Review Draft

COLD DAMAGE POTENTIAL IN NORTHWEST FORESTS

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Preface

The following report was prepared by University scientists through cooperative agreement, project science staff, or contractors as part of the ongoing efforts of the Interior Columbia Basin Ecosystem Management Project, co-managed by the U.S. Forest Service and the Bureau of Land Management. It was prepared for the express purpose of compiling information, reviewing available literature, researching topics related to ecosystems within the Interior Columbia Basin, or exploring relationships among biophysical and economic/social resources.

This report has been reviewed by agency scientists as part of the ongoing ecosystem project. The report may be cited within the primary products produced by the project or it may have served its purposes by furthering our understanding of complex resource issues within the Basin. This report may become the basis for scientific journal articles or technical reports by the USDA Forest Service or USDI Bureau of Land Management. The attached report has not been through all the steps appropriate to final publishing as either a scientific journal article or a technical report.

Abstract. Damage to vegetation can occur when temperatures drop below the present hardiness of the plant. Injury may not become apparent for months after the event. To help anticipate and better plan for potential damage in large ecosystems, a prototype model was developed to show the spatial and temporal variability of freezing conditions. The model uses readily available daily minimum and maximum temperatures as the sole forcing for determination of potentially damaged areas. The potential for cold damage is divided into seasonal components. Autumn damage potential quantifies the smoothness of transition from autumn to winter temperatures and checks for freezing before winter hardiness is established. Winter potential quantifies the damaging effects of midwinter dehardening followed by the rapid onset of extreme cold temperatures. In spring the damage due to exposure of the plant following budburst is quantified. GIS data layers were generated for the Columbia River basin in the northwestern United States and compared with observed damage. The model correctly identifies areas of observed damage to plant life. Recommendations for possible improvements to the model are presented.

Keywords: cold damage; temperature effects; coniferous forest; Columbia River basin; growing degree day; chilling unit; forcing unit; cold hardiness; bud burst; lethal temperature; GIS.

INTRODUCTION

Cold damage in forested ecosystems is an important disturbance process. Unfortunately, the spatial extent and temporal variability of cold damage have not been quantified adequately for

inclusion in decision-making projects. To better understand cold damage and provide tools to help ecosystem management and planning projects, we developed a prototype model for determining the potential for cold damage in coniferous forests of the Pacific Northwest.

Identifying regions in which cold damage to plant life has occurred is difficult. Often the most damaging cold episodes do not become apparent for months or even years later. In the case of basal stem girdle, Eiche (1966) describes damage to northern Sweden's Scots Pine (Pinus Sylvestri) from an event in the 1960/61 winter that did not become apparent for two summers. Mortality of damaged trees continued three years after the cold event. Top dying and stem cankering was noted in the late spring of 1956 in coastal British Columbia in young Douglas-fir (*Pseudotsuga minziesii* (Mirb.) Franco), western Hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western red Cedar (*Thuja plicata* Donn). This damage was attributed to a sudden cold event that occurred the previous November (Porter, 1959). Van der Kamp and Worrall (1990) noted a sudden cold spell in the British Columbia interior in late January 1989 that became apparent in mid-June when Douglas-fir buds failed to flush.

Damage from secondary agents such as disease and insects adds to plant mortality. Klein and Campbell (1991) suggest that trees damaged in a severe winter event in western Montana became susceptible to infestation by bark beetles. Eiche (1966) found that Scots pine, initially showing signs of basal stem girdle, were subsequently colonized by Pissodes weevils and fungi, which caused increased plant mortality in following years. The environmental conditions months to years following the initial cold damage are crucial to the recovery and survival of the affected plants. Trees previously damaged or diseased only can attain a very low degree of winter hardiness (Larcher and Bauer, 1981), making them further susceptible to mortality.

Designing a model to identify areas potentially damaged by cold in a region as diverse as the Columbia River basin in the northwestern United States is an equally difficult task. The basin encompasses large varieties of vegetation types: desert, steppe, forest, and alpine. Deserts in the basin are void of major vegetation. The steppe regions occupy much of the high plateau areas and are characterized by bunch grasses, sagebrush, and juniper. Low elevation forested regions are composed of ponderosa pine (Pinus ponderosa), Douglas-fir (Pseudotsuga menziesii), lodgepole pine (Pinus Contorta), and other species. Higher elevation forests show increasing numbers of grand fir (Abies grandis), western red cedar (Thuja Plicata), western hemlock (Tsuga heterophylla), and Engelmann spruce (Picea engelmannii). Near the tree-line, subalpine fir (Abies lasiocarpa) and whitebark pine (Pinus albicaulis) become evident (Franklin and Dyrness, 1973). In the alpine regions seasonal grasses and shrubs dominate. Within the broad variety of tree species there is a considerable degree of genotypic variation in cold hardiness, length of growing cycle, and other physiological factors (Havranek and Tranquillini, 1995).

In addition to the wide variety of cold hardiness in different species and genotypes, microscale effects, such as topography, slope aspect, and forest stand cause localized variations of damage. Trees on northern and western facing slopes have been shown to receive more damage during winter storms from cold winds that predominate from these directions (Porter, 1959). Those on south facing slopes can be damaged in clear calm winter conditions because of great fluctuations in temperature and desiccation from direct exposure to the sun (MacHattie, 1963).

Saplings located in hollows and valleys are much more prone to frost damage on cold, clear nights from pooling of frigid, dense air (Blennow, 1992). Late frosts cause spring damage mainly on warm slopes or at low elevations (Havranek and Tranquillini, 1995).

As a first order approximation, and to avoid complexities inherent in the variety of species and genotypes, this work concentrated on identifying cold damage potential to conifer trees, the dominant tree specie in the basin's forested regions. Also, we used a grid-cell climate data set that was developed by Thornton and Running (1996) at 2 km spatial resolution. This minimized microscale topographic and land cover variations. Our goal was to develop a simple model that could go backward or forward in time with readily available climate data. Also, by establishing a prototype, we hope to present a modeling framework that can illustrate gaps in our current understanding of temperature effects on landscape-scale systems. More complete understanding of cold damage as a disturbance agent can help land managers anticipate and plan for the linkages between other disturbance processes that combine to impact complex ecosystems.

Three years that represent characteristic climates in the basin were considered; 1982, a cold wet year; 1988, a warm dry year; and 1989, an average year. In addition, a year illustrating potential climate change was modeled. Damage potential was estimated seasonally using a scalar index to define the potential damaging effect of the season's "cold events." As will be described below, damage to plants commonly attributed solely to cold temperatures often is the summation of many other environmental and physiological factors. Unless all these processes are resolved, it is difficult to suggest that a model based on a single forcing alone can accurately identify damaged plant areas. Nonetheless, regions that have experienced temperature patterns, which have the potential to cause damage to conifer trees, can be identified with this prototype model.

The Annual Cycle

Cold damage to plants is a highly complex physiological phenomena. The term "cold hardiness" is used to describe the ability to survive freezing temperatures and this forms the basis for many of our seasonal indices. All plant life in areas prone to freezing temperatures must become cold hardy in order to survive. Cold hardiness is a difficult property to measure and predict because there are complex physiological interactions with the environment. To describe the present hardiness of a plant, a threshold temperature, or the lethal temperature, often is used (Timmis and Flewelling, 1994). This is the temperature at which damage to a fraction of the plants would be expected to occur. Lethal temperature describes a plant's present state of cold hardiness, which is a property of the species, the environmental forcing, and the physiological state of the plant. Not only is there substantial variation of cold hardiness within a family of species (Timmis and Flewelling, 1994), but different parts of a plant exhibit different levels of hardiness. For example, roots are much less tolerant of freezing temperatures than shoots (Havranek and Tranquillini, 1995).

