Recent tree invasion into a range environment near Butte, Montana
by Lara Margaret Dando

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
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A combination of reduced numbers of grazing, livestock, increased spring, precipitation following drought, and the lack of periodic fires appear to have occurred prior to or simultaneous with the changes: in. the distribution of the local vegetation. It is suggested, that this; combination may have influenced tree invasion.

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APPROVAL

of a thesis submitted by

Lara Margaret Dando

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English, usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Near Butte, Montana, Douglas-fir and Rocky Mountain juniper have invaded into the rangeland ecosystem due to alterations in the natural environment. Approximately 320 hectares of the narrow transition zone below the forest border have been invaded. Similarities between the timing of natural and human impact changes and forest distribution changes were determined by examining tree-age data collected at the study site.

A combination of reduced numbers of grazing livestock, increased spring precipitation following drought, and the lack of periodic fires appear to have occurred prior to or simultaneous with the changes in the distribution of the local vegetation. It is suggested that this combination may have influenced tree invasion.

INTRODUCTION

The Problem

There has been an observable change in the biogeography of the lower forest-grassland ecotone near Butte, Montana. Areas bordering older forests, once predominately occupied by shrubs, forbs, and grasses, have been invaded by trees. An apparent alteration has occurred in the natural conditions controlling the stability of the lower forest-grassland ecotone, allowing Douglas-fir (*Pseudotsuga menziesii*) and Rocky Mountain juniper (*Juniperus scopulorum*) to invade portions of the rangeland ecosystem (Figure 1). Numerous trees, relatively short in height and narrow in form, are scattered in various densities across the shrub-grassland landscape. The area also has a unique and environmentally important location, situated between the two nineteenth century mining settlements of Butte and Anaconda.

Recent alterations in the environmental dynamics of the area have resulted in spatial changes of the sensitive transition zone between the forest and grassland ecosystems. These changes have also affected the entire regional environment. The dominance of trees in place of grasses or forbs have caused a loss of agricultural or livestock grazing land due to a decline in forage production, similar to that found by Cottam and Stewart (1940) and Burkhardt and Tisdale (1976). Tree invasion could also increase the potential for crown fires (Arno 1980), alter the biodiversity of the area, and/or encourage the spread of tree diseases.

Figure 1. Tree invasion into a rangeland ecosystem in southwestern Montana.

An area may benefit by the establishment of trees; by possibly creating environments more conducive to wildlife, or by stabilizing the soil in a disturbed area prone to wind or water erosion as found by Millones O (1982).

Vegetation, being unable to migrate rapidly, is continually subjected to the influence of the physical environment, the biotic community, and disturbance events (Vale 1982). Physical environmental parameters to which vegetation is exposed include climate, topography, water availability, and soil and geologic conditions. The biotic community stimulates competition between vegetal types, it provides soil nutrition, and it may locally influence microclimates. Disturbance events affecting vegetation can include those which are natural, such as fires and droughts, and those which are human-induced, such as air pollution, set burning, livestock grazing, and logging. These events or alterations in the environment can make available new resources and habitats and can induce short- or long-term alterations in species composition, depending upon the duration of the disturbance and its intensity (Vale 1982).

Disturbances, natural- or human-induced, may create either opportunities or stress in plant communities and in individual plants. The physiological impact of an environmental stress imposed on one part of a plant often not only affects that particular part, but affects the entire plant as well (Kozlowski 1979). Generally, when a plant is stressed, it responds by slowing down or halting some of its physiologic processes, such as its growth rate, reproductive rate, and/or photosynthetic rate (Treshow 1970; Boyer 1973; Kozlowski 1979). An individual plant's response depends upon the type and duration of the event and the plant's condition when the disturbance occurred.

Objectives of Study

There were three major objectives in this study. The first objective was to determine the geographic extent or amount of area affected by recent tree invasion. Because of all the seedlings and saplings visible throughout the study area, it was suspected that the invasion covered many hectares and had affected a substantial portion of the ecotone. The second objective was to calculate the timing of the invasion(s). It was suspected that there were fluctuating intensities of invasion over time. The final objective was to test the possible effect or probability that certain events caused the invasion. A combination of causal agents, both human and natural in origin, were suspected to have disrupted natural conditions in the study area, creating an environment suitable for tree establishment. Some of the results of this study have been reported previously in Dando and Hansen (1990).

Previous Studies

There have been numerous studies investigating the response of local vegetation to environmental changes. In particular, many researchers have focused on woody plant (trees in particular) invasion into shrub or grasslands. The reduction of grass and forb cover by livestock grazing has been frequently described as an important precursor for the invasion of trees into a shrub-grassland environment (Johnsen 1962; Blackburn and Tueller 1970; Vale 1981; Madany and West 1983; Butler 1986; Taylor 1990). Grazers remove competing vegetation, and as grazing intensifies, a decrease in the total number of plants covering the soil surface may result. Animal hooves compact, scuff, or break up the soil creating new seedbeds or may cause physical damage to the vegetation (Vale 1982). Livestock are also selective feeders (Moore et al. 1979) and as grazing intensifies, the preferred species decrease while the less preferred flourish and dominate. If grazing is heavy and occurs at a critical or stressful period in the plant's growth cycle, plant vigor and reproduction can be retarded. Moreover, the decrease in leaf area due to grazing could prevent root growth and energy assimilation. Light to moderate grazing, on the other hand, can increase some species' vegetative reproduction by encouraging tillering (Vale 1982).

Livestock may also affect soil moisture regimes. Heavy grazing can significantly decrease infiltration rates by increasing soil compaction (Moore et al. 1979; Vale 1982). The reduction of understory vegetation via grazing in forested areas can result in increases in evaporation rates and soil temperatures, and a decrease in soil moisture (Whitman and Wolters 1967).

Fir seedlings' growth rates were found by Hedrick and Keniston (1966) to increase when land was cleared of trees and then grazed by sheep for a short period. Grazing eliminated enough understory competitors to enable tree seedlings to acquire adequate nutrition and sunlight for better growth (Hedrick and Keniston 1966). Rummell (1951) found that at one site, in the absence of grazing (and fire), the amount of litter and vegetation on the ground was very high, inhibiting tree seedling establishment. In contrast, at a second site, heavy grazing was found to reduce the amount of understory vegetation and litter (and to some extent, fire) resulting in tree seedling invasion (Rummell 1951). Madany and West (1983) also found that the combination of grazing and fire suppression led to a successful development of tree stands. Where grazing had been heavy, and fires few, understory vegetation was decreased and tree invasion occurred. On non-grazed sites, where understory vegetation was dense enough to prevent seedling roots from reaching the soil, tree establishment was minimal. Understory vegetation in the non-grazed sites also appeared to out-compete tree seedlings for nutrients and soil moisture (Madany and West 1983). Barney and Frischknecht (1974) concluded that after a fire, heavy grazing by domestic animals can have a great impact on the recovery of an area by reducing the vigor and cover of perennial grasses thereby encouraging the invasion of sagebrush and other shrubby plant species. The livestock may even have aided in the establishment of Utah juniper (Juniperus osteosperma) by trampling the seeds and "planting" them into the soil (Barney and Frischknecht 1974).

A region's climatic regime is often cited in the literature as having considerable influence on tree invasion. Freezing temperatures, for example, when a tree is inadequately cold-hardened, kill shoots, injure the cambium tissue causing lesions and cankers, and can kill the roots or the entire plant (Treshow 1970; Kozlowski 1979). At the other extreme, high temperature stress, occurring when temperatures reach the 45° to 60°C range, can cause stem lesions and bark desiccation (Kozlowski 1979). Adequate moisture conditions are also very important to the establishment and survival of any plant species. Water is required for virtually every aspect of life processes and every chemical reaction. As the amount of water available decreases, the plant could undergo physiological stress, limiting its metabolism, growth, and reproduction (Treshow 1970; Boyer 1973; Kozlowski 1979). Depending upon the specific environmental conditions, periods of tree invasion have been noted to occur in response to a variety of precipitation amounts and periods. Tree invasion along the lower forest border has occurred either during or after periods of above normal spring precipitation (Sindelar 1971). In contrast, a combination of below and above normal precipitation levels has also been associated with tree establishment (Burkhardt and Tisdale 1976; Vale 1981; Taylor 1990). For example, Vale (1981) found understory vegetation vigor decreased when precipitation decreased. This then facilitated tree establishment once precipitation levels increased in the less competitive environment (Vale 1981).

Fire has frequently been cited as playing a role in tree invasion since it can greatly affect the natural chemical and physiological makeup of an environment. Soil properties such as infiltration rates and erosion potential may be altered. There also can be changes in the composition of plant and animal species (Vale 1982). Barney and Frischknecht (1974) demonstrated that fire had the following impacts on the local vegetation: (1) crown cover, basal area, and number of conifers increased with the age of the burn; (2) trees did not rapidly establish after a fire (as evidenced by the absence of trees in the most recent burns); (3) the amount of sagebrush and perennial grasses decreased with time since the burn; and (4) ground litter was lowest on the most recent and the oldest burns.

The absence of fires has been shown to enable various conifers that were once confined to rocky, non-burnable areas, to invade into less rocky areas (Sindelar 1971; Arno and Gruell 1983). Burkhardt and Tisdale's (1976) research in Idaho also showed that the invasion of western juniper (Juniperus occidentalis) into the sagebrush environment was strongly related to the suppression of fires. Vale's 1977 research in the Warner Mountains of California revealed similar results: the establishment of certain trees coincided with the suppression of fire and intensive livestock use.

Tree invasion into grassland ecosystems has also been referred to as being a relatively new phenomenon in southwestern Montana. Bakeman and Nimlos (1985) concluded after analyzing the development of mollisols under fir trees, that little vegetative change has occurred within the past three hundred years. However, due to reduction of fuels by grazing, coupled with fire suppression, tree seedlings and saplings have been encouraged to establish within the older forest as well as in the rangeland (Bakeman and Nimlos 1985).

The impact of multiple disturbance events on the establishment of plant species has been investigated by many scientists. Research conducted by Blackburn and Tueller (1970), Sindelar (1971), Vale (1981), and Taylor (1990) revealed that the combination of grazing, fire suppression, and a change in microclimate disturbed the environment enough for tree invasion to occur in each of their respective study areas. In east-central Nevada, Blackburn and Tueller (1970) discovered a strong relationship between the invasion of pinyon pine (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*) and periods of overgrazing, fire suppression, and fluctuating precipitation regimes. In southwestern Montana, Sindelar (1971) found that Douglas-fir invasion was caused by a decline in the number of grazing livestock coinciding with periods of heavy spring precipitation. The absence of fire in the area allowed the trees to persist.

Two periods of tree invasion in the Cascade Mountains of central and southern Oregon (Vale 1981) appear to have been affected by a combination of the removal of sheep (then grazed by cattle or not at all) and changes in precipitation (one change was characterized by above normal precipitation and near normal spring temperatures, and the second, a sequence of dry conditions followed by moist conditions). The absence of fire also contributed, but to a lesser degree (Vale 1981).

Taylor (1990) found invasion periods in California's Lassen Volcanic National Park was also related to combined variations in the local climate, grazing intensities, and fire history. Most trees established once grazing was reduced or stopped, as well as when precipitation levels were above normal. Again, the suppression of fires were found to have allowed seedlings and saplings to survive (Taylor 1990).

Few studies have related air pollution as a causal factor in tree invasion. It has been documented, however, that vegetation in close proximity to or within urban areas may be subjected to various types of air pollution, sufficient in quantity or quality to cause physiological stress and/or death (Kozlowski 1979). The potential impact that air pollution has on the vegetation is dependent upon levels of pollutants and type of vegetation. Low levels of pollutants may not have significant effect upon the plants. Intermediate amounts, however, can interfere with the plant's physiology, reducing reproduction and growth rates and increasing vulnerability to insect or disease attacks. High levels of pollutants, depending upon the tolerance of the species, could cause increased mortality rates and a change in the local vegetation composition and structure (Vale 1982). Resistance to pollution may involve the plant's ability to prevent the uptake of pollutants, a rapid incorporation of pollutants into less toxic products, or a biochemical resistance (Kozlowski 1979). The impact of air pollution on an ecosystem depends largely on the damage done to the dominant species. Materna (1984) found that if the dominant species are very sensitive, their death and decay may result in space being available for establishment of other, more tolerant plant species. An example of this is the destruction of montane spruce (Picea sp.) forests which can be replaced by birch (Betula sp.) and ash (Sorbus sp.) trees, after a disturbance (Materna 1984).

Fluoride, a byproduct of elemental phosphorus production, is an example of an air pollutant found harmful to the environment (Treshow 1970; Carlson and Dewey 1971). Such a pollutant is being produced at a plant just south of the study area. Fluoride enters a plant primarily through the stomata of the needles and leaves. Once inside the foliar tissue, the fluoride is in a soluble state where it can accumulate at the tips of conifer needles or leaf margins, causing tip or margin necrosis (Treshow 1970; Carlson and Dewey 1971). A reduction in growth, reproduction, and photosynthesis rates may occur with continued exposure, especially during the plant's growing season, and death may follow (National Research Council 1971).

Some examples of fluoride-tolerant or resistant plant species found within this project's study area, similar to those listed by the National Research Council (1971), include junipers (Juniperus spp.), alfalfa (Medicago sp.), currants (Ribes spp.), and willows (Salix spp.). Asters (Aster spp.), aspens (Populus spp.), and some grasses are moderately tolerant, while Douglas-fir is considered susceptible to fluoride (National Research Council 1971).

Study Area

Geography

The study site is situated approximately six kilometers west of Butte and 16 km southeast of Anaconda, Montana (Figure 2). The Deer

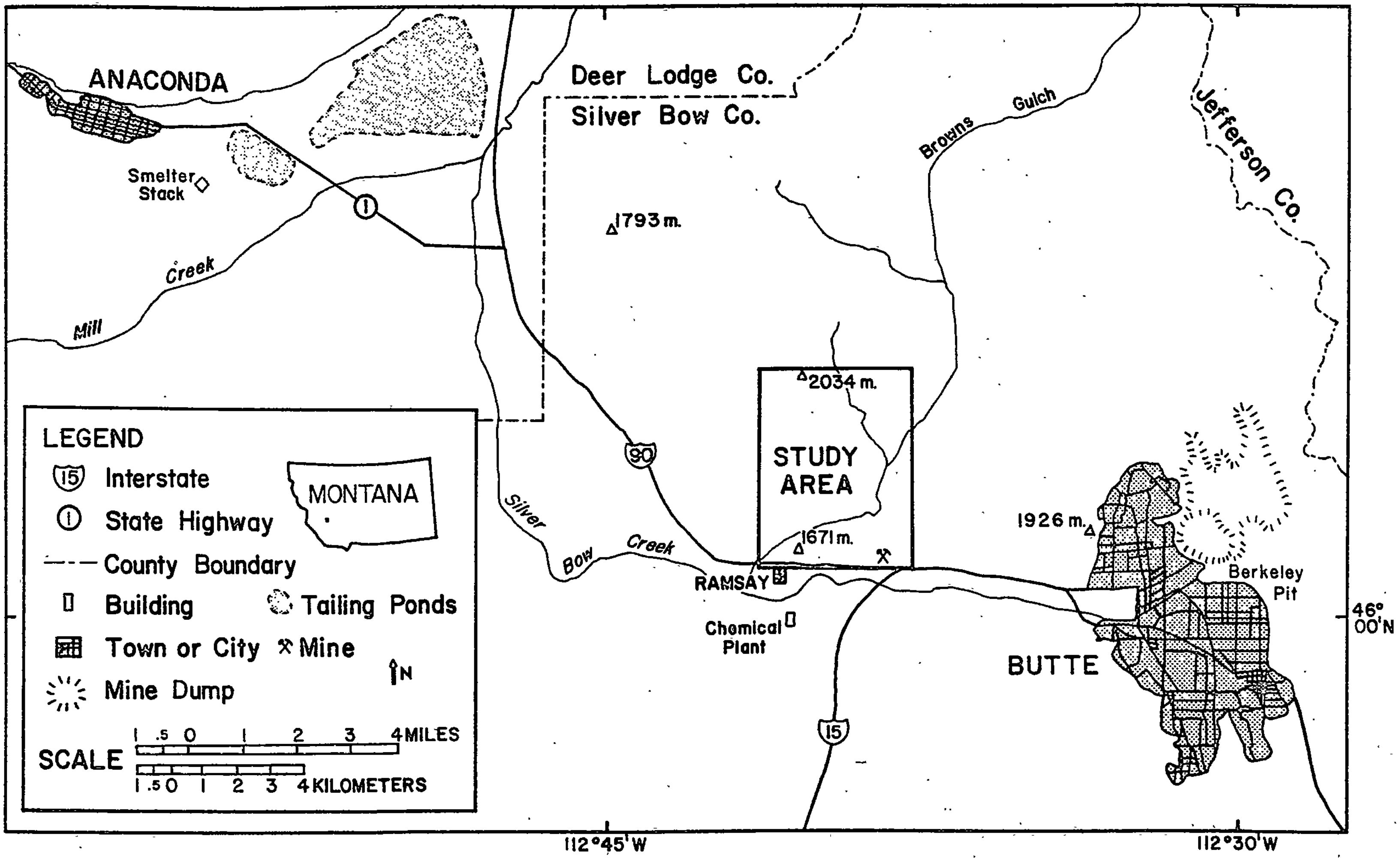

Figure 2. Location of study area in southwestern Montana (Base from U.S.D.A. (Forest Service). 1988. <u>Deerlodge National Forest: Forest Visitor/Travel Map</u>. Washington, D.C.: U.S. Government Printing Office).

Lodge Valley is to the northwest, and to the south, Interstate 90. Encompassing nearly 18 km^2 of private land in Silver Bow County, the study area's boundaries were defined primarily by either ownership accessibility (northern and western boundaries) or by the absence of older forest stands (eastern and southern boundaries). The study area is bounded to the north by mountains with dense forests of predominately Douglas-fir and Rocky Mountain juniper. The undulating plains adjacent to the eastern and southern margins are composed of a combination of cultivated land, shrubs, forbs, and grasses. This rangeland does contain some widely scattered Douglas-fir and Rocky Mountain juniper seedlings and saplings, but to a lesser degree than within the study area. The landscape bordering to the west, an area similar to the study site, is characterized by a predominance of shrubs, forbs, grasses, and invading Douglas-fir and Rocky Mountain juniper.

Elevation ranges between 2034 m in the northwest portion of the study area to 1630 m in the southwest. A series of low mountains and rolling hills dominates (approximately 75 percent) the northern and western portions, while the southern and eastern portions have relatively low local relief. Nine locations throughout the study area were selected for intensive study. Site specific variations in location, aspect, slope, etc. existed within each sampling site or transect (Table 1).

Geology

The study area is composed predominately of Tertiary porphyritic rhyodacites, common rocks found in the northern and western mountainous regions. This unit is composed of plagioclase, biotite, hornblende,

Table 1. Site characteristics for each transect.

Transect	Location	Site Characteristics Aspect	Slope	Length (m)	Area (ha)
1.	SW 1/4 of Section 6, T3N R8W	168°	13°	90	90
2.	SE 1/4 of Section 36, T4N R9W	40°	10°	180	180
3.	NW 1/4 of Section 18, T3N R8W	306°	14°	260	260
4.	NW 1/4 of Section 1, T3N R9W	183°	16°	80	80
5.	NE 1/4 of Section 11, T3N R9W	240°	13°	190	190
6.	NE 1/4 of Section 1, T3N R9W	290°	12°	190	190
7.	SW 1/4 of Section 7, T3N R8W	145°	14°	190	190
8.	NE 1/4 of Section 2, T3N R9W	190°	8°	*	*
9.	NW 1/4 of Section 6, T3N R8W	80°	6°	50	50

* Not measured

quartz, and pyroxene phenocrysts. Thickness of this unit varies, between 90 and 300 m. The plains consist of a mixture of alluvial and fluvial materials deposited in the early Quaternary Period. The alluvial deposits are unconsolidated, stratified, and poorly sorted. Fluvial deposits are also unconsolidated and stratified, light-gray to light-brown, and are possible remnants of a former alluvial plain. Deposits of sandstone and siltstone are found in the southeastern portion of the study area. Underlying the region and exposed in the southeast is the Boulder batholith. It is composed predominately of Cretaceous Butte Quartz Monzonite with some smaller deposits of alaskite, aplite, and pegmatite. There are no faults evident within the study area itself, however, several exist to the north and northwest (Derkey and Bartholomew 1988).

