be interpreted as such.

An area frequency is a mean fire-return interval for a unit area of landscape. It is commonly used in fire regimes where the only botanical evidence in most stands is of the last fire, so that evidence must be compiled from many stands across the landscape. Fire scars may be used, but stand ages are a more common data source. From the stand age data, the extent of past fires may be reconstructed, or the present stand age data may be fit to a mathematical model, from which fire frequency characteristics can be derived.

SELECTION OF SAMPLES

The landscape evidence of fire will determine whether a point or area frequency technique is applicable. Where fire scars are abundant, fire regimes of low to moderate severity are implied, and point frequency techniques can be used. Several techniques for point frequency sampling are summarized by McBride (1983); these include sampling within reconnaissance transects, adjacent to points on a grid, or randomly. The area should be stratified so that sample units reflect homogeneous units of physiography or forest habitat types, which are likely to have similar fire histories. Sampling density for point frequencies can be 100 percent of the scarred trees or some lesser percentage determined by total area and budget. The clustering of samples may be important if combinations of samples are to be interpreted as a point frequency.

In fire regimes of moderate to high severity, sampling density depends on the complexity of the fire regime and the degree to which it is desirable to reconstruct the past disturbances. Table 4.2 (adapted from Morrison and Swanson 1990, with some additions) shows sampling schemes ranging from less than 1 to more than 50 trees per km^2. Agee (1991) suggests that in the extremely complex fire regime of the mixed-evergreen forests of southwestern Oregon,

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TABLE 4.2

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TABLE 4.2. SAMPLING DENSITIES OF SELECTED FIRE HISTORY STUDIES

Study	*Location*	*Trees Sampled (per km²)*	*Origin and Probable Fire Scar Dates (per km²)*	*Study Area Size (km²)*
Agee (1991)	Southwestern Oregon	52	5.6	2.5
Teensma (1987)	Central Cascades	19.7	24.9	109.7
Morrison and Swanson (1990)	Central Oregon Cascades	13.8	19.8	39
Hemstrom and Franklin (1982)	Mount Rainier	1.3	1.3	770
Tande (1979)	Jasper Nat. Park, Alberta	8.1	9.6	432
Kilgore and Taylor (1979)	Southern Sierra Nevada	12.1	36.6	18
Arno (1976)	Northern Rocky Mtns.	2.3	14.5	73
Heinselman (1973)	Minnesota	0.8	0.9	3,480

SOURCE: Adapted from Morrison and Swanson 1990.

a sampling density higher than commonly used in other places was still not sufficient to address all the aspects of the fire history, even on a very small area. Similarly, Morrison and Swanson (1990) felt their high sampling density was not sufficient in the western Cascades of Oregon. They note, however, that for even-aged stands with one or two fires per site, little is gained by extremely intensive sampling. Some knowledge of the fire regime is very helpful in planning sampling density for fire history.

DETERMINING A POINT FREQUENCY

The tree is the ideal sampling locus for determining fire-return intervals, being both a repository of fire scar information and essentially a point on the landscape. Selection of trees to sample requires a thorough survey of the study area. Look for trees with multiple fire scars. Each scar will present itself as a vertical seam with the usually triangular "catface" (Fig. 4.8). The best sample trees can be marked with flagging for ease of location. On slopes, most of the fire scars will be on the upslope side of the tree, so reconnaissance is most effective working downslope from ridgetops to valleys.

Two techniques for sampling fire scars on live trees are commonly employed: cutting sections out of live trees, and using increment boring techniques for dating fire scars.

The cleanest and most accurate way to sample a scar or series of scars on an individual tree is to cut the tree down and take an entire cross-section back to the laboratory. Because this kills the tree, and creates a very bulky sample collection, an alternative sampling

FIG. 4.8. *An eastern Cascades Douglas-fir with two fire scars: the blackened strip down the center of the tree, and the whiter strip to either side.*

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technique is preferred. Techniques for sampling partial cross-sections of fire scars without killing the tree are summarized by Arno and Sneck (1977). Two parallel cuts about 5 cm apart are made on one side of the catface at a height that will include the most scars (Fig. 4.9). A vertical cut is then made on the interior portion to include the scars, and finally the tip of the saw is pushed in vertically behind the parallel cuts to free the partial cross-section. Once the sample has been removed, excess portions can be trimmed off. Two problems with this approach are that the resulting cuts on the tree are unsightly and the tree will be at increased risk for windthrow. A technique for thinner, less conspicuous sections was presented by McBride and Laven (1976). They took thin wedge-shaped sections, not necessarily to the pith, thus avoiding the need to place a chainsaw-wide vertical cut behind two parallel cuts. This technique may not be feasible for deeply embedded scars. Trees with significant

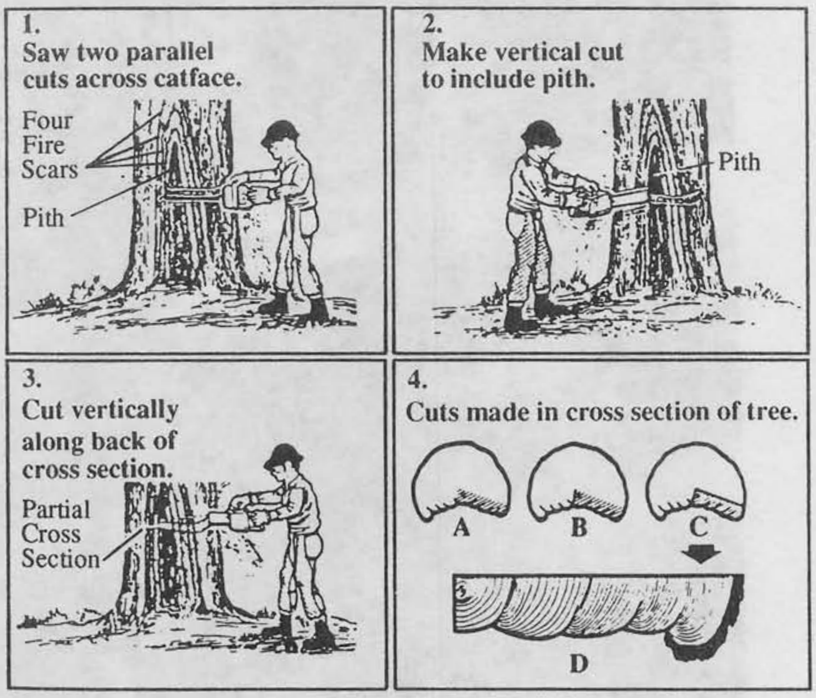

FIG. 4.9. *Method of collecting a partial cross-section from a large tree with a chain saw.*
(From Arno and Sneck 1977)

sections removed are at increased risk for windthrow from lack of ability to resist compression or tension stress (Fig. 4.10). The section can be filled with cement or a flattened rock to avoid compression stress, and metal straps can be nailed vertically across the cut to reduce tension stress. However, if the straps are later grown over, they can pose a safety hazard if the tree is cut at that height.