During the summer growing season trees have minimum hardiness. The lethal temperature at which 50% mortality occurs (LT_{50}) varies depending on plant species, plant age, and part of the plant affected. Some values for various unhardened plant species have been determined in previous studies. Risto and Repo (1987) observed 50% mortality at -4 °C for two- to seven-week old Scots Pine. Burr and others (1990) found the stem LT_{50} to be -16 °C for Ponderosa pine (*Pinus Ponderosa* var. scopulorum) and -11 °C for Douglas fir (*Pseudotsuga menziesii* var. glauca) seedlings. Repo (1992) looked at previous-year shoots in 15- to 25-year old Scots pine and Norway spruce (Picea Abies) and found LT_{50} to vary between -3.5 °C and -7.0 °C. Berntsen (1967) observed mortality in Lodgepole and Ponderosa pine seedlings at -5 °C, with near 80%-90% mortality observed in both species at -9.5 °C. These temperatures often make allowances for a difference between the measured air temperature and the temperature at the surface of the plant due to radiational cooling. It has been shown that in extreme circumstances, plant surface temperatures may be as much as 6.5 °C cooler than measured air temperatures (Levitt, 1980), but more common values are on the order of one to two degrees (Cannell and Smith, 1984; Levitt, 1980). Generally, lethal temperature values used in models for unhardened conifer trees range from -2.5 °C to -6 °C.

In the autumn, plants begin to acquire winter hardiness. The dominant environmental forcings that induce hardiness are temperature and photoperiod (Levitt, 1980; Larcher, 1995). Water, nutrients, and genetic factors also play a role (Repo, 1992). Conifer trees in particular develop cold hardiness in a stepped process (Larcher and Bauer, 1981). The first step occurs as photoperiod decreases. The second step is from exposure to temperatures between 0 °C and 10 °C. It is during this second step that the rate of hardening is greatest (Burr and others, 1989). As plants are exposed to steadily decreasing temperatures, winter hardiness increases and lethal temperatures decrease. A substantial transition period into winter dormancy is a prerequisite for acquiring sufficient hardiness (Havranek and Tranquillini, 1995) and the process generally occurs in 4 to 6 weeks (Burr and others, 1989; Levitt, 1980). In addition, water resources influence winter hardiness; dry conditions induce hardiness while moist conditions suppress it (Levitt; 1980). A genetically controlled rhythmicity, precisely controlled by temperature and photoperiod (Havranek and Tranuillini, 1995), complicates the prediction of the hardening process.

This study quantifies three factors responsible for damage in the autumn. First, the affinity for the plants to grow, which has been shown to be related to temperature (Levitt, 1980). This is determined by calculation of the number of growing degree days. Second, the plant's exposure to temperatures in the optimum range to induce hardiness is determined. Finally, the smooth transition to colder temperatures is quantified by weighting daily minimum temperatures with time. A 30-day time period is used to determine the transition into winter hardiness. Photoperiod and water availability are not presently considered.

In winter, plants enter a state of dormancy and attainment of maximum cold hardiness is realized. In the first stage of dormancy, called the rest period, buds remain dormant regardless of the prevailing environmental factors (Hänninen and Pelkonen, 1988). Rest is broken, usually in midwinter, after the plant is exposed to a genotype-specific amount of time when temperatures are in the "chilling" range. A quiescent period follows and warm temperatures are required to cause dormancy release and bud break.

Warm spells have been shown to decrease winter hardiness, the degree of dehardening being proportional to both the duration and magnitude of the warming event (Levitt, 1980). A rapid decrease in temperatures following an unseasonably warm wintertime event has been shown to cause extensive damage, especially to trees less than 20 to 30 years in age (Van der Kamp and Worrall, 1990; Porter, 1959; Eiche, 1966; Horntvedt and Venn, 1980). Very young trees, however, often avoid midwinter damage while insulated by snow cover. Diurnal extremes in temperatures also have been shown to be harmful, especially large amplitude fluctuations about the freezing point (Levitt, 1980). For example, the "Red Belt" phenomena, common throughout both the Canadian and American Rockies, has been attributed to diurnal fluctuations about the freezing point (McHattie, 1963). Therefore, in estimating winter damage potential multiple day periods are considered. The degree of dehardening during the warm period is determined by using a growing degree days method. The rapidity and depth of the subsequent cold snap also is quantified and the winter potential damage index is based on these two values.

The spring dehardening process begins when plants are exposed to warmer temperatures and increasing photoperiod. Repo (1992) found that certain northern conifers deharden in the spring and harden in the autumn at about the same range of daily mean temperature, although spring dehardening occurs more rapidly than autumn hardening (Glerum, 1973). The timing of dormancy release and bud break is critical for identifying spring cold damage. Damage occurs to buds when an early onset of growth is followed by subsequent exposure to lethal temperatures. Cold hardiness also has been found to be at a seasonal minimum at the time of bud break (Burr and others, 1989). Spring cold damage is assessed by predicting a time period of dormancy release and budburst when the plants have minimum hardiness (Repo, 1992). A model developed by Hänninen (1990) is used for predicting dormancy release. Spring damage is a function of the fraction of trees which have ended dormancy and the low temperature encountered afterward.

Several studies (Timmis, 1994; Eiche, 1966; Berntsen, 1967) have found that damage to infant species and agricultural crops is most prevalent in spring, contrary to a 1962 study that states most damage to plants occurs during autumn (Washington State University, 1962). In forested ecosystems, however, the only documented cases of cold damage to mature trees have been those that occur during winter (Van der Kamp and Worrel, 1990; Porter, 1959). We did not weight damage in any season to be more significant than another season. Because of available data from winter-damage case studies, however, there is more confidence in the winter damage index than other seasons.

METHODS

The model determines potential damage to trees by identifying areas in which climatic events have exhibited temperature characteristics known to cause cold damage. To determine the frequency and spatial extent of cold damage across long time periods and large domains, several simplifying assumptions are necessary. First, rather than attempting to model the precise physiological state for the various species, the model concentrates on identifying and quantifying climatic effects on the plants. Because many physiological states were not explicitly resolved, several parameters in the model equations are only estimates of an actual condition. Also, input temperature values were interpolated spatially from observation sites throughout the basin (Running and Thornton, 1996). Although regression techniques were used to account for elevation effects and sophisticated statistical tools were used to interpolate observations, errors of several degrees in data sparse regions are possible. In addition, the spatial climate data were available only for the calendar year. This caused potential damage in both the beginning and the end of the calendar year to be missed.

First and last freeze day

The model begins by identifying the last freeze day (*LFD*) and first freeze day (*FFD*). These are the Julian day of the last and first time temperatures fall below a critical threshold. A threshold temperature of -3.4°C was chosen because it coincides with the chill unit value cited by Hänninen (1990) for use in his budburst model and it is slightly warmer than the average lethal temperature that damages unhardened trees. This allows the model to be more sensitive in areas where other stressors may have lowered the normal cold hardiness. Model iterations begin well in advance of normally expected first and last freeze days.