Soils

Soils in the study area are quite varied. On the plains, loamy, mixed, aridic Argiborolls and Haploborolls and fine-loamy, mixed frigid Ustic Torrifluvents are the predominant soil classes found. These soils are characteristically poorly to well drained, formed in alluvium, and vary in depth (Soil Conservation Service study in progress). Little soil development has occurred on the more rugged terrain. Some areas, such as rocky outcrops, are completely devoid of soil, while others have a thin layer of coarse gravel underlain by igneous bedrock.

Climate

Winter and summer temperature ranges are extreme due in part to the study area's continental location; temperatures of +34°C and -42°C have been recorded in Butte, Montana (National Climatic Data Center 1989). Air temperatures range from an average -7.6° C in January, to 17.1° C in July, with an annual mean temperature of 4.3° C (U.S. Weather Bureau 1895-1966; Environmental Data Service 1967-76; National Climatic Center 1977-83; National Climatic Data Center 1984-89). The frost-free season is 70 days (Montagne et al. 1982).

Precipitation in nearby Butte averages 32.0 cm annually with a late spring maximum (U.S. Weather Bureau 1895-1966; Environmental Data

Service 1967-76; National Climatic Center 1977-83; National Climatic Data Center 1984-89). Most precipitation comes in the form of snow in fall, winter, and spring. Wintertime precipitation is associated primarily with migrating mid-latitude cyclones. Total snow (and sleet) accumulation averages approximately 137 cm a year (National Climatic Center 1978-83; National Climatic Data Center 1984-88). Summertime rains are often in the form of relatively short convective thunder showers. Precipitation, on average, is recorded on approximately 107 days each year. Maximum precipitation occurs in June due to the influence of northward moving maritime tropical air colliding with the prevailing westerly flow (National Climatic Data Center 1989). On the average approximately 5.7 cm of precipitation are received during June, usually occurring as intermittent showers.

At times, warm mini-chinook winds move down the east slopes of the mountains into the area, melting snow and enabling animals to graze on the exposed grass. In contrast, very cold and dry arctic air masses occasionally may flow into the region in mid-winter.

Vegetation

Vegetation in the area is composed of a mixture of rangeland grasses, forbs, shrubs, and a small variety of tree species. The dominant tree species (which are expanding the forest-grassland ecotone) are Rocky Mountain juniper and Douglas-fir.

The Rocky Mountain juniper (Juniperus scopulorum) typically develops into a tall, narrow, and rounded-crowned tree (Sudworth 1915), growing to heights of approximately 17 m (Preston 1940). This particular species has the broadest distribution of any North American western juniper. Its distribution includes the drier, lower mountains and foothills of central British Columbia and southwest Alberta, to the east side of the Continental Divide in New Mexico (Fowells 1965). It can be found in a wide range of elevations and is relatively drought resistant (Preston 1940), thriving in dry, subhumid or moist climatic regimes. Any extended period of moisture stress decreases the rate of height and trunk diameter growth (Fowells 1965). The tree is moderately tolerant to intense light (Sudworth 1915) and therefore can be found in pure open stands or in mixed forests (Fowells 1965; Burns 1983).

Rocky Mountain juniper's extensive distribution throughout the Rocky Mountains and Great Plains is the result of its relative adaptability to a variety of soil types and conditions (such as those derived from basalt, limestone, sandstone, and shale) and its effective seed distribution via birds (Kirkwood 1922) and mammals. Fowells (1965) found, however, that if the soil moisture and soil temperature regimes are not adequate, proper tree development will not occur. In general, Juniperus species have been noted to invade bordering grasslands after competing vegetation is reduced, for example by overgrazing (Emerson 1932; Johnsen 1962; Fowells 1965; Blackburn and Tueller 1970; West 1984).

The second dominant tree species found in the study site, Douglas-fir (Pseudotsuga menziesii), can also be found throughout the mountainous regions of the western United States and southwestern Canada (Porter 1964), on a variety of soil types (Fowells 1965). It may reach heights of approximately 30 m, with a crown narrow and rounded at the top (Porter 1964). Climatically, Douglas-fir is found predominately within humid or moist, subhumid regimes. This particular tree is usually associated with a variety of common forest tree species due to the fact that it is intermediately tolerant to competition from other species. Douglas-fir has also been noted to invade neighboring grasslands once previous plant inhabitants have been removed by disturbance, such as overgrazing (Hedrick and Keniston 1966; Sindelar 1971; Butler 1986).

Douglas-fir establishment is improved by partial shade and the presence of litter, assuming the litter does not prohibit seeds from reaching the soil and does not absorb most of the available moisture. Seedlings thrive better in previously established forests (having twice as fast a growth rate) and in sites which have undergone selective cutting than in an open and exposed clear-cut. Douglas-fir is more shade tolerant than Rocky Mountain juniper (Fowells 1965).

Understory vegetation in the study area includes big sagebrush (Artemisia tridentata), silver sagebrush (Artemisia cana), common yarrow (Achillea millefolium), asters (Aster spp.), Idaho fescue (Festuca idahoensis), and rabbit brush (Chrysothamnus nauseousus).

The southern, gentler sloping portion of the study area is partly under cultivation. Some crested wheat (Agropyron sp.) and ryegrass (Lolium sp.) are planted for cattle fodder, along with alfalfa (Medicago sativa) and hay. Most of the uncultivated land within the study area is to the north and west, on the steeper slopes of the surrounding mountains and hills, where the forest is most dense.

Human-Related Activities

The area in which tree invasion has occurred is located in a historic mining region. Butte, east of the study area, is underlain by rich mineral deposits and, until recently, was a center of mining activities. Butte's legacy as one of the premier metal mining camps, began in the mid-1860s when shallow placer gold deposits were found along Silver Bow Creek (Malone 1981). Eventually, the gold deposits were exhausted and the population decreased. Then in 1874, silver was discovered, and once again Butte became a thriving community. In 1882, copper mining and related activities began to dominate the landscape and have continued until recent times (Wyckoff and Lageson 1989). With the mining industry, came leaders like William A. Clark from Pennsylvania and Marcus Daly from Ireland (Malone 1981). Their contributions to the settlement and development of southwestern Montana are legendary (see Glasscock 1935; Marcosson 1957; Malone 1981). As the number of settlers increased, the demands for food, lumber, and land also increased, putting immense pressures on the physical environment.

In 1883, Marcus Daly built the town of Anaconda along Warm Springs Creek, approximately 28 km northwest of Butte, in a valley to the west of Deer Lodge Valley (northwest of study area). There, he constructed copper smelters for his Butte mines (MacMillan 1973; Malone 1981). Anaconda's "ore smelting kingdom" lasted until 1980 when the last smelter was closed and dismantled (Vine 1983). During the time smelters were active, the Butte/Anaconda area went through decades of unregulated emissions of toxic substances that were found to harm plants, animals, and humans. MacMillan noted:

> In the normally clear and bracing atmosphere the smoke stream, pouring out of the stack a thousand feet above the valley, could be seen trailing northward down the Deer Lodge Valley for thirty miles towards the town of Garrison, or often flowing eastward toward Butte, or swinging around to the south and sweeping up Mill Valley and filling the narrow ravines leading down from the Continental Divide fourteen miles away (MacMillan 1973, 120).

At least seven copper ore smelters were operating in nearby Butte and Anaconda in the early 1880s. At times, the smoke plumes were so thick that they blotted out the sun. People living in Butte, Anaconda, and the Deer Lodge Valley complained of vomiting, troubled breathing, nose bleeds, and other ailments caused by inhaling the sulphur-tainted smoke (MacMillan 1972, 1984). Mortality rates were high not only for mine workers, but for the rest of the populace as well. The local vegetation and livestock were also thought to have been injured and/or killed by the emissions from the smelters (MacMillan 1973).

Haywood (1907, 1908) studying the impact of sulphur dioxide upon the local vegetation, found that although the damage decreased with increased distance from the smelter, sulphur dioxide damaged the forests as far away as 32 km north, 13 km south, 24 km west, and an indefinite distance east of the smelter in Anaconda. In 1908, Swain and Harkins sampled the vegetation in the Deer Lodge Valley and surrounding areas for arsenic and copper after it was discovered that local livestock became ill or died shortly after a new smelter was constructed. Their results indicated that the smelter smoke was transporting toxic metals into the area, and these metals were then accumulating in the tissues of local vegetation (Swain and Harkins 1908). As might be expected, concentrations of trace elements such as arsenic, cadmium, lead, copper, and zinc were found to decrease away from the smelter stack. The topography and prevailing wind patterns were thought to have influenced concentration levels (Tetra Tech 1987). In a study carried out by the Air Quality Bureau (Raisch et al. 1979) in Deer Lodge and Silver Bow Counties, human mortality rates from lung disease, cerebrovascular disease, and respiratory cancer were found to have increased between 1968 and 1973. The study contributed these diseases to continued air pollution emissions from nearby smelters (Raisch et al. 1979). And, just before the smelter closed in Anaconda in 1980, the air quality of the Butte/Anaconda area was tested. It was discovered that federal and state standard levels of suspended particulates were exceeded for generally all the areas sampled (Gelhaus 1981).

There are still scars on the landscape from the mining era: abandoned steel hoist frames, smoke stacks, company buildings, tailing piles, settling ponds, open pits, and changes in the natural biotic community (Renewable Technologies 1985). Silver Bow Creek (south of study area) is so polluted that the Environmental Protection Agency declared a large portion, from Butte to the Warm Springs settling ponds (northwest of study area), an ecological disaster--a biological desert (Weisel 1972).

Posing potential past, present, and future environmental problems to the invasion site and its surrounding region is the Rhone-Poulenc Chemical Plant, immediately south of the study area (see Figure 2). It began producing elemental phosphorus in 1951 (Schwennesen 1976). The effects of this facility on the local environment have been noticeable.

Fluoride, a byproduct of phosphorus production emitted in the smoke, causes serious health problems in local livestock. Some cattle, after eating fluoride-tainted vegetation, became ill, developed fluorosis, or fluoride poisoning, lost teeth, and died as a result of contamination. Windows in Ramsay (just south of study area) have been permanently clouded by chemical etching. Conifers, grasses, and shrubs growing 10 km downwind of the plant and up to five kilometers in lateral directions have also being affected (Schwennesen 1976).

Since 1975, the Environmental Studies Laboratory at the University of Montana in Missoula has been monitoring the levels of fluoride accumulating in vegetation surrounding the phosphorus plant (Steffel and Losher 1979). Several locations near the plant and to the northwest (including a site just inside this research's study area) were sampled. Their findings show that the emissions from the phosphorus plant had been adversely affecting the local environment since it began production in the early 1950s. Approximately 50 percent of the grasses, 70 percent of the shrubs, 90 percent of the trees, 70 percent of the conifers, and 40 percent of the domesticated plants were found to contain levels of fluoride exceeding the state standard of 35 parts per million (ppm) (Steffel and Losher 1979).

Logging has never been a major economic activity within the study region except for small areas in the northwest in the early 1900s. Currently, only minimal cutting occurs for home fuel or for fence posts (Ueland 1989).

Grazing of domestic animals, such as cattle, horses, mules, and sheep, has occurred within the study area over the past 100 years. In the early 1900s, movement of sheep, horses, cattle, and mules in herds was common in the narrow zone where the interstate highway now crosses the study area. The animals were allowed to range freely while they were herded to market. This practice halted when the current landowners built fences. A trail traversing the southern portion of the study area was used for transporting goods and travellers between Butte and Anaconda (Ueland 1989).

METHODS

Mapping and Measuring Tree Distribution

A quantitative, spatial analysis of the extent of recent tree invasion was made using 1954 and 1979 black and white aerial photographs. The selection of air photos was based on the quality and availability of imagery. Areas with 15 percent or greater tree crown closure were identified (using transparent density scale overlays adjusted to the appropriate photo scale) and delineated on both sets of photographs. Shadowed areas (making trees undistinguishable) were not used. Fifteen percent crown closure or greater was chosen to keep the mapped invasion boundaries as close to the forest-grassland ecotone as possible and for easier tree-identification and delineation on the photographs. Because the photographs were at different scales, areas delineated on the 1954 photographs (scale = 1:37,400) had to be enlarged, using a Saltzman projector, to the same scale as the 1979 photographs (scale = 1:16,000), for easier comparison.

Once areas occupied by trees had been delineated, a map was constructed illustrating changes in tree coverage over the 25 year period. Areas with trees found only on the 1979 overlay indicated increased tree coverage since 1954. Tree cover was then digitized using the computer program Sigma Scan 3.10 (Acker and Mitchell 1987), and the total areal coverage was calculated using the computer "panograph" program, Lotus 1-2-3 (Posner et al. 1983). The differences (increases) in tree cover were then calculated by subtracting the areal amount of cover found to be similar on both the 1954 and 1979 photographs from that found only on the 1979 photographs.

The methods used to determine biogeographic change within the study area had several drawbacks that may have affected the accuracy of the results. First, in the delineation process (tree crown cover 15 percent or greater), the transparent density scales had to be photographically reduced or enlarged to adjust to the scale of the photographs. This could have distorted the scales causing interpretation error. Other sources of error were the possible tilt, displacement, and distortion inherent in the 1954 and 1979 aerial photographs. These sources of error caused features on the photographs not to register as precisely as would have been ideal when the 1954 overlay was enlarged (using the Saltzman projector) to the scale of the 1979 photographs (scale = 1:16,000). If it had been possible to use aerial photography and crown closure overlays of the same scale without having to reduce or enlarge, some of the error could have been eliminated. Finally, because areas within the forest stands that had been recently invaded (evident by increased forest density) were not a major focus of this study, and therefore not measured, there could have been an underestimation of the amount of biogeographic change within the study area. Factors causing invasion into the grassland were probably effective in the open forest stands as well.

Determining Periods of Ecotonal Expansion

In order to determine the periods of recent invasion, the second objective of this study, an age structure analysis was conducted using field and laboratory techniques (summer and fall, 1989). The locations of the individual sampling transects for age structure analysis were chosen in order to sample within the older forest and in the invasion area. This selection allowed a better overall picture of trends or periods of establishment to be detected. The mosaic patterns of forest cover prevented a complete randomization of site selection, and coupled with the fact that the region was privately owned, the precise location of each transect depended on both access permission from the individual landowner and on the presence of invasion. Care was taken, however, to be as non-objective as possible in the selection of transect positions. The number of transects sampled depended both on the length of the field season and on collecting an adequate sample size for statistical analysis.

Nine transects were sampled, each beginning in older forest, upslope of the invaded grass-shrubland ecosystem, and extending downslope, through the area of invasion and into the shrub and grass-dominated ecosystem (Figure 3). The length varied depending upon the extent of trees into the grassland. Each transect was 10 m wide.

Trees larger than four centimeters in diameter at the base were cored to determine age, at approximately 20 cm above the ground. Care was taken to reach the center of the tree. This 20 cm coring height was as close to the ground as the increment borer's handle would permit. Trees less than approximately four centimeters in diameter were measured

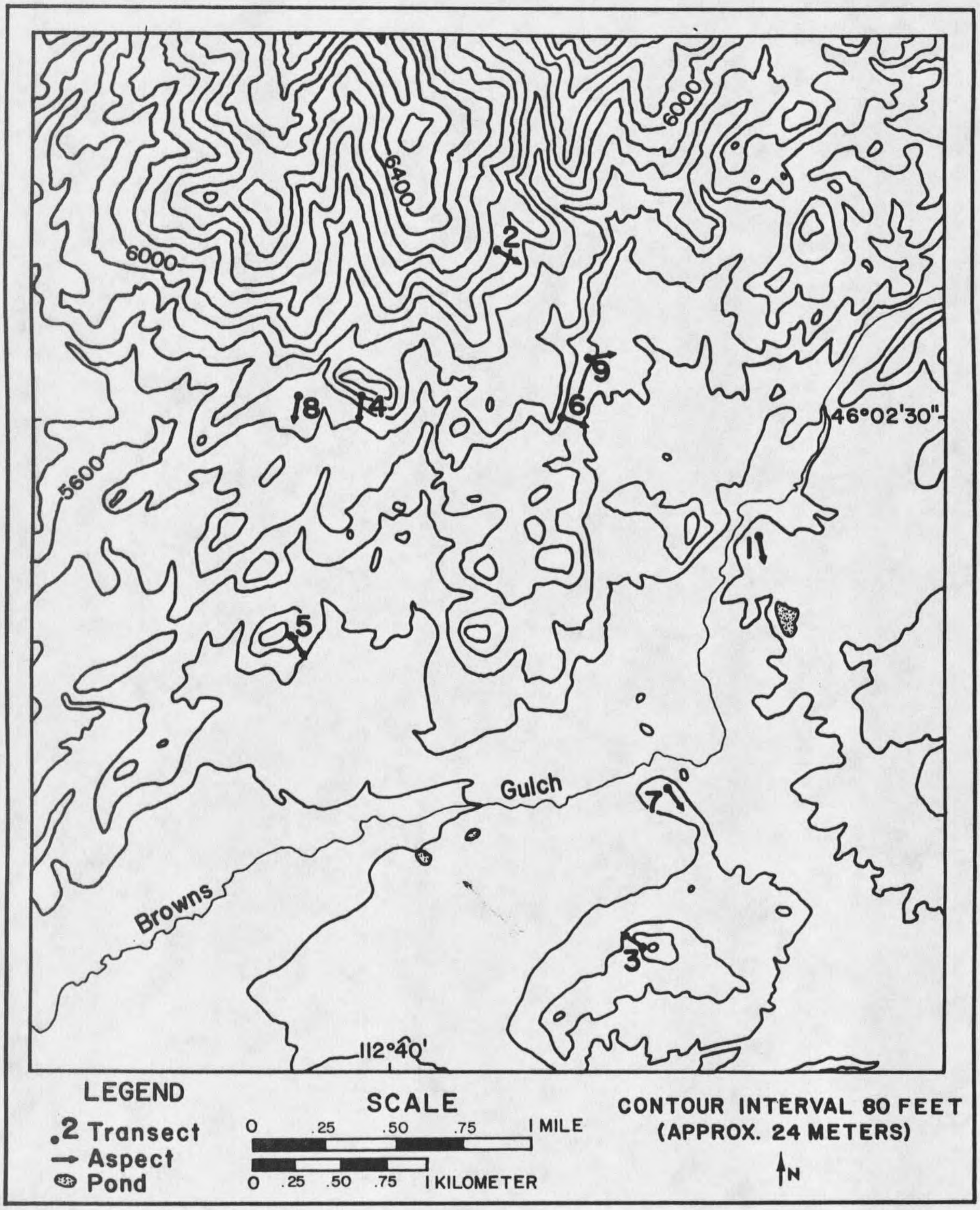

Figure 3. Location of individual transects within the study area. Arrows indicate direction of downward extent (Base from U.S.G.S. 1978. Butte North S.W. Quadrangle, Silver Bow County, Montana, 7.5 minute series.).

only for height because the coring device caused extensive damage (splitting) of the trunk. Species identifications were made on all trees in each transect. To help determine a more accurate tree age, a training sample of trees, varying in species, height, and width, was selected inside each transect. This training sample was composed of cross sections of trees cut as close to the ground as possible and at 20 cm. Eight transects were sampled in such manner. The ninth transect, however, was sampled by only cutting down trees in order to increase the number of trees within the training sample and to improve statistical calculations. All tree cores were taken to the laboratory where they were mounted on a wood base and sanded. Cross sections were made of the cut trees (at zero centimeters and at 20 cm) and sanded to expose annual growth rings. The exact number of tree rings within each sample were counted with a 10X microscope.

