United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

General Technical
Report
PNW-GTR-355
October 1995

Historical and Current Forest Landscapes in Eastern Oregon and Washington.

Part II: Linking Vegetation Characteristics to Potential Fire Behavior and Related Smoke Production

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Robert E. Vihnanek, John F. Lehmkuhl,
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From Volume III: Assessment

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Eastside Forest Ecosystem Health Assessment

Richard L. Everett, Assessment Team Leader

Published by:
U.S. Department of Agriculture, Forest Service
Pacific Northwest Research Station
General Technical Report PNW-GTR-355
October 1995

In cooperation with:
U.S. Department of Agriculture, Forest Service
Pacific Northwest Region

Abstract

Huff, Mark H.; Ottmar, Roger D.; Alvarado, Ernesto; Vihnanek, Robert E.; Lehmkuhl, John F.; Hessburg, Paul F.; Everett, Richard L. 1995. Historical and current forest landscapes in eastern Oregon and Washington. Part II: Linking vegetation characteristics to potential fire behavior and related smoke production. Gen. Tech. Rep. PNW-GTR-355. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 43 p. (Everett, Richard L., team leader; Eastside forest ecosystem health assessment; Hessburg, Paul F., science team leader and tech. ed., Volume III: assessment.)

We compared the potential fire behavior and smoke production of historical and current time periods based on vegetative conditions in forty-nine 5100- to 13 5OO-hectare watersheds in six river basins in eastern Oregon and Washington. Vegetation composition, structure, and patterns were attributed and mapped from aerial photographs taken from 1932 to 1959 (historical) and from 1981 to 1992 (current). Vegetation with homogeneous composition and structure were delineated as patches. Each patch was assigned a potential rate of spread, flame length, fuel loading, and smoke production from published information that matched the closest characteristics of the vegetation and downed fuels and assigned a uniform fuel moisture, wind speed, and slope. Potential rate of spread of fire, flame length, and smoke production were highly variable among sample watersheds in any given river basin. In general, rate of spread and flame length were positively correlated with the proportion of area logged in the sample watersheds. There were large increases in potential smoke production from the historical to the current periods for many sample watersheds due to changes in fuel loadings associated with management activities and, presumably, fire suppression. Wildfires were shown to produce nearly twice the amount of smoke as prescribed fire for the current period for all river basins. Understanding these and other tradeoffs will assist managers and society in making informed decisions about how to implement prescribed fire and manage wildfire to address air quality and forest health problems. Because of the variability of fuel or vegetative conditions observed among the sample watersheds, we recommend an extensive characterization of these conditions before large-scale restoration and maintenance of fire-related processes are undertaken.

Keywords: Air quality, emissions (PM10), fire risk assessment, fire management, fuel loading, landscape-level assessment, smoke management.

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INTRODUCTION

Ecological diversity in eastern Washington and Oregon is rich and complex owing to different climates, landforms, and natural processes (Daubenmire and Daubenmire 1968, Franklin and Dyrness 1973, Thomas 1979). Processes strongly linked to recurring fires have been critical to maintaining this diversity (Agee 1981, 1990; Hall 1976). Ecological characteristics of a broad range of terrestrial communities from dry sagebrush to mesic high-elevation subalpine environments are closely related to recurring fires (Agee 1993). Natural fire regimes range from low-severity frequent fires, typified by the ***Pinus ponderosa*** series, to high-severity infrequent fires characteristic of subalpine forests.

The dynamic role fire plays in framing landscape attributes is exceedingly complex (Turner 1987, 1989). Myriad variables, primarily related to weather, topography, and fuel characteristics, interact to define fire occurrence, behavior, and effect on biotic communities, including vegetation composition and structure (that is, fuels; see for example, Agee 1994, Kauffman 1990) and abiotic resources (such as air quality; for example, Ottmar 1993, Peterson 1993). At a landscape scale, patch size, shape, extent, patterns, and diversity of structure and composition among patches (area of relatively homogeneous structure and composition) are strongly influenced by past fires (for example, Agee 1990, Heinselman 1973, Hemstrom and Franklin 1982) and other disturbances, such as insect and disease outbreaks (for example, Anderson and others 1987, Gara and others 1985, Stuart and others 1989) and timber harvesting (Franklin and Forman 1987, Ripple and others 1991, Spies and others 1994).

Little information is available on how shifts in forest composition and structure over long periods have changed potential fire behavior (hereafter, fire behavior) and affected related smoke production across landscapes. Studies have focused primarily on fuel and fire behavior characteristics at the stand (patch) level and how fuel characteristics differ for various forest conditions (for example, Brown and See 1981, Fahnestock 1976). Fuel and fire behavior characteristics have been quantified extensively in the Pacific Northwest and other regions through a photo series approach (for example, Fischer 1981, Maxwell and Ward 1980). In this approach, prototypes of potential fire behavior were modeled at the stand scale based on composite forest structure and composition and fuel characteristics under given topographic and weather constants. This information is available for a wide variety of vegetation communities and structural conditions, so that the effects of vegetation change on fuel conditions could be evaluated at the landscape scale as an assemblage of patches having various potentials for fire behavior and related smoke production.

The objectives of this study were to examine changes in vegetation structure and composition in eastern Oregon and Washington from about 35 to 50 years ago to the present and to project the effects of vegetation changes on potential fire behavior and production of smoke. Our study questions were, (1) Has potential fire behavior and smoke production from fire changed since the 1930 to 195Os? (2) Have management activities over the last 35 to 50 years influenced the current potential fire behavior patterns and smoke production? and (3) What are the tradeoffs in fire behavior potential and production of smoke for managed fire, wildfire, and forest health?

This is the second paper of a two-part study. Each study part compared the biological and physical conditions of six river basins in eastern Oregon and Washington between the same historical and current periods. Part I examined vegetation composition and patterns and associated insect and disease hazard (Lehmkuhl and others 1994).

METHODS

Design

Our study focused on National Forest lands in six river basins: the Pend Oreille, Methow, Wenatchee, and Yakima basins of eastern Washington, and the Deschutes and Grande Ronde basins of eastern Oregon (fig. 1). Each river basin was divided into watersheds ranging from 5100 to 13 500 hectares. Watersheds were grouped, depending on basin size, into two to eight subbasin strata to distribute a random sample of watersheds evenly across the basin. At least 15 percent of the area within each stratum was sampled, hence the number of sample watersheds differed among strata and river basins (table 1). We eliminated strong biases associated with variable watershed sizes by delimiting large watersheds; Lehmkuhl and Raphael (1993) report that landscape pattern variables do not vary significantly as a function of landscape area when landscapes are large (> 3250 hectares).

Mapping

Mapping teams were formed to interpret historical and current dominant vegetation composition and structure from aerial photographs for the selected watersheds within the six river basins. Historical vegetation was mapped primarily from archived black and white aerial photographs, l:20,000 scale, taken from the 1930s to the 1950s. Our initial goal was to limit the historical period to aerial photographs from the 1930s to 1940s; however, photographs of that vintage were not available for some of the sample watersheds, and 1950-era photographs had to be substituted as needed (table 1). Current aerial photographs were in color and 1:12,000 scale.

Personnel at National Forests who have field experience and expert knowledge of local conditions within a given river basin interpreted the physical features and vegetation composition and structure of each sample watershed from the photographs. Standardized criteria for delineating vegetation patches and mapping procedures were established, and one photointerpreter attributed vegetation composition and structure and characteristics of both current and historical watershed samples.

Patches were defined as areas of homogeneous vegetation in both composition or structure and included physical features, such as lakes and rock outcrops $\geq$ 4 hectares. The delineated information was transferred to Mylar overlays on geo-referenced orthophotographs.[1] Mylar map quads of sample watersheds were digitally scanned, edited, and edge matched by using the LT + software, and then entered into the ARC/INFO geographic information system (GIS) software. Attributes (for example, dominant tree species) of each patch were interpreted and numerically linked to the digitally scanned maps.

Patch attribute data derived by photointerpretation formed the basis from which all subsequent analyses were done. Overstory species composition and stand structural class attributes were combined to classify patches into structural-vegetation types (hereafter, vegetation types). The structure classes were estimated as seedling-sapling-pole-l canopy layer and trees $\leq$ 13 centimeters in diameter at breast height (d.b.h.); young-2 canopy layers, overstory trees - 13 to - 40 centimeters d.b.h. and understory trees $\leq$ 23 centimeters in d.b.h.; mature- $\geq$ 2 canopy layers, overstory -41 to -64 centimeters in d.b.h. and understory $\leq$ 40 centimeters in d.b.h.; mature parklike-l or 2 canopy layers, overstory $\geq$ 40 centimeters in d.b.h. and understory absent or $\leq$ 13 centimeters in d.b.h.; and old forest- $\geq$ 2 canopy layers, overstory trees $\geq$ 64 centimeters in d.b.h. and understory - 13 to - 64 centimeters in d.b.h. The primary overstory species or species groups were ponderosa pine *(Pinus ponderosa* Dougl. ex Laws.), western larch (Larix occidentalis Nutt.), lodgepole pine (P. *contorta* var. *latifolia* Engelm.), Douglas-fir *(Pseudotsuga* ***menziesii*** (Mirb.) Franco), grand fir *(Abies grandis* (Dougl. ex D. Don) Lindl.)/white fir (A. concolor (Gord. & Glend.) Lindl. ***ex*** Hildebr.), Pacific silver fir ***(A. amabilis*** Dougl. ex Forbes), subalpine fir (A. *lasiocarpa* (Hook.) Nutt.)/Engelmann spruce *(Picea engelmannii* Parry ex Engelm.),

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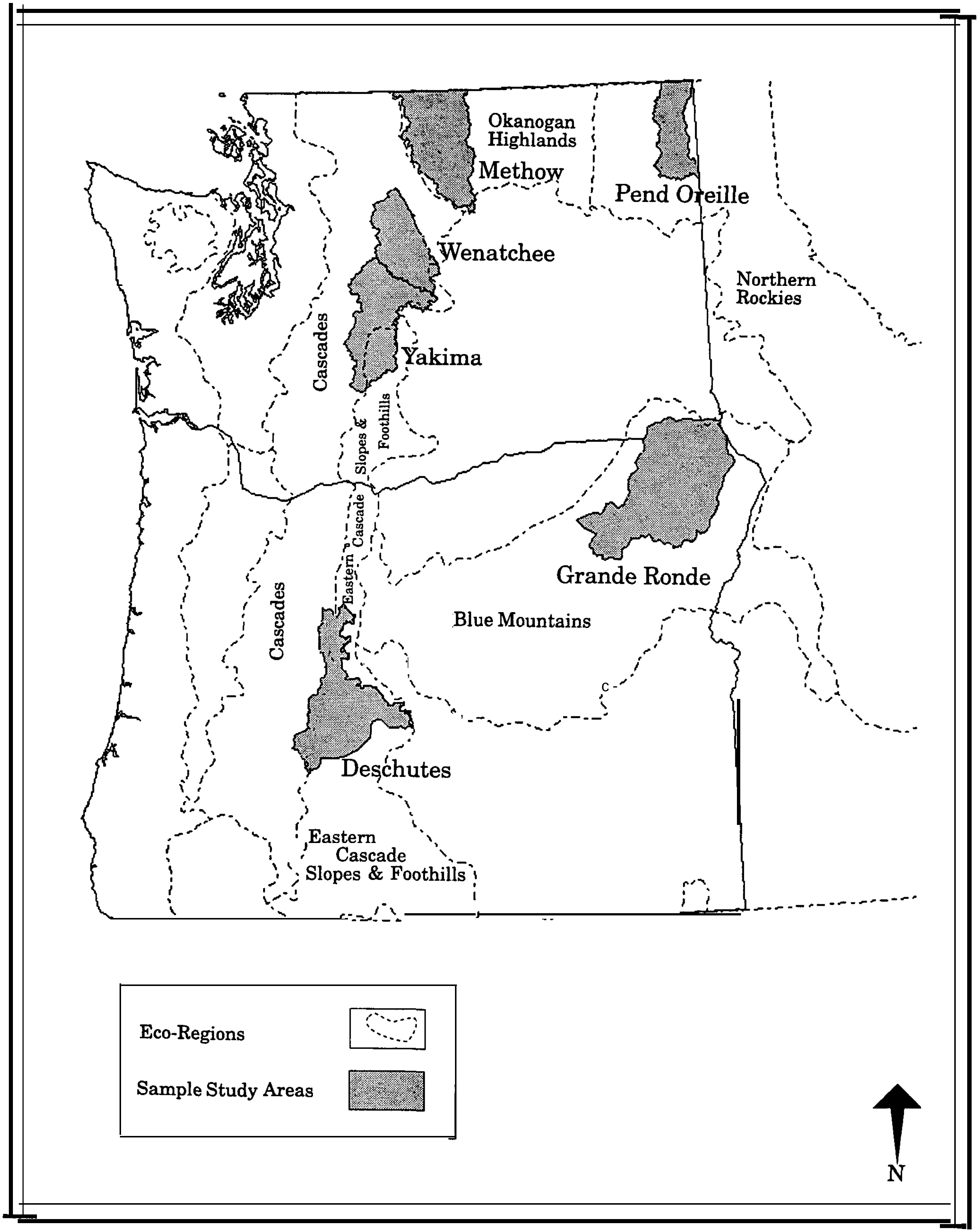

Figure 1 —Location of the six river basins studied in eastern Washington and Oregon.

western hemlock (Tsuga *heterophylla (Raf.) Sarg.)*/western redcedar *(Thuja plicatu (Donn ex* D. Don)), mountain hemlock (Tsuga *mertensiana* (Bong.) Carr.), whitebark pine (pinus albicaulis Engelm.)/subalpine larch *(L. lyallii* Pad.), *western* white pine *(P. monticola* Dougl. ex D. Don)/sugar pine (P. *Lambertiana* Dougl.), deciduous woodland, and western juniper *(Juniperus occidentalis* Hook.).

Additional information on mapping procedures is given in Lehmkuhl and others (1994). Because field tests were not done to determine the accuracy of the aerial-photograph interpretations by the mapping teams, results of this study are interpreted cautiously.

Table 1 -Historical and current dates for photographs and sample size used to map vegetation patterns in six river basins, eastern Oregon and Washington

	Aerial photographs		
River basin	Sample watersheds	Historical	Current
	Number	----year----	
Deschutes		1959	1991
	4	1943	1991
Total	10		
Grande Ronde	5	1938	1987
		1948	1987
	4	1955	1987
Total	10		
Methow	1	1954	1992
	1	1955	1992
	5	1956	1992
		1955	1981
	4	1956	1981
Total	10		
Pend Oreille	1	1932	1985
	3	1935	1985
	1	1934	1986
	1	1955	1985
Total	6		
Wenatchee	6	1949	1992
Yakima	1	1942	1992
	5	1949	1992
	I	1955	1992
Total	7		
Total, all basins	49		

Fuel Loading and Fire Behavior

We used published fuel and fire behavior information to derive ground fuel loadings (volume of downed woody material by size classes, litter, and duff) and characteristics of surface fire behavior (rate of spread and flame length) for each patch in the sample watersheds. The closest situation represented in one of several fuel and fire behavior photo series (Fischer 1981; Maxwell and Ward 1976, 1980) was matched to interpreted attributes from photos of patches by developing a key based on vegetation composition and structure. Once matched, information from the photo series on fuel loading by size class, rate of spread, and flame length prescribed for the different fuel and fire behaviors was used as our database. We assumed that rate of spread is the rate of lineal advance and that flame length approximates fire intensity (Rothermel 1991). The only factor influencing rate of spread and flame length that we allowed to change among patches was the fuel complex. We based estimates of rate of spread and flame length described for each fuel complex in the photo series on constant conditions given by the photo series: zero percent slope, 6.5 kilometers/hour midflame wind, and 4 percent fuel moisture for fuels $\leq$ 7.6 centimeters in diameter.