Autumn Potential Damage Index

In autumn the rate of growth is inversely related to hardiness (Levitt, 1980). Therefore, formulation of the autumn potential damage index (*APDI*) is determined by looking at the growing degree days in the 15 days preceding and 15 days following the first freeze day where it is assumed that sufficient winter hardiness will occur in 30 days. To quantify the growth, degree days were computed for each of the 15 days preceding the first freeze day, by assuming a linear diurnal temperature profile between the daily maximum and minimum temperatures,

$$
\begin{aligned}
GDD &= 0, && \text{if } T_X \le T_G, \\
GDD &= \sum_{i=0}^{1} \left[0.25 \times (T_X - T_G) \times \frac{(T_X - T_G)}{(T_X - T_{Ni})} \right], && \text{if } T_{Ni} \le T_G, \\
GDD &= \sum_{i=0}^{1} \ 0.5 \times [0.5 \times (T_X - T_{Ni}) + (T_X - T_G)], && \text{if } T_{Ni} > T_G,
\end{aligned}
\qquad (1)
$$

where T_X is the daily maximum temperature, $T_{Ni=0}$ is the daily minimum temperature, $T_{Ni=1}$ is the minimum temperature observed on the following day, and T_G is the growing threshold temperature.

In autumn, T_G is set at 7 °C, which was a consensus value from various studies (Timmis, 1994; Repo, 1992; Hänninen, 1990). The degree day is the area under the curve above the threshold growing temperature T_G. This function better approximates growing units than a standard mean value approach, which by design cannot account for large diurnal temperature fluctuations.

Total *GDD* units for the two week period are weighted to favor those closer to the day of first freeze,

$$GDD_{TOT} = \sum_{i=0}^{-15} 0.15 \times GDD_i \times \left(1 - \left| \frac{i}{15} \right| \right), \qquad (2)$$

where *I* is the iterative day before the *FFD*.

The empirically derived constant of 0.15 was determined by analyzing a few available 15-day temperature profiles that induced different levels of hardiness in conifers. The sparsity of data cause uncertainty in this constant. The function returns relatively low values of total growing degree days when temperatures are below the growing threshold T_G, and higher values when temperatures are above T_G.

The degree of hardening induced by cold temperatures was found by determining the chilling units (*CU*) in the 15 days prior to the first freeze date, a formula given by Hänninen (1990):

$$
\begin{aligned}
CU &= 0, && \text{if } \bar{T} \le -3.4, \\
CU &= (0.159 \times \bar{T}) + 0.506, && \text{if } -3.4 < \bar{T} \le 3.5, \\
CU &= (-0.159 \times \bar{T}) + 1.621, && \text{if } 3.5 < \bar{T} \le 10.4, \\
CU &= 0, && \text{if } \bar{T} > 10.4,
\end{aligned}
\qquad (3)
$$

where $\bar{T}$ is the daily mean temperature.

By determining the end of the rest phase in plant dormancy one can effectively isolate those temperatures that allow for maximum hardening in the autumn (Repo, 1992; Burr and others, 1989). The total chill units (CU_{TOT}) for the 15 day period is then given by,

$$
CU_{TOT} = 1 - \left[\frac{\sum_{i=0}^{-15} CU_i}{\sum_{i=0}^{-15} 1.0625 \times \left(1 - \left| \frac{i}{15} \right| \right)} \right], \qquad (4)
$$

where CU_i is the daily chill value and the index *I* iterates backward from the first freeze date.

The demoninator in equation 4 weights values closest to the current day with the constant, 1.0625, being the value of equation 3 when $\bar{T} = 3.5$ °C. This normalizes CU_{TOT} to range between zero and one, with zero indicating maximum hardiness (mean daily temperatures at optimum chilling value).

The temperature profile in the days following the *FFD* are important in determining damage potential. To include this important time period into the model, a formula for quantifying the transition to colder temperatures was derived. The total weighted extreme (WE_{TOT}) is the summation of the severity of the low temperatures for the 15 days following the *FFD*,

$$WE_{TOT} = \sum_{i=0}^{15} 0.13 \times (T_{Ni} - LT_{50}) \times \left(1 - \frac{i}{15}\right), \qquad (5)$$

where T_{Ni} is the daily minimum temperature, I is the iterative day following the *FFD*, and LT_{50} is the lethal temperature at which 50% mortality occurs (-3.4 °C).

The constant 0.13 is an assumed value that attempts to quantify the transition to cold conditions, which has been qualitatively described in literature (Burr et al. 1989; Levitt 1980; Havranek and Tranquillini 1995). This function determines how smoothly daily low temperatures transition into a colder state. Relatively abrupt transitions yield high values, smooth transitions smaller values. The autumn potential damage index (*APDI*) is the product of the three values,

$$APDI = GDD_{TOT} \times CU_{TOT} \times WE_{TOT}. \qquad (6)$$

Low values of the *APDI* indicate slow growth with optimal hardening temperatures and a smooth transition to colder temperatures.

Winter Potential Damage Index

The winter damage portion of the algorithm first identifies days during the winter season that show an abrupt transition from relatively warm (above freezing) to very cold temperatures. The model identifies periods of rapid onset of extreme cold temperatures during the winter period, defined here as the period between the first freeze day and the last freeze day. To qualify as a rapid onset to extreme cold event, two criteria must be met. First, the weighted temperature change (*WTC*), which quantifies the rapidity of the onset of cold temperatures, must exceed a threshold value. Second, the cold temperatures must be low enough to cause damage. Previous winter damage studies (Van der Kamp and Worrall, 1990; Eiche, 1966; Levitt, 1980) attributed midwinter damage to both dehardening and the subsequent rapid onset to very cold temperatures. In all cases the onset of cold temperatures was completed within four days, with damage being proportional to both the rate of onset and the degree of cold temperatures. The functional form of a weighted temperature change (*WTC*) was quantified by analyzing the observed temperature change in a four day period from available winter-damage case studies (Van der Kamp and Worrall 1990; Porter 1959):

$$WTC = \sum_{i=1}^{4} \left[\frac{\left(\bar{T}_0 - \bar{T}_i\right) - 16}{6} \right] e^{-\frac{(i-1)}{2}}, \qquad (7)$$

where $\bar{T}_0$ is the mean temperature on the day in question and $\bar{T}_i$ is the mean temperature the four following days.

An exponential decay constant of 2 days is estimated from the previous literature studies (Van der Kamp and Worrall, 1990; Levitt,1980; Eiche, 1966). This allows temperature values on days closest to the onset of the cold temperature to be weighted more heavily than those later in the four day period. When *WTC* is greater than one the 'rapidity of onset' criteria is met. This threshold value was determined by examining the temperature time series for several separate damage events. If the temperature on any of the four iterative days is lower than the critical temperature of -3.4°C, the extreme cold criteria is met.