Using the training (cut) sample, probable growth rates for each tree species were determined by calculating the number of years for a tree to grow to coring height (20 cm). However, because of inaccuracies in assuming a constant growth rate for all trees to grow to coring height (Harper 1977), a model designed by Hansen et al. (in progress) was utilized to apply the varying growth rates to the core-determined tree ages. These rates were then applied or "smeared" onto the core ages by species, to produce a probable distribution of when trees most likely became established (for the exact formula and methodology, see Appendix A). These individual tree probability distributions were then weighted by the relative frequencies of the core-determined tree ages and combined into one data set for each transect utilizing a statistical process known as convolution (Hansen et al. in progress). In order to increase the sample size and to create a regional history of the timing of the invasions, all of the individual transects' probability distributions were combined into one large data set. A graph was developed to display the probability or strength of invasions over time using this combined data set.

Testing the significance of the various peaks in the regional invasion graph is not possible at this time but is under further investigation (Banfield 1991). Because of this, no statistical tests could be conducted on the possible relationships between the peaks in the invasion graph and the various causes of invasion addressed in this study. All results and conclusions were therefore based on visual comparisons and, to a smaller extent, on the current literature.

Causes of Invasion

The third and final objective of this investigation was to determine the disturbance events that induced the biogeographic changes that occurred within the study area. Studies of tree invasion by Vale (1982), Arno and Gruell (1986), Taylor (1990), and Hansen et al. (in progress) indicate that climatic variability, fire suppression, and domestic livestock grazing had caused changes in the environment that induced tree invasion. Based on their findings, similar causal factors were addressed in this study. The region's mining and logging histories and the possible effect of air-borne pollutants on the local vegetation were also addressed, but to a lesser degree.

Climatic Data

Temperature and precipitation are seasonally critical to the germination and survival of vegetation (Treshow 1970; Kozlowski 1979), and, therefore, averages of these variables over a 94 year period (1894-1988) were calculated on a seasonal time scale: spring (April-June); summer (July-August); fall (September-October); and winter (November-March). Clustering of monthly climatic data was based partially on techniques utilized by Hansen-Bristow et al. (1988). This climatic information was obtained from the United States Weather Bureau weather station in Butte, the closest station to the study area. Because differences in elevations and site locations are minimal between the two areas, it is assumed that the climate histories are comparable.

Fire History

In order to establish a fire history of the study area, all cores and cross sections were analyzed for fire scars. Landowners were interviewed and previous studies in southwestern Montana were also reviewed for both a site specific and a general regional fire history.

Land Use History

Livestock grazing, logging, mining, and agricultural histories were reconstructed for the transects in the study area by interviewing landowners and by using a written questionnaire (see Appendix B). Information obtained included: (1) the type of domestic animals grazed (cattle, horses, or sheep); (2) the approximate number of animals grazed each year; (3) the years each type of animal was grazed and the duration; (4) the sites of logging activity; (5) the timing and varieties of mining activities that may have occurred; and (6) the amount and type of agricultural activity practiced in the area. Since the study area was entirely on private land, grazing permits and grazing allotment records did not exist.

Measuring Effects of Pollution

The impact of air-borne pollutants on the local vegetation was addressed briefly in this because of the large amount, and therefore probable importance, of smeltering, chemical production, and other related activities that occurred in this area. Previous studies conducted both in the vicinity of the smelters and chemical plant, and elsewhere, were reviewed. However, actual testing of the soil, vegetation, and other aspects of the environment for toxic substances was not carried out in this study.

RESULTS

The Geographic Magnitude of Tree Invasion

The map of tree cover in 1954 and in 1979 (Figure 4) delineates areas having 15 percent or greater tree crown cover. During this 25 year period, at least 320 hectares (792 acres), or 35 percent of the shrub-grassland, have been invaded by Douglas-fir and Rocky Mountain juniper. This amount illustrates only the increase in tree coverage having occurred along the lower forest edge.

Periods of Invasion

Of the 435 trees which were either cored or cut down throughout the study area, 292 (67 percent) were Rocky Mountain juniper and 143 (33 percent) Douglas-fir. Using the training sample (98 cut trees), a probability was developed of the number of years for each tree to grow from ground level to 20 cm (Figure 5). After applying, via the probability function (see Methods), these probable growth rates onto the ages at coring height (see Appendix C), a probability time curve was created illustrating the strengths of tree establishment or invasion periods for each individual transect (Figures 6 through 9). The heights of the curves above each date are an empirical estimate of the probability that a tree, independent of species and randomly chosen from that particular transect, would have germinated in that year. Taller peaks illustrate a stronger probability that an invasion occurred.

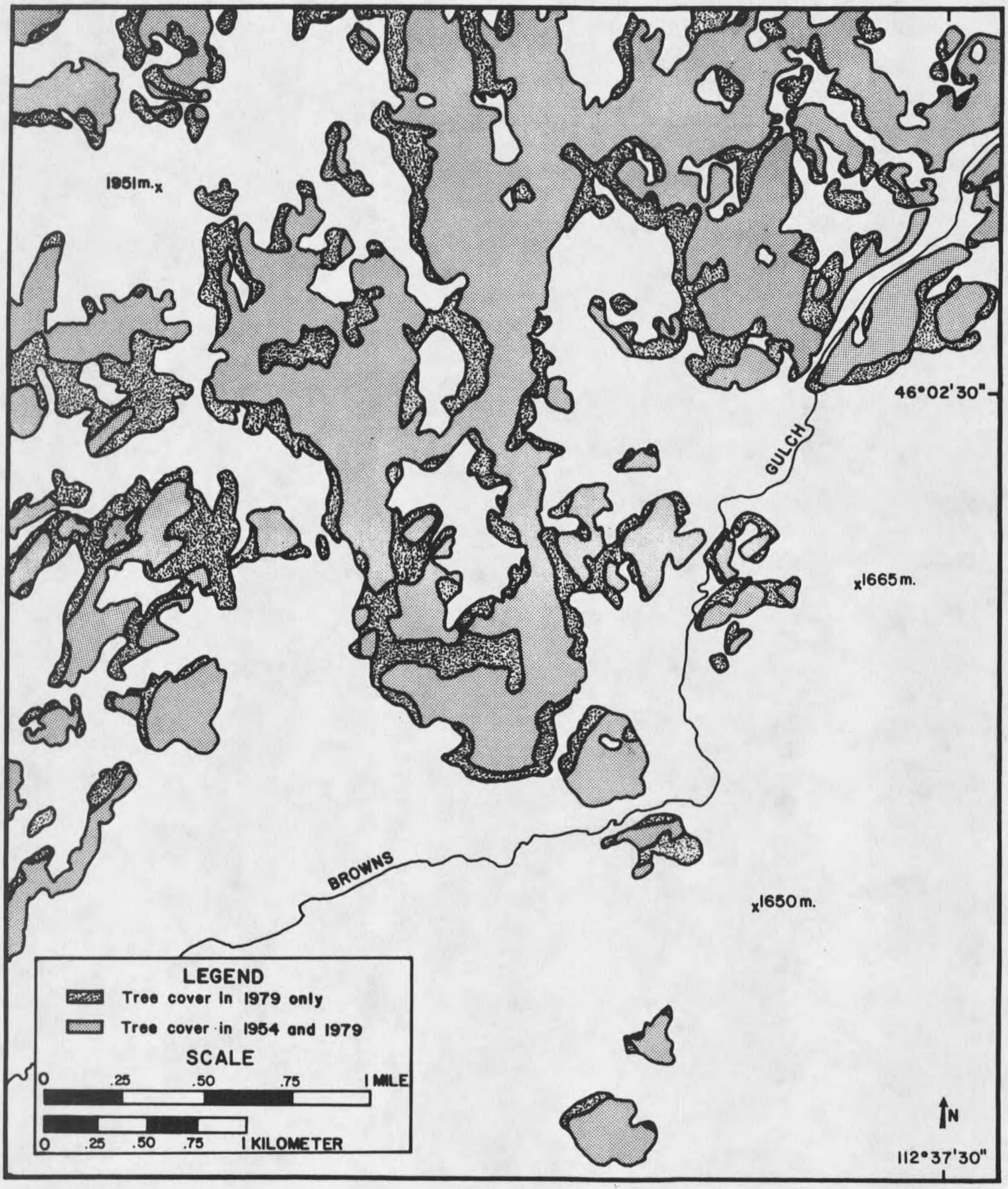

Figure 4. Extent of 15 percent or greater tree crown cover within the study area in 1954 and in 1979. The net gain of trees (due to invasion) is clearly illustrated by the areas labeled as only having tree cover in 1979.

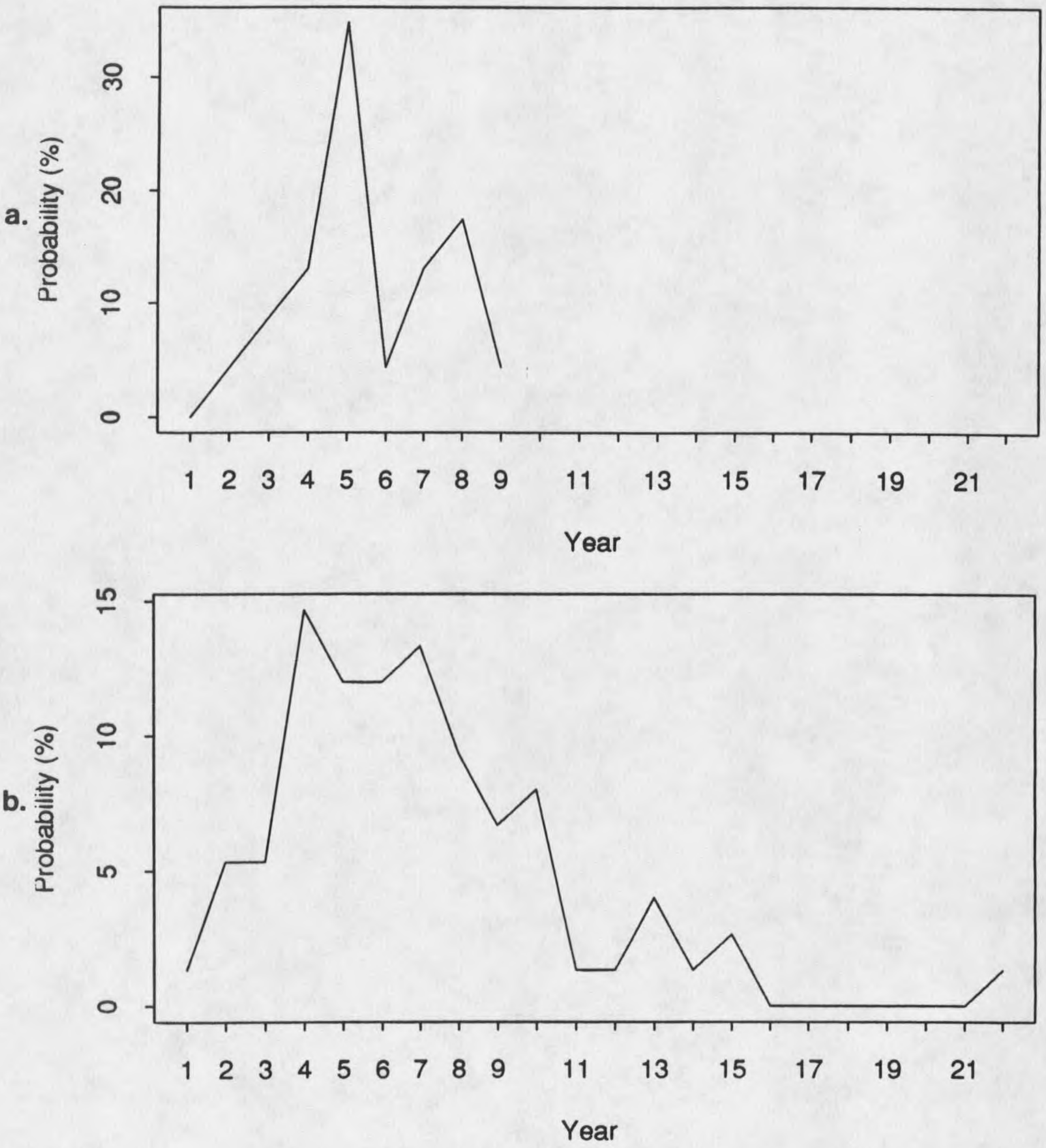

Figure 5. Probability of the number of years required for (a) Douglas-fir (n = 23, $\bar{x}$ = 4.6, s = 1.9) and (b) Rocky Mountain juniper (n = 75, $\bar{x}$ = 5.8, s = 3.2), to grow from ground level to coring height (20 centimeters).

Also the number of trees sampled at a site regulates the strengths of the peak. For example, Site 1 (Figure 6a) has a sample size of 18 (see Appendix C), producing small peaks in the graph, whereas Site 6 (Figure

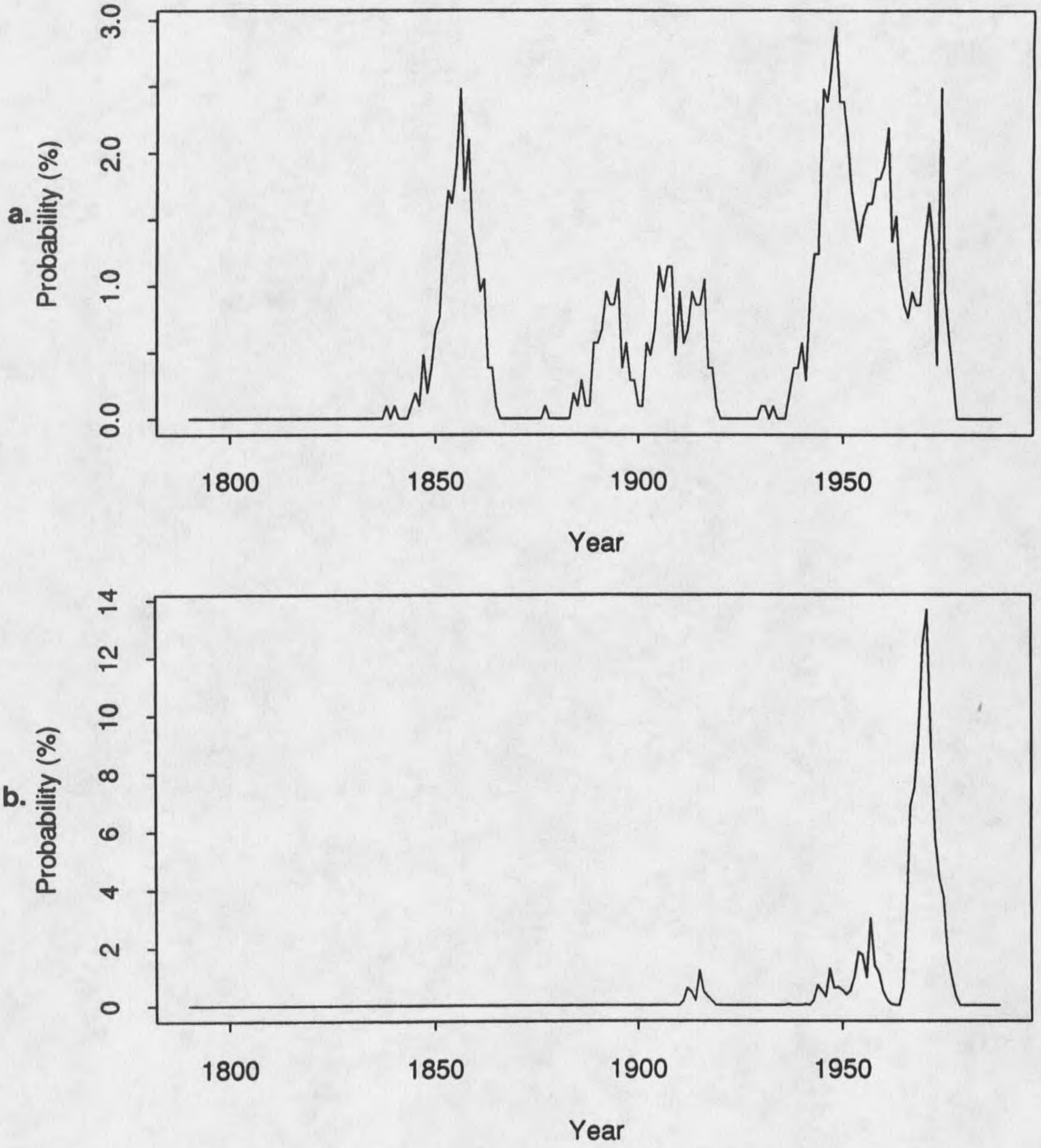

Figure 6. Probable distribution for Site 1 (a) and Site 2 (b).

8b) has definite, pronounced peaks due to the larger sample size (124 trees). (There is no graph for Site 8 because it was used as part of the training sample described in Methods). The data were then combined to form a regional invasion history (Figure 10). It appears that there

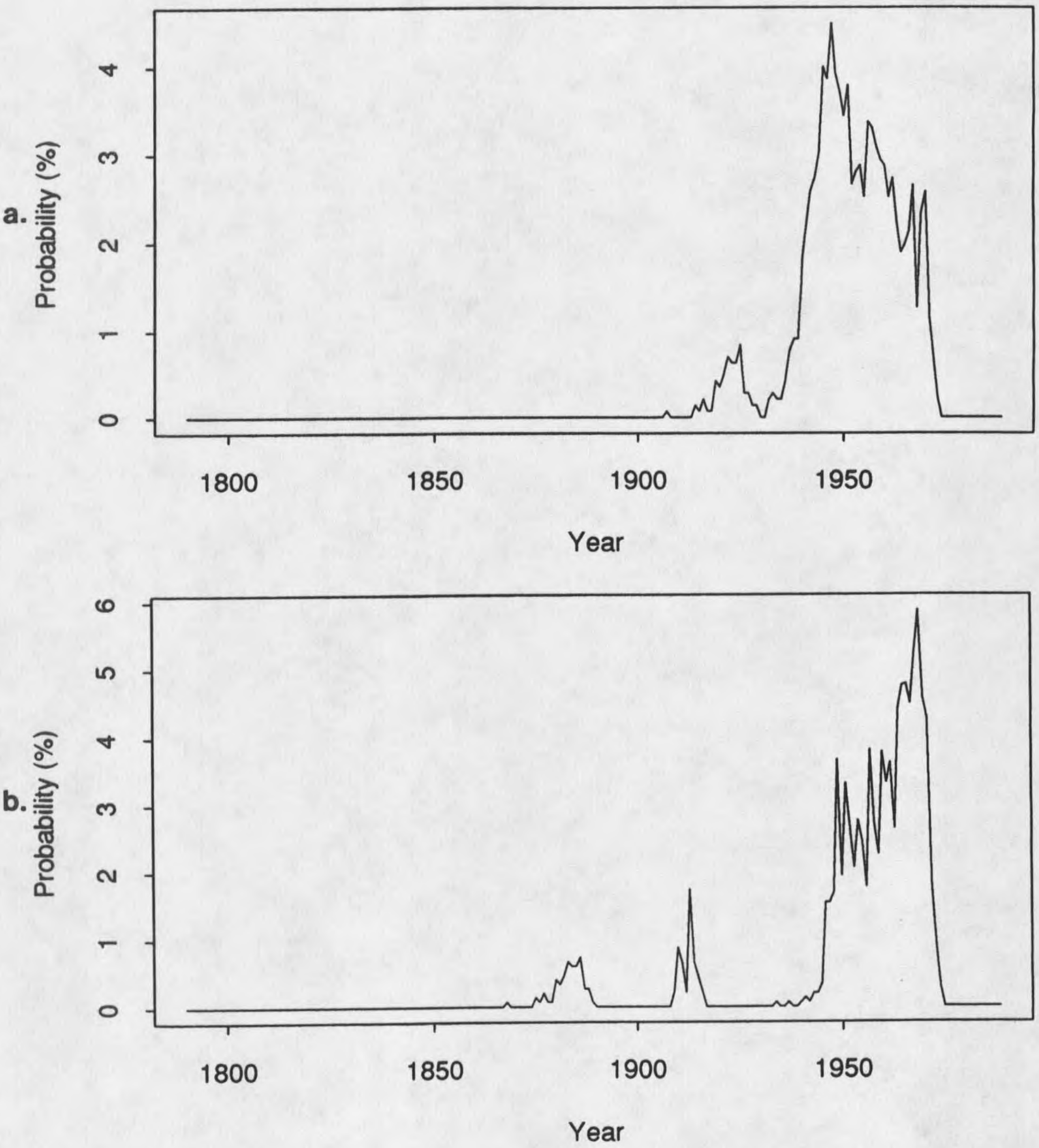

Figure 7. Probable distribution for Site 3 (a) and Site 4 (b).

were two distinct periods of regional invasions centered on the late 1940s to the mid-1950s, and the late 1960s and early 1970s.