Our study covers only surface and moderate- to low-intensity understory fires. Predicting crown fire behavior is difficult (Rothermel 1991) and beyond the scope of this study. Slope characteristics and other geographic features strongly influencing fire behavior were not described for the individual patches during data collection. Because our main objective was to determine the vegetation changes between periods and the effects of these changes on potential fire behavior and smoke production, we assumed that holding slope and weather conditions constant would have minimal overall effect on the outcome of these comparisons. Because estimates of potential fire behavior were identified for only one set of environmental conditions, these estimates poorly reflect risks associated with the broad range of conditions under which fires burn.

We used vegetation and nonvegetation types as the primary variables to develop our key to link fuel data associated with photo series to unmanaged (not logged) patches. Initially more than 100 vegetation composition-structure types and nonvegetated types were identified. These were aggregated into 53 types (Lehmkuhl and others 1994: app. B). Information on tree density and understory characteristics for individual patches was not easily interpreted from aerial photographs, and we therefore identified only 36 fuel and fire behavior photos or stylized models to represent the range of fuel conditions within the six river basins. These included nonforests (for example, grasslands), unmanaged forests (not logged), and forests with logging, thinning, and other management activities. Where fuels and fire behavior appeared similar among vegetation types, we grouped vegetation types. Additional attributes, such as overstory crown closure, were used to clarify differences among vegetation types not distinct enough to assign specific fuels or fire behavior. Some nonforest types were keyed directly without reference to vegetation type.

For managed (logged) patches, vegetation type was not used in the key. Because information was limited, we assumed that fuels and fire behavior would be relatively consistent across vegetation types within each class of logging activity. To differentiate within each activity category, we used available stand structure attributes, primarily the number of canopy layers and crown closure. A photo series depicting activity (postlogging) fuels (Maxwell and Ward 1976) and fire behavior (Ward and Sandberg 1981) was selected to represent managed stands. We used fuel information from Fischer (1981) for conditions where no photo in Maxwell and Ward (1976) was applicable; the fire behavior for these fuel situations was derived from a corollary National Fire Danger Rating System fuel model (Anderson 1982). We assigned nonforested patches fuel loading and fire behavior characteristics from any of the three photo series mentioned, or we stylized new ones by making adjustments from those photos to reflect special conditions.

Patches recently logged or burned were mapped as nonvegetated and described as bare ground, burned, or logged. These patches were given a relatively low rate of spread and flame length. No method or information was available to determine if activity fuels (harvesting residues) were treated in patches where logging had occurred several years before the aerial photographs were taken. Fuels in these patches were assigned to a specific fuel and fire behavior photo series that matched older logging slash within the appropriate harvest management activity (for example, thinning, selective cut). Patches with untreated activity fuels, resulting from very recent tree harvesting, could not be separated from older harvests, so they were given the same rate of spread and flame length, even though recent, untreated activity fuels produce much higher rates of spread and flame length, and present a hazardous fire management situation.

Smoke Production

Peterson (1988) describes four variables that affect the production of smoke during prescribed fires and wildfires: (1) fuel loading (see above), (2) area burned, (3) fuel consumption, and (4) emission factors. We used these variables to estimate potential smoke production for each sample watershed. Recent research in the Pacific Northwest and Intermountain Regions has led to improved fuel consumption models and emission characterizations; these have greatly improved the ability to estimate smoke production and inventory emissions (Deane and others 1994, Ottmar and others 1993, Ward and Hardy 1991).

Area burned by prescribed fires and wildfires-The areas recently burned by prescribed fire were determined from smoke-management reports for 1990 and 1991.[2,3] Location and size of the burns were tallied for each sample watershed based on these reports. In addition, published literature, related surveys taken from Ranger District fuel management officers, and discussions with experts at universities were used to determine past and future prescribed burning occurrence.

We limited the wildfire occurrence, size, and location information data to 1970 to 1988. We obtained this information from electronic records stored at the National Interagency Fire Management Integrated Database, managed by the U.S. Department of Agriculture Computer Center, Kansas City, KS. Records before 1970 were unavailable for this study.

Fuel consumption-We used the computer model CONSUME to estimate fuel consumption (megagrams/hectare) (Ottmar and others 1993). Most of the model inputs were held constant except moisture for large fuels (7.6- to 22.9-centimeter-in-diameter woody material) and fuel loadings among the different patches. For all estimates of fuel consumption derived by the model, we assigned a constant wind speed of 4.8 kilometers/hour, slope of 12 percent, 12 percent fuel moisture content for 0.64- to 2.54-centimeter-in-diameter woody material, ignition time of 22 minutes, and 15 days since significant rain.

Wildfires and prescribed fires were assigned different average moisture contents for large fuels. Wildfires occur most often during the dry summer months, and fire managers usually set prescribed fires during springlike conditions when fuel moisture is high. Because of the environmental differences between these fires, we assigned large-fuel moisture content of 20 and 40 percent for wildfires and prescribed fires, respectively.[4]

Emission factors-We assigned a fire-average emission factor for prescribed fire corresponding to each set of fuels and fire behavior data. Emission factors were defined as the amount of particulate matter (in grams) less than 10 micrometers in size (PM10) emitted per kilogram of fuel consumed. Most current smoke emissions regulation is based on PM10 standards.

The PM10 emission factors for prescribed fires were values inferred from real measurements collected for all particulate matter and for particulate matter of less than 2.5 microns. Forested patches were assigned one of four Pacific Northwest forest types for which PM10 emission factors were available: Douglas-fir/hemlock, ponderosa pine/lodgepole pine, mixed conifers, or hardwoods. Emission factors ranged from

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[2] Stender, Richard. Unpublished data. On file with: Washington State Department of Natural Resources, 1111 Washington Street SE., Olympia, WA 98512.

[3] Ziolko Mike. Unpublished data. On file with: Oregon State Department of Forestry, 2600 State Street, Salem, OR 97310.

[4] Ottmar, R.D.; Hall, J.N.; Vihnanek, R.E. 1990. Improved prediction of fuel consumption during spring-like prescribed burns. Unpublished final report, ODIN Corporation contract 89-617. 56 p. On file with: Pacific Northwest Research Station, Forestry Sciences Laboratory, 4043 Roosevelt Way NE, Seattle, WA 98105-6497.

12.5 to 10.2 grams/kilogram[5] (Ward and Hardy **1991).** Patches dominated by shrubs were assigned the emission factor of 10.6 grams/kilogram per ton, approximating either chaparral[6] or sagebrush.' Patches dominated by grass were assigned the emission factor of 10.0 grams/kilogram (U.S. Environmental Protection Agency 1991). All logged patches were assigned an emission factor of **11.5** grams/kilogram, which is close to being the average of the four Pacific Northwest forest types (see footnote 5).

For wildfire emissions, we derived a ratio of average PM10 emission factor of 14.9 grams/kilogram, as calculated by Hardy and others (1992), divided by the prescribed fire emission factor for Douglas-fir/hemlock (the fuel type closest to that of wildfire). This ratio was then multiplied by each prescribed fire emission factor to determine a wildfire emission factor, except for grass and shrub vegetation types.

Production of smoke-To determine smoke emissions production (kilograms/hectare), we multiplied the amount of fuel consumed, derived by the CONSUME model, by the associated emission factor; this was multiplied by total area burned (hectares) to determined total smoke emission produced (megagrams). Potential emissions per hectare were estimated for current prescribed burning and for historical and current wildfire.

Analyses

A stratified, random sampling procedure was used to select sample watersheds within each of the river basins (see Lehmkuhl and others 1994). Sample watersheds (not patches) were the units in which change was measured between historical and current periods. Change in a watershed was estimated as the difference between historical and current values, and not as the percentage of change since the historical period.

To collect the data, a sample watershed was divided in homogeneous patches and the ecological attributes were assigned to them. We assigned a rate of spread, flame length, fuel load, fuel consumption, and smoke production and smoke emission factor to each patch within each sample watershed from the key we developed. The rate of spread, flame length, fuel load, fuel consumption, and smoke production and smoke emission factor of each patch was multiplied by the patch size, divided by area within the sample watershed, and then summed among patches for a given sample watershed. In that way, all patches within a watershed were combined to obtain a value for fire behavior and smoke-related attributes for each sample watershed. To compensate for the differences in patch sizes, a weighted average (Hoshmand 1988) was used so that the contribution by each patch to the overall watershed value was proportional to its size. A watershed value was derived for each of the following variables: fuel loading (megagrams/hectare), fuel consumption (megagrams/hectare) for prescribed fire and wildfire scenarios, fire rate of spread (meters/minute), flame length (meters), smoke emission factors of PM10 (grams/kilogram) of fuel consumed, and smoke production of PM10 (kilograms/hectare) for prescribed fire and wildfire.

Means, standard errors, and confidence intervals of fire behavior and smoke-related variables were estimated for each river basin from sample watershed values by using methods for standard stratified random sampling (Cochran 1977). The 90-percent confidence interval around the mean difference for each river basin was calculated to detect significant differences between historical and current periods. If the confidence interval included zero, no significant change occurred within a river basin at $P \leq 0.10$.

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[5] **Ward, D.E.; Hardy, C.C.; Sandberg, D.V.; Reinhardt, T.E. 1989. Mitigation of prescribed fire atmospheric pollution throu h increased utilization of hardwoods, piled residues, and long-needled conifers. Part 3: emissions characterization. Unpublished final report, Bonneville Power Admmistration contract IAG DE-AI179-85BP18509 (PNW-85-423). 97 p. On file with: Pacific Northwest Research Station, Forestry Sciences Laboratory, 4043 Roosevelt Way NE, Seattle, WA 98105-6497.**

[6] **Hardy, CC,; Teesdale, D.R. 1992. Source characterization and control of smoke emissions from prescribed burning of southern California chaparral. Unpublished final report, California Department of Forest contract IAG CDF-8CA96071. On file with: Pacific Northwest Research Station, Forestry Sciences Laboratory, 4043 Roosevel t Way NE, Seattle, WA 98105-6497.**

[7] **Hardy, CC.; Teesdale, D.R. 1991. Smoke emissions from prescribed fires in western juni per and big-basin sagebrush of central Oregon. Unpublished final report, BLM/PNW contract IAG PNW 88-564. On file with: Pacific Northwest Research Station,** Forestry **Sciences Laboratory, 4043 Roosevelt Way NE, Seattle, WA 98105-6497.**

We calculated product-moment correlation coefficients to estimate covariation of rate of spread and flame length with the proportion of area logged in a given sample watershed. The association of rate of spread and flame length with proportion of area logged by harvest technique (for example, cleat-cut, thinning) was examined individually by the same correlation methods. Variables were weighted within a given stratum by the number of sample watersheds in a stratum (whole population) divided by the number of sample watersheds selected (examined) from the stratum. In addition, we selected three example watersheds to illustrate the watershed-level patterns of fuel loading, fire behavior, and emission production during historical and current periods; data summaries and maps were produced for this scale.

RESULTS

Fuel Loading

Fuel loading averages for each of the six river basins ranged from 75.3 megagrams/hectare for the Methow River basin (current) to 102.7 megagrams/hectare for the Yakima River basin (historical) (table 2 and fig. 2A). The fuel loading differences between the historical and current periods at the river basin levels were very small, ranging from an increase of 7.9 megagrams/hectare for the Deschutes River basin to a decrease of 11.7 megagrams/hectare for the Yakima River basin (table 2). Basin differences between periods were not statistically significant ($P > 0.10$). Alternatively, the fuel loading differences between the historical and current periods at the watershed levels often were relatively large. For example, the fuel loadings ranged from 55.4 megagrams/hectare for the Grande Ronde 35 watershed (current) to 122.0 megagrams/hectare for the Yakima 30 watershed (historical), with a decrease from historical to current times of 54 megagrams/hectare for Yakima 30 and an increase of 35.1 megagrams/hectare for Grande Ronde 55 (table 3).

Fire Behavior

Measures of vegetation-based fire behavior did not differ ($P > 0.10$) between current and historical periods in any of the six river basins (fig. 3, table 2). Mean rate of spread in the current period ranged from 1.8 to 3.2 meters/minute for the Wenatchee and Grande Ronde River basins, respectively; the historical period ranged similarly from 1.5 to 4.0 for the Wenatchee and Grande Ronde River basins (fig. 3A, table 2). The Grande Ronde River basin had the largest decrease in rate of spread: 0.8 meter/minute from the historical to the present time. The largest increase of rate of spread was for the Yakima and Wenatchee River basins, although these increases were not significant ($P > 0.10$).

Mean potential flame length in current landscapes was highest for the Grande Ronde and lowest for the Wenatchee River basins (fig. 3B, table 2). In historical landscapes, mean potential flame length was highest for the Pend Oreille basins and lowest for the Methow River basin. Few of the river basins showed much change in mean flame length from historical to current times. The largest increase and decrease were for the Grande Ronde and Pend Oreille, respectively, although these differences were not significant ($P > 0.10$).

The amount of change from historical to current periods was highly variable within a river basin; both large increases and decreases of potential rate of spread and flame length were observed among the sample watersheds (table 4 and figs. 4 and 5). Thus, detecting significant change between historical and current rate of spread and flame lengths in any of the river basins was problematic. Change in rate of spread from historical to current periods differed most among watersheds for the Deschutes, Grande Ronde, and Yakima River basins (fig. 4 and table 4). Flame length differed most among watersheds for the Deschutes, Grande Ronde, and Pend Oreille River basins (fig. 5 and table 4). An increase in rate of spread and flame length was detected for 50 percent or more of the sample watersheds for all but the Grande Ronde and Wenatchee River basins, respectively (table 4).

In general, rate of spread and flame length were positively correlated with the proportion of area logged (hereafter, area logged) for the sample watersheds. Correlation coefficients of area logged with rate of spread were ≥ **0.57** for five of the six river basins (table 5). Rate of spread for the Pend Oreille and Wenatchee River basins was strongly associated (r-0.89) with area logged. Correlation of area logged with flame length were ≥ 0.42 for four of six river basins (table 5). The Deschutes and Methow River basins showed the strongest relations. All harvest techniques were associated with increasing rate of spread and flame length, but strength of the associations differed greatly among river basins and harvesting methods.

Smoke Production

Area burned by prescribed fire and wildfire-Average area burned per year with prescribed fire for the sample watersheds within each basin during 1990 and 1991 (current) is shown in figure 6. No prescribed burning had occurred for sample watersheds before the year in which they were mapped for historical composition, because prescribed burning by State and Federal land managers did not begin for eastern Oregon and eastern Washington until about 1970.[8] Current prescribed burning ranged from 420 hectares/year for the Deschutes River basin to 43 hectares/year for the Methow River basin. Area burned for the Methow River basin by prescribed fire was low because many of the sample watersheds are in wilderness areas where prescribed fire is not allowed.