After a rapid onset to cold temperature event is identified, the amount of "warmth" preceding the event is determined using the growing degree method described in equation (1). In this case, however, the value of T_G is 0°C, a temperature above which rapid winter dehardening has been observed (Repo, 1992; Burr and others, 1989). Only ten days, instead of 15, prior to a rapid cold onset event are examined to determine the degree of dehardening because winter dehardening usually occurs in less than this time (Levitt, 1980). The dehardening is quantified by finding the average of the growing degree days before the onset of the cold,

$$GDD_{Avg} = \sum_{i=0}^{-10} \frac{GDD_i}{10}. \qquad (8)$$

The winter potential damage index (*WPDI*) is given by,

$$WPDI = WTC \times GDD_{Avg}. \qquad (9)$$

The index was calibrated by adjusting the constants in equation 7 to give values between zero and ten when added to GDD_{Avg}. A *WPDI* value of ten is indicative of a very warm 10 day period (maximum dehardening) followed by extremely rapid onset to much colder temperatures.

Spring Potential Damage Index

Determining the date of dormancy release and bud break is essential in ascertaining damage in spring. Unfortunately it is difficult to predict. The model used for determining bud break was developed by Hänninen (1987) who analyzed dormancy release in northern European conifer forests. This model assumes a rest period that ends when a critical sum of genotype specific chilling units (equation 3) has been achieved, followed by a quiescent period during which forcing units (*FU*) are accumulated,

$$\begin{aligned} FU &= 0, && if\ \bar{T} \leq 0, \\ FU &= \frac{28.361}{1 + e^{\left[-0.185 \times \left(\bar{T} - 18.431\right)\right]}}, && if\ \bar{T} > 0, \end{aligned} \qquad (10)$$

where $\bar{T}$ is the daily mean temperature.

Dormancy release and subsequent bud break takes place when the sum of forcing units attains a genotype-specific critical value. The model is very sensitive to the critical definition for summed values of *CU* and *FU*, which varies according to species. Hänninen (1990) found values of 30 to 50 for CU_{crit} and 100 for FU_{crit} during a research winter (1963-1964) in central Finnish Scots pine.

To account for the broad range in CU_{crit} and FU_{crit}, the fraction of trees that reach budburst on any given day is approximated with two indices; the earliest dormancy release day (*EDRD*) and the latest dormancy release day (*LDRD*). Each index is the sum of *CU*s and *FU*s since the beginning of the winter season. Because our input data began on January 1, however, we assume that CU_{crit} is satisfied before then, which appears reasonable (Hänninen, 1990). Therefore, only force units are summed to determine each index. The critical sum of *FU*s for EDRD is approximated to be 75 and FU_{crit} for LDRD is approximated to be 150. These values are somewhat arbitrary but do not differ greatly from those determined by Hänninen. The dormancy release ratio (*DRR*) is the fraction of trees that reach budburst on day *I*,

$$DRR = Min\left[\frac{(i-EDRD)}{(LDRD-EDRD)},\ 1\right]. \qquad (11)$$

Because there is a degree of uncertainty in the actual values for force units, the dormancy release ratio is used to provide a time period of dormancy release, rather than a specific day. Further research in dormancy release and budburst would allow refinement of these values. The spring potential (*SPDI*) damage index is then found by,

$$SPDI = Max\left[DRR \times \left(T_B - \bar{T}_i\right),\ 1\right], \qquad (12)$$

where T_B is the threshold budburst temperature (0°C) and $\bar{T}_i$ is the mean temperature on day *I*.

The value will produce a maximum of ten if there is 100% budbreak (trees at minimum hardiness) at the time temperatures fall below -13.4 °C, the temperature at which maximum damage is expected to all parts of the conifers (Glerum, 1973; Burr and others, 1989; Repo, 1992). If the *EDRD* follows the last freeze day a value of zero will be returned, indicating no potential for damage.

RESULTS

Potential damage plots were generated for each seasonal component in 1982, 1988, and 1989. These years were selected by the Interior Columbia Basin Ecosystem Management Project's Scientific Integration Team (see U.S. Department of Agriculture, Forest Service, 1996 for a description of the project) to help show characteristic climate patterns in the basin. The criteria for selection was based on mean annual temperature and total annual precipitation. The year 1982 was a cold, wet year; 1988 was warm and dry; and 1989 was close to normal. Daily observation data were distributed over the landscape at 2 km spatial resolution by Thornton and Running (1996) using their model, MTCLIM-3D. These data were used as input to the potential cold damage algorithms.

In 1982, only spring showed any appreciable potential damage (Figure 1). Substantial potential for damage is located in southeastern Oregon, and to a lesser degree, southern Idaho. Average to above average temperatures were observed in these areas from late February to early April, at which time a cold outbreak occurred. Record breaking cold temperatures were encountered with frost damage a "major concern" in eastern Oregon (U.S. Department of Commerce and U.S. Department of Agriculture, 1982). Damage was noted to peach trees.

Characterized as a warm, dry year in the region, the 1988 spring potential damage plot (Figure 2) again shows the potential for moderate damage across south central Oregon. The autumn potential damage plot (Figure 3) shows a limited area of significant potential for damage in north central Nevada. No reports, however, were found of any type of damage anywhere in region. There were no potentially damaged areas identified in the winter plots.

The winter potential damage plot for 1989 (Figure 4) highlights areas of damage throughout western Montana and northwestern Wyoming. This plot is generally consistent with damage areas identified by Klein (1989) in his research of this event that occurred in early February. Figure 5 shows the temperature profile at Helena, Montana during this event. Temperatures fell below -30 °C for several days in 1989 at locations throughout western Montana. Although the rest of the basin also experienced cold February temperatures, cold damage potential was not triggered in Oregon until spring (Figure 6). Damage to fruit trees was observed in Oregon throughout the spring (U.S. Department of Commerce and U.S. Department of Agriculture 1989). The spring damage index may have been triggered by warmer that normal January temperatures that could have caused the sum of forcing units to exceed 75 early in the month.

In all years, the model identified significant areas of potential damage at very high elevations. These areas include the Wind and Absoroka Ranges in Wyoming, the Bitteroot and Rocky Mountains in Montana, and several other ranges in Idaho, Oregon and Nevada. These areas most often are at or above current tree-line. When imposing the model on a climate change scenario (Ferguson 1997) we see that damage at high elevations is expanded (Figure 7), perhaps due to weaker or shorter hardening periods caused by warmer overall temperatures (Becwar and Burke, 1982). Note that this change scenario assumes the same daily variation as 1989 and, because cold damage is a function of daily sequences, a true examination of climate change impacts on cold damage potential should consider changes in daily variability.

DISCUSSION

The most obvious observation from the seasonal potential damage plots is the prevalence of potential spring damage in the basin, especially the southern portions. Although there is some basis for damage in these areas, especially in the 1982 season, it appears that the values used for dormancy release may not be applicable to the entire basin, particularly in the more southern regions. This is not surprising, as the values for forcing units, and the dormancy release model itself, were taken from a study of conifers in northern Europe. It is expected that this model would be more applicable to conifers in the northern regions of the basin. Further research into dormancy release is needed to improve this portion of the model.

The absence of appreciable areas identified as potentially damaged in autumn is expected. This is consistent with observations that spring damage is more prevalent than fall damage (Timmis and Flewelling, 1994; Berntsen, 1967; Eiche, 1966). The verification sources made no mention of significant areas of autumn damage in any of the three years. Also expected was the relative infrequency of potentially damaged areas in the winter season. There is some confidence in this result because, unlike autumn and spring indices, no assumptions about growth characteristics were needed to determine winter damage potential and a few available winter case studies helped to tune the index equations.