Because of the inaccuracies found in assigning ages to trees based solely on their height (for those too small to core) (Harper 1977) and because of the different technique used in determining the ages of those

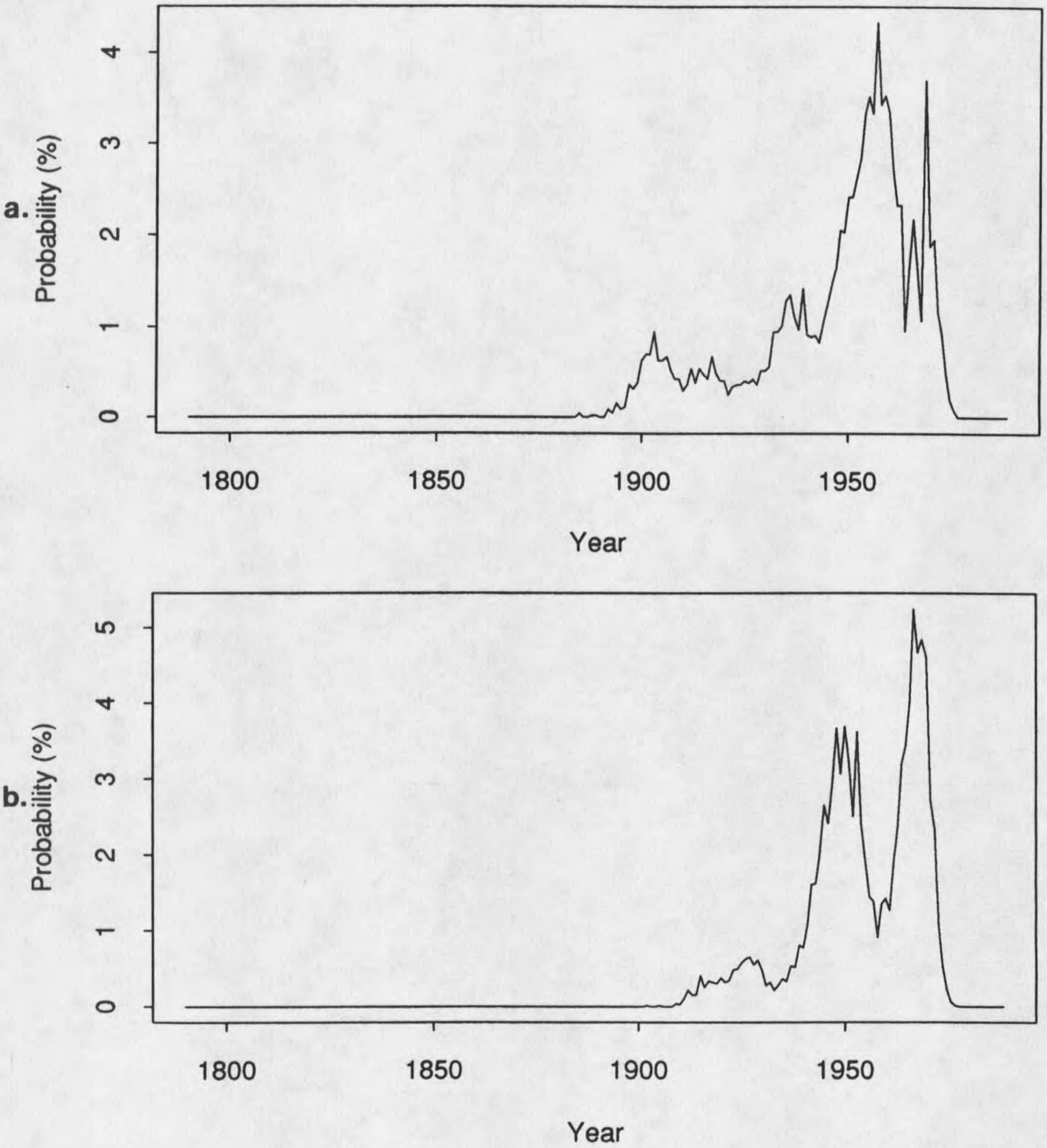

Figure 8. Probable distribution for Site 5 (a) and Site 6 (b).

trees cut versus those cored, the more recent invasions (if any) after the 1970s did not appear on the invasion graphs. However, it should be noted that there are many seedlings and saplings scattered throughout the study area at this time (Table 2).

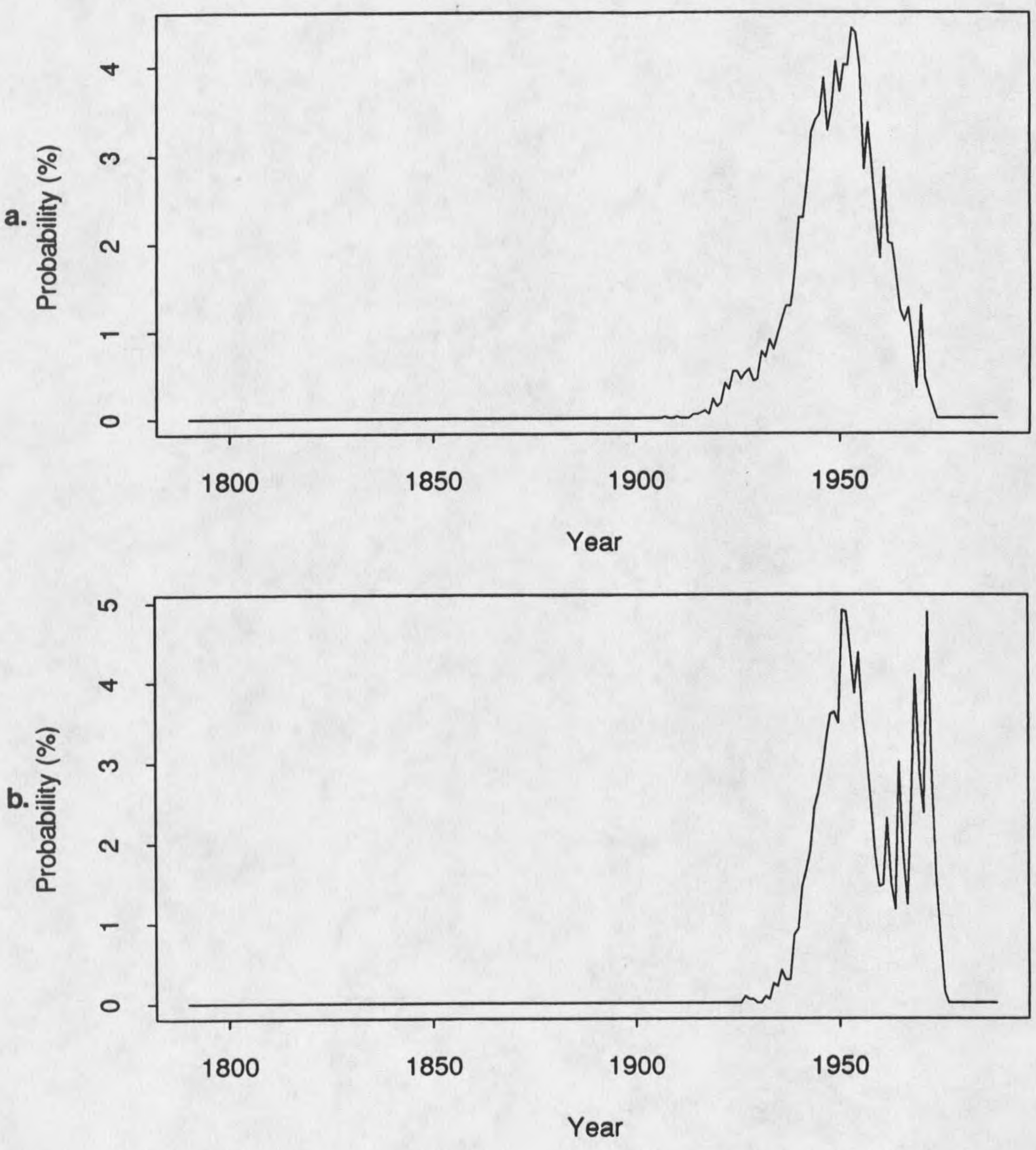

Figure 9. Probable distribution for Site 7 (a) and Site 9 (b).

Disturbance Factors Influencing Invasion

Climatic Factors

In all seasons, the area's precipitation regime can be characterized as having cyclic periods of drought followed by several

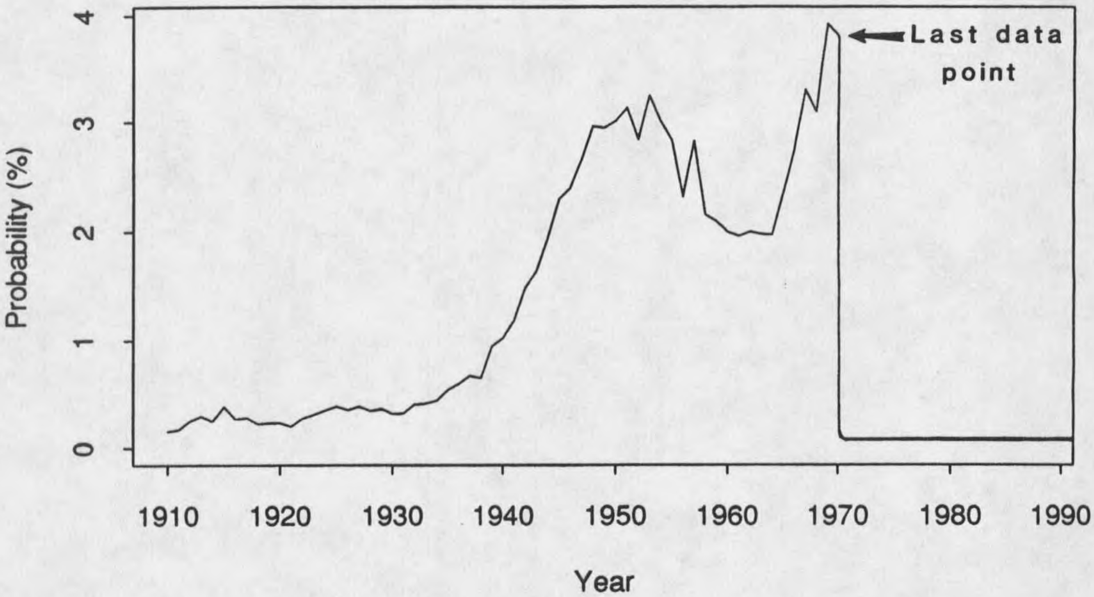

Figure 10. Probability distribution that any tree became established or invaded during any particular year. Decline in graph after early 1970s due to sampling technique (see Methods).

Table 2. Number of seedlings and saplings (too small in diameter to core) found in each transect.

Transect	Douglas-fir	Juniper	Total
1.	2	17	19
2.	126	16	142
3.	21	2	23
4.	6	6	12
5.	63	15	78
6.	124	40	164
7.	21	75	96
8.	NA	NA	NA
9.	24	7	31
Total	386	179	565

NA = No data available

years of above average precipitation. In the spring (April-June) (Figure 11a), these fluctuating moisture conditions are most obvious between the late 1920s and late 1930s, the late 1940s and mid-1960s, and the late 1960s and early 1980s. In summer (July-August) (Figure 11b) the cyclic pattern or fluctuations became extreme between the early 1890s and late 1900s, the late 1910s and mid-1920s, the mid-1920s and mid-1940s, the early 1960s and late 1970s, and the late 1970s and late 1980s. The periods of drought followed by increased precipitation are more noticeable when observing the fall (September-October) precipitation graph (Figure 12a). The cycles are most obvious between the early 1900s and early 1910s, early 1910s and late 1910s, the late 1910s and late 1940s, and the late 1940s and late 1970s. And finally, analyzing the average annual winter (November-March) precipitation data (Figure 12b), similar moisture fluctuations were found between the late 1890s and late 1910s, the late 1910s and late 1920s, the late 1920s and late 1930s, and the early 1950s and early 1970s. Butte's temperature patterns showed some obvious periods of warmer temperatures followed by cooler temperatures. This is especially noticeable after the late 1920s when average annual spring temperatures (Figure 13a), after reaching a high of approximately 11°C in the late 1920s, steadily declined until the late 1960s, before a warming trend began in the early 1970s. The pattern is evident for summer temperatures (Figure 13b) starting in the early 1930s and continuing until the early 1980s. The fall temperature regime (Figure 14a) can be characterized as having a gradual decline in temperatures. Finally, winter temperatures (Figure 14b) declined from approximately -2°C in the early 1920s, to -6°C in the late 1940s, and remained relatively low throughout the rest of the climatic record.

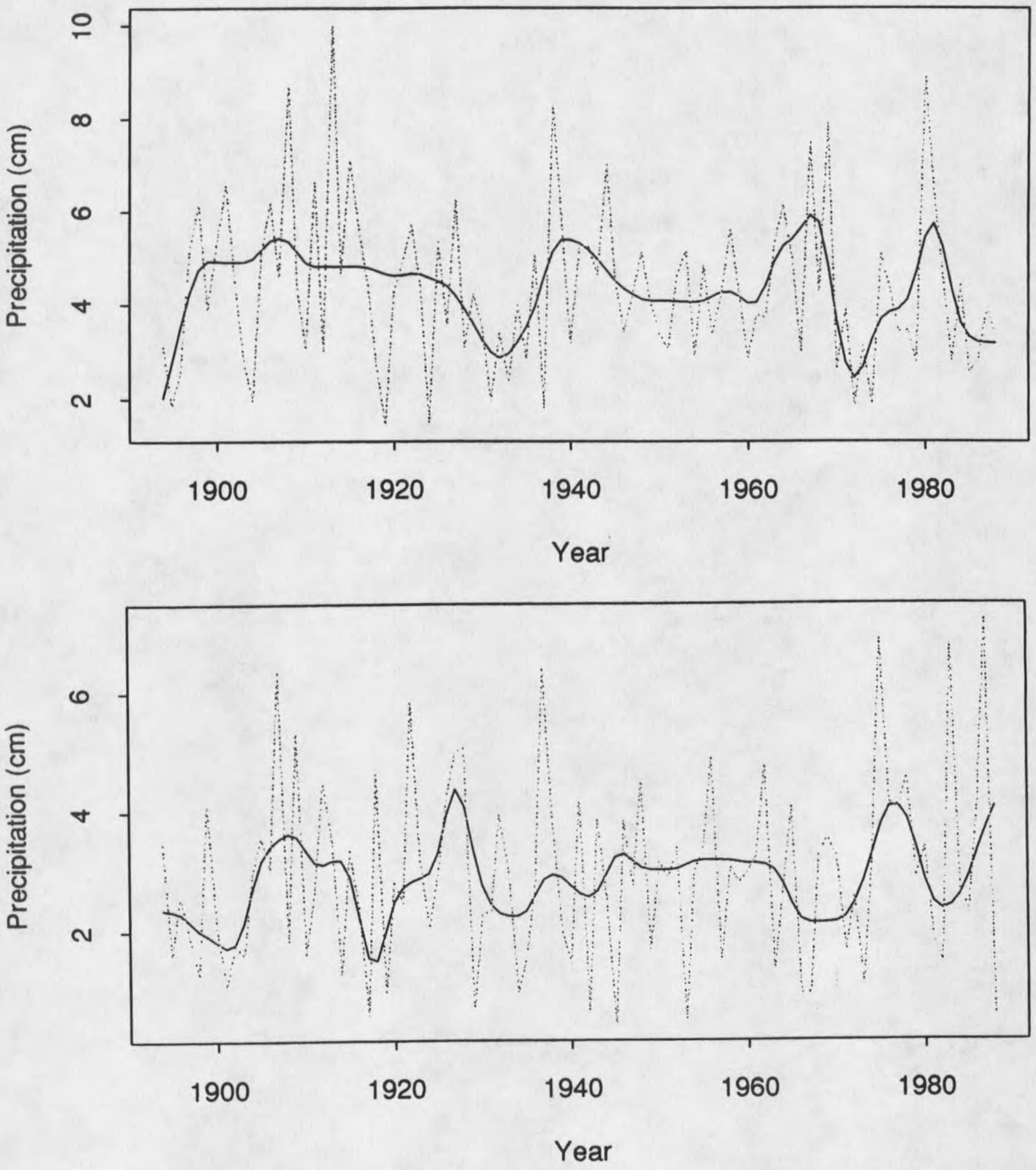

Figure 11. Spring (a) and summer (b) precipitation data (smoothed and not smoothed) from 1894 to 1988 for Butte, Montana (U.S. Weather Bureau 1895-1966; Environmental Data Service 1967-76; National Climatic Center 1977-83; National Climatic Data Center 1984-89).

Fire History

An analysis of the tree cores, cross sections, and interviews with landowners produced no evidence of fires having occurred within the

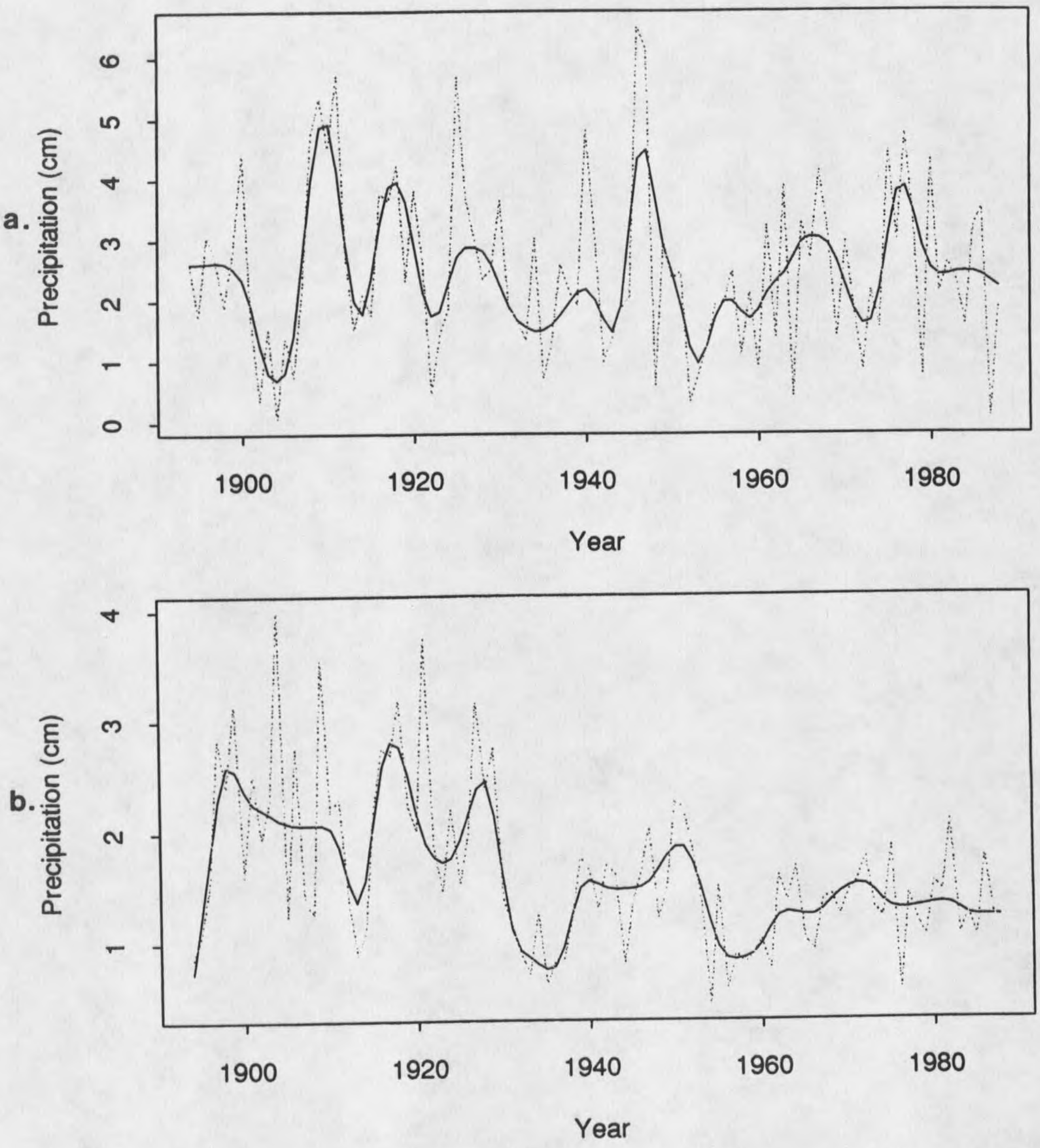

Figure 12. Fall (a) and winter (b) precipitation data (smoothed and not smoothed) from 1894 to 1988 for Butte, Montana (U.S. Weather Bureau 1895-1966; Environmental Data Service 1967-76; National Climatic Center 1977-83; National Climatic Data Center 1984-89).