Areas burned by wildfire were analyzed for the three example watersheds (Grande Ronde River basin watersheds 35 and 55 and Yakima River basin watershed 30) for 1970 to 1988. For watershed 35, 10 fires were reported for a total of 4482 hectares burned and an annual average of 249 hectares. This included two large fires of 3780 and 947 hectares. For watershed 55, there were 24 fires during the same period that burned a total of 14 hectares, or an average of 0.8 hectare/year; no fire was larger than 2 hectares. For Yakima River basin watershed 30, 33 fires were reported that burned 3298 hectares or an average of 183 hectares annually; most of the acres burned in just one fire (3278 hectares), though.

Fuel consumption-Estimates of average prescribed fire fuel consumption for the six river basins ranged from 37.3 megagrams/hectare for the Deschutes River basin (current) to 30.9 megagrams/hectare for the Methow River basin (historical) (fig. 2B, table 2). Potential wildfire fuel consumption averages were about double those for prescribed fire, ranging from 57.3 megagrams/hectare for the Deschutes River basin (current) and Yakima River basin (historical) to 48.1 megagrams/hectare for the Methow River basin (historical) (fig. 2C). The Grande Ronde River basin and Methow River basin were the only areas with significant differences in fuel consumption between the historical and current periods. For wildfire fuel consumption, the Wenatchee River basin was the only one showing a significant difference in historical and current periods.

In the example watersheds, the potential fuel consumption of prescribed fires ranged from 26.2 to 42.1 megagrams/hectare (table 3). The fuel consumption differences between the historical and current periods at the watershed levels ranged from a decrease of 4.8 megagrams/hectare to an increase of 11.7 megagrams/hectare (table 3). The fuel consumption of wildfires was nearly double that of prescribed fires, ranging from 40.2 to 62.8 megagrams/hectare. The fuel consumption differences between the historical and current periods at the watershed levels ranged from a decrease of 14.3 megagrams/hectare to an increase of 17.7 megagrams/hectare.

Emission factors (PM10)-Average emission factors for the river basins ranged from 10.3 grams/kilogram for prescribed fire for the Grande Ronde River basin (historical) to 14.6 grams/kilogram for wildfire for the Pend Oreille River basin (historical) (fig. 7). Current emission factors for prescribed fire were

[8] **Personal communication. 1993. Stewart G. Pickford, Professor of Fire Science,** College of Forest Resources, **AR-10, University of Washington, Seattle, WA 98195.**

significantly higher ($P \leq 0.10$) for the Grande Ronde but lower ($P \leq 0.10$) for the Deschutes and Pend Oreille River basins, when compared with the historical emission factors. Current wildfire emission factors were higher ($P \leq 0.10$) than in the past for the Grande Ronde, Methow, and Yakima basins but lower ($P \leq 0.10$) for the Deschutes and Pend Oreille River basins.

The PM10 emission factors for the three example watersheds ranged from 9.2 grams/kilogram for historical prescribed fires to 13.5 grams/kilogram for wildfire during the current period (table 3). The greatest emission factor difference between the historical and current periods at the watershed levels was an increase of 0.6 gram/kilogram (table 3).

Production of smoke-Prescribed fire smoke production was highest, 409 kilograms/hectare, for the Deschutes River basin (current and historical) and lowest, 323.6 kilograms/hectare, for the Grande Ronde River basin (historical) (fig. 8A and table 2). The greatest difference between historical and current results for prescribed fires was for the Grande Ronde River basin, with an increase of 48.3 kilograms/hectare. The Methow and the Grand Ronde River basins showed significant increase for smoke production for prescribed fires from the historical to current period ($P \leq 0.10$).

Wildfire smoke production was highest, 799.2 kilograms/hectare, for the Deschutes basin (current) and lowest, 622.1 kilograms/hectare, for the Grande Ronde basin (historical) (fig. 8B and table 2). The largest difference between historical and current results for wildfires was for the Grande Ronde basin, with an increase of 89.7 kilograms/hectare. No significant differences were detected between periods for any of the river basins, however.

The prescribed fire smoke production for the example watersheds ranged from 245.6 to 434.9 kilograms/hectare (table 3). The prescribed fire differences between the historical and current periods ranged from a decrease of 38.5 kilograms/hectare to an increase of 121.5 kilograms/hectare (table 3). PM10 smoke production for the example watersheds was twice as high for wildfire as for prescribed fire for both historical and current periods (table 3). Smoke production from wildfires ranged from 481.1 to 824.6 kilograms/hectare (table 3). The smoke production differences between the historical and current periods decreased 158.8 and 98.1 kilograms/hectare for Yakima 30 and Grande Ronde 35, respectively, and increased 257.6 kilograms/hectare for Grande Ronde 55 (table 3).

The average total smoke PM10 produced per year during prescribed fires (current, 1990-91) was highest for the Deschutes basin (171 megagrams) and lowest for the Methow basin (30 megagrams) (fig. 9). Average annual wildfire area burned, and hence total emission, was determined only for the example watersheds. Total emissions were 177 and 135 megagrams per year for Grande Ronde watershed 35 and Yakima watershed 30, respectively, but < 1 milligram per year for Grande Ronde watershed 55.

(Text continues on page 20)

Table 2-Historical and current forest fuels, fire behavior, and smoke emissions for prescribed fires and wildfires in eastern Oregon and Washington river basins

		River basin					
Variable	Period	Deschutes	Grande Ronde	Methow	Pend Oreille	Wenatchee	Yakima
Forest fuels (megagrams/hectare)	Historical	85.06	84.50	75.33	83.98	98.09	102.65
	Current	92.95	83.27	75.28	85.33	92.89	90.97
	Change	7.89	-1.23	-.04	1.35	-5.20	-11.68
Fire rate of spread (meters/minute)	Historical	2.08	4.02	.21	1.72	1.5	
	Current	2.19	3.21	2.11	1.91	1.77	2.27
	Change	.11	-.79	-.1	.19	.27	.37
Flame length (meters)	Historical	1.12	1.14	.95	1.19	.98	1.09
	Current	1.06	1.25	.96	1.12	.96	1.16
	Change	-.06	.11	.02	-.07	-.02	.08
Fuel consumption (prescribed fires) (megagrams/hectare)	Historical	37.24	31.43	30.89	36.14	33.92	35.96
	Current	37.32	34.59	32.17	35.08	31.97	35.20
	Change	.08	3.16	1.28	-1.05	-1.95	-.76
Fuel consumption (wildfires) (megagramslhectare)	Historical	56.31	48.39	48.05	53.77	55.16	57.34
	Current	57.34	52.31	49.64	53.70	51.71	54.85
	Change	1.03	3.93	1.59	-.07	-3.45	-2.49
Smoke emission[a] (prescribed fires) (grams/kilogram)[b]	Historical	10.96	10.28	10.80	11.31	10.46	10.42
	Current	10.89	10.76	10.87	11.02	10.57	10.53
	Change	-.06	.48	.06	-.29	.11	.11
Smoke emission[a] (wildfires) (grams/kilogram)[b]	Historical	14.09	12.73	13.72	14.56	13.23	13.30
	Current	13.93	13.56	13.85	14.16	13.35	13.47
	Change	-.15	.83	.13	-.39	.12	.17
Smoke production[a] (prescribed fires) (kilograms/hectare)	Historical	409.00	323.60	332.54	408.34	354.50	375.15
	Current	408.00	371.93	349.23	386.04	338.04	371.44
	Change	-1.00	48.33	16.69	-22.30	-16.45	-3.71
Smoke production” (wildfires) (kilograms/hectare)	Historical	793.07	622.06	656.87	781.10	730.19	762.93
	Current	799.19	711.71	686.37	759.31	690.94	739.82
	Change	6.12	89.65	29.50	-21.79	-39.25	-23.11

[a] PM10.
[b] Consumed.

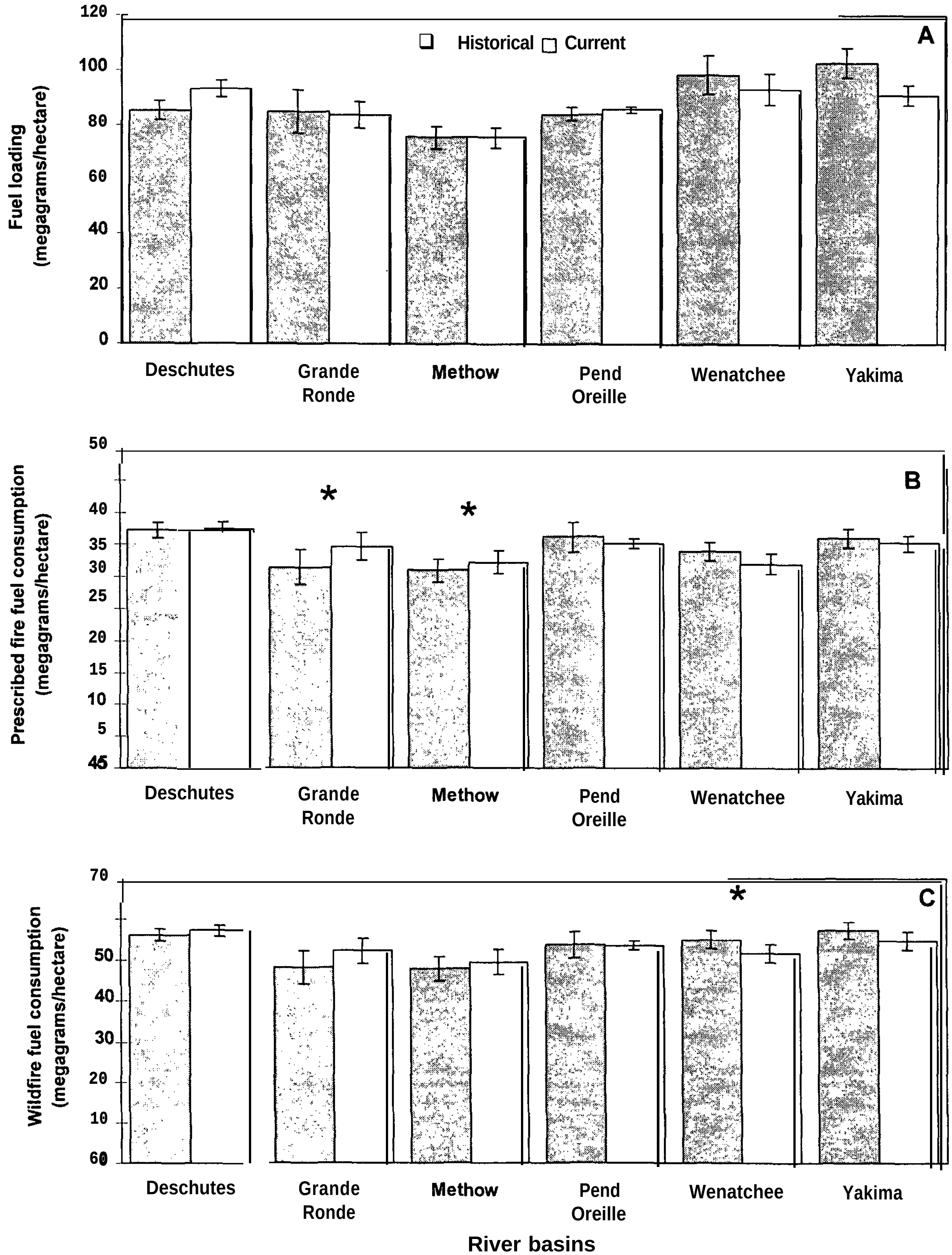

Figure 2-Average fuel loadings (A) and average fuel consumption for prescribed fires (B) and wildfires (C) for the historical and current periods. Stars indicate significant differences at $P = 0.10$. Error bars are the standard error of the stratified mean estimate.

Table 3-Historical and current fuel loading, fuel consumption, emission factors and smoke production for 3 watersheds, eastern Oregon and Washington

Variable	Period	River basin: Grande Ronde 35	Grande Ronde 55	Yakima 30
Fuel loading (megagrams/hectare)	Historical	102.22	81.74	122.04
	Current	55.42	116.86	68.09
	Change	-46.80	35.12	-53.95
Fuel consumption (prescribed fires) (megagrams/hectare)	Historical	30.56	30.31	31.08
	Current	28.93	42.05	26.22
	Change	-1.63	11.74	-4.85
Fuel consumption (wildfires) (megagrams/hectare)	Historical	53.88	45.09	54.40
	Current	44.70	62.77	40.15
	Change	-9.18	17.68	-14.25
Emission factors (PM10) (prescribed fires) (grams/kilogram)	Historical	10.28	10.35	9.15
	Current	10.46	10.35	9.37
	Change	.18	0	.22
Emission factor (PM 10) (wildfires) (grams/kilogram)	Historical	12.99	12.58	11.77
	Current	13.46	13.14	11.99
	Change	.47	.56	.22
Smoke production (PM10) (prescribed fires) (kilograms/hectare)	Historical	313.94	313.48	284.12
	Current	302.38	434.94	245.63
	Change	-11.56	121.46	-38.49
Smoke production (PM10) (wildfires) (kilograms/hectare)	Historical	699.59	566.96	639.93
	Current	601.53	824.55	481.13
	Change	-98.06	257.59	-158.81