A shortcoming of the present study was the consideration of damage within the calendar year. Cold damage, as defined in this study, only occurs in the time period between the first and last freeze days. A better approach would be to examine a wintertime season in its entirety. The consideration of a calendar year created problems in both the formulation of the winter and spring potential damage indices. In the case of the winter damage potential, the model determines the degree of dehardening due to warm temperatures in the 10 days leading up to the cold event. If this event occurred before January 10th, assumptions had to be made concerning earlier temperatures.

As for the spring potential damage, Hänninen (1990) began accumulation of chilling units on September 1st. Others have used the autumn first frost day, the day of greatest accumulation of autumn chilling units, or November 1st. For this study it was assumed that chill units had already been satisfied as of January 1st due to the lack of temperature data in the preceding months. This will introduce some error into the correct prediction of the dormancy release dates. Another problem was that the FU_{crit} values were based on studies of trees in central Finland, which may or may not be applicable to conifers within the Columbia River basin. A wide separation between the earliest and latest dormancy release days is a consequence of this. Specifically, further research on CU_{crit} and FU_{crit} values that are more representative to the local species is needed. Also, the prediction of dormancy release needs improvement and future studies should examine water years rather than calendar years.

As stated earlier, model parameters were selected to simulate worst case conditions because there are a number of processes not explicitly resolved. Inclusion of these other processes (i.e., water relations, snowpack, photoperiod, etc.) into future models would allow the seasonal indices to be refined.

There was no correlation found between the generalization of the year's climate (i.e., wet or, warm or cold, etc.) and the identification of regions of potential damage. This also is to be expected because water relations were not considered in the model and damage to plants is not ordinarily the result of average temperature conditions. Rather, damage most often is the result of a unique sequence of daily events in which low temperatures exceed the present hardiness of the plant. Indeed, colder than normal seasonal averaged temperatures would induce a greater degree of hardiness in the plants (Levitt, 1980; Burr and others, 1989), making them less likely to deharden during a warm spell.

Several improvements or modifications would greatly increase the applicability and accuracy of the model. They include:

a) Adapt the model to other species and input mapped vegetation-type data to determine cold damage potential across the landscape. Currently the model considers only conifer species. Therefore, it produces unrealistic results in desert and steppe regions and at high elevations above tree-line.

b) Wind is important in determining damage in all seasons. In basins and valleys wind can help reduce the risk of freezing damage by mixing the lower planetary boundary layer and decreasing the low level temperature inversion. More commonly, however, winds during an arctic outbreak can enhance damage by increasing evaporative heat loss.

c) The insulating effect of a winter snowpack is critical for the survival of younger trees. Insulation effects are so dramatic that snow level can be determined by the level on the tree at which damage is noted, which often is at or slightly above snow level (Eiche, 1966). Also, the absence of an insulating snowpack significantly increases the threat of damage to roots (Levitt, 1980), roots having hardiness levels much lower than the above ground portions of the plant.

d) Photoperiod is a major factor in the inducement of hardening in the fall. Because plants adapt to the forcing of their microclimate, attempting to resolve the dependence of hardiness on photoperiod in a highly orographic and heterogeneously vegetated region is difficult. A method to implicitly take this into account would be to determine the normal first and last frost days at each grid point. If one considers photoperiod to be the sole forcing for the inducement of hardiness, an earlier than normal frost would find the plants less hardened, a later than normal frost more hardened. This type of analysis will be possible when long-period daily time series of temperature data for high-resolution grid points becomes available.

e) Many studies have shown the relationship between deviations from average rainfall and level of normal hardiness attained. Differences between a statistical average summer rainfall and the actual summer rainfalls could be determined. The variable could act to decrease both the degree and rate of hardening in the autumn. Also, in growing seasons following cold damage episodes, below normal rainfalls have been shown to increase mortality while above normal rainfalls aid in the recovery of the injured plants (Eiche, 1966).

f) A more consistent method for determining damage would be to explicitly model the LT_{50} temperature of the conifer species within the region throughout the entire winter season (see Timmis and Flewelling, 1995). Temperatures that are lower than the current LT_{50} temperature of the specie would indicate damage at a particular location. The difficulties in this approach are the large genetic variations between species and sub species within a large geographic region. The present lack of specific values required to accurately model one plant's physiological state at a particular location is a major difficulty, the only solution at present may be to continue with a descriptive model. One may expect that a relationship between chilling (or forcing) units and statistical mean growing degree days, freezing degree days, etc., may be found for conifer species. Further research in this area is needed.

g) Damage and mortality of plants is a complicated phenomena seldom attributable to a single factor or event. Rather than determining potential damage from a single forcing in isolation, all the separate forcings should be included in a comprehensive model. Rather than identify regions of potential cold damage, develop an index reflective of the present health state of the forest. The index should encompass the physiological and environmental processes responsible for the deterioration or recovery of the stand, all of which are interdependent and should not be considered in isolation from one another. The phenomena and associated potential for causing damage (or a weakened state) would be carried forward in time, being allowed to interact with future environmental events. Identification of areas of potential ecosystem stress or damage would allow land managers to objectively assess the health of a forest. As stated earlier, the manifestations of damage are often not conspicuous. A forest area may be in a weakened state, making it vulnerable to other threats such as disease or insects, but not outwardly appear so. An objective appraisal of forest health would provide a tool for managers to identify areas where additional resources may need to be allocated or aid in decisions concerning the long term use of forested lands.

Despite the limits of this prototype model, it is able to identify potential cold damage across a landscape with readily available climate data. Also, it has identified significant gaps in our current understanding of temperature effects at landscape scales and provides a framework for which more comprehensive models can be developed. Subsequent maps can be overlain with other data layers in a Geographical Information System (GIS) to help anticipate and plan for the effects of cold damage, in combination with other disturbance agents, on forested ecosystems.