The use of increment borers to date scars provides an alternative to wedge sections. This technique has been in use for many years, but a clear description of the methods was published only in 1988 (Barrett and Arno 1988). For a tree with a single scar, several cores

FIG. 4.10. *Ponderosa pine windthrown in first winter after fire scar removal by method shown in Figure 4.9. Due to substantial growth since the last fire, a significant portion of the tree cross-section was necessarily removed in sampling.*

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can be taken along the scar edge, combined with a "back boring" core to better represent the growth pattern of the tree (Fig. 4.11A). The cores along the scar must include one at or very near the scar tip. The back-bored core should have a growth anomaly corresponding to the year represented on the scar tip. It may be a significant growth decline, representing damage to the tree, such as crown scorch; a significant growth increase, representing little tree damage but loss of surrounding competitors; or an initial growth loss followed by a growth increase, representing some tree damage but less than that suffered by competitors (Barrett and Arno 1988). Another single-scar technique recommended by Barrett and Arno is the face-boring procedure, best used on small trees that can be completely bored through (Fig. 4.11B).

The accuracy of the increment core procedure, if cores are cross-dated, compares favorably with that from wedges (Sheppard et al. 1988). Cross-dating is a method of matching annual ring patterns of a sample with known annual ring patterns from a master chronology. The master chronology is often built from the ring patterns of 10–20 mature, undisturbed trees in the local area. Such a comparison will help identify missing or false rings in the sample and correct aging errors on the non-cross-dated sample. In Douglas-fir and western hemlock, Means (1989) found no age difference in 21 core samples compared to wedge samples, with the remaining 4 samples off by 1, 2, 3, and 4 yr. More significant errors were found if cores were not cross-dated.

Techniques for boring multiple scars are also summarized by Barrett and Arno (1988). These procedures tend to stretch the limits of the increment borer technique for determining fire history, but can be very useful in trees of diameter <60cm. Extensive experience with increment boring and with coring fire-scarred trees is necessary for successful application of increment boring techniques on multiple fire scars.

CALCULATING A MEAN FIRE-RETURN INTERVAL

The simplest way to calculate a mean fire-return interval is to establish the set of fire-return intervals from a single point sample and take the arithmetic average. Typically, the interval between

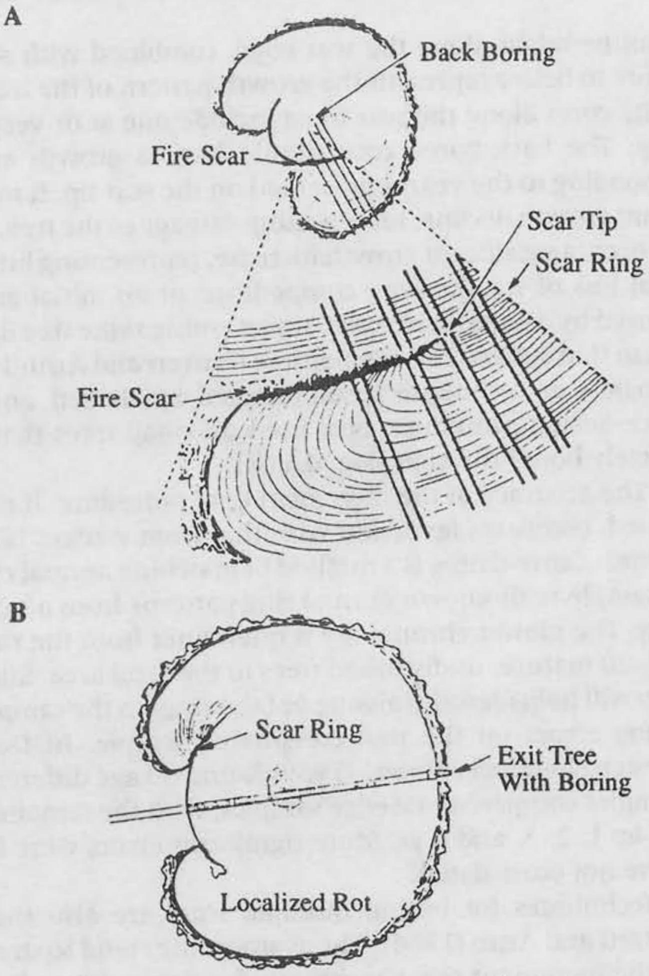

FIG. 4.11. A: *Scar-boring procedures for a tree with a single scar.* B: *Face-boring procedures for a tree with a single scar (assumes borer is long enough to pass completely through tree).* (From Barrett and Arno 1988)

scarring events is determined and then averaged within the sample (Laven et al. 1980). In some cases, the number of years from the pith to the first scar has been included as the first interval (e.g., Houston 1973), but this is not commonly done. The sample may be cross-dated (Stokes and Smiley 1968) to establish the exact year of each event—a step that may have value beyond the scope of the

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initial study, if regional comparisons are made later (e.g., Swetnam and Betancourt 1990). If a sample has rot, soaking the sample in water and freezing it allows a clear razor-knife-cut surface to be prepared and counted, without significant radial expansion of the specimen (Herman et al. 1972).

The problem with using a single point sample to derive a point estimate of fire frequency is that not every fire will scar every tree, and some scars will have been burned out by later fires (Kilgore and Taylor 1979). When fire does scar the tree, it may not do so across the entire existing catface (Dieterich and Swetnam 1984). Therefore, the mean fire-return interval derived from any single tree can overestimate the true mean fire-return interval. The average of a set of single mean fire-return intervals does not correct the problem. In Table 4.3, the mean fire-return interval for individual point samples ranges from 20.4 yr to 25.6 yr. An arithmetic average of these over the 50 ha study area is 23.4 yr. Yet it is probable that not every fire

TABLE 4.3 HYPOTHETICAL FIRE DATES DETERMINED ON SINGLE TREES AND THEIR USE IN DETERMINING MEAN FIRE-RETURN INTERVALS

Tree 1	*Tree 2*	*Tree 3*	*Tree 4*	*Tree 5*
Point				
0.25 ha				
1 ha				
10 ha				
50 ha				
1910	1902	1910	1920	1902
1902	1884	1884	1902	1890
1875	1840	1864	1864	1870
1850	1825	1825	1835	1842
1840		1810	1825	1805
1800		1800	1800	1800
Mean Fire Intervals				
22	25.6	25	24	20.4
13.8				
11.0				
10.0				
7.5				

passing a point leaves a fire scar record, so that the fire scar records of multiple trees in the vicinity may provide a better estimate of the mean fire-return interval.