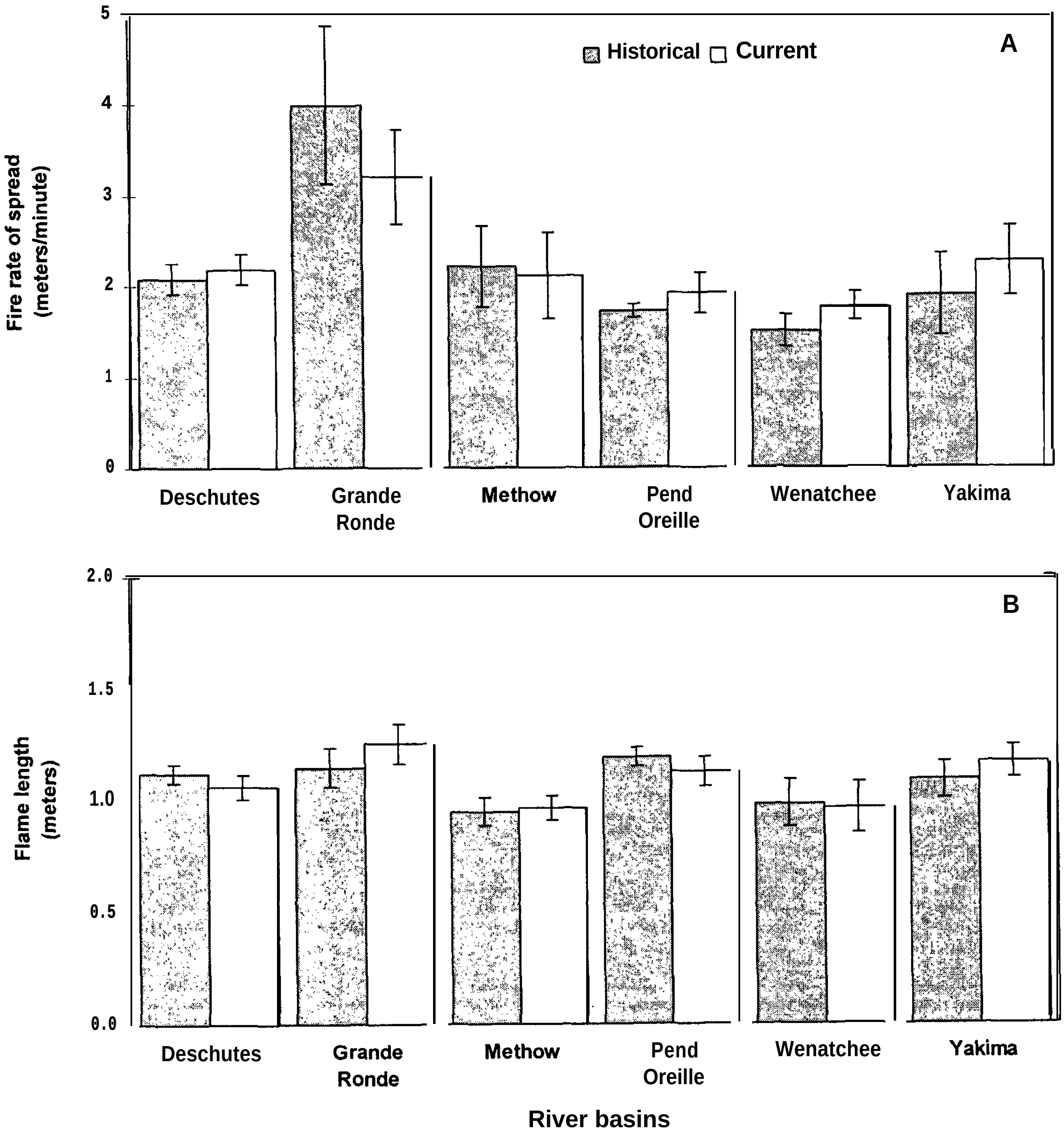

Figure 3-Historical and current mean potential rates of fire spread (A) and flame lengths (B) in six river basins in eastern Washington and Oregon. Error bars are the standard error of the stratified mean estimate

Table 4--Ranges and direction of change from historical to current periods in estimates of fire rate of spread (ROS; meters/minute), flame length (FL; meters), and percentage of sample watersheds in Washington and Oregon river basins where rate of spread and flame length increased

	River basin					
Variable	Deschutes	Grande Ronde	Methow	Pend Oreille	Wenatchee	Yakima
Rate of spread:						
Maximum (+ change)	1.60	1.24	0.80	1.67	0.99	3.12
Minimum (- change)	-2.61	-2.85	-1.99	-.66	-.46	-1.33
Flame length:						
Maximum (+ change)	.32	.43	.12	.38	.13	.30
Minimum (- change)	-.54	-.29	-.16	-.50	-.13	-.02
Percentage increases?						
ROS	50.00	50.00	70.00	66.67	83.33	71.43
FL	50.00	70.00	60.00	50.00	16.67	57.14

[a] Percentage of increase in number of watersheds.

Table 5-Correlation coefficients of rate of spread and flame length correlated with percentage of area logged in sample watersheds by harvest types for eastern Washington and Oregon river basins in the current time period

	River basin					
Variable	Deschutes	Grande Ronde	Methow	Pend Oreille	Wenatchee	Yakima
Rate of spread:						
Harvest types -						
Clearcut/shelterwood	0.69	0.09	0.79	0.69	0.85	0.83
Selective	.62	-.05	.48	.97	.92	.04
Thinning	.42	-.14	-.18	.01	.51	.46
Patch clearcut[a]	-.38	.05	.12	.78	.87	-.04
Total, harvest	.72	-.03	.57	.89	.89	.68
Flame length:						
Harvest types -						
Clearcut/shelterwood	.87	.47	.51	-.11	.36	.18
Selective	.58	.33	.75	.44	.52	.09
Thinning	.60	.08	.15	-.47	.22	.06
Patch clearcut	-.27	.18	-.09	.33	.47	.31
Total harvest	.81	.42	.77	.20	.46	.24

[a] Size <4 hectares.

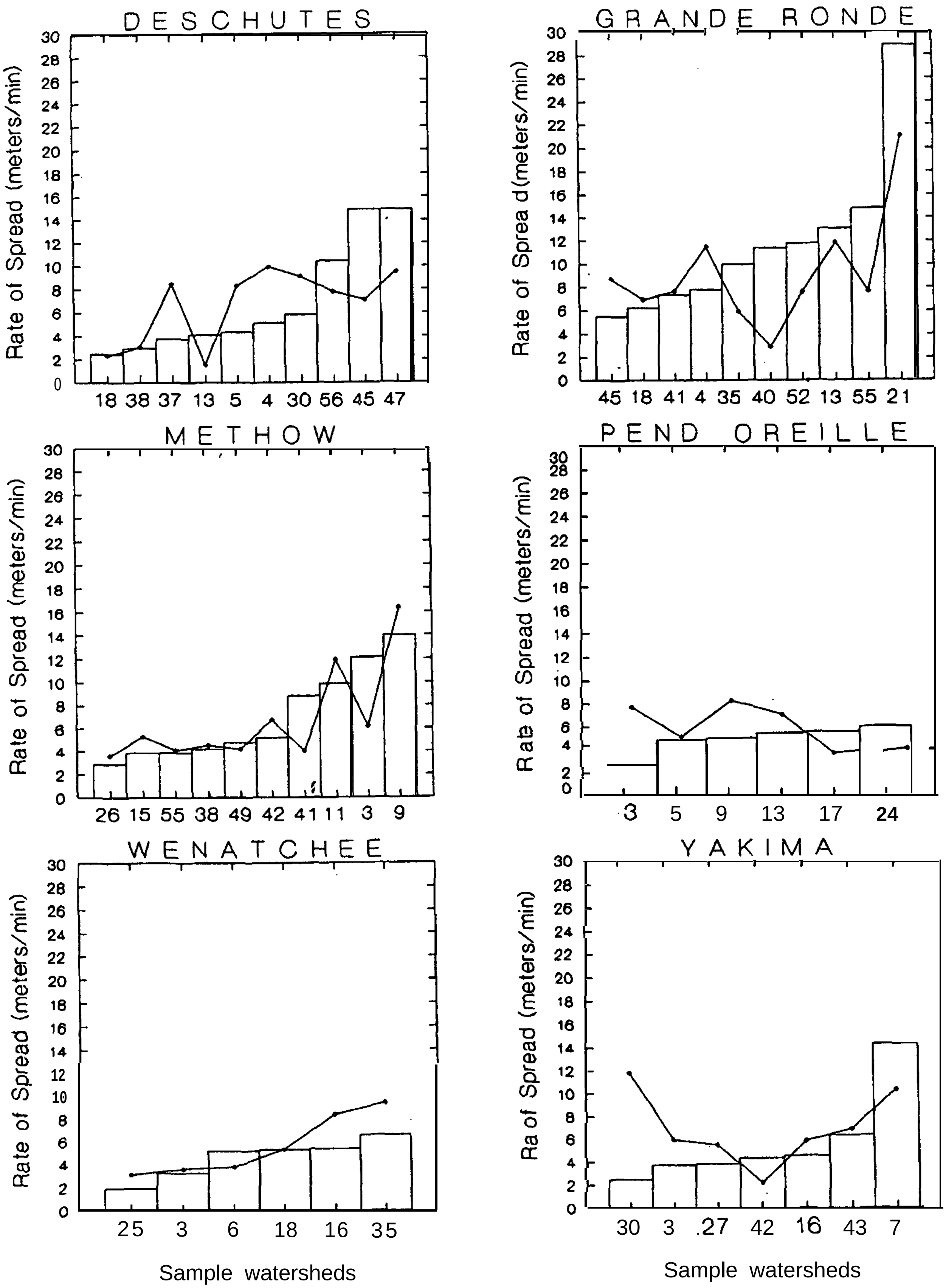

Figure 4-Profile comparison of historical (bars) and current (line) fire potential rates of spread by sample watersheds within six eastern Washington and Oregon river basins.

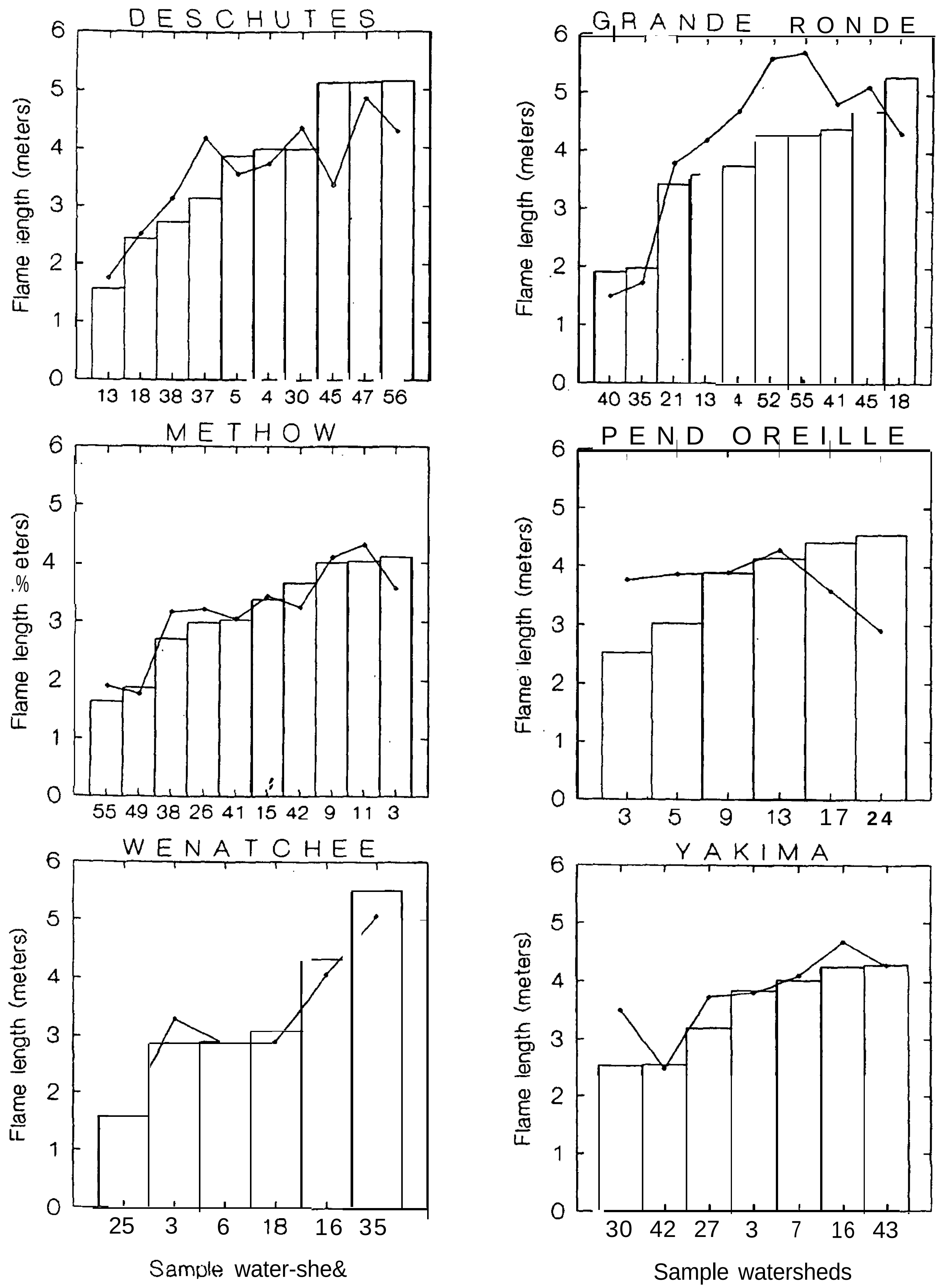

Figure 5-Profile comparison of historical (bars) and current (line) fire potential flame lengths by sample watersheds within six eastern Washington and Oregon river basins.

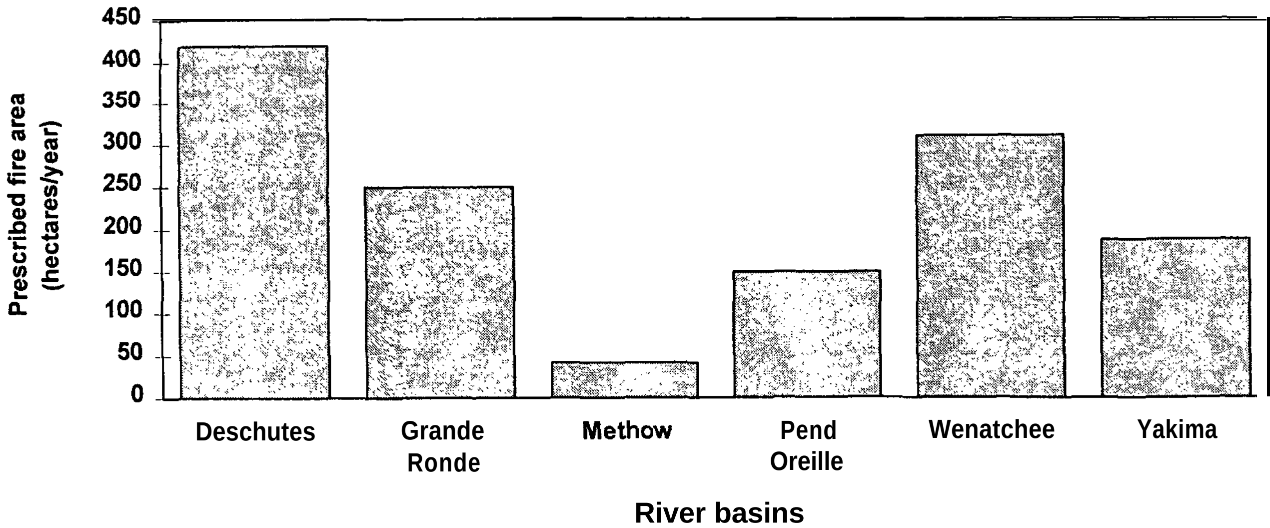

Figure 6-Average area burned by prescribed fires within the sample watersheds.