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LIST OF FIGURES

Fig 1

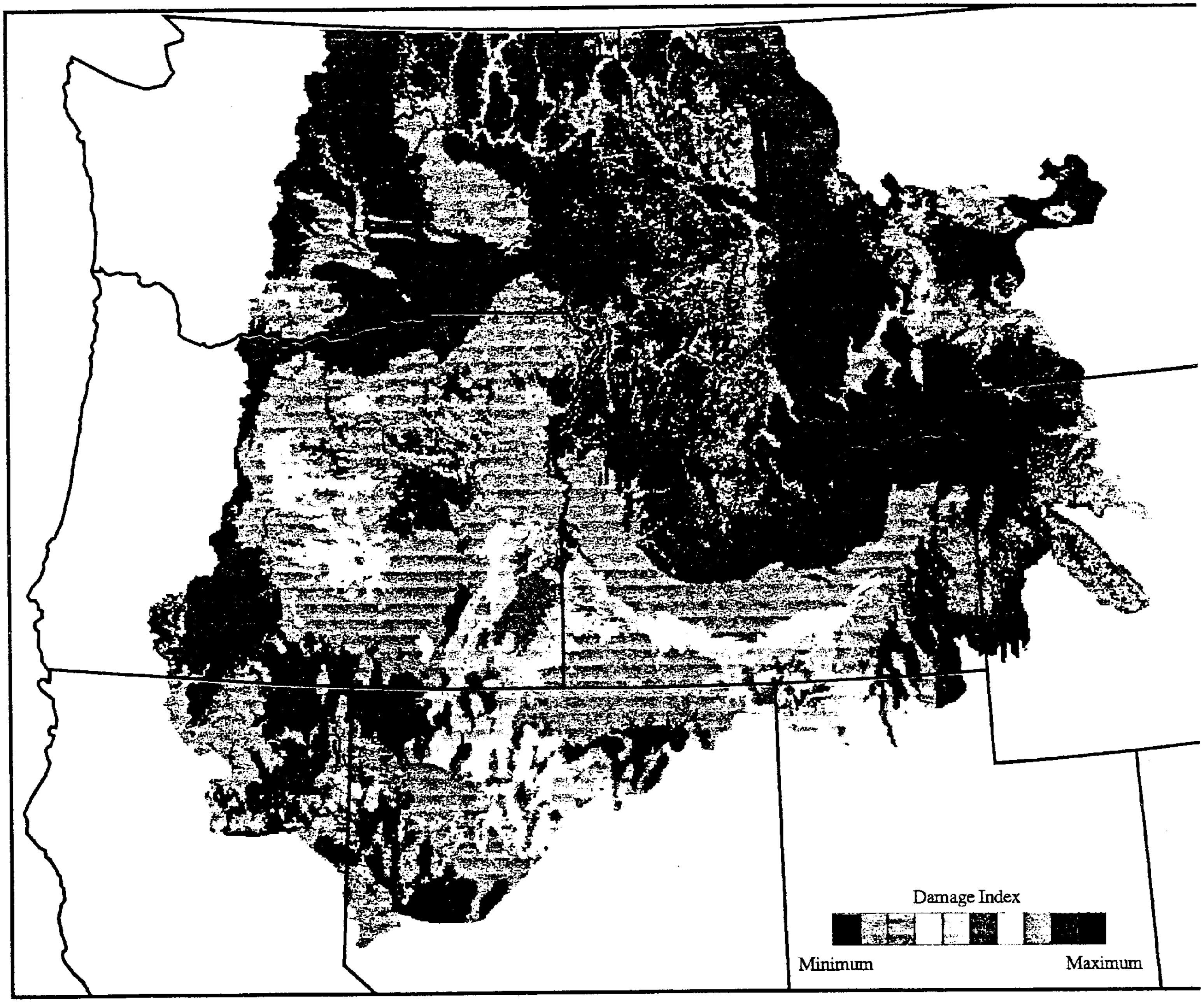


Fig 2

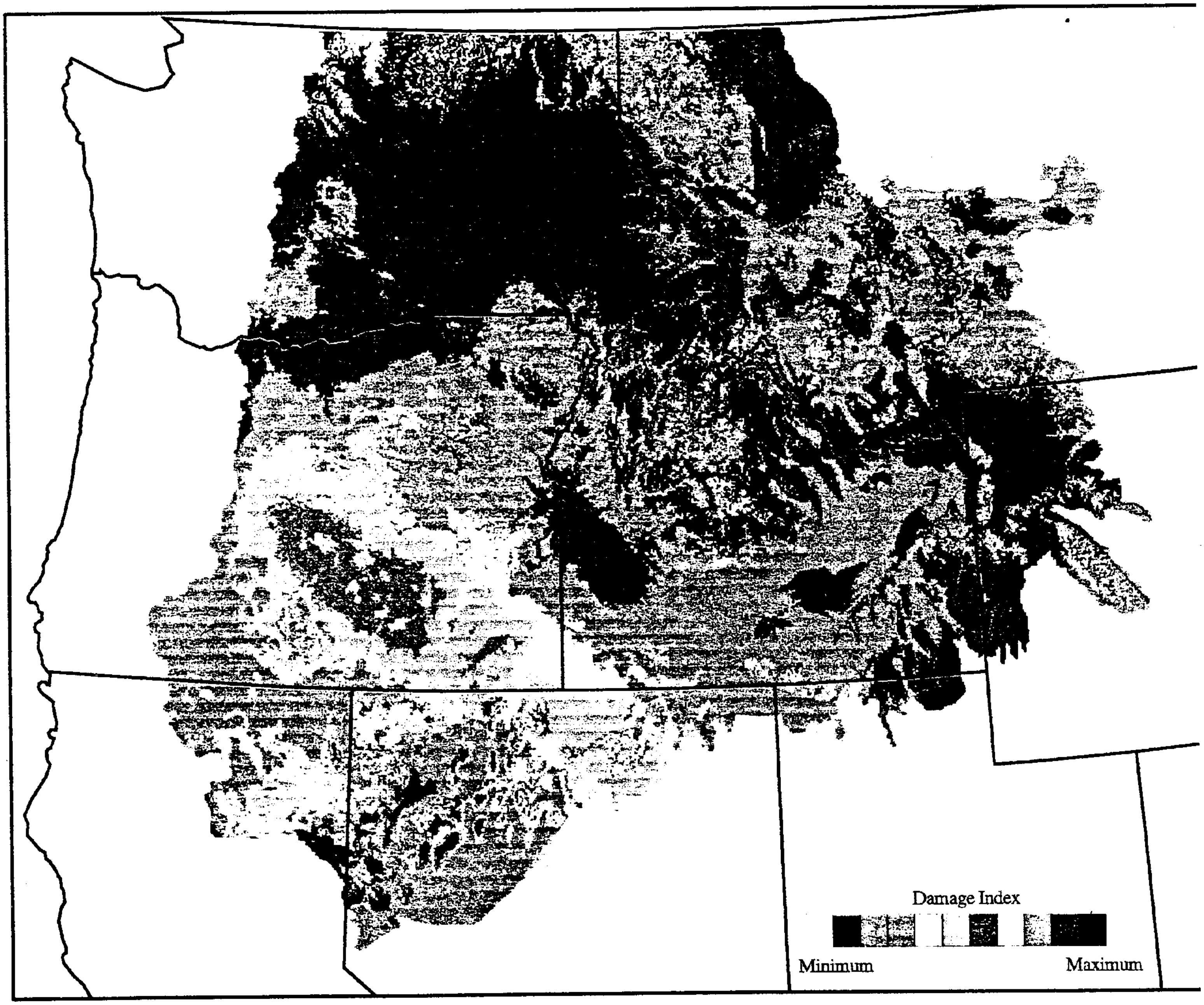
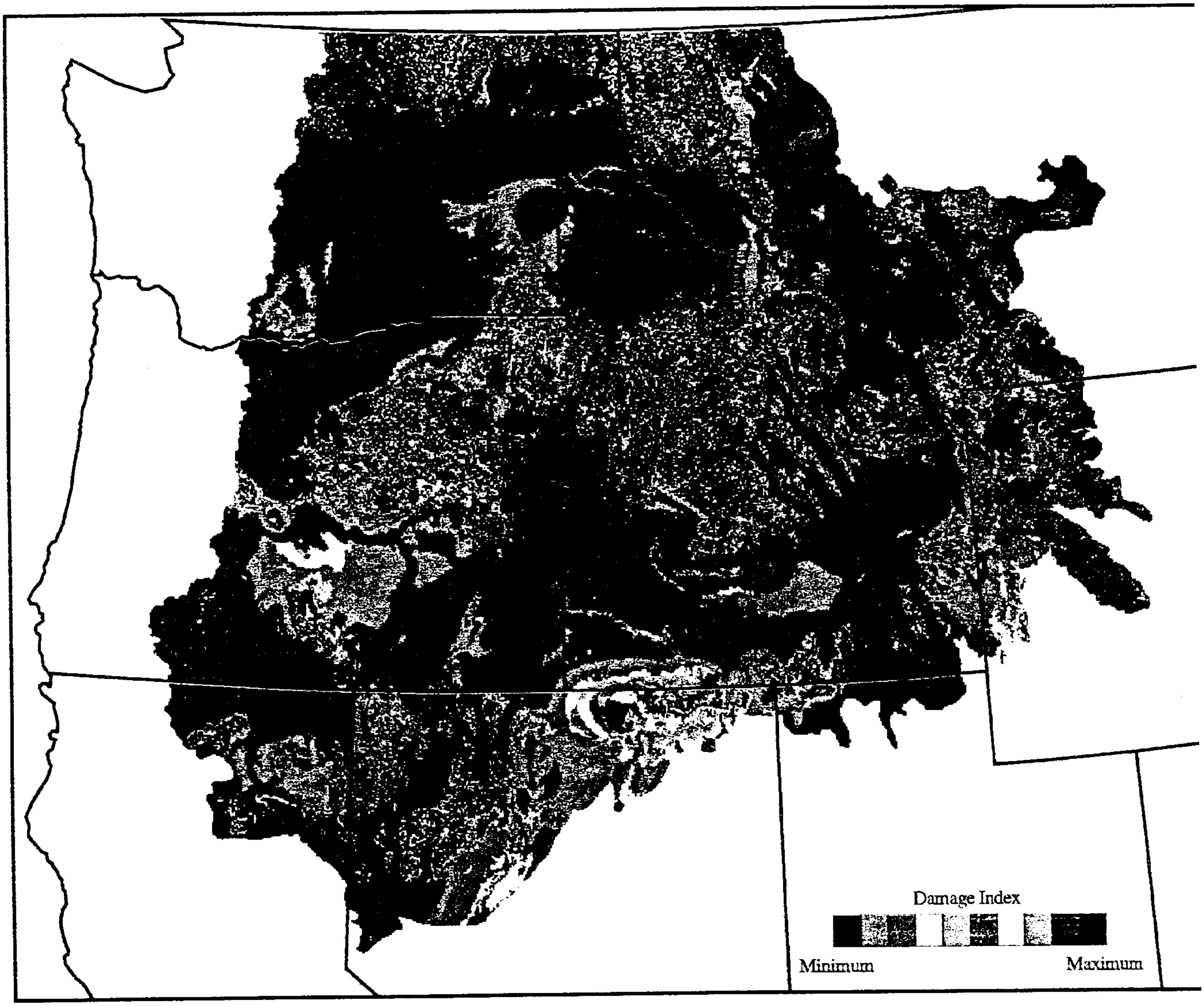