study area since the late 1800s. None of the older trees (dating to the mid-1880s) showed signs of fire damage. After studying fire-scar sequences on old-growth trees and historical photographs in southwestern

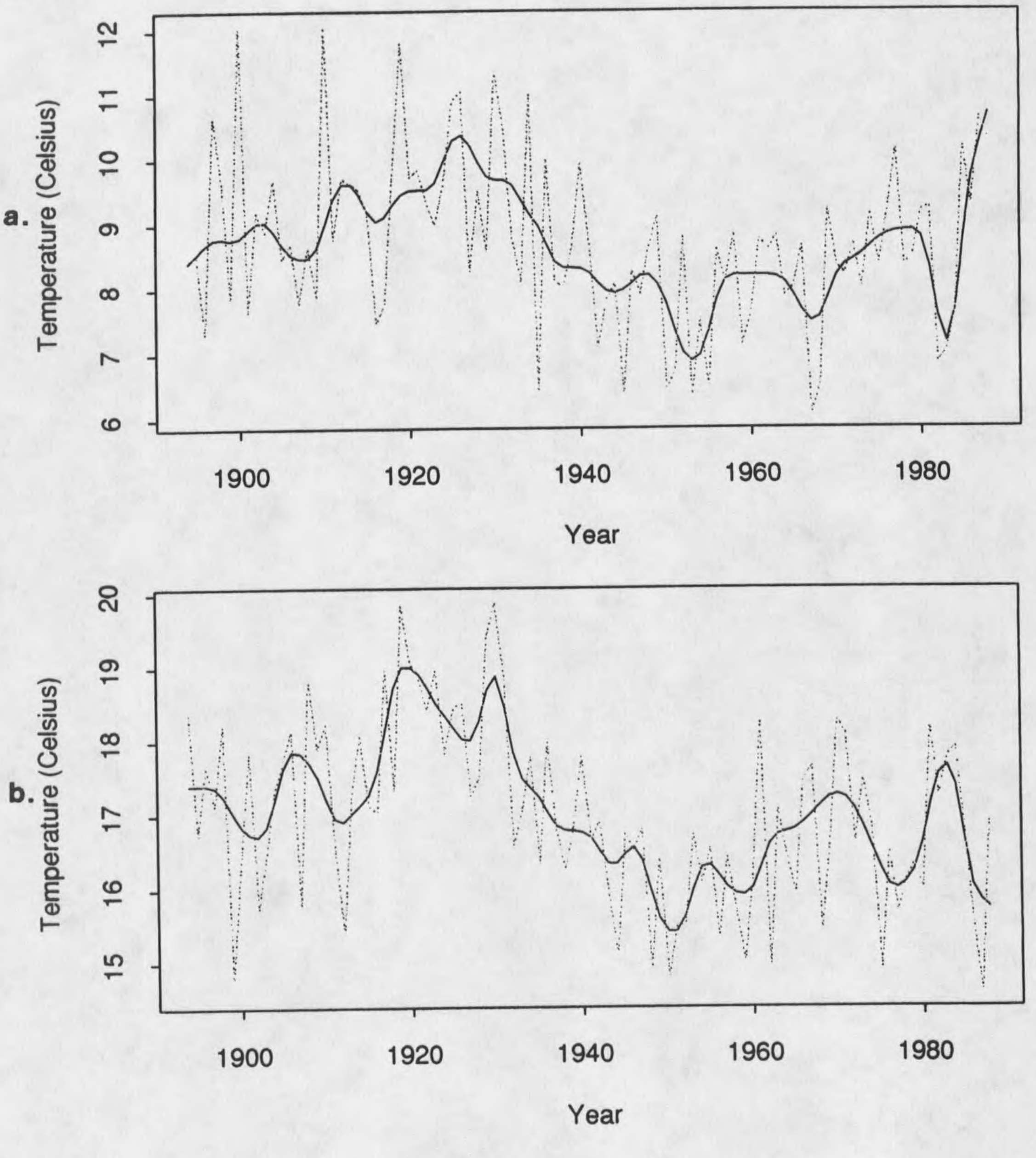

Figure 13. Spring (a) and summer (b) temperature data (smoothed and not smoothed) from 1894 to 1988 for Butte, Montana (U.S. Weather Bureau 1895-1966; Environmental Data Service 1967-76; National Climatic Center 1977-83; National Climatic Data Center 1984-89).

Montana, Arno and Gruell (1983) found that before the early 1900s, the mean fire intervals for Douglas-fir forest-grassland ecotones ranged between 35 to 40 years. These previous fires were most likely natural,

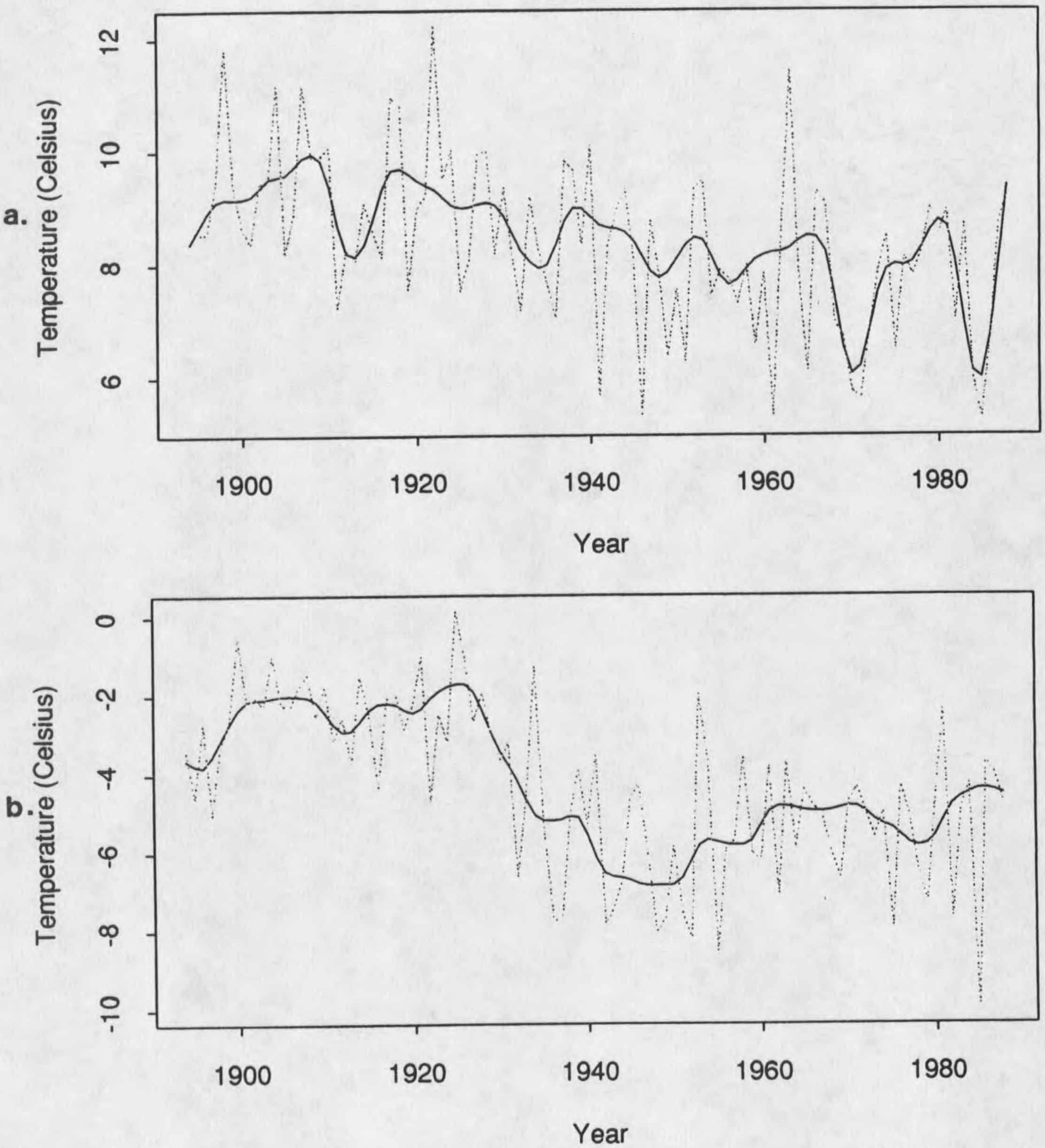

Figure 14. Fall (a) and winter (b) temperature data (smoothed and not smoothed) from 1894 to 1988 for Butte, Montana (U.S. Weather Bureau 1895-1966; Environmental Data Service 1967-76; National Climatic Center 1977-83; National Climatic Data Center 1984-89).

however, some may have been set by Native Americans. Arno and Gruell's (1986) Galena Gulch study area near Boulder, Montana, (where a similar conifer invasion occurred), had been burned intermittently prior to settlement and the establishment of ranches in the late 1880s. These settlers allowed the area to be overgrazed by livestock and then logged (Arno and Gruell 1986). Madany and West (1983) found that without frequent periods of fire and domestic grazing, tree invasion was hampered by the dense development of understory vegetation. The reduction of non-tree species by grazers decreased the amount of ground fuel available for natural- or human-induced ground fires (Madany and West 1983).

Grazing History

Livestock grazing within the study area began in the early 1900s (Table 3). However, because of landownership patterns and therefore varied grazing practices, the study area has been divided, virtually by a fence, into a western half and an eastern half. Between 1920 and 1930, the western half (see Figure 3) had at least 200 grazing horses. By the early 1930s, the numbers had risen to 600, along with the addition of 50 cattle. Due to a short market demand for horses, their numbers dwindled to approximately 25 by 1950, while cattle numbers rose to 100. Today, there are between 5-10 horses and less than 100 cattle grazed seasonally throughout the western portion of the study area (Craddock 1990). In contrast, the eastern half has been continually grazed, predominately by cattle, since the early 1900s. This portion of the study area was a dairy farm (exact numbers of livestock not known) until the current landowners began acquiring the land in the 1930s or 1940s (Ueland 1989) and began raising beef cattle. Until more recent times, an average of 300 cattle grazed, predominately, during the summer

Table 3. General grazing history for the study area based on interviews and questionnaires.

Transects		Livestock		
		Cattle	Horses	Sheep
East:	1.	Pre-1900-1989	Pre-1900-1954	NA
	3.	Pre-1900-1989	Pre-1900-1959	1900-40s
	6.	Pre-1900-1989	Pre-1900-1984	NA
	7.	Pre-1900-1989	Pre-1900-1954	NA
	9.	Pre-1900-1989	Pre-1900-1984	NA
West:	2.	Pre-1900-1989	Pre-1900-1959, 1965-69	NA
	4.	Pre-1900-1989	Pre-1900-1954, 1965-69, 1975-79, 1985-89	NA
	5.	Pre-1900-1989	1905-89	NA
	8.	Pre-1900-1989	1905-54, 1965-69	NA

NA = No data available

season (Ueland 1990, 1991). Presently there are approximately 1000 cattle and 15 horses grazed seasonally (Ueland 1990).

The grazing of sheep has never been extensive nor has it been commonly practiced throughout the study area, except for brief periods in the northwestern portion during the early 1900s and in the southern portion until the 1940s. Concurrently, the southern portion was grazed by horses, cattle, and mules as they were left to range freely or were driven to livestock markets in the late 1800s and mid-1900s (Craddock 1989; Ueland 1989, 1991). Although the exact number of these animals is not known, it is suspected that there might have been some periods of heavier grazing than normal (in other words, a substantial amount of vegetation removal, soil exposure, etc.) (Ueland 1989).

Logging, Agriculture, and Local Mines

Minor, small-scale logging was carried out in the northwest portion of the study area at the turn of the century. A few scattered stumps are visible in this area, surrounded by old and new growth. Since then, some trees have been cut for fuel and fence posts or dug-up for ornamental use in landscaping by landowners. The impact of these activities is quite minor, most likely not affecting tree invasion. There are also areas on the southern plains where irrigated alfalfa, hay, crested wheat, and ryegrass are currently grown (Ueland 1989). There is also evidence of abandoned, small-scale placer mines just north of Interstate 90 (southern portion of study area, see Figure 2).

Air-borne Pollution

Few studies investigated the possible impact of air-borne pollutants on vegetation in the study area. Also, since an in depth investigation was not carried out in this particular research project, no conclusions can be made as to the influence the smelters or chemical plant might have had on the periods of invasion that occurred within the study area.

DISCUSSION

Geographic Magnitude

Thirty-five percent or 320 hectares of the shrub-grassland surrounding the older forest cover in the study area has been recently invaded by Douglas-fir and Rocky Mountain juniper. This is a substantial amount of biogeographic change over a relatively short period (25 years) and demonstrates the impact disturbance events have on the natural environment. Most of the invasion appears to have occurred on north and northwest facing slopes, particularly in the northern and western portions of the study area. It was in these same areas that seasonal grazing of cattle and horses (and sheep for a short period of time) was practiced, and where the older forest cover predominates. In portions of the eastern and southern sections, which were either recently or historically under cultivation, less measurable invasion is evident.

Timing of Invasions

The periods of Douglas-fir and Rocky Mountain juniper invasion occurred during two distinct time intervals. During these periods (late 1940s and mid-1950s, and late 1960s and early 1970s), tree establishment was distinctly greater (indicated by the height of the curve in Figure 10) than in previous years. The apparent lack of establishment of trees in the data after the early 1970s was due to sampling and analysis techniques and not the absence of trees. The ecosystem was still in an unstable stage because continued tree establishment is evident.

Causes of Invasions

It appears that there were several probable causal agents or disturbance events, perhaps working in combination, creating an unstable forest-grassland ecotone in the study area. The combination of short-term climatic changes and variations in the intensity of livestock grazing may have disturbed the environment sufficiently to allow for invasion. Similar responses were noted by Blackburn and Tueller (1970), Sindelar (1971), Vale (1981), and Taylor (1990), as mentioned in the Previous Studies section. Also, fire suppression may have allowed the trees following germination to germinate.

Climate

Fluctuating precipitation regimes have been considered an important causal agent in the tree invasion process (Blackburn and Tueller 1970; Sindelar 1971; Vale 1981; Taylor 1990; Hansen et al. in progress) and appear to have some influence on the tree invasion within the study area as well. Similarities between precipitation and the timing of regional invasions were most pronounced when a visual comparison was made using spring (April-June) data (Figure 11) (see Appendix D for comparisons between the other seasonal climate data and regional invasions). The years between the late 1920s and late 1930s, the mid-1940s and mid-1960s, and the late 1960s and early 1980s are all characterized by a decrease in spring precipitation followed by a substantial increase. It appears that the invasions occurred once the

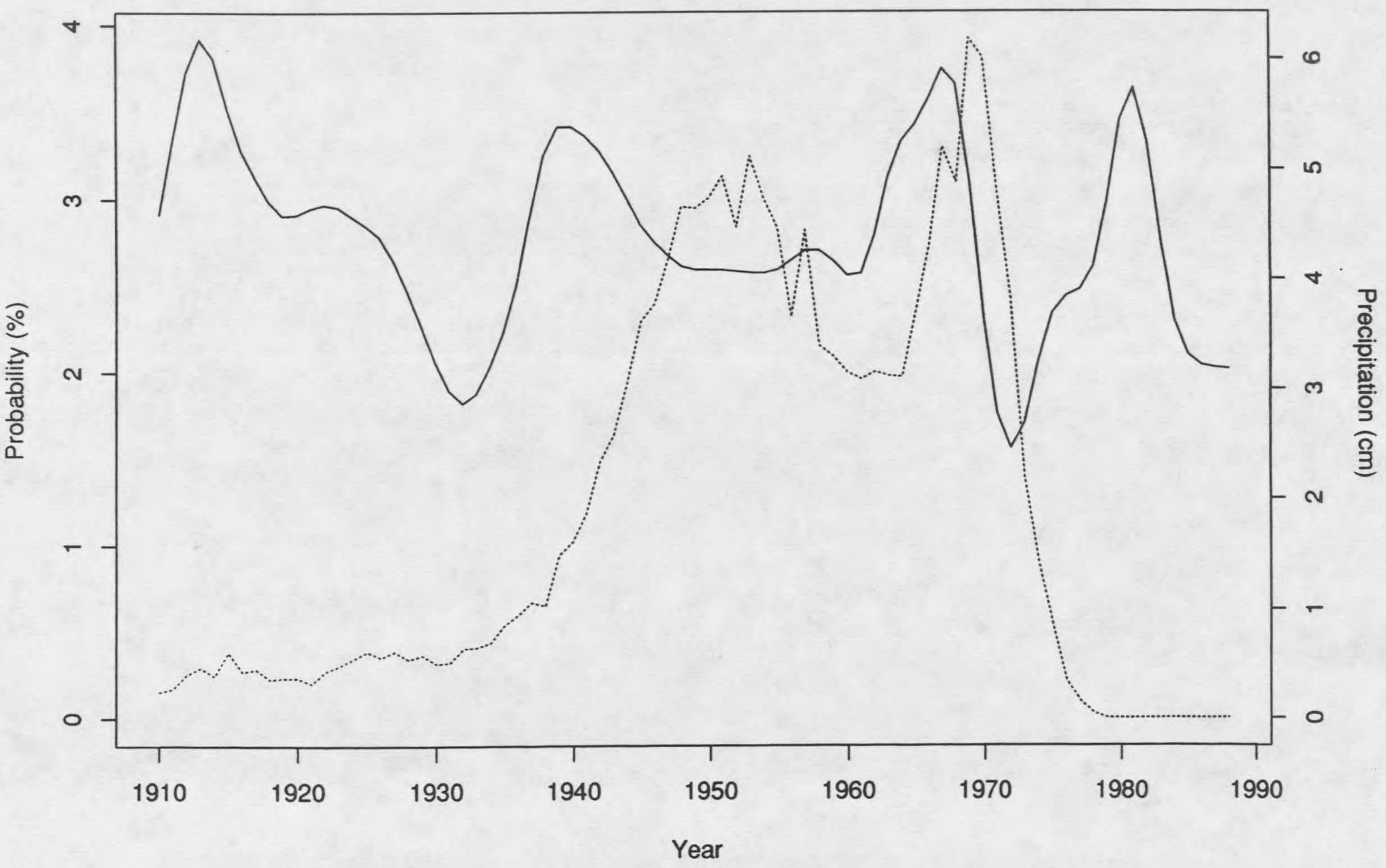

Figure 15. Comparison between regional invasion probability (···) and smoothed spring precipitation (—) graphs.

drought ended and the precipitation increased. A similar climatic pattern was also noticeable between the late 1960s and early 1980s; however, due to a different sampling technique, tree invasion was not quantified (see Figure 10) during this period. Similar responses of invasion following periods of drought and then increased moisture were noted by Vale (1981) in Oregon, Taylor (1990) in California, and Hansen et al. (in progress) in Montana. During drought, vegetation responds by wilting, decreasing photosynthesis and growth rates, and suppressing the formation of reproductive organs (cones and flower buds) (Kozlowski 1979). The less tolerant plants may even die. Seeds, however, especially those of junipers, can be resistant to drought. Viable seeds buried under the soil surface may survive long dry periods and germinate once moisture levels increase (Johnsen 1962). Once moister conditions return, mature and older plants' pre-drought physiological processes may return. In newly opened areas (perhaps opened by grazing) in this post-drought environment, Douglas-fir and Rocky Mountain juniper seedlings may have become established or the surviving trees may have established dominance. Weaver and Albertson (1956) found grassland vegetation composition did become altered after a period of drought. During dry periods, species adapted to variable climatic conditions were able to become dormant or semi-dormant; those species less drought resistant, wilted or died. Overgrazing occurred on rangelands seriously impacted by the drought. After the precipitation levels returned to normal, the vegetation slowly began to recover (Weaver and Albertson 1956).