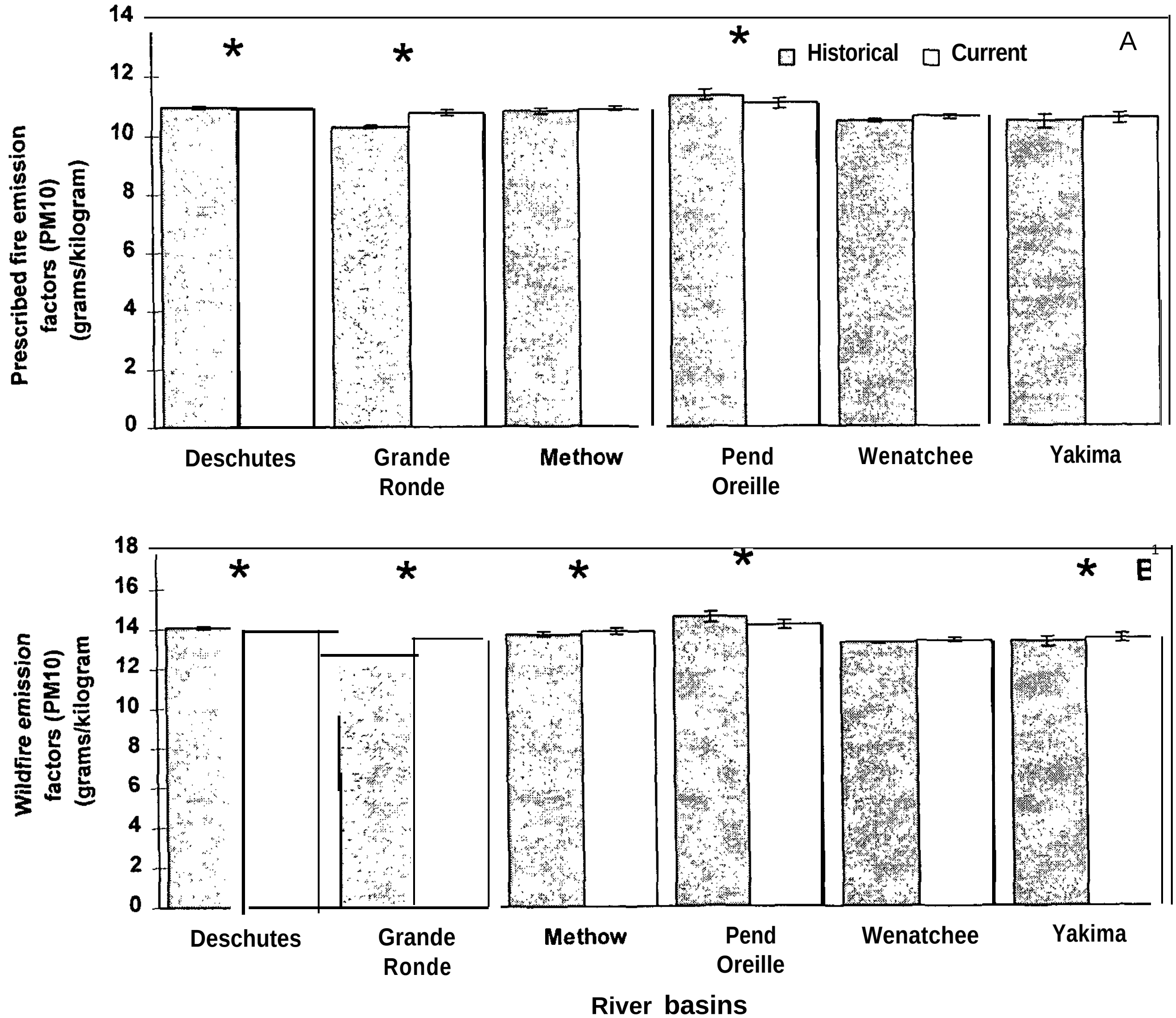

Figure 7-Prescribed fire (A) and wildfire (B) emission factors for historical and current periods. Stars indicate significant differences at $P =$ 0.10. Error bars are the standard error of the stratified mean estimate.

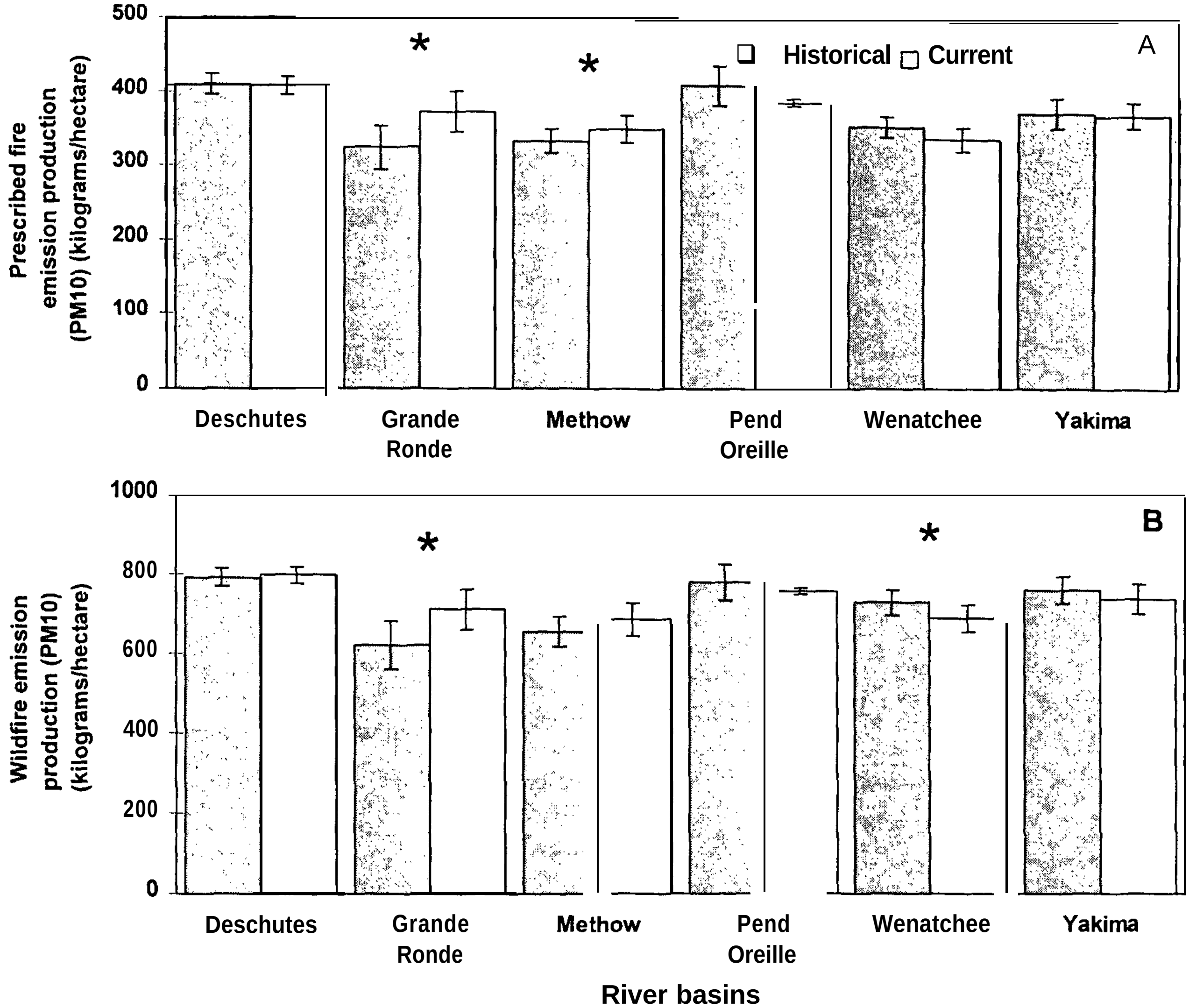

Figure 8-Averages of prescribed fire (A) and wildfire (B) smoke production for historical and current periods. Stars indicate significant differences at *P* = 0.10. Error bars are the standard error of the stratified mean estimate.

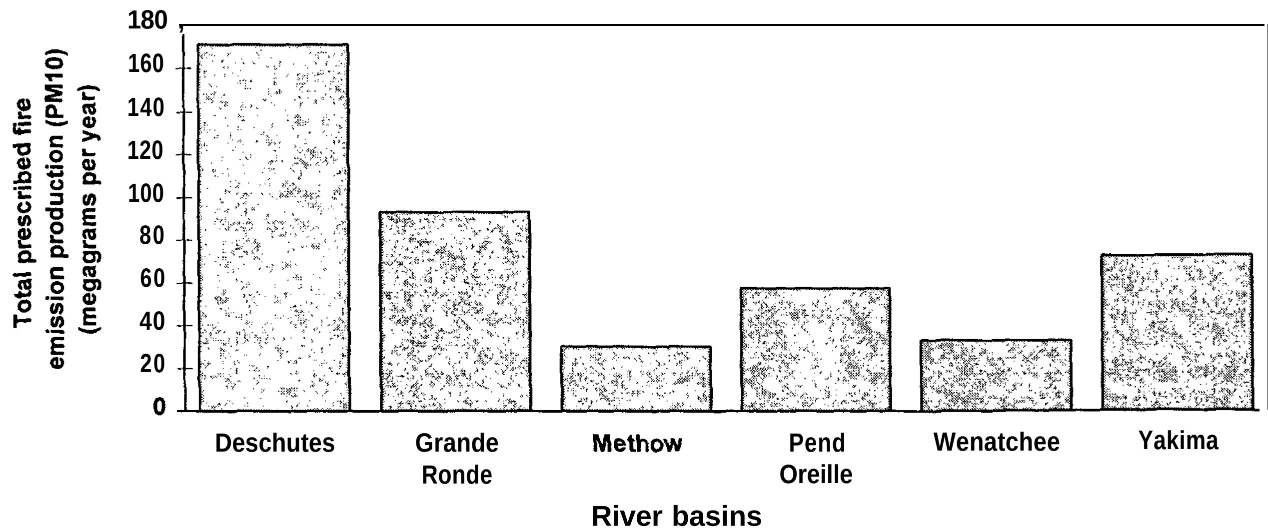

Figure 9 -Prescribed fire smoke production for area prescription burned in the river basins during 1990 and 1991.

DISCUSSION

Change and Variability Over Time

To detect significant change, fuel loading, fire behavior, and smoke-related variables had to change similarIy among sample watersheds and sample strata for a given river basin. Although the two periods, historical and current, were reasonably fixed within a river basin, it was obvious that the historical vegetative conditions (starting points), which were the basis for detecting change, were highly variable among the sample watersheds. Past disturbances originating from fires, logging, and other factors have created widely different matrices of vegetative composition and structure among the sample watersheds, and they most likely obscured our ability to ascertain change for these variables at the river basin scale.

A prominent source of variability among sample watersheds was the diverse land management practices that ranged from unlogged wilderness areas to intensively managed ones with > 50 percent of the area logged. In landscape-scale studies, the amount and type of management activities are difficult factors to control. Landscapes managed primarily for wilderness are expected to be changing at different rates and in different directions than ones more intensively managed for forest products. Any sample of watersheds within river basins with multiple-use land management objectives would expectably have high variability. Comparing wilderness-dominated sample watersheds with intensively managed ones had limited application, however, because wilderness areas were concentrated in high-elevation ecosystems, whereas harvesting and other management activities were concentrated at lower and middle elevations with different vegetative characteristics. The effects of management activities, such as fire suppression, that are more subtle than those produced by tree harvesting also could differ significantly among sample watersheds.

Other potential sources of variation included differences in quality between the current and historical aerial photographs, different periods being sampled among watersheds within a given river basin (table l), and differences in interpretation among those working with the photos. Steps were taken to minimize this last variation, but interpreters noted that attributing black and white, 1:20,000-scale historical photographs taken 35 to 50 years ago was more difficult than assessing the current-day, 1:12,000-scale color photographs. Although we sampled at least 15 percent of the area within each river basin, this is a relatively small sample size considering geographic extent and spatial heterogeneity of the different river basins. With only 6 to 10 watersheds sampled within each river basin and only one to three sample watersheds per stratum, the likelihood is high of falsely accepting that no differences exist.

Presumably much change in vegetation composition and structure had taken place because of fire suppression in the interior west before our historical sample period of 35 to 50 years ago (as shown by Gruell and others 1982). How much change and exactly where is poorly understood, however. It has long been recognized that fire exclusion has allowed unnatural fuel accumulations to occur throughout eastern Oregon and Washington where wildland fires were frequent (Agee 1994, Deeming 1990, Martin and others 1976, Mutch and others 1993). McNeil and Zobel(1980) found that a substantial pulse of tree establishment had occurred in the dry mixed-conifer forests of the Cascade Range in southern Oregon before and during our historical sample period. Here and presumably elsewhere throughout the region, major effects of fire suppression on potential fire behavior and smoke production had already taken place by about our chosen historical period. Because of this, river basins that changed or did not change from historical to current conditions should not be and were not interpreted as effects from a presettlement condition. Whether our results are within a range of natural variation also is unknown. Yet, the information on the amount and direction of change over a relatively long time and over a large geographic area provides insights to how much change (rates) can be expected from both temporal and spatial perspectives. It also provides the framework from which several management alternatives can be developed and tested.

Diverse patterns resulting from natural disturbances and processes, management activities, and other factors observed in these and other sample watersheds may be too variable to detect change at the river basin scale with 5000- to 13 500-hectare sample units. Additional tests are needed to determine what landscape scales and criteria provide the most control of intersample area variability. Criteria for grouping samples by patterns of historical landscape composition and management activities should be examined.

Fuel Loading

Although no statistically significant differences between historical and current fuel loadings were detected at the basin scale, many of the sample watersheds within river basins displayed large changes related to natural disturbances or human activities (logging and presumably fire suppression). The Grande Ronde River basin, for example, exhibited an overall decrease in fuel loading of only 1.2 megagrams/hectare between historical and current periods, but watershed 35 decreased 46.8 megagrams/hectare and watershed 55 increased 35.9 megagrams/hectare (fig. 10, A and B, and table 2). Grand Ronde watershed 35, located in the Eagle Cap Wilderness area where no harvesting activities had occurred, showed major shifts in vegetation composition from historical to current times. Subalpine fir and Englemann spruce forests decreased from 69 to 30 percent of the area, and whitebark pine and subalpine larch forests increased from 0 to 38 percent. Large areas in the watershed were burned by several wildfires over the past 20 years, which accounted for rapid shifts in vegetation composition and a decrease in fuel loading. Exhibiting the opposite trend, Grande Ronde watershed 55 in the Wenaha-Tucanon Wilderness, where no harvesting has occurred, has had no large wildfires since 1970. Here, shifts in vegetation composition and structure were to later seral conditions, which is indicative of widespread absence of fire. Vegetation changed from open ponderosa pine and small Douglas-fir to dominance by larger Douglas-fir, true fir *(abies* spp.), and a much thicker canopy cover, all substantially increasing the fuel loading.

In the Yakima River basin, where the largest decrease in fuel loading (11.7 megagrams/hectare) over time was detected (not statistically significant), the individual watersheds displayed much larger changes, too; for example, a decrease of 54.0 megagrams/hectare in fuel loading was noted for sample watershed 30 (fig. 10C). Here, a combination of wildfire and harvest activity shifted a portion of the vegetation type to stands of smaller trees with relatively low fuel loadings. The uneven-aged old-growth true fir, western hemlock, and western redcedar forest types decreased from 41 to 5 percent of the area. Younger, even-aged true fir, western hemlock, and western redcedar increased from 7 to 28 percent; the young, even-aged Douglas-fir and true fir stands increased from 1 to 21 percent.

In this study, we examined only the fuel loading for the duff and the dead-woody fuels on the ground. Because we were unable to address the tree crown fuels and live vegetation, we probably underestimated fuel loading by 5 to 50 percent (Anderson 1982, Snell and Anholt 1981, Snell and Brown 1980). Consequently, the amount of fuel consumed and smoke produced also was underestimated for this study.