Fig 3



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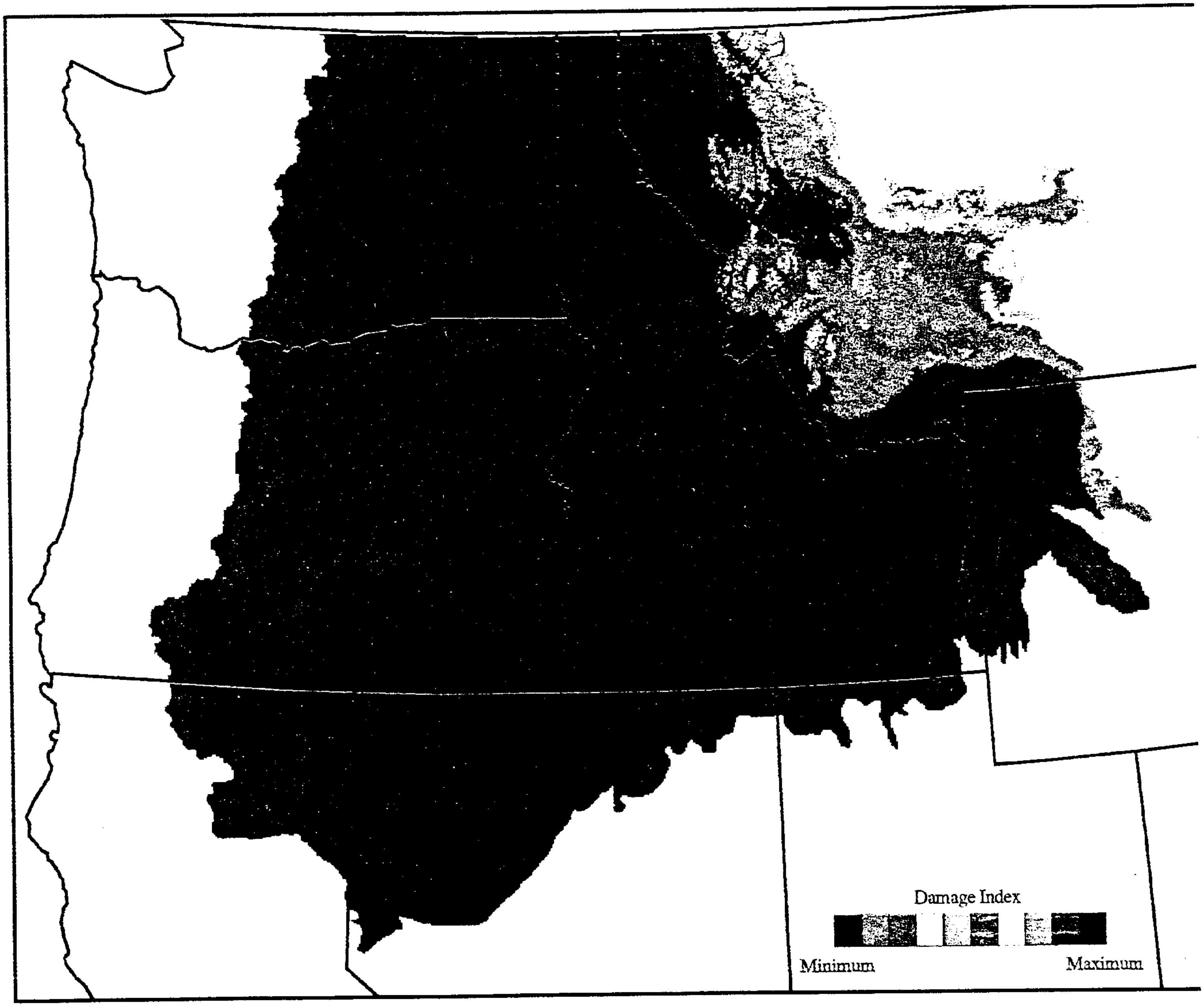
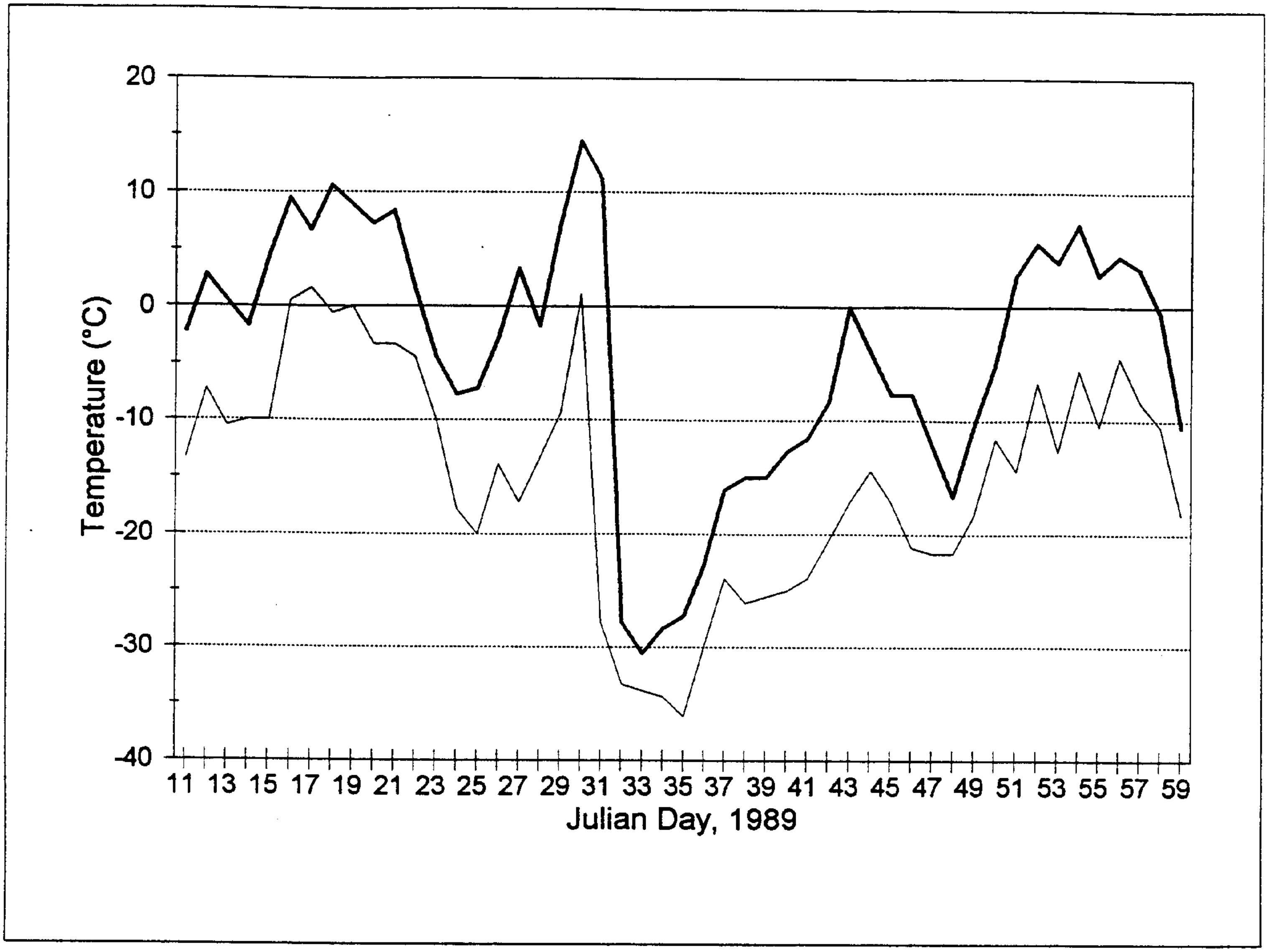