The integration of fire scar records from multiple trees is called the composite fire interval. It allows separate records to be combined in a single estimate of mean fire-return interval. If the records of trees 1 and 2 (Table 4.3) are assumed accurate and combined, the composite mean fire-return interval is roughly half the individual mean fire-return intervals. In this example, increasing the area within which records are combined continues to decrease the mean fire-return interval. At some area size, the mean fire-return interval ceases to function as a point estimate of fire frequency and becomes instead an area estimate.

One of the key assumptions in developing a composite mean fire interval is that the date of each event at each point is accurate. Inaccurate dates can lead to significant errors in calculating mean fire-return intervals. Sheppard et al. (1988) present a simple example. Assume that four single-scarred trees, all adjacent, are tentatively fire-dated to 1810, 1860, 1863, and 1910. The mean fire-return interval is 33 yr. If the 1860 and 1863 events are assumed to be the same fire event, and if the record is adjusted accordingly, the mean fire-return interval is 50 yr.

There are two methods to produce a database (a master fire chronology) for developing a composite mean fire-return interval. The first (Arno and Sneck 1977) is less accurate but may be sufficient for some purposes. It requires the plotting of all dates from all trees on a chart with tree number along the top (arranged in some geographical order) and year along the side. The dates for each tree are then reconsidered based on the records of nearby trees. Trees with poor quality sections are usually adjusted to coincide with records of nearby trees. Preference is given to adding years to a given scar date, since missing rings are more common than false rings (Soeriaatmadja 1966, Madany et al. 1982). When a given date is moved back in time, all preceding dates for that tree are similarly moved in the same direction.

The second method involves some degree of cross-dating specimens based on the overall ring-width patterns of the sample (Madany et al. 1982). The patterns on the fire-scarred samples are compared to composite skeleton plots of rings from unscarred trees

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or from regional master chronologies (Stokes and Smiley 1968, Fritts 1976). Missing or false rings are accounted for, and the scars are then dated according to the apparent rings in which they occurred. Whether or not to cross-date samples depends on the purposes of the study and the fire regime involved (Madany et al. 1982). In ponderosa pine and other forest types with historically high fire occurrence, the cross-dating approach should be employed, although it can greatly increase the time required for analysis. In ecosystems with longer fire-return intervals, the first method may suffice (Madany et al. 1982). Means (1989) showed that for western hemlock and Douglas-fir, the absence of cross-dating resulted in negligible dating error on 20 of 22 single-scar specimens, with 1 specimen having a 3 yr error, and one having a 22 yr error due to missing rings.

Interpretation of a composite fire interval requires knowledge of how it was produced, how large an area was included in the estimate, and what time interval was considered. The decrease in mean fire-return interval with size of area, hypothetically shown in Table 4.3, is common. Kilgore and Taylor (1979), in giant sequoia–mixed conifer forests of California, showed a decrease in mean fire-return interval from 13–22 yr to 2 yr as area considered increased from single-tree estimates to about 1,000 ha. Data regraphed from Arno and Peterson (1983) show the same trend (Fig. 4.12). In what must be considered the "record" low mean fire-return interval for forests, Dieterich (1980a) found the mean fire-return interval on a 40 ha site in Arizona between 1790 and 1900 to be 1.8 yr, with one point sample having a mean fire-return interval of 4.1 yr. As the area increases in size, one might eventually produce a composite mean fire-return interval of less than one year, so the area bias inherent in composite methods must be taken into account in interpreting the ecological significance of such intervals.

Two other examples indicate the need for careful interpretation of composite fire intervals. The first is an evaluation of Native American burning in Montana (Barrett and Arno 1982). Stands ranging in size from 80 to 230 ha were sampled, and fire-return intervals for various periods were calculated for stands with little Native American use and those with heavy use. Unless one assumes that each fire event covered all of each area, there is an area bias of unknown magnitude associated with a threefold variation in stand size.

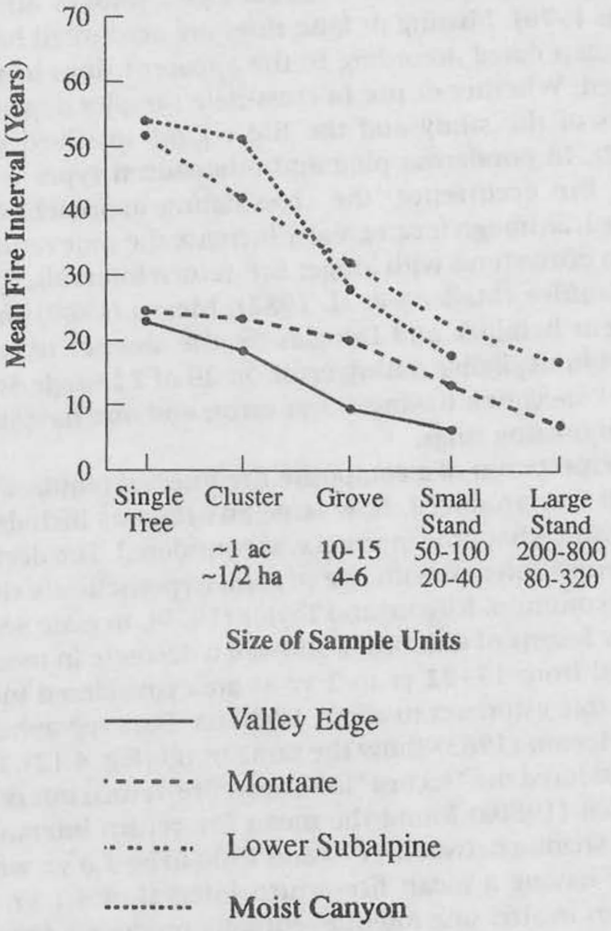

FIG. 4.12. *Shrinking fire-return intervals as the area considered increases from a point to a large stand.* (From Arno and Peterson 1983)