Fire Behavior

Even though no significant changes in rate of spread and flame length were detected from historical to current periods at the river basin scale (fig. 3), large shifts occurred within many individual sample watersheds (figs. 4 and 5). Likely causes of these shifts differed among the watersheds. Maps of structural stage, rate of spread, and flame length for 3 of the 49 sample watersheds are shown in figures 11 through 13 to depict and discuss the range of management activities, natural processes, and other factors that contributed to the variable landscape patterns and fire behavior. Because Grande Ronde watershed 35 had several large wildfires in the wilderness area between historical and current times, the vegetation of the current period was mostly in seed-sapling-pole and young structural stages (fig. 11A). Few fires burned in watershed 55 in the Wenaha-Tucanon Wilderness, which shifted the historical mix of structural stages to a current condition dominated by mature and old forests (fig. 11B). For the Yakima River basin, watershed 30 was logged extensively between historical and current periods, thereby shifting the dominant structural stage from old forest to seedling-sapling-pole (fig. 1lC).

Despite large differences in landscape composition and structure between the two Grande Ronde sample watersheds, rate of spread decreased about 100 percent between historical and current times for both sample watersheds (figs. 4 and 12, A and B), while substantial changes in flame length were detected only for the Wenaha-Tucanon Wilderness, where the decrease was about 35 percent (figs. 5 and 13, A and B). Reductions in rate of spread may be attributed to substantial decreases in grass fuel-types, which have a high rate of spread. Area in grass-dominated openings decreased from 16 to 6 percent for watershed 55 from historical to current periods, while forest area with grass understories decreased from 19 and 28 percent of the total area to <2 percent for watersheds 55 and 35, respectively (Lehmkuhl and others 1994). Vegetation succession associated with successful fire exclusion, as for the Wenaha-Tucanon Wilderness, could cause major shifts in vegetation composition away from grass-dominated vegetation types to ones dominated with shrubs and tree regeneration (for example, Biswell 1973, Gruell and others 1982). Seed-sapling-pole and young forests that developed after stand-replacement fires in the Eagle Cap Wilderness are at a stage where grass understories often are not present; however, a landscape primarily in this structural stage still has a relatively high rate of spread (fig. 4).

For watershed 30 in the Yakima River basin, rate of spread increased >300 percent and flame length increased >40 percent from historical to current periods (figs. 12C and 13C). These increases coincide with an increase in area logged from 3 to 53 percent, altering vertical and horizontal forest vegetation structure in the watershed to one supporting potentially more hazardous fire behavior conditions.

Logged areas generally showed a strong association with increased rate of spread and flame length (table 5), thereby suggesting that tree harvesting could affect the potential fire behavior within landscapes. Wilson and Dell (1971) describe two main reasons for the fuel and potential fire problems in Pacific Northwest forests and rangelands: fire exclusion has allowed unnatural and hazardous levels of fuels to accumulate, and intensive forest management annually produces high fuel loadings associated with logging residues. As a by-product of clearcutting, thinning, and other tree-removal activities, activity fuels create both short- and long-term fire hazards to ecosystems. The potential rate of spread and intensity of fires associated with recently cut logging residues is high (see for example, Anderson 1982, Maxwell and Ward 1976), especially the first year or two as the material decays. High fire-behavior hazards associated with the residues can extend, however, for many years depending on the tree species (Olson and Fahnestock 1955). Even though these hazards diminish, their influence on fire behavior can linger for up to 30 years in the dry forest ecosystems of eastern Washington and Oregon. Disposal of logging residue using prescribed fires, the most common approach, also has an associated high risk of an escaped wildfire (Deeming 1990). The link between slash fires and escaped wildfires has a history of large conflagrations for Washington and Oregon (Agee 1989, Deeming 1990).

A

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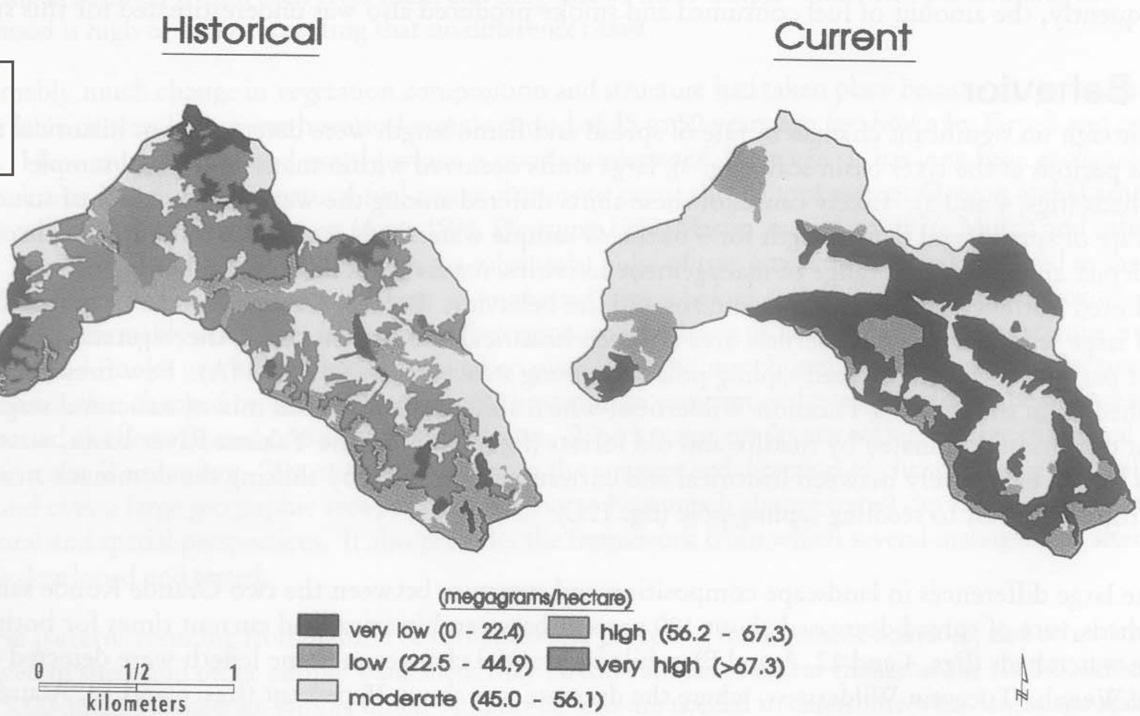

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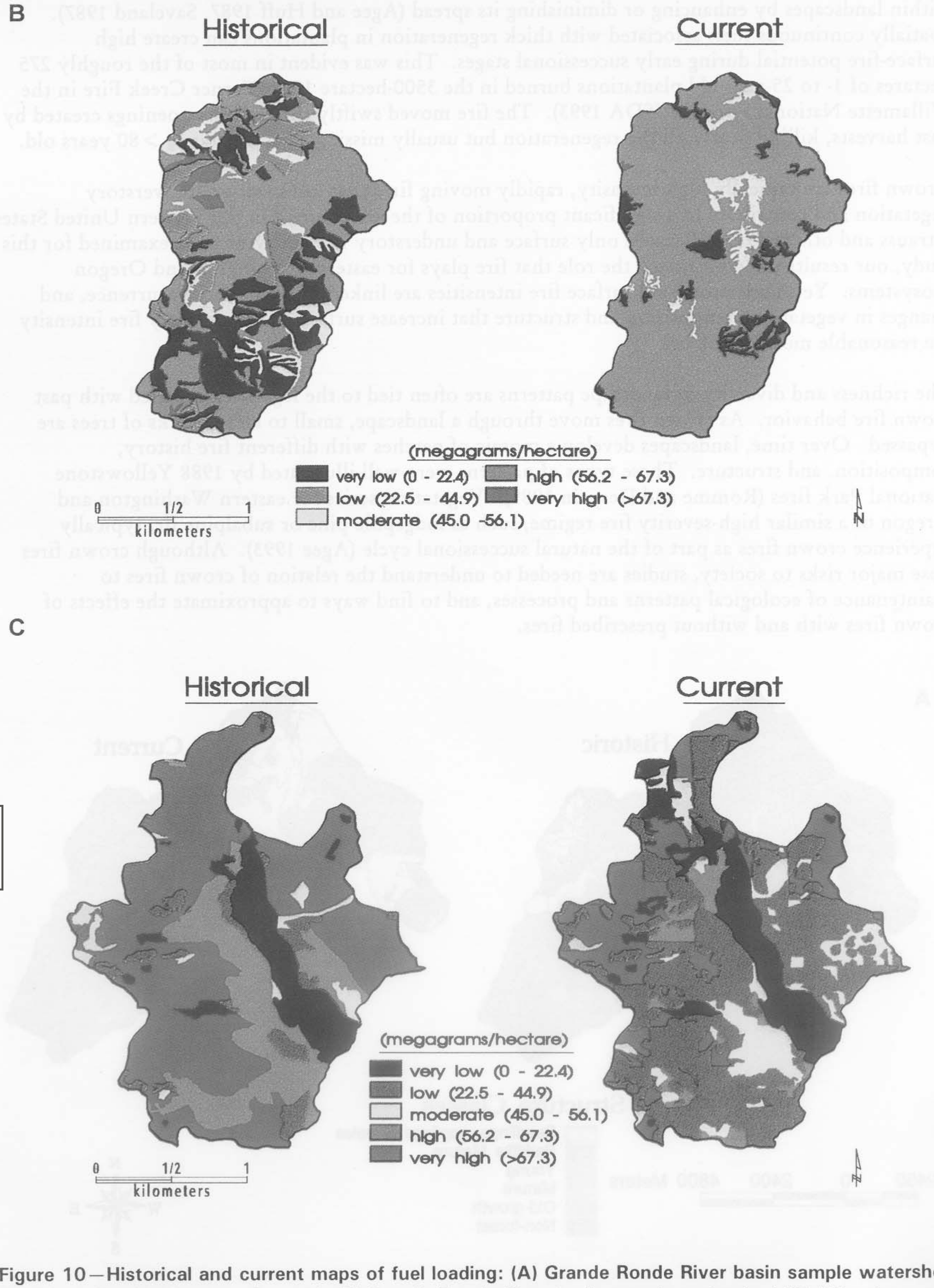
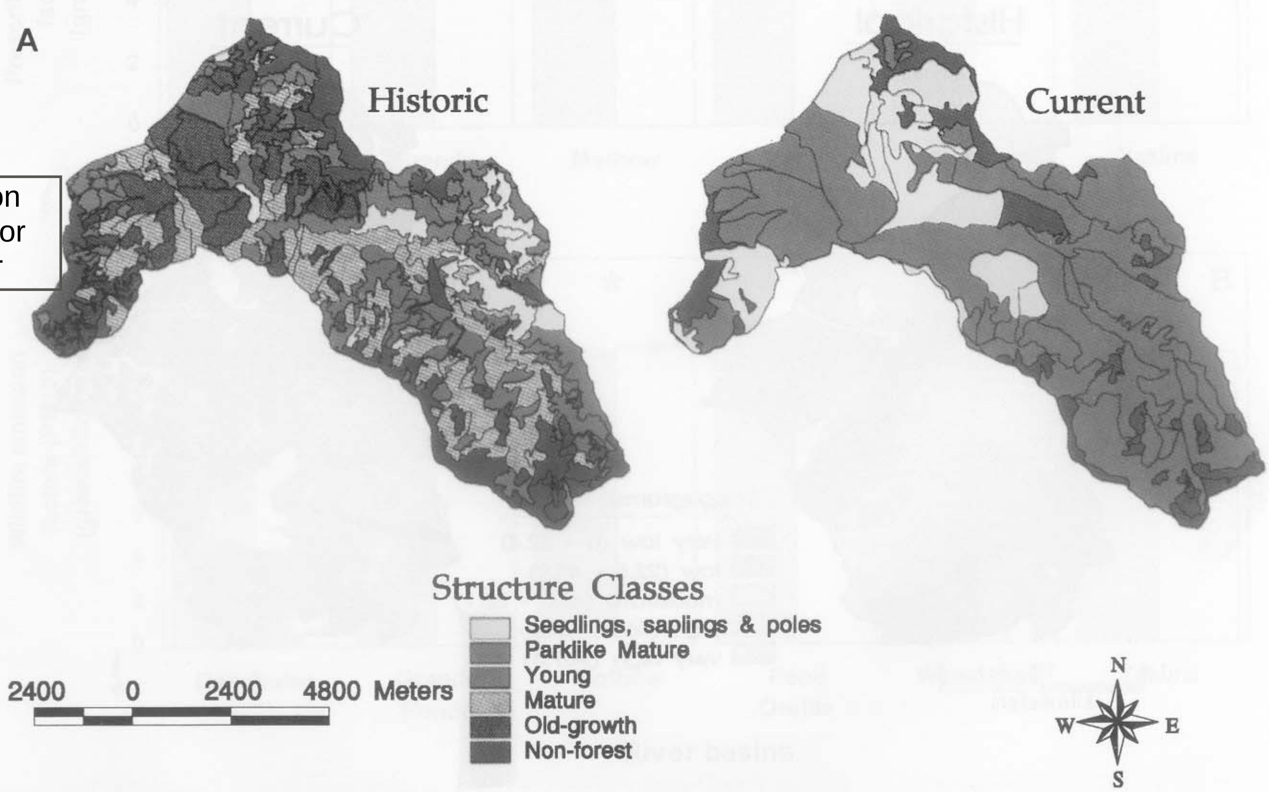


Figure 10—Historical and current maps of fuel loading: (A) Grande Ronde River basin sample watershed 35 (Eagle Cap Wilderness, Oregon), (B) Grande Ronde River basin sample watershed 55 (Wenaha-Tucanon Wilderness, Oregon), and (C) Yakima River basin sample watershed 30 (Washington).

Regeneration and seral development patterns can have a profound effect on potential fire behavior within landscapes by enhancing or diminishing its spread (Agee and Huff 1987, Saveland 1987). Spatially continuous fuels associated with thick regeneration in plantations can create high surface-fire potential during early successional stages. This was evident in most of the roughly 275 hectares of 1- to 25-year-old plantations burned in the 3500-hectare 1991 Warner Creek Fire in the Willamette National Forest[9] (USDA 1993). The fire moved swiftly through the openings created by past harvests, killing nearly all the regeneration but usually missing adjacent stands >80 years old.

Crown fires are typically high-intensity, rapidly moving fires that kill most or all overstory vegetation and contribute to a significant proportion of the area burned in the Western United States (Strauss and others 1989). Because only surface and understory fire behavior were examined for this study, our results underestimated the role that fire plays for eastern Washington and Oregon ecosystems. Yet, understory and surface fire intensities are linked to crown fire occurrence, and changes in vegetation composition and structure that increase surface and understory fire intensity are reasonable measures of risk.

The richness and diversity of landscape patterns are often tied to the legacies associated with past crown fire behavior. As crown fires move through a landscape, small to large blocks of trees are bypassed. Over time, landscapes develop a mosaic of patches with different fire history, composition, and structure. These types of patterns were well illustrated by 1988 Yellowstone National Park fires (Romme and Despain 1989). Vegetation series for eastern Washington and Oregon of a similar high-severity fire regime, such as lodgepole pine or subalpine fir, typically experience crown fires as part of the natural successional cycle (Agee 1993). Although crown fires pose major risks to society, studies are needed to understand the relation of crown fires to maintenance of ecological patterns and processes, and to find ways to approximate the effects of crown fires with and without prescribed fires.