Fig 5



20
10
0
-10
-20
-30
-40
Temperature (°C)
11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49 51 53 55 57 59
Julian Day, 1989

Fig 6

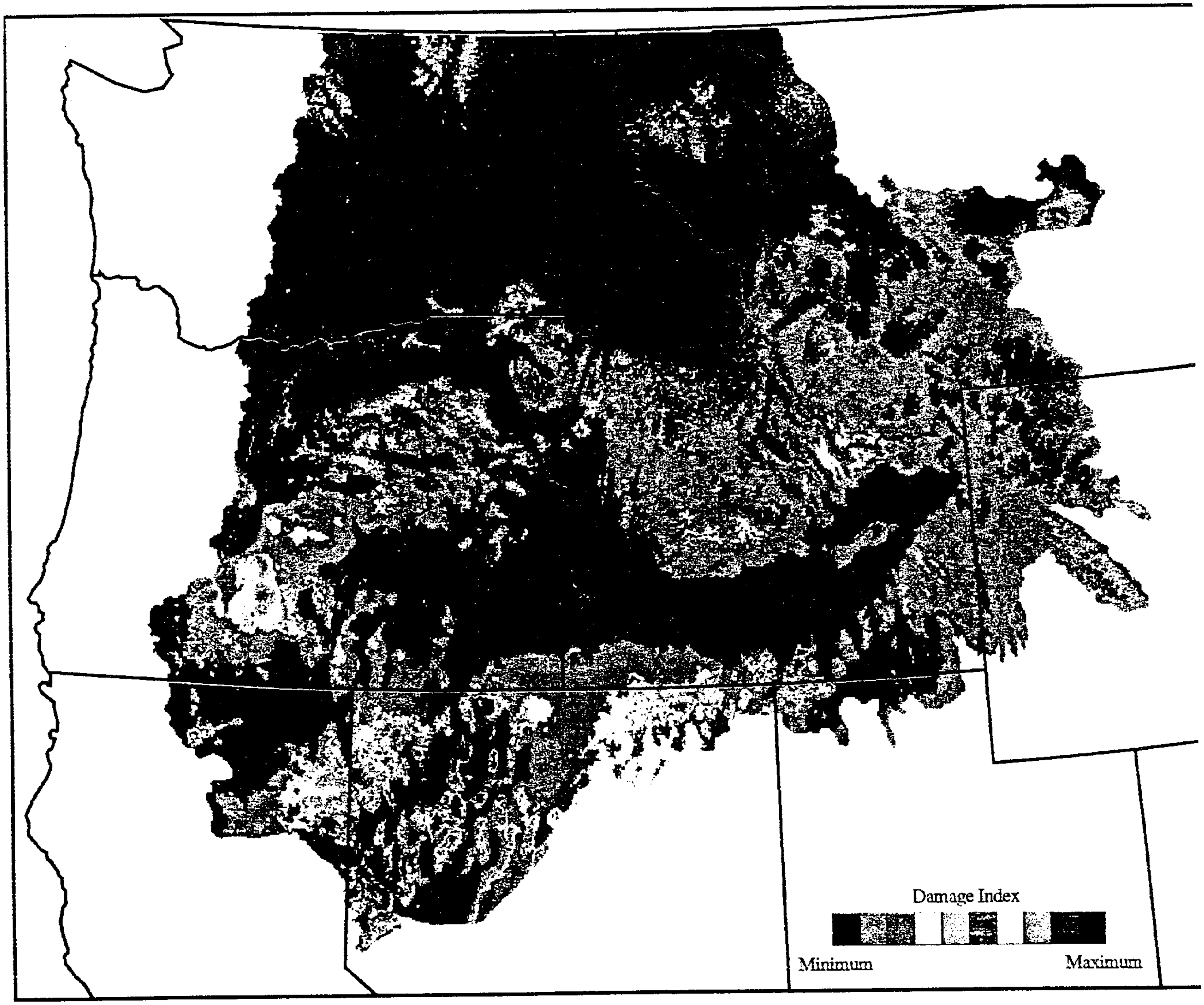


Fig 7