No obvious correlation exists between periods of regional tree invasion and annual temperature fluctuations. However, in Oregon local temperature fluctuations have been mentioned as having a role in tree establishment (Vale 1981). Vale's research revealed that a period of warm temperatures, coupled with low moisture levels, may have contributed to tree invasion (Vale 1981).

Fire

Based on the results of the reconstructed regional fire history, there has not been a natural- or human-induced fire within the study area since the late 1800s. In other areas, fire has been cited as being responsible for the maintenance of grasslands and forest, so much so that the repression of these burns triggered tree invasion (Jameson 1962; Wellner 1970; Vale 1981; Arno and Gruell 1983). Burkhardt and Tisdale (1976) conclude that fire was an important environmental factor in southwestern Idaho before European settlement. Grazing, trails, roads, fire prevention programs (Burkhardt and Tisdale 1976), and cultivation have led to the decline in fires throughout the western United States. Therefore, it can be assumed that without the periodic fires of pre-European settlement time, tree seedlings have a better chance of surviving in the older forest and in the grassland ecosystem once environmental conditions have been altered by other factors favoring tree establishment.

Grazing

Moderate to heavy grazing, as well as the selective nature of domestic livestock grazing, may have contributed to the invasion of Douglas-fir and Rocky Mountain juniper into the grassland ecosystem within the study area. Similar results were found by Johnsen (1962) in

Arizona, Blackburn and Tueller (1970) in Nevada, Madany and West (1983) in Utah, Butler (1986) in Idaho, and Taylor (1990) in California. Although grazing practices varied between the eastern half and western half of the study area, there did not appear to be obvious discrepancies between the individual transect's probability distributions (see Results) found in each half. In other words, there appears to be no localized differences between when trees became established and the intensity or type of grazing practiced. This may be due to changing livestock densities over time as current landowners purchased or sold land parcels (Ueland 1989).

In the western portion (see Figure 3), the increased number of grazers in the late 1920s and early 1930s may have assisted the initial establishment of seedlings. Nevertheless, it was not until the number of grazers declined by 1950 that major tree invasion occurred. Since 1950, with reduced grazing, the west continues to see increased tree establishment. In the eastern portion, constant numbers of grazing cattle may have encouraged seedling establishment by removing or weakening competing understory vegetation (Moore et al. 1979; Vale 1982) and/or by disturbing the soil, making available seedbeds for the tree seeds. Even with the increase in the number of grazers in more recent times, there is tree establishment occurring. However, the full impact of this increased seasonal grazing pressure is not known.

Other Activities

Current agricultural practices (especially plowing) on the flatter portions of the study area appear to have discouraged tree establishment by destroying the seedlings before they had a chance to develop. In areas where such land use has been absent or curtailed for several years (in the areas of Sites 1, 3, and 6) (see Figure 3), tree invasion is taking place. The small-scale lumbering in the northwest portion of the study area occurred several decades prior to major periods of invasion and therefore does not appear to have had any influence. Similarly, the placer-mining activities do not seem to have encouraged or discouraged tree establishment since no trees appear to have been cut or damaged when placer-mining was in operation.

Summary

An estimated 320 hectares of the shrub-grasslands within the study area has been invaded by Douglas-fir and Rocky Mountain juniper. Based on the results of this study, it appears that a combination of disturbance events created an environment favoring tree invasion.

Before the turn of this century, frequent local grass fires may have retarded tree establishment. Stands of older trees were probably restricted to rocky areas by periodic fires sweeping through the area where there would have been little ground cover capable of supporting fire (Johnsen 1962; Burkhardt and Tisdale 1976; Arno and Gruell 1983). However, periods of low spring precipitation and heavier grazing may also have weakened or removed competing understory vegetation. Once spring precipitation levels increased, possibly coupled with decreased or constant grazing livestock, the environment may have changed to one favoring the establishment of trees over grasses, forbs, and shrubs. Then, when trees began to establish, the chances of being killed by fire may have been minimal since there would have been less ground cover sufficient to support a fire (Johnsen 1962; Arno and Gruell 1986).

CONCLUSIONS

Comparisons made using aerial photography show that over a 25 year period, major biogeographical changes have taken place in the study area west of Butte, Montana. Previous investigations of tree invasion into grassland ecosystems have cited several possible causal agents. In this study, similar causal agents were evaluated for their role in tree invasion and establishment. Invasion of Douglas-fir and Rocky Mountain juniper into the grassland ecosystem appears related to a combination of precipitation fluctuations, livestock grazing practices, and cessation of periodic fires.

Major periods of invasion occurred between the late 1940s and mid-1950s, and the late 1960s and early 1970s. These tree invasion happened almost simultaneously with periods of decreased spring moisture, followed by a notable increase in spring precipitation. There was a fairly constant number of cattle and horses grazing in the study area at this time. As drought conditions impacted vegetation, livestock may have been forced to be less selective. They may have consumed all or most of the available forage, seriously depleting the herbaceous and grass ground cover. Then as spring precipitation levels increased, the less vegetatively competitive environment enabled tree seeds to germinate. Without fires to destroy them, the newly germinated trees survived.

Implications of Invasion

Fire suppression, moderate to heavy livestock grazing, and natural climatic fluctuations appear to have caused a widespread biogeographic change within the study area. The resultant change in the geography of the forest-grassland ecotone has the potential of having serious, as well as positive, ramifications on the environment. As the number of trees increase within an area, the amount of litter, a fire fuel source, increases. It is possible that animal and plant biodiversity also alters, as the environment changes, to one favoring species that thrives in more forested conditions. There is also a possible decrease in the amount of grazing land suitable for domestic animals. This loss of grazing land due to increased establishment of trees and changing biodiversity could potentially affect the grazing industry in the study area (as found by Madany and West (1983), Arno and Gruell (1986), and Taylor (1990)).

However, as the local vegetation structure shifts from the dominance of only grasses, forbs, and shrubs, to a co-dominance with woody vegetation, new biologic habitats may be created. Tree invasion was found to be an important factor in increased mule deer populations of the Madison Range in Southwestern Montana between the 1930s and 1960s (Gruell 1986). Also, the establishment of trees in areas disturbed by extensive grazing, logging, and/or fires, has been found to help stabilize the soil surface, decreasing erosion potential (Millones O 1982). And finally, invading trees may be used for firewood, fence posts, and pulpwood (Arno and Gruell 1986).

Suggestions for Future Study

Air-borne Pollution Impact

Copper Smelters. The region in which the study area exists has not been thoroughly investigated for the total impact of copper smelter activities on the local vegetation. Therefore, further research is needed to understand the role air-borne pollution from the smelters in Butte and Anaconda has had on tree invasion.

Vegetational parameters of species composition, density, and cover, as well as soil contamination levels, could be studied for possible relationships with copper, sulphur, lead, and other byproducts of the smelters at various distances from the source (Wood and Nash 1976). Such studies have been done (Haywood 1907; 1908; Swain and Harkins 1908; Tetra Tech 1987), but sampling did not occur near the study site and thus could not be specifically used with field generated data in this particular study.

Phosphorus Plant. The impact of fluoride and other compounds produced at the elemental phosphorus plant south of the study area on indigenous plant species needs further study. Work carried out by the University of Montana's Environmental Studies Department (Steffel and Losher 1979) in the vicinity of the chemical plant provided some valuable insights as to the levels of contamination within the surrounding area. Investigations should be made to analyze the species composition, cover, and density at various distances from the plant. With this information it might be possible to determine if relationships exist between tree establishment, understory vegetation, fluoride levels, and distance from the chemical plant.

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APPENDICES

APPENDIX A

CALCULATING PROBABILITY OF TREE ESTABLISHMENT

Figure 16. Program for calculating probability of tree establishment (Banfield 1989).

```
{
     transect.matrix <- eval(parse(text = paste (name, "2", sep = "")))
     transect <- transect.matrix[,2]
     speciesname <- eval(parse(text = paste(name, "sp", set = "")))
     accumulator <- rep(0, 200)
     index <- c(1:length(transect))[!is.na(transect)]
     print(name)
     for(i in index) {
            species <- speciesname[i]
            if((species == "DF") : (species == "LP") : (species == "JP"))
                 {
                 dist <- paste(species, ".dist", sep = "")
                 accumulator <- accumulator + padvec(length(accumulator),
                         transect[i], dist)
            }
     }
     return(accumulator)
{
```

Figure 17. Mathematical calculations for estimating tree invasion probability (Lee 1990).

Step 1 -- Assume that the age of a tree was the number of years it took to reach 20 cm (coring height) plus the number of years since it was 20 cm tall. Therefore, let X be the tree ring count at coring height, Y be the number of years the tree took to reach coring height, and Z be the estimated age of the tree:

$$Z = X + Y$$

Step 2 -- In order to determine the periods of tree invasion, the distribution of tree ages, Z, must be calculated. However, before Z can be determined, the distribution of X and Y have to be estimated. Using the training samples collected at each transect, the number of years it took to reach 20 cm for each species can be determined by subtracting the age of the tree at 20 cm from the age at the base. The relative frequency at which these times are observed provides estimates of the probability that Y takes on the different values for the number of years it took to reach 20 cm. These values form an estimated probability density function, f_y, for Y. These probabilities are then applied to each tree cored to calculate an estimated age.

Step 3 -- Averaging the individual probability distributions for all the trees at each transect forms a new probability distribution representing the estimated ages of the trees at that particular transect. Because trees of the same age have the same probability distribution, the age information can be condensed by finding the relative frequencies at which different ages were determined. These relative frequencies also provide an estimate for the probability density function, f_x, for X. The average of all the individual distributions will be the sum of all the possible different age distributions weighted by their relative frequency. This will represent the probabilities of ages for trees at this site, or f_z (probability density function for X). Peaks in this distribution will correspond to the probability that a tree, randomly selected, will be z years old.

Step 4 -- Remember, Z = X + Y. Given a value for X, for example x, this means that Z gets a given value, z, when a value of Y, y, equals z minus x. The formula can be expressed as so:

$$P(Z = z|X = x) = P(Y = z - x|X = x)$$

However, X can take on a wide range of values; therefore in order to calculate the total probability that Z = z, the probability that Y = z - x and X = x must be summed over all the possible values X can assume. The total probability that Z takes on a given value can be expressed as:

$$P(Z = z) = \sum_{x} P(Y = z - x \text{ and } X = x)$$

Figure 17. (continued).

Step 5 -- Now assuming that the distribution of the time it takes to reach 20 cm is the same for each tree, regardless of how old the tree is at the 20 cm core, the probability that Y = z - x is independent of the probability that X = x. Because of this, the probability that Y = z - x and X = x can be stated as being the product of each other:

$$P(Z = z) = \sum_{x} P(Y = z - x)P(X = x)$$

The formula above can also be expressed as:

$$f_z(z) = \sum_{x} f_y(z - x)f_x(x)$$

because P(Z = z) is also the estimated probability function for Z (f_z). This sum is called the convolution of the two probability density functions f_y and f_x.

Step 6 -- In order to combine estimated age distributions for each species sampled into one total age distribution, f_t, a weighted average of the distributions can be calculated:

$$f_t(t) = \sum_{z} \sum_{i=1}^{s} \pi_i f_{zi}(z)$$

where π_i is the proportion of total sampled trees which were from the ith species, f_{zi} is the estimated probability density function for the ith species, and s is the number of species sampled in the study area.

APPENDIX B

LAND USE QUESTIONNAIRE

Figure 18. Land use history questionnaire based on a five year interval. One page shown as an example.

Pre-1900

Land Use Activity					Site No.				
	1	2	3	4	5	6	7	8	9
A. Grazing									
1. Cattle	X	X	X	X	X	X	X	X	X
2. Sheep									
3. Horses	X	X	X	X					
4. Other ( )									
B. Crops									
1. Hay									
2. Grains									
a. Wheat									
b. Barley									
c. Oats									
d. Other( )									
C. Mining Activities									
1. Underground									
2. Above Ground									
3. Other( )									
D. Other Uses									
1.									
2.									

1900-1904

Land Use Activity					Site No.				
	1	2	3	4	5	6	7	8	9
A. Grazing									
1. Cattle									
2. Sheep									
3. Horses									
4. Other( )									
B. Crops									
1. Hay									
2. Grains									
a. Wheat									
b. Barley									
c. Oats									
d. Other( )									
C. Mining Activities									
1. Underground									
2. Above Ground									
3. Other( )									
D. Other Uses									
1.									
2.									

X = Indicates where activity was practiced.

APPENDIX C

TREE RING AGES, HEIGHTS, AND SPECIES FOR EACH SITE

Table 4. Tree ring ages, heights, and species for Site 1. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
1	35	41	6.0	182.9	JP
1	78	NA	15.0	457.2	JP
1	130	NA	20.0	609.6	JP
1	25	NA	9.0	274.3	JP
1	128	NA	15.0	457.2	JP
2	70	NA	15.0	457.2	JP
2	35	39	5.0	152.4	JP
2	124	NA	15.0	457.2	JP
3	11	NA	6.0	182.9	DF
3	30	36	3.5	106.7	JP
3	37	NA	8.0	243.8	JP
4	38	NA	8.0	243.8	JP
4	30	NA	5.5	167.6	JP
5	23	NA	6.5	198.1	JP
5	91	NA	22.0	670.6	JP
6	35	NA	10.0	304.8	JP
7	32	34	3.5	106.7	JP
7	16	NA	6.0	182.9	JP

Table 5. Tree ring ages, heights, and species for Site 2. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
1	31	NA	7.0	213.4	JP
1	17	21	3.5	106.7	DF
1	16	24	5.7	173.7	DF
1	38	NA	35.0	1066.8	DF
1	17	21	106.7	3252.2	DF
1	16	24	172.8	5266.9	DF
2	14	NA	6.3	192.9	DF
2	14	NA	6.3	192.9	DF
2	10	NA	7.0	213.4	DF
2	16	NA	12.0	365.8	DF
3	31	35	10.0	304.8	JP
3	15	NA	7.5	228.6	DF
3	14	NA	8.0	243.8	DF
3	15	NA	14.0	426.7	DF
4	16	NA	20.0	609.6	DF
4	12	NA	12.0	365.8	DF
4	16	NA	8.0	243.8	DF
4	14	NA	8.0	243.8	DF
5	15	16	4.0	121.9	DF
6	15	NA	6.5	198.1	DF
7	15	NA	8.0	243.8	DF
7	15	NA	8.0	243.8	DF
7	15	NA	12.0	365.8	DF
8	29	38	8.5	259.1	JP
10	14	NA	8.5	259.1	DF
11	27	NA	4.5	137.2	JP
11	11	NA	12.0	365.8	DF
11	14	NA	10.0	304.8	DF
11	11	NA	8.0	243.8	DF
11	16	NA	7.0	213.4	DF
13	13	NA	7.0	213.4	DF
13	15	NA	12.0	365.8	DF
13	10	NA	7.5	228.6	DF
17	24	29	4.5	137.2	JP
18	32	36	8.0	243.8	JP
18	70	NA	50.0	1524.0	DF
18	28	NA	35.0	1066.8	DF
18	28	NA	25.0	762.0	DF

Table 6. Tree ring ages, heights, and species for Site 3. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
1	25	34	5.8	177.7	JP
1	20	25	4.5	137.2	JP
3	17	38	7.5	228.6	JP
3	39	NA	12.0	365.8	JP
3	36	NA	8.0	243.8	JP
4	6	10	2.7	81.4	DF
4	30	NA	6.1	185.9	JP
5	40	NA	5.8	175.3	JP
6	35	NA	10.0	304.8	JP
6	35	NA	10.0	304.8	JP
6	21	NA	10.0	304.8	JP
6	26	NA	11.0	335.3	JP
8	11	16	3.5	106.7	JP
8	12	26	3.5	106.7	JP
8	6	9	2.0	61.0	DF
9	16	NA	12.0	365.8	DF
9	11	14	5.2	157.6	DF
11	15	NA	13.5	411.5	DF
11	8	10	3.5	106.7	DF
12	19	NA	11.0	335.3	JP
15	37	43	20.0	609.6	JP
16	36	46	10.0	304.8	JP
16	11	15	4.0	121.9	DF
17	28	NA	10.0	304.8	JP
18	24	NA	12.0	365.8	JP
20	29	NA	10.0	304.8	JP
20	23	NA	12.0	365.8	JP
20	28	39	5.3	162.5	JP
23	61	NA	22.0	670.6	JP
24	39	NA	22.0	670.6	JP
24	43	NA	25.0	762.0	JP
25	35	NA	12.0	365.8	JP
26	16	23	6.3	190.5	JP
26	19	26	6.3	190.5	JP
26	19	26	6.3	190.5	JP

Table 7. Tree ring ages, heights, and species for Site 4. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
1	72	NA	30.0	914.4	DF
1	28	NA	12.0	365.8	DF
1	34	NA	15.0	457.2	DF
2	36	NA	20.0	609.6	DF
2	16	NA	15.0	457.2	DF
2	24	30	6.2	188.1	JP
2	21	NA	10.0	304.8	JP
3	22	NA	20.0	609.6	JP
3	16	NA	25.0	762.0	DF
4	15	17	5.0	152.4	DF
4	17	NA	30.0	914.4	DF
4	27	28	4.0	121.9	JP
4	100	NA	30.0	914.4	JP
4	31	NA	20.0	609.6	JP
4	34	NA	20.0	609.6	JP
5	15	NA	20.0	609.6	DF
6	21	NA	6.0	182.9	JP
7	15	NA	10.0	304.8	JP
7	25	NA	15.0	457.2	DF
7	21	NA	15.0	457.2	DF
8	14	NA	7.0	213.4	DF
8	28	NA	12.0	365.8	JP
8	18	NA	10.0	304.8	JP
14	25	28	3.0	91.4	JP
18	17	26	3.3	101.5	JP

Table 8. Tree ring ages, heights, and species for Site 5. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
1	46	NA	30.0	914.4	DF
1	16	NA	8.0	243.8	DF
1	27	NA	9.0	274.3	JP
2	48	NA	13.0	396.2	JP
2	31	NA	8.0	243.8	JP
2	51	NA	15.0	457.2	JP
3	83	NA	14.0	426.7	JP
3	50	NA	16.0	487.7	JP
3	28	NA	8.0	243.8	JP
3	69	NA	10.0	304.8	JP
3	44	NA	9.0	274.3	JP
3	20	NA	15.0	457.2	DF
4	41	43	9.0	274.3	JP
4	33	NA	5.5	167.6	JP
4	34	NA	7.0	213.4	JP
5	24	29	5.7	172.8	JP
5	21	NA	6.0	182.9	JP
5	35	NA	11.0	335.3	JP
5	31	NA	12.0	365.8	JP
5	36	NA	10.0	304.8	JP
5	29	NA	6.0	182.9	JP
5	16	NA	8.0	243.8	DF
6	12	NA	7.0	213.4	DF
6	16	NA	10.0	304.8	DF
6	63	NA	10.0	304.8	JP
6	25	NA	10.0	304.8	JP
7	58	NA	20.0	609.6	JP
7	25	NA	9.0	274.3	JP
7	27	NA	9.0	274.3	JP
8	NA	15	2.0	61.0	JP
8	30	34	8.5	259.1	JP
8	32	NA	15.0	457.2	JP
9	37	NA	15.0	457.2	JP
9	30	NA	15.0	457.2	JP
9	23	NA	12.0	365.8	JP
10	24	27	5.5	167.6	JP
10	68	NA	12.0	365.8	JP
10	16	NA	8.0	243.8	DF
11	14	NA	6.5	198.1	JP
11	83	NA	30.0	914.4	JP
11	14	NA	7.0	213.4	JP
11	80	NA	30.0	914.4	JP