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[9] Huff, Mark H. Unpublished data. On file with: Pacific Northwest Research Station, P.O. Box 3890, Portland, OR 97208-3890.

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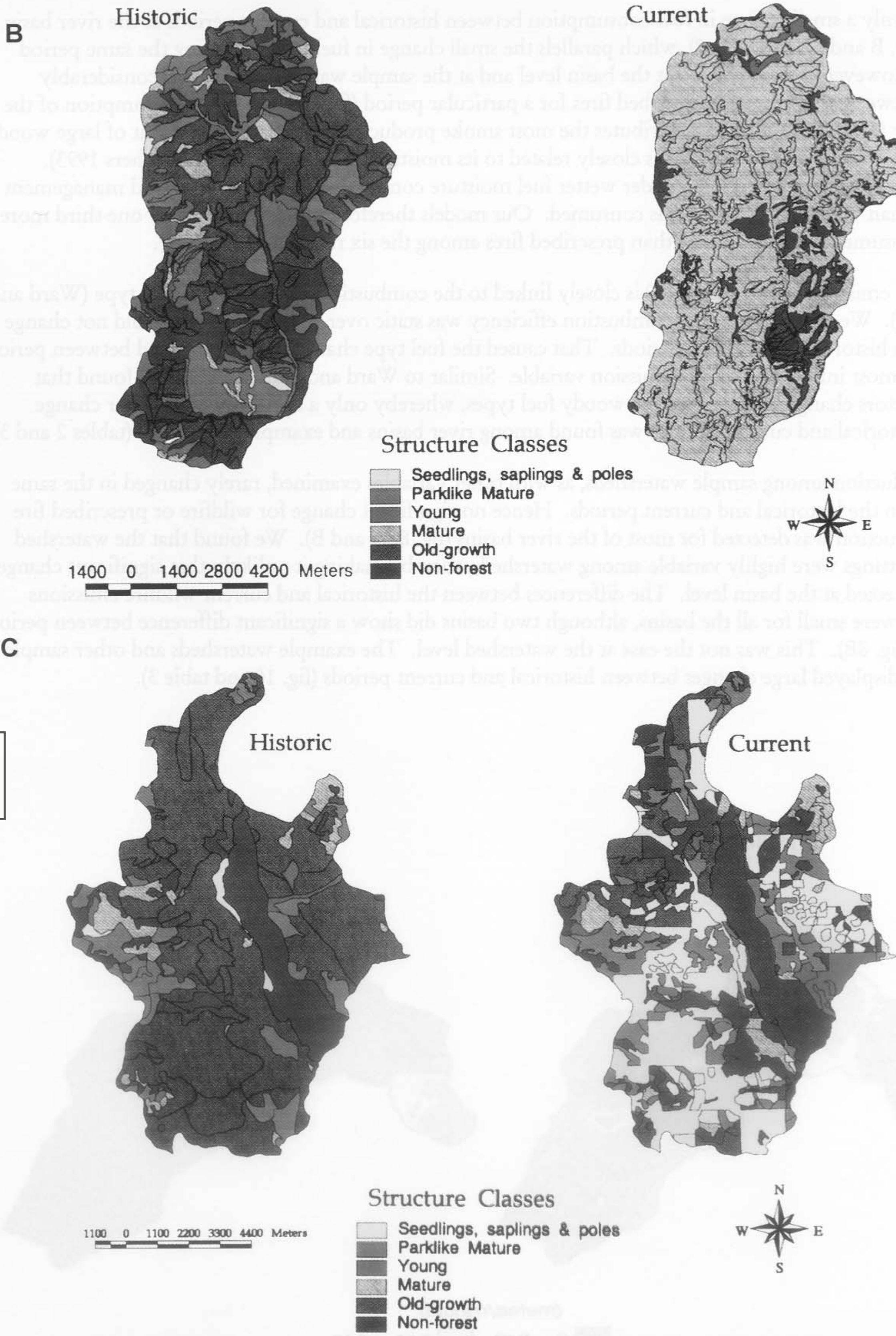

Figure 11—Historical and current maps of overstory structure: (A) Grande Ronde River basin sample watershed 35 (Eagle Cap Wilderness, Oregon), (B) Grande Ronde River basin sample watershed 55 (Wenaha-Tucanon Wilderness, Oregon), and (C) Yakima River basin sample watershed 30 (Washington).

Smoke Production

There was only a small change in fuel consumption between historical and current periods at the river basin scale (fig. 10, B and C, and table 2), which parallels the small change in fuel loading during the same period (fig. 3A). However, fuel consumed at the basin level and at the sample watershed level was considerably different between wildfires and prescribed fires for a particular period (figs. 14 and 15). Consumption of the large woody fuels and duff often contributes the most smoke produced by a fire. The amount of large woody material and duff consumed by a fire is closely related to its moisture content (Ottmar and others 1993). Because prescribed fires often burn under wetter fuel moisture conditions to meet specific land management objectives than wildfires do, less fuel is consumed. Our models therefore projected that over one-third more fuel was consumed during wildfires than prescribed fires among the six river basins (table 2).

The level of emission factors for PM10 is closely linked to the combustion efficiency and fuel type (Ward and Hardy 1991). We assumed that the combustion efficiency was static over time and therefore did not change between the historical and current periods. That caused the fuel type change, which occurred between periods, to have the most influence over the emission variable. Similar to Ward and Hardy (1991), we found that emission factors changed little across the woody fuel types, whereby only a slight emission factor change between historical and current periods was found among river basins and example watersheds (tables 2 and 3).

Smoke production among sample watersheds, as with other variables examined, rarely changed in the same way between the historical and current periods. Hence no significant change for wildfire or prescribed fire smoke production was detected for most of the river basins (fig. 8, A and B). We found that the watershed landscape settings were highly variable among watersheds, thereby making it unlikely that significant change could be detected at the basin level. The differences between the historical and current wildfire emissions production were small for all the basins, although two basins did show a significant difference between periods ($P < 0.10$; fig. 8B). This was not the case at the watershed level. The example watersheds and other sample watersheds displayed large changes between historical and current periods (fig. 16 and table 3).

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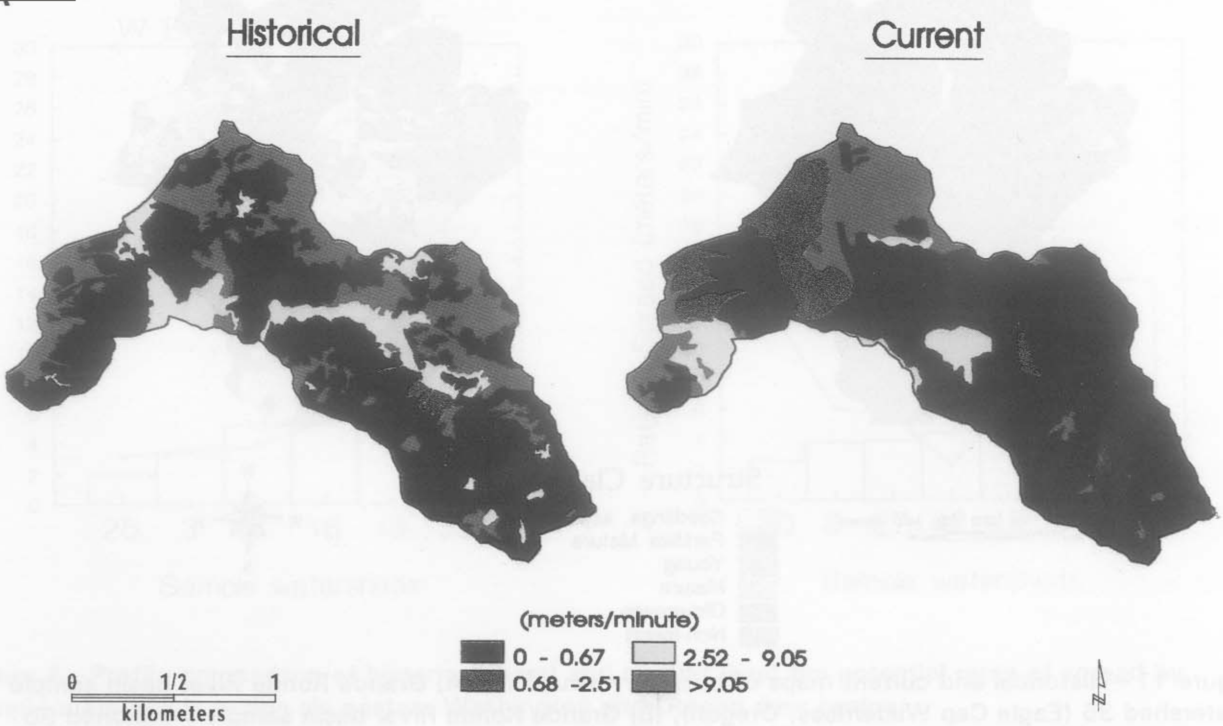
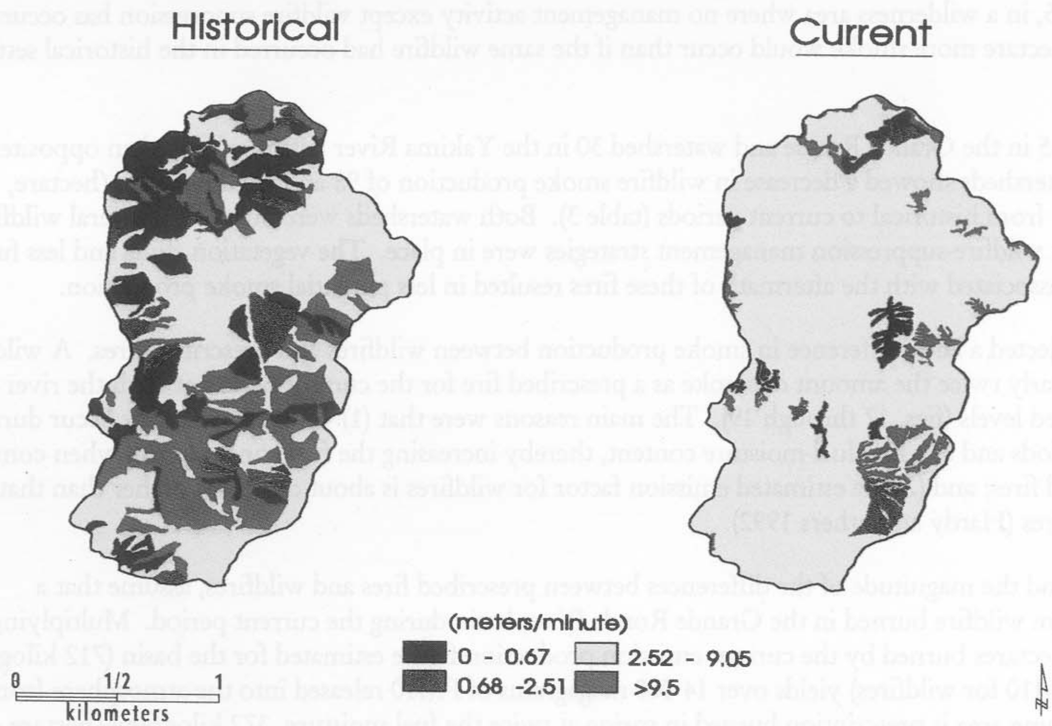


B



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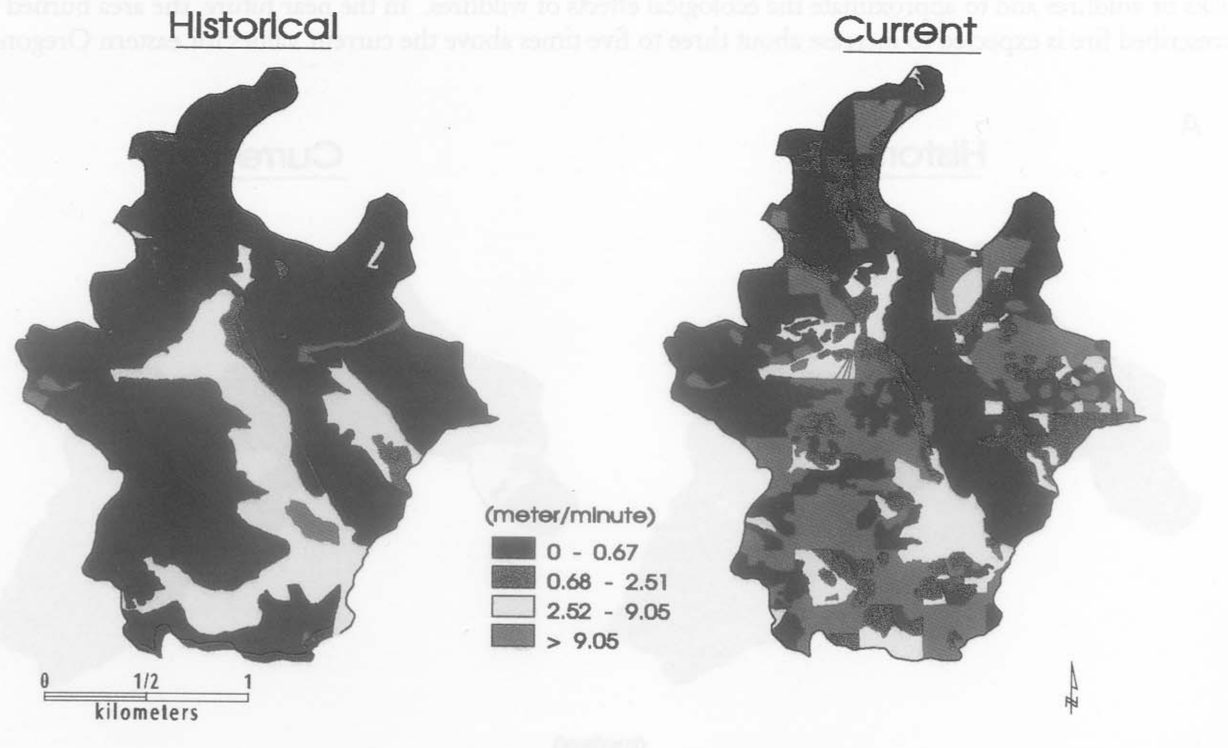

Figure 12—Historical and current maps of fire potential rate of spread: (A) Grande Ronde River basin sample watershed 35 (Eagle Cap Wilderness, Oregon), (B) Grande Ronde River basin sample watershed 55 (Wenaha-Tucanon Wilderness, Oregon), and (C) Yakima River basin sample watershed 30 (Washington).

Areas where fire had been excluded showed a trend toward higher fuel loadings and, consequently, potentially higher smoke production from wildfires. For example, if a wildfire occurred today in Grande Ronde watershed 55, in a wilderness area where no management activity except wildfire suppression has occurred, 258 kilograms/hectare more smoke would occur than if the same wildfire had occurred in the historical setting (table 3).

Watershed 35 in the Grande Ronde and watershed 30 in the Yakima River basins exhibited an opposite trend. The two watersheds showed a decrease in wildfire smoke production of 98 and 159 kilograms/hectare, respectively, from historical to current periods (table 3). Both watersheds were burned by several wildfires, even though wildfire-suppression management strategies were in place. The vegetation shifts and less fuel on the ground associated with the aftermath of these fires resulted in less potential smoke production.