The second example comes from data of Weaver (1959) and Bork (1985). Weaver's estimates of fire frequency were based on individual point samples, and he found on several north-central Oregon *Pinus ponderosa/Purshia tridentata* sites mean fire-return intervals of 11–16 yr. Bork, working in similar vegetation about 80 km to the south at Pringle Butte, found a mean site fire-return interval of 4 yr. Did Weaver miscount his samples, or is the fire frequency so much higher to the south? In fact, the authors are probably expressing

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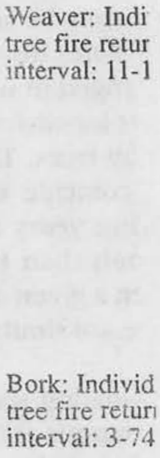

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similar data in different ways (Fig. 4.13). Weaver presented only single-tree point estimates, while Bork had similar point estimates but also developed a variety of area estimates. Although Bork's composite fire-return intervals are shorter, the mean fire-return intervals for individual trees show a wider variation.

In most Pacific Northwest studies of fire history, fire-return intervals tend to lengthen in periods earlier than about 1650, due to the lack of available sample trees and associated problems in developing good composite fire chronologies. Comparisons between sites must be interpreted very conservatively before the mid-seventeenth century if based on fire-scarred trees.

Determining an Area Frequency

Area fire frequencies are mean fire-return intervals meant to represent landscape rather than point fire frequencies. Sometimes mean fire-return intervals calculated solely from fire scars represent area frequencies rather than point frequencies. More commonly, area frequencies are applied to landscapes where fire scars are less common and forest stand ages are a primary source of fire evidence.

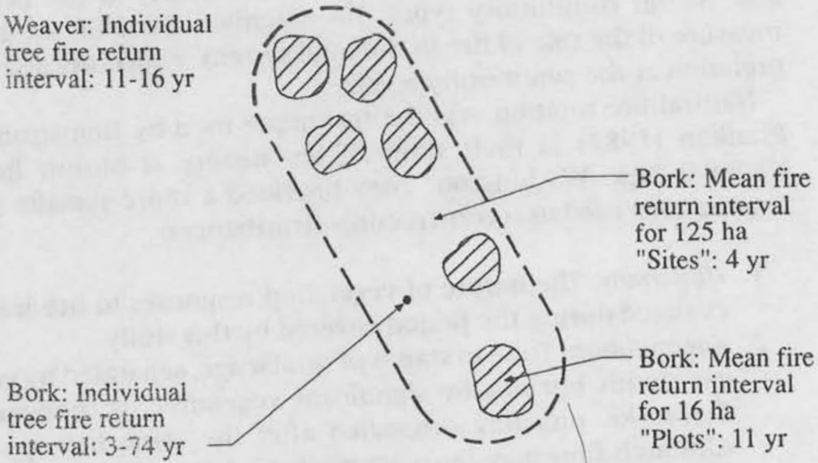

FIG. 4.13. *Comparison of fire-return-interval data from Weaver (1959) and Bork (1985). Weaver's data would be represented as a point frequency, while Bork's data in a similar ponderosa pine/bitterbrush community represents varying levels of area frequencies.*

Mean fire-return intervals represent a landscape average of fire frequency.

The first method of determining area frequency is called the natural fire rotation method. It was first proposed by Heinselman (1973) in his classic paper on fire in the Boundary Waters Canoe Area of Minnesota. Using forest age class and fire scar evidence, and interpretations of natural fire barriers such as swamps, lakes, and streams, he reconstructed historic fires that had burned across the area back to A.D. 1595. He expressed measures of different fire intervals over time by percent area burned per century, and then proposed a new term, *natural fire rotation* (NFR): the average number of years required in nature to burn over and reproduce an area equal to the total area under consideration. In simple mathematical terms, the calculation becomes:

$$\text{NFR (yr)} = \frac{\text{Total time period}}{\text{Proportion of area burned in period}}$$

For example, if an area of 10,000 ha has a total of 40,000 ha burned in 200 yr, the NFR is calculated as 200/[40,000/10,000] = 200/4 = 50 yr. Over such a long time period, some points on the landscape will burn four or five times and some not at all. Variation or periodicity is not directly considered in the calculation, which as Heinselman (1973) recognized masked the variability in fire between and within community types. He described the NFR as a valid measure of the role of fire in the total system, which needed interpretation at the community level.

Natural fire rotation was the technique used by Hemstrom and Franklin (1982) in their study of fire history at Mount Rainier National Park, Washington. They provided a more specific set of assumptions used in reconstructing disturbances:

1. *Uniformity.* The nature of vegetation responses to fire has not changed during the period covered by this study.
2. *Age continuity.* Trees in stands of similar age, separated by younger stands but not by significant vegetative or topographic firebreaks, probably originated after the same fire episode. Although fires may burn across them, large expanses of subalpine parkland, rocky ridges, and distances of more than 4–5 km were considered significant firebreaks.