Table 8. (continued).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
12	23	26	7.0	213.4	JP
12	51	NA	30.0	914.4	JP
12	16	NA	7.0	213.4	DF
13	25	NA	35.0	1066.8	DF
13	22	NA	9.0	274.3	DF
13	38	NA	11.0	335.3	JP
13	28	NA	35.0	1066.8	DF
14	23	NA	5.0	152.4	DF
14	14	NA	15.0	457.2	DF
15	74	NA	30.0	914.4	JP
15	48	NA	25.0	762.0	JP
15	25	NA	10.0	304.8	JP
16	21	30	3.0	91.4	JP
16	79	NA	30.0	914.4	JP
16	29	NA	20.0	609.6	JP
16	29	NA	20.0	609.6	JP
16	27	NA	20.0	609.6	JP
16	29	NA	9.0	274.3	JP
17	25	NA	7.0	213.4	JP
17	23	NA	6.0	182.9	JP
18	28	36	7.0	213.4	JP
19	23	27	7.0	213.4	JP
19	41	NA	15.0	457.2	JP
19	27	NA	10.0	304.8	JP
19	36	NA	8.0	243.8	JP
19	26	NA	8.0	243.8	JP

Table 9. Tree ring ages, heights, and species for Site 6. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
1	37	NA	20.0	609.6	DF
1	70	NA	30.0	914.4	DF
1	NA	56	13.0	396.2	JP
2	24	29	3.2	96.6	JP
2	27	30	4.3	129.5	JP
3	32	NA	25.0	762.0	DF
3	NA	41	8.5	259.1	JP
3	24	36	4.2	127.1	JP
3	36	NA	8.5	259.1	JP
4	27	NA	8.0	243.8	JP
4	16	22	4.9	149.7	DF
5	16	NA	30.0	914.4	DF
5	32	NA	7.0	213.4	DF
5	22	NA	24.0	731.5	DF
5	15	NA	20.0	609.6	DF
5	14	NA	20.0	609.6	DF
5	51	NA	20.0	609.6	JP
5	21	NA	7.4	225.6	JP
5	27	NA	5.5	167.6	JP
5	43	NA	10.0	304.8	JP
5	34	NA	6.5	198.1	JP
5	24	27	5.8	175.3	JP
5	37	38	7.4	225.6	JP
5	28	31	6.3	192.9	JP
6	14	18	5.3	160.0	DF
6	37	NA	32.0	975.4	DF
6	36	38	7.0	213.4	JP
6	56	NA	15.0	457.2	JP
6	21	NA	11.8	358.1	JP
6	58	NA	10.0	304.8	JP
7	29	36	3.5	106.7	JP
7	31	35	3.0	91.4	JP
7	35	NA	11.0	335.3	JP
7	35	NA	9.5	289.6	JP
7	38	NA	6.5	198.1	JP
7	37	NA	11.0	335.3	JP
7	18	NA	4.5	137.2	DF
8	17	NA	8.8	266.7	DF
8	13	NA	9.5	289.6	DF
8	20	NA	14.0	426.7	DF
8	16	NA	15.5	472.4	DF
8	18	NA	9.3	281.9	DF

Table 9. (continued).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
8	32	NA	35.0	1066.8	DF
8	30	NA	8.0	243.8	JP
8	43	NA	11.0	335.3	JP
8	32	NA	9.5	289.6	JP
9	NA	28	1.5	45.7	JP
9	39	NA	9.0	274.3	JP
9	28	28	4.8	144.8	JP
9	14	19	4.5	137.2	JP
9	18	NA	16.0	487.7	DF
9	66	NA	23.0	701.0	JP
9	16	NA	20.0	609.6	DF
9	13	NA	6.0	182.9	DF
9	17	NA	15.0	457.2	DF
9	19	NA	18.0	548.6	DF
9	14	NA	7.0	213.4	DF
10	29	33	4.8	144.8	DF
10	19	NA	20.0	609.6	DF
10	16	NA	6.5	198.1	DF
10	21	NA	10.0	304.8	DF
10	38	NA	8.0	243.8	JP
10	38	NA	10.0	304.8	JP
10	39	NA	7.5	228.6	JP
10	38	NA	17.0	518.2	JP
10	38	NA	10.0	304.8	JP
10	57	NA	15.0	457.2	JP
10	33	NA	6.0	182.9	JP
11	36	37	5.0	152.4	JP
11	32	34	4.0	121.9	JP
11	33	NA	7.5	228.6	JP
11	32	NA	10.0	304.8	JP
11	15	NA	9.5	289.6	DF
11	15	NA	9.5	289.6	DF
11	15	NA	21.0	640.1	DF
11	15	NA	16.0	487.7	DF
11	31	NA	9.0	274.3	JP
11	63	NA	20.0	609.6	JP
11	41	NA	18.0	548.6	JP
11	17	NA	14.0	426.7	DF
12	29	NA	12.0	365.8	JP
12	45	NA	15.0	457.2	JP
12	33	NA	11.0	335.3	JP
12	41	NA	9.5	289.6	JP
12	16	NA	10.5	320.0	DF
12	18	NA	21.0	640.1	DF
12	18	NA	20.0	609.6	DF
13	57	NA	20.0	609.6	JP

Table 9. (continued).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
13	19	NA	27.0	823.0	DF
13	17	NA	12.0	365.8	DF
13	13	NA	8.0	243.8	DF
13	33	NA	11.0	335.3	JP
13	27	NA	10.0	304.8	JP
14	22	28	4.5	137.2	JP
14	59	NA	30.0	914.4	JP
14	23	NA	22.0	670.6	DF
15	16	NA	12.0	365.8	DF
15	25	NA	20.0	609.6	DF
15	16	NA	8.0	243.8	DF
15	39	NA	12.0	365.8	JP
15	35	NA	12.0	365.8	JP
15	34	NA	15.0	457.2	JP
16	36	NA	12.0	365.8	JP
16	29	NA	15.0	457.2	JP
16	13	NA	6.0	182.9	JP
16	33	NA	12.0	365.8	JP
16	38	NA	17.0	518.2	JP
16	33	NA	12.0	365.8	JP
16	22	NA	13.0	396.2	DF
17	15	NA	6.0	182.9	DF
17	17	NA	15.0	457.2	DF
17	18	NA	18.0	548.6	DF
17	31	NA	24.0	731.5	JP
17	33	NA	15.0	457.2	JP
17	21	NA	10.0	304.8	JP
17	35	NA	19.0	579.1	JP
17	33	NA	10.0	304.8	JP
17	NA	25	3.5	106.7	JP
18	24	27	4.8	144.8	JP
18	18	NA	8.0	243.8	JP
18	15	NA	9.5	289.6	DF
18	28	NA	33.0	1005.8	DF
19	21	NA	7.0	213.4	DF
19	23	NA	9.0	274.3	DF
19	12	NA	13.0	396.2	JP
19	32	NA	3.5	106.7	JP
19	13	19	3.0	91.4	JP
19	34	37	5.0	152.4	JP

Table 10. Tree ring ages, heights, and species for Site 7. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
1	24	NA	13.0	396.2	DF
1	32	NA	7.5	228.6	DF
1	15	NA	6.0	182.9	DF
1	31	NA	12.0	365.8	JP
1	30	34	10.0	304.8	JP
1	30	36	6.0	182.9	JP
2	NA	37	10.0	304.8	JP
2	19	NA	8.0	243.8	JP
2	30	NA	7.0	213.4	JP
2	40	NA	17.0	518.2	JP
2	28	NA	21.0	640.1	DF
3	24	NA	16.0	487.7	DF
3	15	NA	20.0	609.6	DF
3	44	NA	14.0	426.7	JP
3	35	NA	16.0	487.7	JP
3	23	NA	10.0	304.8	JP
3	32	36	10.0	304.8	JP
3	15	27	4.0	121.9	JP
4	16	23	7.0	213.4	DF
4	29	36	7.5	228.6	JP
4	37	NA	10.0	304.8	JP
4	39	NA	10.0	304.8	JP
4	29	NA	13.0	396.2	JP
4	36	NA	10.0	304.8	JP
4	29	NA	8.0	243.8	JP
4	37	NA	11.0	335.3	JP
4	28	NA	10.0	304.8	JP
5	61	NA	12.0	365.8	JP
5	31	NA	8.0	243.8	JP
5	23	NA	8.0	243.8	JP
6	37	NA	9.5	289.6	JP
6	40	NA	15.0	457.2	JP
6	22	NA	20.0	609.6	JP
6	31	NA	10.0	304.8	JP
6	41	NA	11.0	335.3	JP
6	23	28	6.5	198.1	JP
7	37	NA	10.0	304.8	JP
7	36	NA	16.0	487.7	JP
7	32	NA	10.0	304.8	JP
7	33	37	11.3	342.9	JP
8	32	NA	12.0	365.8	JP
9	27	34	14.0	426.7	JP

Table 10. (continued).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
9	37	NA	11.0	335.3	JP
10	25	NA	9.5	289.6	JP
10	18	NA	9.5	289.6	JP
11	32	NA	8.5	259.1	JP
11	44	NA	14.0	426.7	JP
12	34	35	10.0	304.8	JP
12	40	NA	10.0	304.8	JP
12	33	NA	10.0	304.8	JP
12	28	NA	12.5	381.0	JP
12	32	NA	10.0	304.8	JP
14	40	NA	13.0	396.2	JP
14	58	NA	15.0	457.2	JP
14	42	NA	12.0	365.8	JP
14	49	NA	15.0	457.2	JP
14	51	NA	20.0	609.6	JP
15	27	NA	9.0	274.3	JP
15	21	NA	8.0	243.8	JP
15	34	NA	9.0	274.3	JP
16	53	NA	12.0	365.8	JP
17	20	NA	10.0	304.8	JP
18	31	NA	10.0	304.8	JP
18	28	40	6.5	198.1	JP
18	41	NA	13.0	396.2	JP
18	44	NA	9.0	274.3	JP
18	33	NA	9.0	274.3	JP
18	29	NA	11.5	350.5	JP
18	22	NA	6.5	198.1	JP
19	43	NA	14.0	426.7	JP
19	31	NA	14.0	426.7	JP

Table 11. Tree ring ages, heights, and species for Site 8. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
NA	22	28	7.0	213.4	JP
NA	33	36	4.0	121.9	JP
NA	14	18	5.0	152.4	DF
NA	21	34	5.0	152.4	JP
NA	10	16	2.5	76.2	JP
NA	9	13	3.0	91.4	DF
NA	15	22	6.5	198.1	DF
NA	17	25	6.3	190.5	JP
NA	16	21	3.4	104.2	JP
NA	32	40	10.0	304.8	JP
NA	33	40	9.0	274.3	JP
NA	14	21	6.3	190.5	DF
NA	20	29	6.3	190.5	JP
NA	18	32	2.4	73.8	JP
NA	8	14	4.0	121.9	DF
NA	15	22	3.0	91.4	DF
NA	15	18	4.4	134.7	JP

Table 12. Tree ring ages, heights, and species for Site 9. Ages found in both the 20 cm and zero centimeters columns indicate those trees that were incorporated into the training sample. (NA = No data available, JP = Rocky Mountain juniper, and DF = Douglas-fir).

Band No.	Age at 20 cm	Age at 0 cm	Height in Feet	Height in cm	Species
1	10	15	2.9	88.7	DF
1	20	NA	15.0	457.2	DF
1	30	NA	30.0	914.4	DF
1	34	NA	20.0	609.6	DF
1	14	NA	6.0	182.9	DF
1	27	35	3.9	119.2	JP
1	13	16	1.9	58.2	JP
1	29	34	6.5	198.1	JP
1	13	19	2.0	61.0	JP
1	24	NA	10.0	304.8	JP
1	32	NA	30.0	914.4	JP
1	24	NA	7.0	213.4	JP
1	29	NA	10.0	304.8	JP
1	39	NA	10.0	304.8	JP
1	31	NA	12.0	365.8	JP
1	28	NA	8.0	243.8	JP
1	40	NA	8.0	243.8	JP
2	13	NA	10.0	304.8	DF
3	9	12	2.2	66.1	DF
3	13	NA	8.0	243.8	DF
3	12	NA	10.0	304.8	DF
3	16	25	2.1	63.4	JP
3	19	28	2.7	81.4	JP
3	29	NA	8.0	243.8	JP
3	41	NA	8.0	243.8	JP
3	22	NA	15.0	457.2	JP
3	34	NA	7.0	213.4	JP
4	33	NA	8.0	243.8	JP
4	35	NA	10.0	304.8	JP
4	29	NA	9.0	274.3	JP
4	36	NA	11.0	335.3	JP
4	28	NA	12.0	365.8	JP
4	34	NA	20.0	609.6	JP
4	30	NA	11.0	335.3	JP
4	13	21	2.8	83.8	JP
4	13	NA	15.0	457.2	DF
4	20	NA	40.0	1219.2	DF
4	13	NA	15.0	457.2	DF
4	16	NA	20.0	609.6	DF
5	17	NA	20.0	609.6	DF
5	41	NA	20.0	609.6	JP
5	36	NA	18.0	548.6	JP

APPENDIX D

REGIONAL INVASION AND SEASONAL CLIMATE GRAPHS

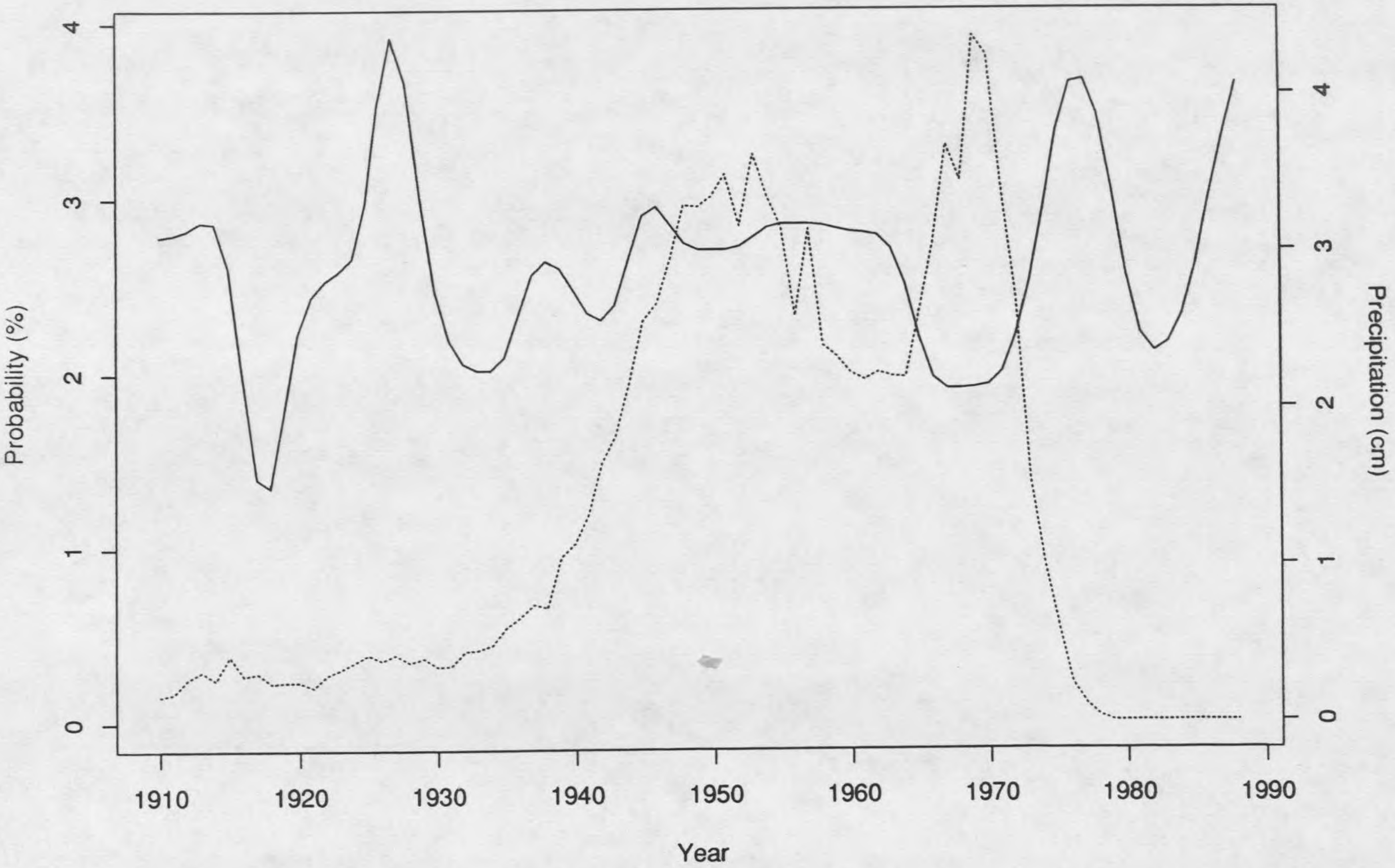

Figure 19. Comparison between regional invasion probability (····) and smoothed summer precipitation (—) graphs.

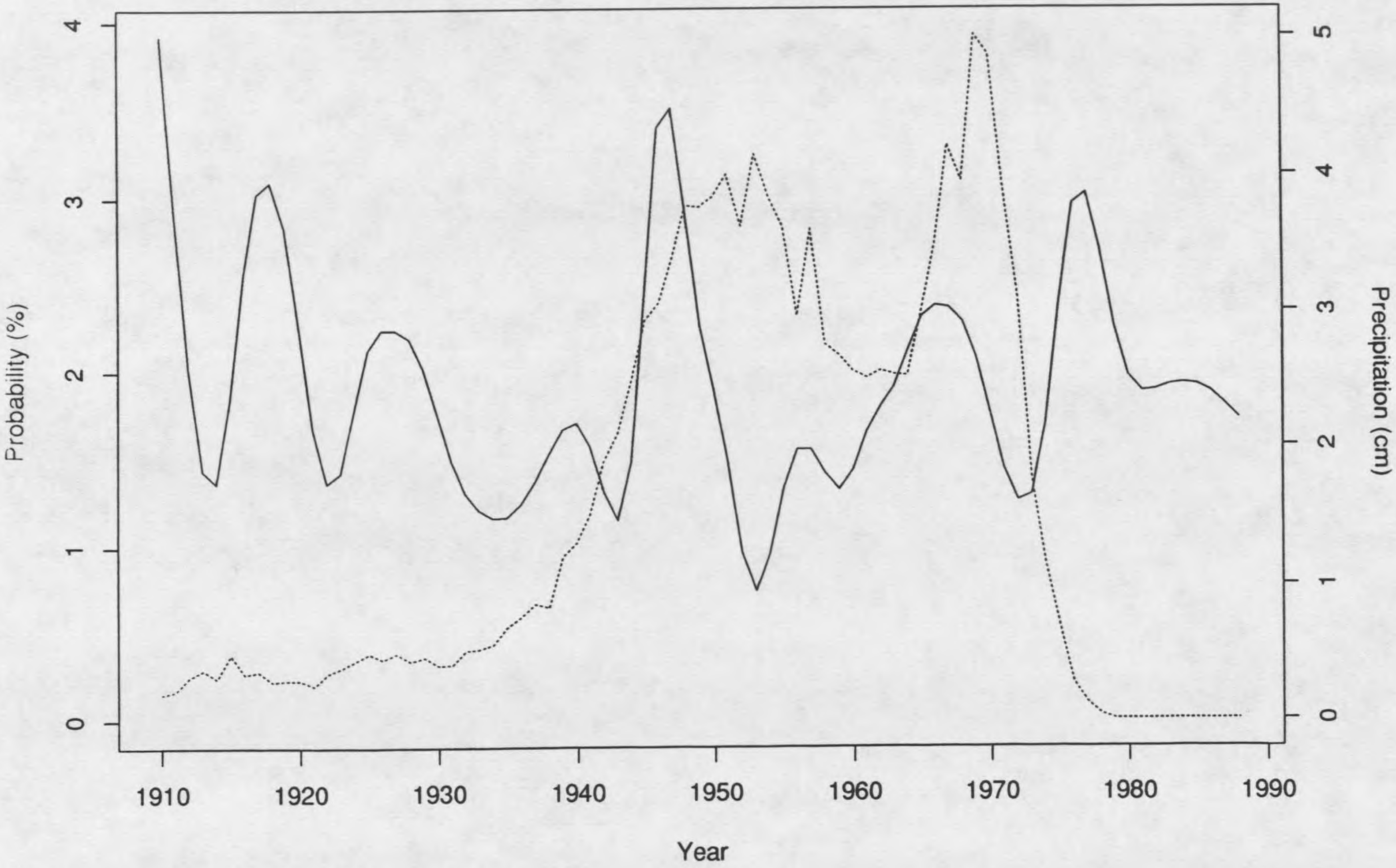

Figure 20. Comparison between regional invasion probability (···) and smoothed fall precipitation (—) graphs.

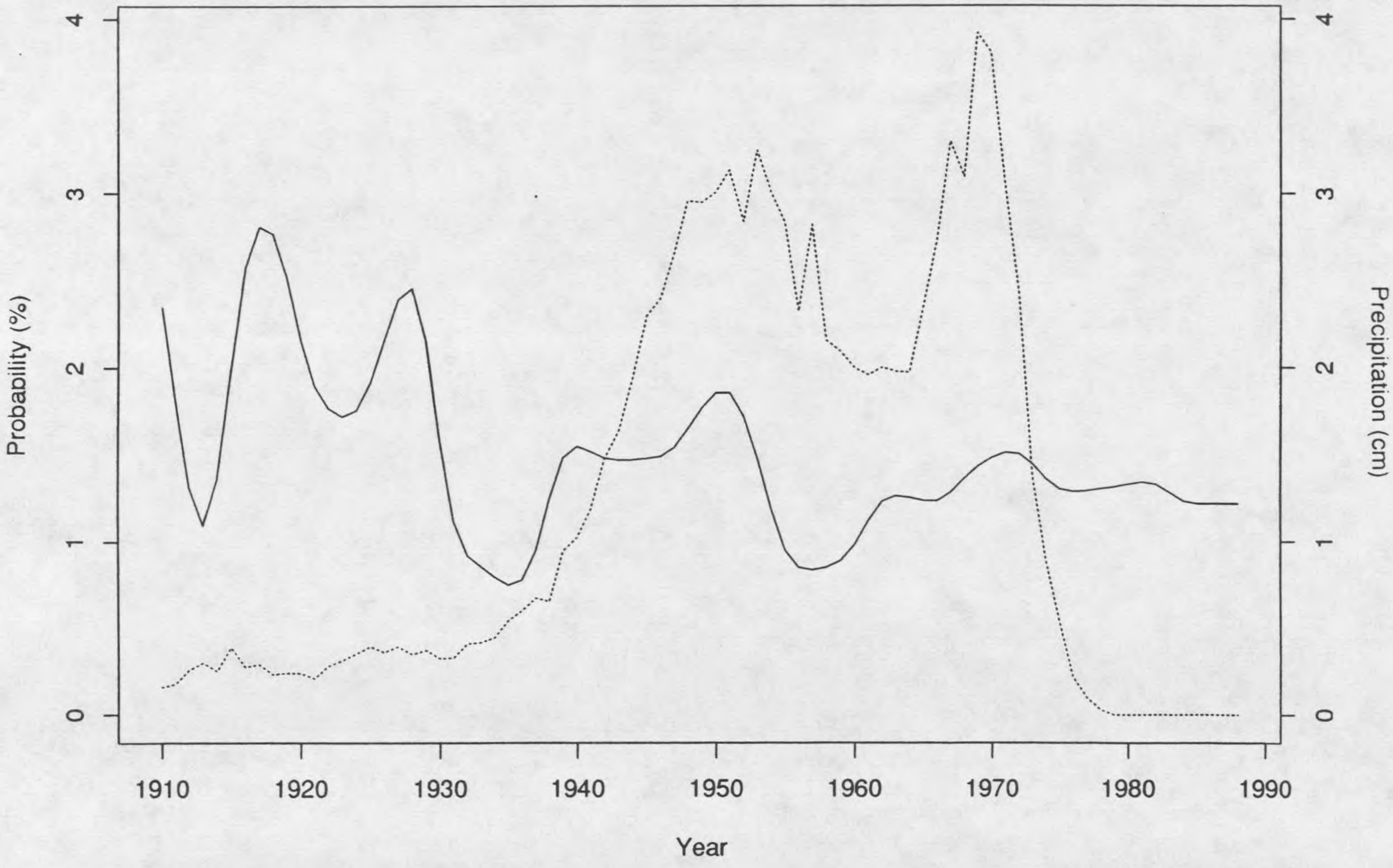

Figure 21. Comparison between regional invasion probability (····) and smoothed winter precipitation (—) graphs.

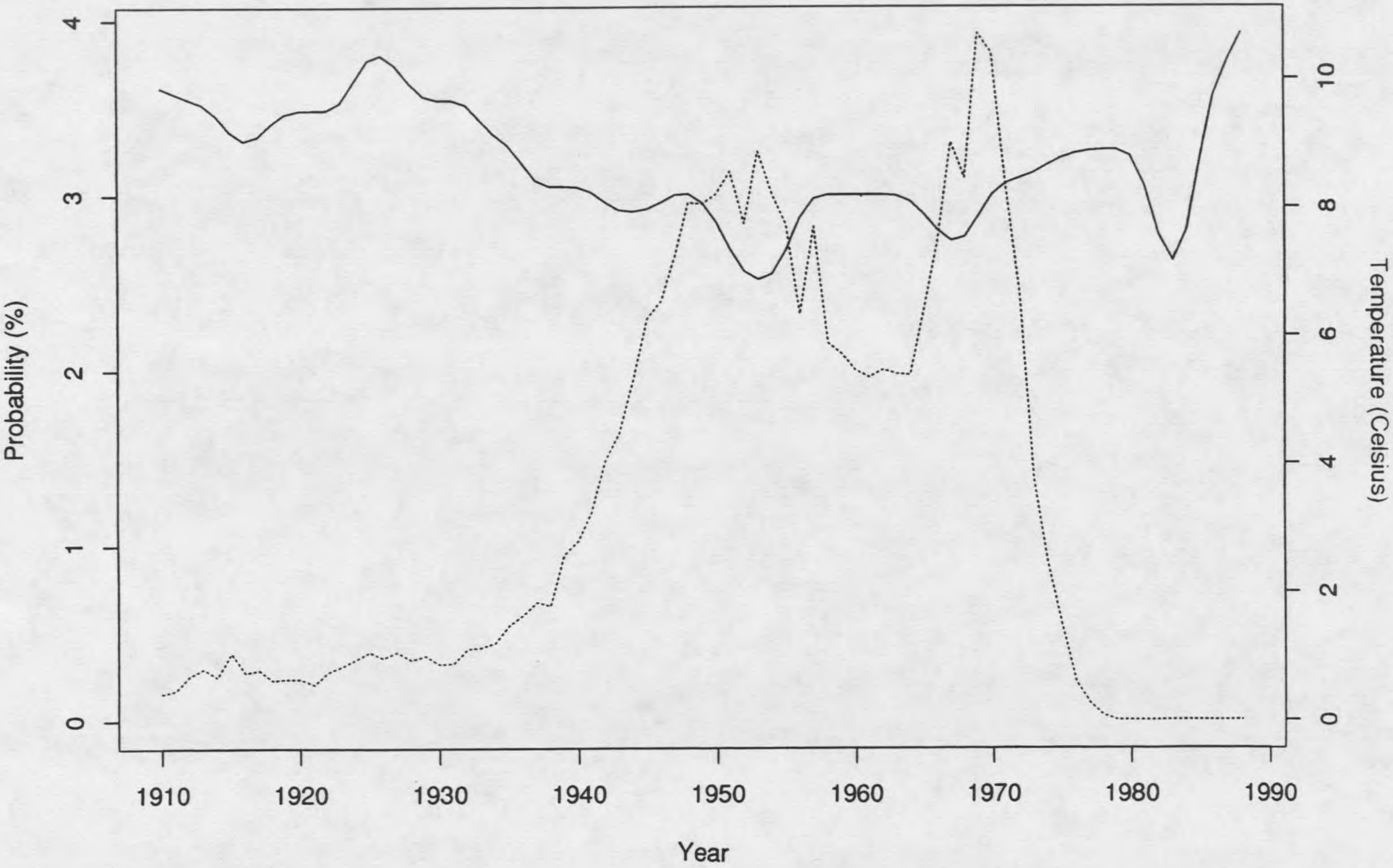

Figure 22. Comparison between regional invasion probability (···) and smoothed spring temperature (—) graphs.

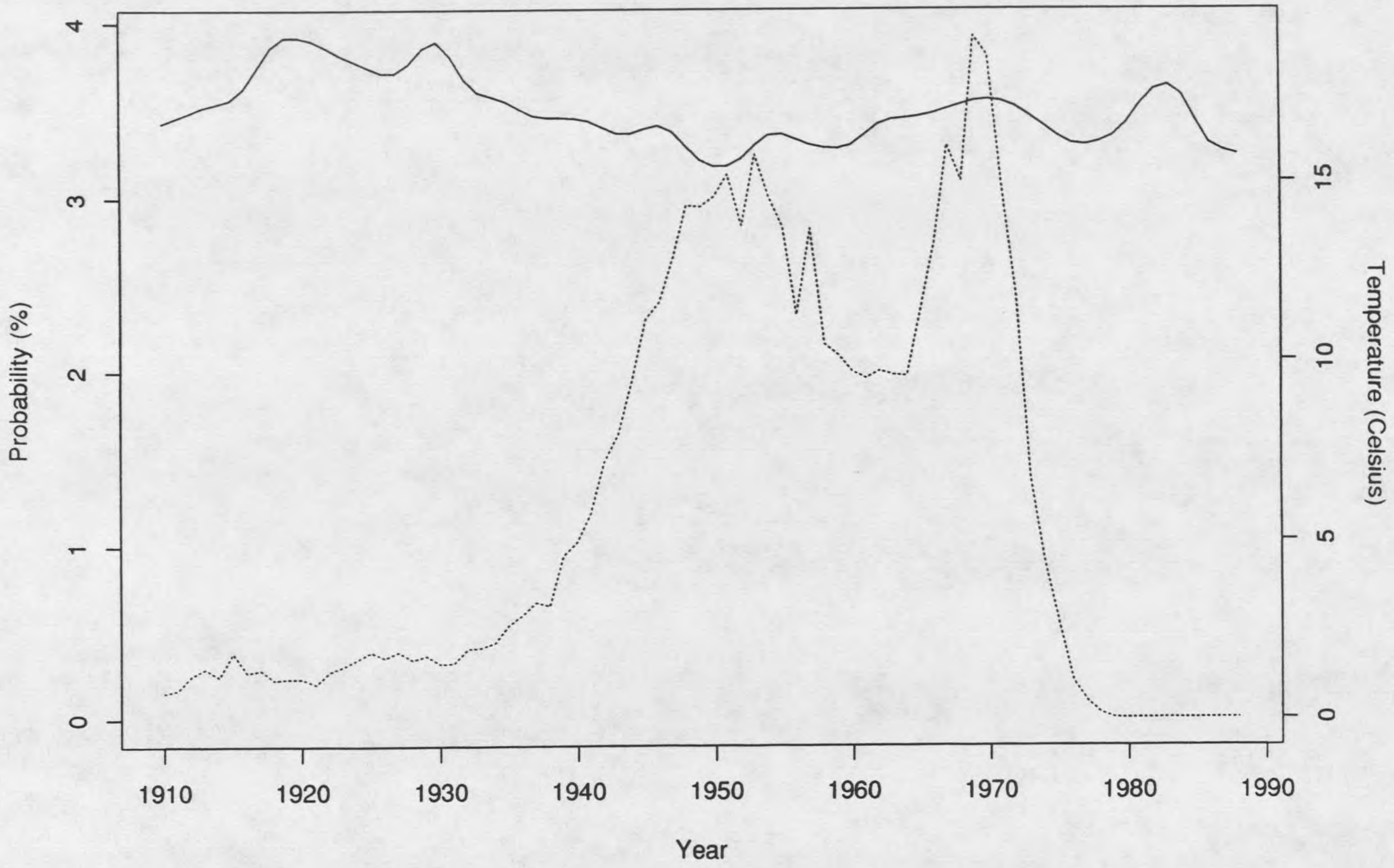

Figure 23. Comparison between regional invasion probability (···) and smoothed summer temperature (—) graphs.

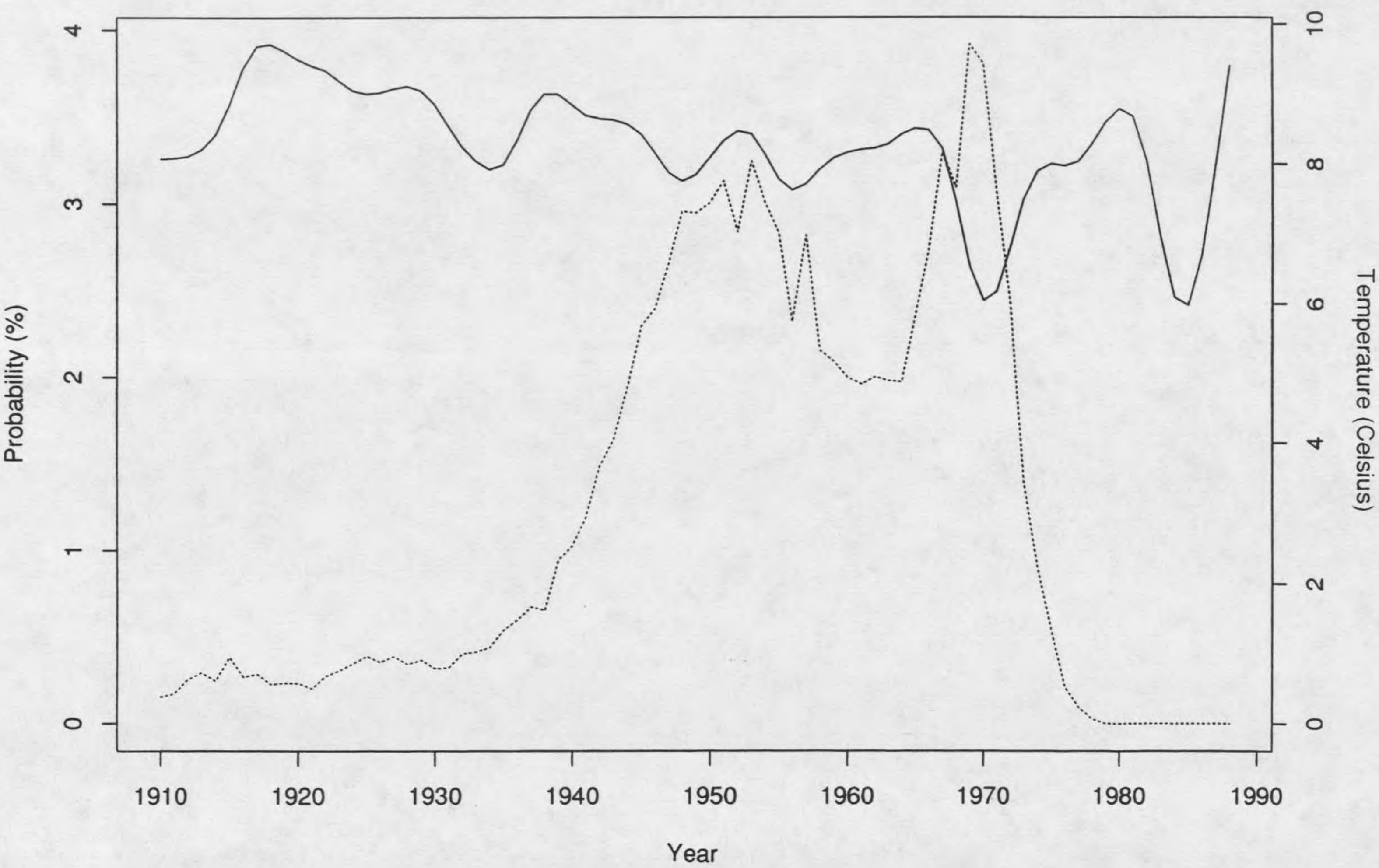

Figure 24. Comparison between regional invasion probability (···) and smoothed fall temperature (—) graphs.

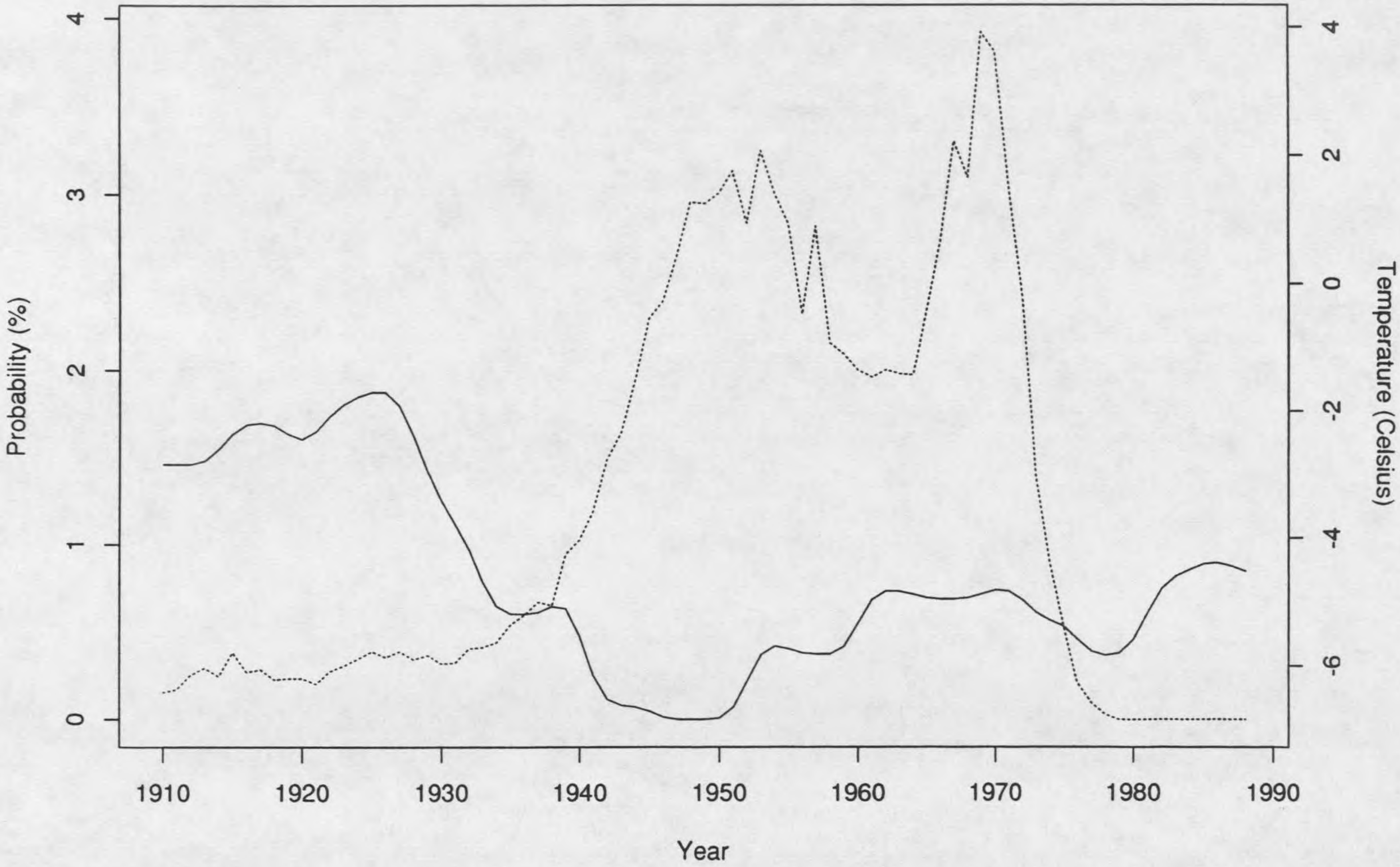

Figure 25. Comparison between regional invasion probability (····) and smoothed winter temperature (—) graphs.