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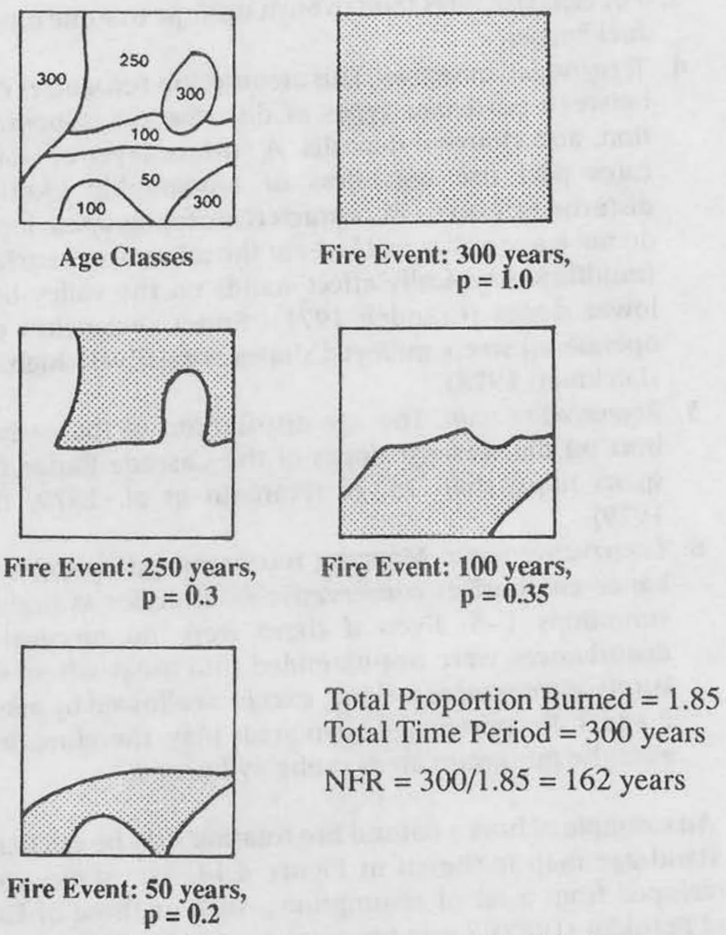
3. *Fire behavior.* Fires tend to burn upslope to some topographic or fuel barrier.
4. *Topographic consistency.* This assumption recognizes correlations between particular types of disturbances, topographic location, and charcoal deposits. A surface layer of charcoal indicates past fire regardless of topographic location. Other disturbances occur in characteristic topographic locations and do not leave a charcoal layer at the mineral soil surface. Lahars (mudflows) typically affect stands on the valley bottom and lower slopes (Crandell 1971). Snow avalanches commonly operate on steep, gulleyed slopes at relatively high elevations (Luckman 1978).
5. *Regeneration span.* The age distribution of the early seral cohort on the western slopes of the Cascade Range frequently spans more than 75 yr (Franklin et al. 1979, Hemstrom 1979).
6. *Conservative limits.* Mapping reconstructed episodes of disturbance emphasizes conservative boundaries as limited by assumptions 1–5. Even if there were no physical barriers, disturbances were not extended into areas where indicative survivor trees were lacking, except as allowed by assumptions 2 and 3. Reconstructed burn areas may, therefore, be considered the minimum areas probably burned.

An example of how a natural fire rotation may be calculated from a stand-age map is shown in Figure 4.14. The stand-age map is developed from a set of assumptions, such as those of Hemstrom and Franklin (1982), using fire scars, stand ages, and an interpretation of fire barriers. On smaller areas, the broad kinds of fire barriers used in these studies may not be present. In southwestern Oregon, natural fire rotations were calculated on a 200 ha area by using tree age and fire scar evidence to establish disturbance points, and then by drawing circles of 250 m radius around each point and connecting areas of closely spaced circles (Fig. 4.15; Agee 1991). In their advice to refrain from "storytelling" Johnson and Van Wagner (1985) are partly criticizing the potential bias introduced by this type of reconstruction. Objective techniques perhaps biased in unknown ways due to lack of point evidence of fire can result in biased natural fire rotations. The erasure of earlier fire evidence by later



Age Classes

Fire Event: 300 years, p = 1.0

Fire Event: 250 years, p = 0.3

Fire Event: 100 years, p = 0.35

Fire Event: 50 years, p = 0.2

Total Proportion Burned = 1.85
Total Time Period = 300 years

NFR = 300/1.85 = 162 years

FIG. 4.14. *Example of a natural fire rotation (NFR) calculation.*

fires results in limited records of early periods, and perhaps longer natural fire rotations.

Variation in natural fire rotation for a specific area can be defined in several ways. Hemstrom and Franklin (1982) divided their long temporal period into three segments: a modern fire suppression era (NFR = 2,583 yr), a settlement period (NFR = 226 yr), and a 650 yr presettlement era (NFR = 465 yr). At Desolation Peak in the North Cascades, natural fire rotations were calculated by century, by aspect, and by community type (Agee et al. 1990), addressing Heinselman's suggestion to more specifically interpret the natural fire

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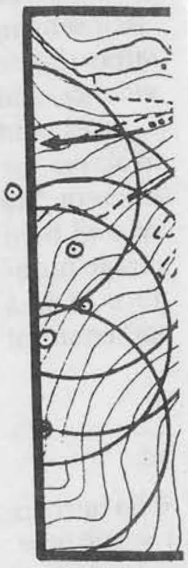

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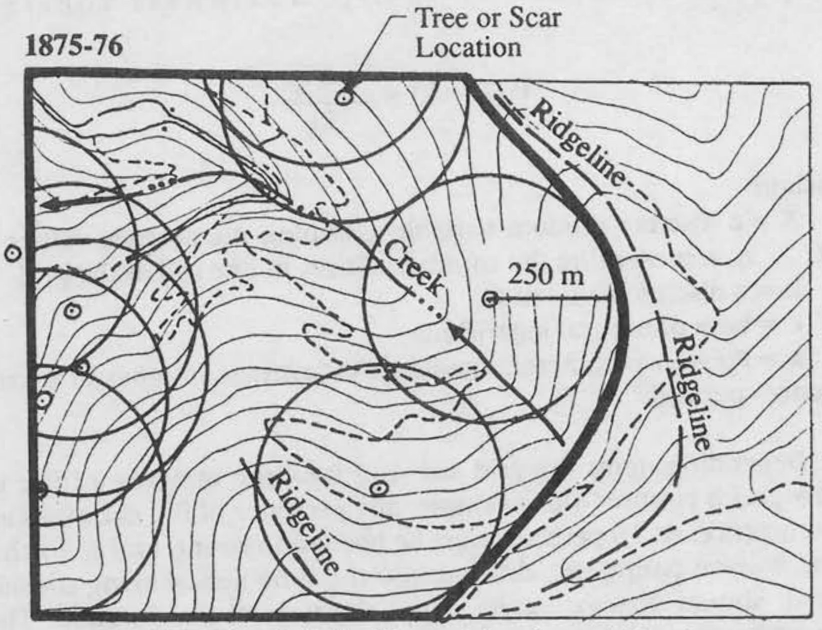


FIG. 4.15. *Reconstruction of individual fire events based on multiple point evidence of fire (fire scar or age class). In this case, circles of 250 m radius were drawn around each point at each time period. For 1875–76, shown here, roughly two-thirds of the area is included in the reconstructed burn.*
(From J. K. Agee, "Fire History along an Elevational Gradient in the Siskiyou Mountains, Oregon," Northwest Science 65 [1991]: 197. Copyright 1991 by Washington State University Press, Pullman. All rights reserved. Reprinted by permission of the publisher.)

rotation. Variation in fire severity was presented by Morrison and Swanson (1990) and Teensma (1987), who calculated separate natural fire rotations for fires of low to moderate and high severity in the central Oregon Cascades.

A mathematical method of addressing the variability in natural fire rotation over the whole area is outlined by Sugita (S. Sugita, University of Minnesota, personal communication, 1992). Sugita divided the Boundary Waters Canoe Area into 131 grids, each about 7 km on a side. He counted the number of fire occurrences in each grid over 362 years from Heinselman (1973). He then assumed that the distribution of fire frequencies (from none in some grids to eight in others) followed a Poisson distribution:

$$P\ (X = k) = \frac{e^{-a}\ a^{k}}{k!}$$

where

X = a discrete random variable assuming the possible values 0, 1, . . . n, representing the number of fires in one cell of the grid

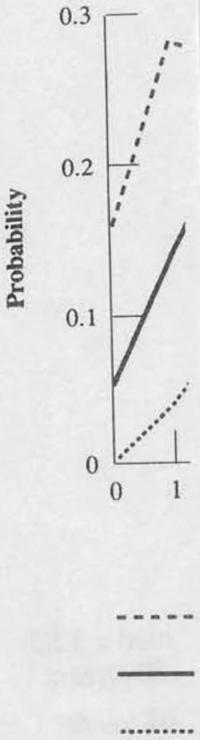
k = a discrete value of X

e = base of natural logarithms

a = Poisson parameter, estimated by average number of occurrences per cell.

Depending upon the grid size and how the presence of fire in any grid is counted (for example, any presence of fire counts as an occurrence, or 10 percent must be burned to count, and so forth), the Poisson parameter, divided into the time period being considered, should approximately equal the natural fire rotation. The two figures will not be exactly equal because of the transformation of a continuous area into a discrete grid. With the assumption that the fire frequency approximates a Poisson distribution, the probability of 0, 1, 2, ... n fires (Fig. 4.16), and associated natural fire rotations, in the period of interest can be calculated. For the Boundary Waters Canoe Area, Sugita found a = 3.0922, or a natural fire rotation of 117 yr, comparable to Heinselman's estimate of 100 yr for the same time period. The actual distribution of fire frequencies did not significantly differ from a Poisson distribution (Kolmogorov-Smirnov test). The variability of frequency over the landscape is apparent from such an analysis: Some areas burn repeatedly and others not at all. Inspection of the grid map will indicate the spatial distribution of this variability.

A similar analysis was applied to the Mount Rainier data of Hemstrom and Franklin (1982). Their natural fire rotation for the forested portion of the park for the entire time period was 405 yr. The average number of occurrences that burned more than 20 percent of a cell within a grid size approximately 1,700 m on a side (2.9 km^2) resulted in a = 1.9209, equivalent to a natural fire rotation of 420 yr. Compared to the Boundary Waters Canoe Area, there is higher probability of no fires within any cell and lower probability of multiple fires (Fig. 4.16). The observed distribution of fire frequency



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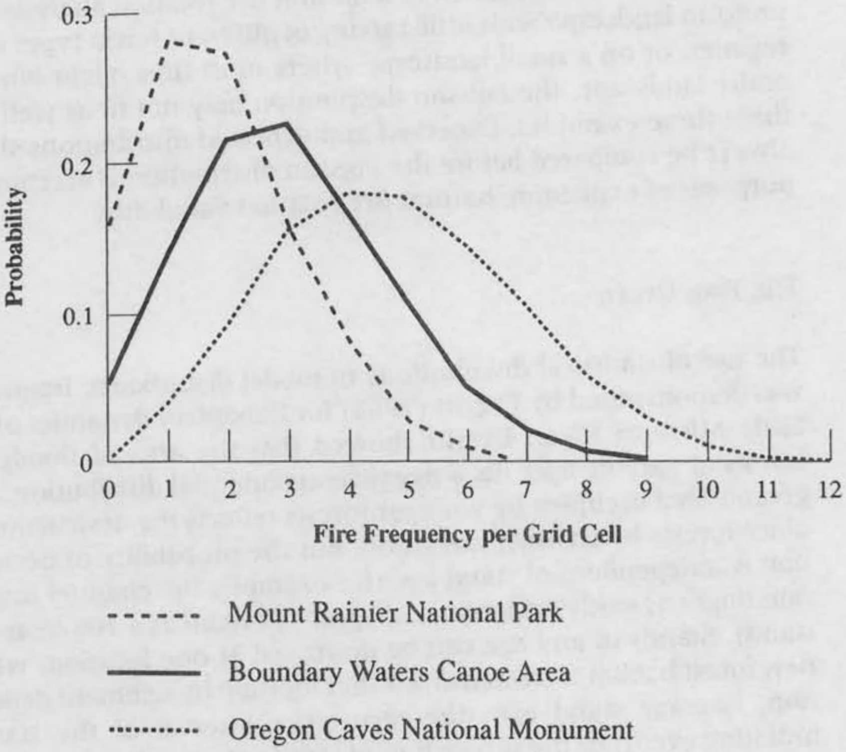

FIG. 4.16. *The Poisson distribution for fire presence in landscape grids for three natural fire rotations: Mount Rainier, Boundary Waters Canoe Area, and Oregon Caves. The cell size is different for each example shown.*

at Mount Rainier was also not significantly different from a Poisson distribution (Kolmogorov-Smirnov test). A third comparison was made with data from Oregon Caves National Monument (Agee 1991), a small preserve (200 ha) with a natural fire rotation of 73 yr since 1650. A grid size of 0.67 ha was used, and presence of any fire in the grid was counted as an occurrence. The Poisson parameter was calculated as 4.954, equivalent to a natural fire rotation of 69 yr, and the observed and expected distributions, as in the other comparisons, did not significantly differ from one another. On an area this small, the fit of a Poisson distribution is remarkable because of the expectation that in such a small area every fire would burn much or all of the area.

This technique may be quite useful in explaining the variability across landscapes subjected to a natural fire rotation analysis. On a uniform landscape with little mixing of different forest types or fire regimes, or on a small landscape where most fires might burn the entire landscape, the Poisson distribution may not fit as well as in these three examples. Observed and expected distributions should always be compared before the Poisson distribution is accepted for purposes of explaining natural fire rotation variability.

THE FIRE CYCLE

The use of statistical distributions to model disturbance frequency was demonstrated by Everitt (1968) for floodplain dynamics of the Little Missouri River. Everitt showed that the area of floodplain forests of varying ages fits a negative exponential distribution. The greater area occupied by younger forests reflects the destruction of older forests by channel migration, but the probability of destruction is independent of stand age (for example, the channel migration might as easily undercut a 25-year-old stand as a 100-year-old stand). Stands of any age can be destroyed at one location, while new forest habitat is created at another location by sediment deposition. Average stand age (the recurrence interval of the stand-initiating event) or the proportion of stands greater than any specified age can be calculated once the shape of the curve is known. The use of this same statistical distribution to model fire disturbances was proposed by Van Wagner (1978). Its major advantage is reliance on present age classes across the landscape; reconstruction of all past fire events is not necessary. If the present age-class mosaic is not steady-state, however, significant bias may appear in a fire cycle calculation based on age structure at one point in time (Baker 1989).

Van Wagner's idealized scenario assumes a simple forest on a uniform site, composed of many equal-sized stands, all of equal flammability regardless of age. Climate is uniform, such that lightning, over the study period, causes an equal number of fires per year at random, and each fire burns only one stand. The frequency of an age-class x then follows a geometric distribution. If p is the probability of a fire in any single year, and the fire cycle exceeds about 20

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yr, so that $p < 0.05$, then the distribution can be approximated by the negative exponential distribution:

$$f(x) = pe^{-px}$$

where

$f(x)$ = frequency of an age class
e = base of natural logarithms
p = probability of fire in any one year.

The negative exponential distribution has several convenient properties. The mean age of all stands, or the fire cycle (C), is equal to $1/p$. The median age is 0.693 C. The cumulative proportion of all stands up to age x is

$$\Sigma f(x) = 1 - e^{-px}$$

This expression approaches 1 as x approaches infinity. The probability of a stand burning n times during one cycle is $e^{-1}/n!$, and the probability of survival throughout a rotation is e^{-1}, or 36.8 percent.

The negative exponential distribution is best applied to large areas composed of many stands (Fig. 4.17), such that only a small proportion of the area is likely to burn at any one time. Johnson and Van Wagner (1985) and Baker (1989) note that the study area must be large relative to the size of the largest expected fire event. Hemstrom and Franklin (1982) found the method inapplicable to individual watersheds at Mount Rainier that were less than 4,000 ha in size, although it produced reasonable results for the entire park (53,000 ha). A regional forest-type application by Fahnestock and Agee (1983), using the cumulative form of the distribution and dealing with areas greater than 50,000 ha, again appeared to produce reasonable results. Van Wagner (1978) noted that the model is fairly robust against departures from admittedly narrow constraints. The assumption most open to question is that of uniform flammability with age. Without much other than empirical observations, some researchers believe that older forests are more flammable than younger forests, but objective evidence is hard to find (Van

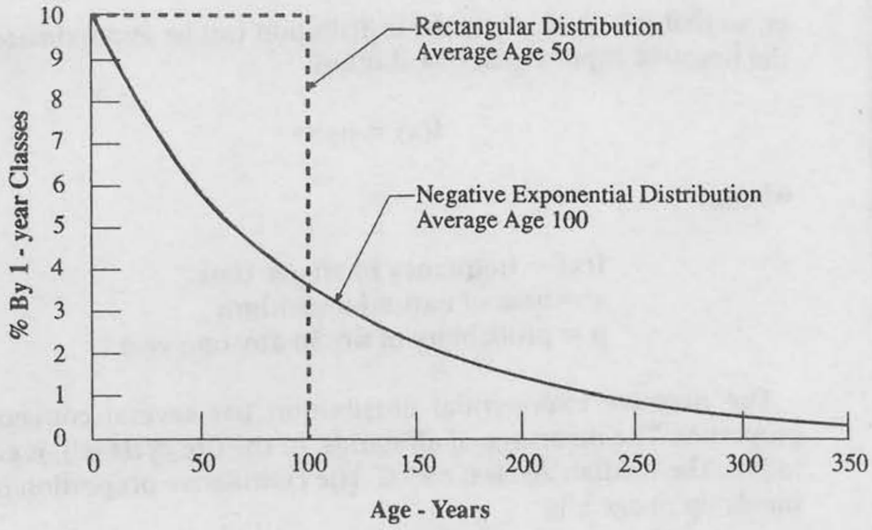

FIG. 4.17. *Comparison of two age-class distributions: the negative exponential, with average age 100, and a balanced rectangular age distribution, with average age 50.* (From Van Wagner 1978)

Wagner 1978). In Douglas-fir forest burned with crown scorch intensity, the youngest forests had the highest potential surface fire behavior, with a pronounced dip in mid-succession and an increase in late succession (Agee and Huff 1987). Given the variability from stand to stand, the assumption of equal flammability may not be terribly flawed.

The negative exponential method was applied to the Boundary Waters Canoe Area data of Heinselman (1973). Although the natural fire rotation method of reconstructed fire events resulted in a fire rotation of 100 yr, the fire cycle calculated from present stand ages was 50 yr. Van Wagner (1978) suggested that since the negative exponential distribution did not rely on event reconstruction but on Heinselman's more precise age-class maps, it produced an estimate closer to reality. Heinselman (1973) noted at the time that his estimates were conservative, and he later agreed (Heinselman 1981) that the negative exponential calculations from his data appeared to better describe fire frequency in the Boundary Waters Canoe Area. Another analysis of the same data (Baker 1989) suggested that the area could be divided into three fire regions, and that the negative exponential model appeared inappropriate to describe

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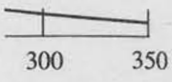

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any of the three. The negative exponential distribution, applied to the Mount Rainier data, produced a fire cycle of 306 yr, considerably less than the natural fire rotation method, but with a poor goodness-of-fit, generally <0.60 (Hemstrom 1979).

The negative exponential model, with a constant flammability regardless of age, is in fact a special case of a more flexible but less easily calculated model, the Weibull distribution. The Weibull requires a similar set of assumptions to the negative exponential but its shape parameter, c (equivalent to flammability), can vary (Johnson and Van Wagner 1985). The Weibull distribution can be expressed either as a fire interval distribution (Fig. 4.18A) or as a time-since-fire distribution (Fig. 4.18B). The cumulative fire interval distribution is:

$$F(t) = 1 - \exp[-(t/b)^c]$$

where

b = a scaling parameter (annual percent burned, with 1/b the fire cycle)

exp = e (base of natural logarithms)

c = shape parameter (>0) interpreted as a flammability index for fire studies (c < 1: decreasing flammability with age; c = 1: equal flammability with age; c > 1: increasing flammability with age).

In the southern Canadian Rockies, Johnson and Larsen (1991) used the time-since-fire distribution to partition two time components of a 380 yr fire record. The fire cycle (C), or 1/b, was calculated from the Weibull distribution for the periods 1600–1730 (C = 60 yr), and 1730–1980 (C = 90 yr). The time periods were separated on the basis of a graphical method to determine the break in slope when data on stand age were plotted on semilog paper (Fig. 4.19). This graphical technique should be cautiously applied, because omitted from the real data is the theoretical tail of the curve, so that semilog plots will appear to descend with increasingly negative slope over the range of age classes (M. Finney, in prep.).

The probability-density fire interval function is the frequency or probability of having fires with intervals of age t:

$$f(t) = [ct^{c-1}/b^c]\exp[-(t/b)^c]$$

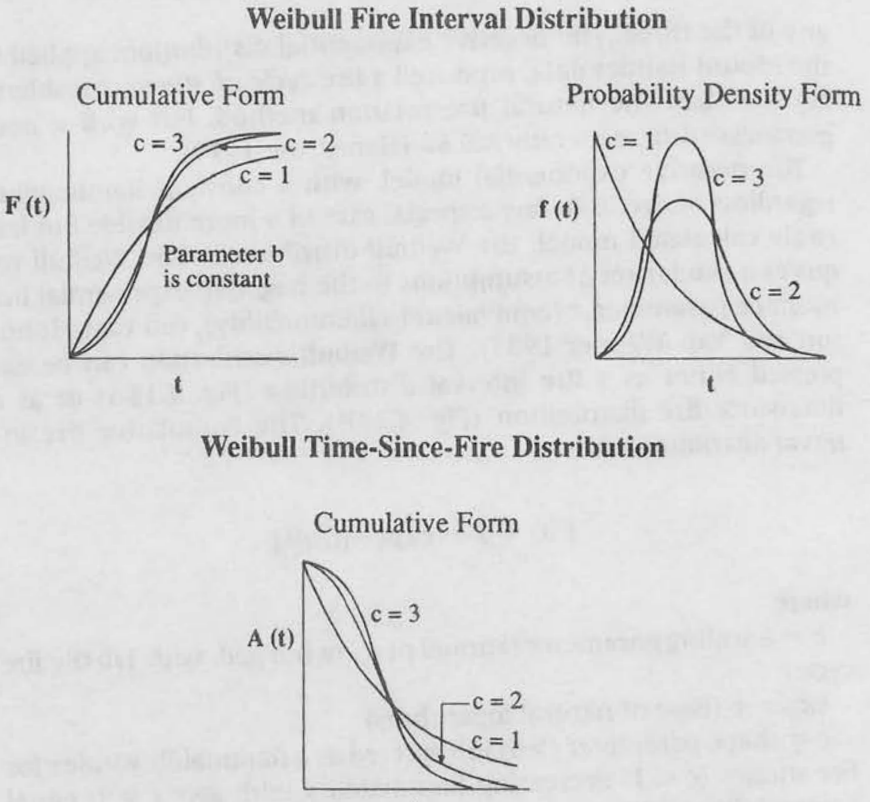

FIG. 4.18. *The different distributions for the Weibull fire history model. Graphs show distributions with different shape parameter* (*c*) *settings and constant fire recurrence or scale parameter* (*b*).
(From Johnson and Van Wagner 1985)

Note that when $c = 1$ and $1/b = p$, the equation reduces to the probability density function of the negative exponential distribution. Johnson (1979) applied this form of the Weibull model to fire recurrence in the subarctic. He collected data in several recently burned stands and observed directly the fire interval data. Although the Weibull function can be used on point frequency data, describing fire recurrence at a point, it is also used to describe fire frequency on an area basis, combining fire recurrence data over many stands.

The cumulative time-since-fire distribution is:

$$A(t) = 1 - F(t) = \exp[-(t/b)^c]$$

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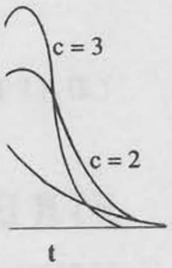

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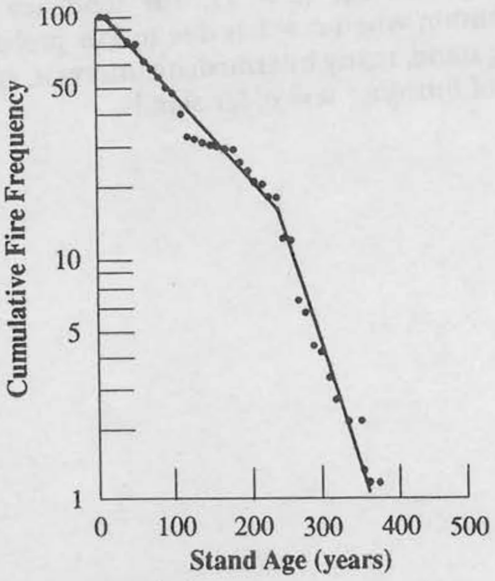

FIG. 4.19. *A mixed time-since-fire distribution from the southern Canadian Rockies. The dots represent 10 yr age classes. Once segregated, the data are individually rescaled to 100, and separate estimates of fire cycles are then calculated.*
(From E. A. Johnson and C.P.S. Larsen, "Climatically Induced Change in Fire Frequency in the Southern Canadian Rockies," Ecology 72 [1991]: 194–201. Copyright 1991 by Ecological Society of America. Reprinted by permission.)

In this equation, Johnson and Van Wagner (1985) note that t is interpreted not as a fire interval but as the time that has passed since the last fire, the "running time." Age-class distributions can be calculated from A(t) when it is multiplied by another factor (see Johnson and Van Wagner 1985 for details).

The negative exponential model is essentially a random selection model, which burns equal numbers of stands chosen randomly from all stand ages. The greater number of younger stands (Fig. 4.17) is due to the annual depletion across all cohorts, which then begin as new stands. The tail of the distribution, composed of old stands, exists because of chance, not because of decreased flammability with age. The Weibull model is an age-selection model, ranging from decreasing flammability with age ($c < 1$), to no selection ($c = 1$; the negative exponential) to increasing flammability with age ($c > 1$). The tendency toward a bell-shaped distribution when $c > 1$ is due to low probability of selection of a young stand, many intermediate intervals, and (due to high probability of burning) few older stands.

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