We also projected a large difference in smoke production between wildfires and prescribed fires. A wildfire produced nearly twice the amount of smoke as a prescribed fire for the current period at both the river basin and watershed levels (figs. 17 through 19). The main reasons were that (1) wildfires generally occur during drought periods and at a low fuel-moisture content, thereby increasing the fuel consumption when compared to prescribed fires; and (2) the estimated emission factor for wildfires is about one-third higher than that for prescribed fires (Hardy and others 1992).

To understand the magnitude of the differences between prescribed fires and wildfires, assume that a 20 000-hectare wildfire burned in the Grande Ronde River basin during the current period. Multiplying the number of hectares burned by the current emission production figure estimated for the basin (712 kilograms/hectare of PM10 for wildfires) yields over 14 000 megagrams of PM10 released into the atmosphere from the fire. If the same area is prescription burned in spring at twice the fuel moisture, 372 kilograms/hectare of smoke would be produced and over 7000 megagrams of PM10 would be released into the atmosphere, about half the projected emissions for a wildfire in the same area.

It is likely that prescribed fire will be an important tool in managing ecosystems to reduce ecological and social risks of wildfires and to approximate the ecological effects of wildfires. In the near future, the area burned by prescribed fire is expected to increase about three to five times above the current values for eastern Oregon and

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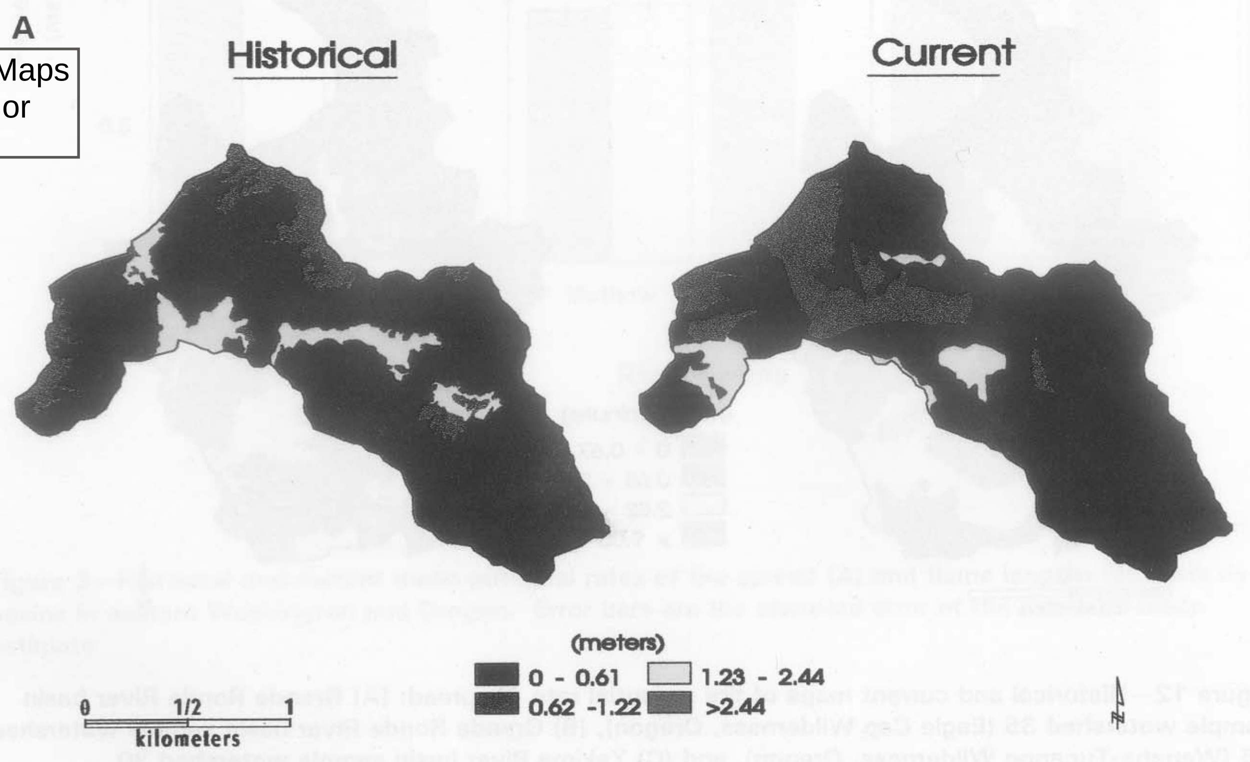

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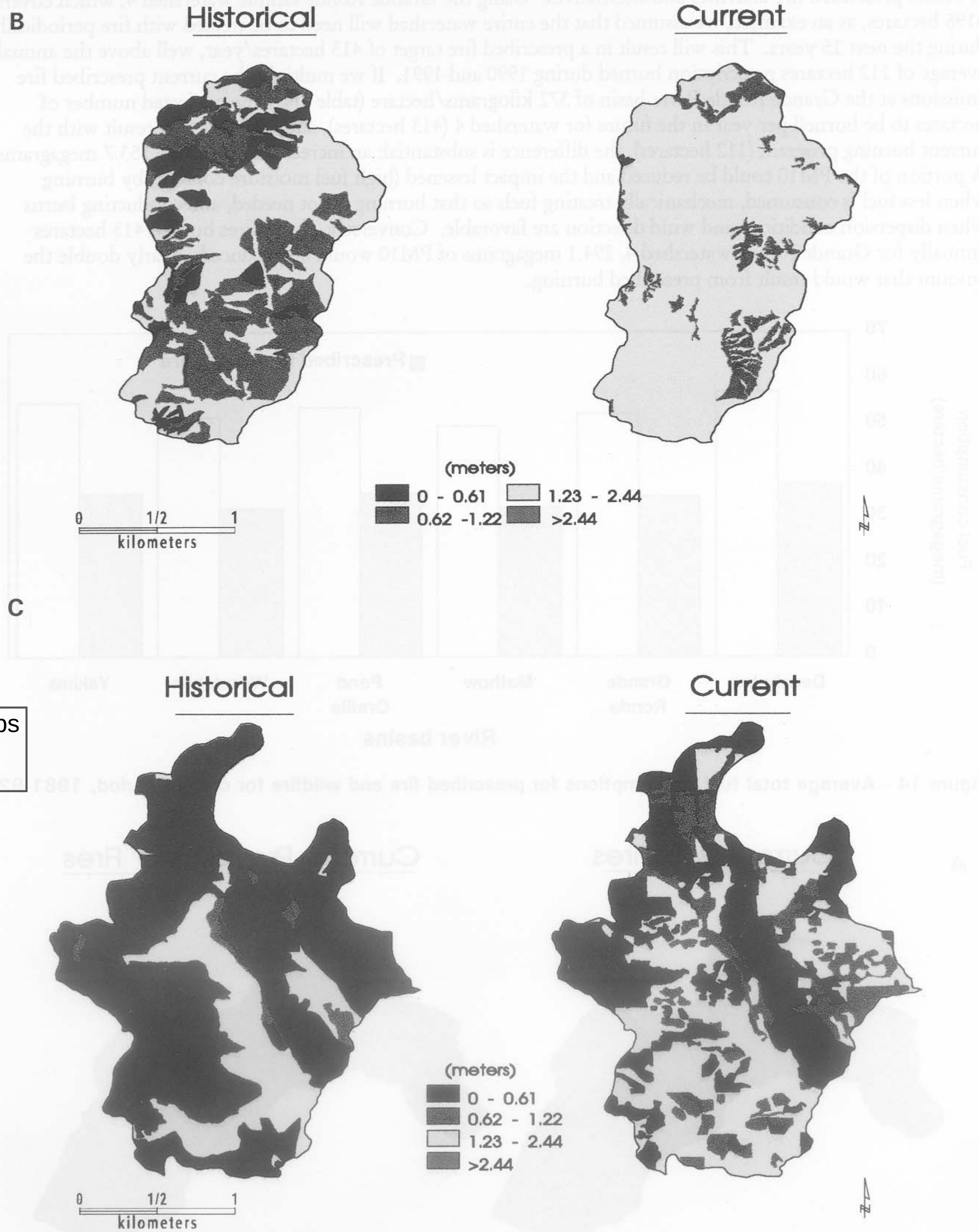

Figure 13—Historical and current maps of potential flame length: (A) Grande Ronde River basin sample watershed 35 (Eagle Cap Wilderness, Oregon), (B) Grande Ronde River basin sample watershed 55 (Wenaha-Tucanon Wilderness, Oregon), and (C) Yakima River basin sample watershed 30 (Washington).

Washington (Ottmar 1993). Methods similar to those used in this study can project PM10 smoke production of future prescribed fire activities and alternatives. Using the Grande Ronde sample watershed 4, which covers 6196 hectares, as an example, we assumed that the entire watershed will need to be treated with fire periodically during the next 15 years. This will result in a prescribed fire target of 413 hectares/year, well above the annual average of 112 hectares prescription burned during 1990 and 1991. If we multiply the current prescribed fire emissions at the Grande Ronde River basin of 372 kilograms/hectare (table 2) by the projected number of hectares to be burned per year in the future for watershed 4 (413 hectares), and compare that result with the current burning program (112 hectares), the difference is substantial: an increase from 41.7 to 153.7 megagrams. A portion of the PM10 could be reduced and the impact lessened (high fuel moisture content) by burning when less fuel is consumed, mechanically treating fuels so that burning is not needed, and conducting burns when dispersion conditions and wind direction are favorable. Conversely, if wildfires burned 413 hectares annually for Grande Ronde watershed 4, 294.1 megagrams of PM10 would be produced—nearly double the amount that would result from prescribed burning.

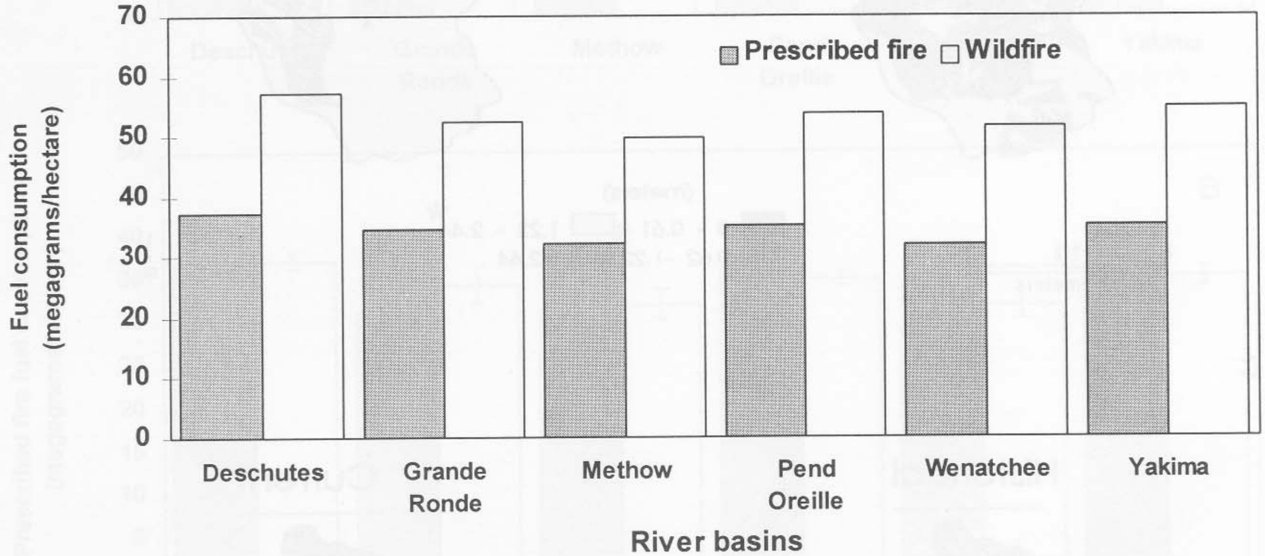

Figure 14—Average total fuel consumptions for prescribed fire and wildfire for current period, 1981-92.

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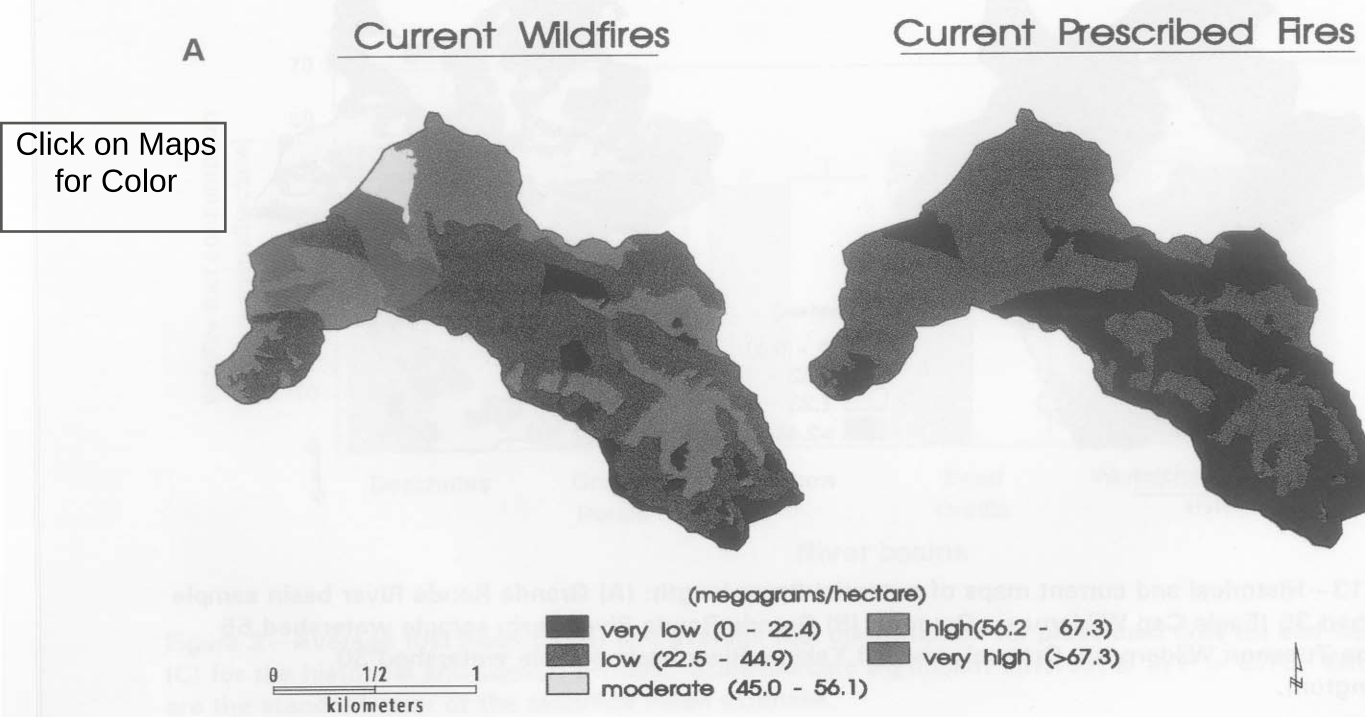

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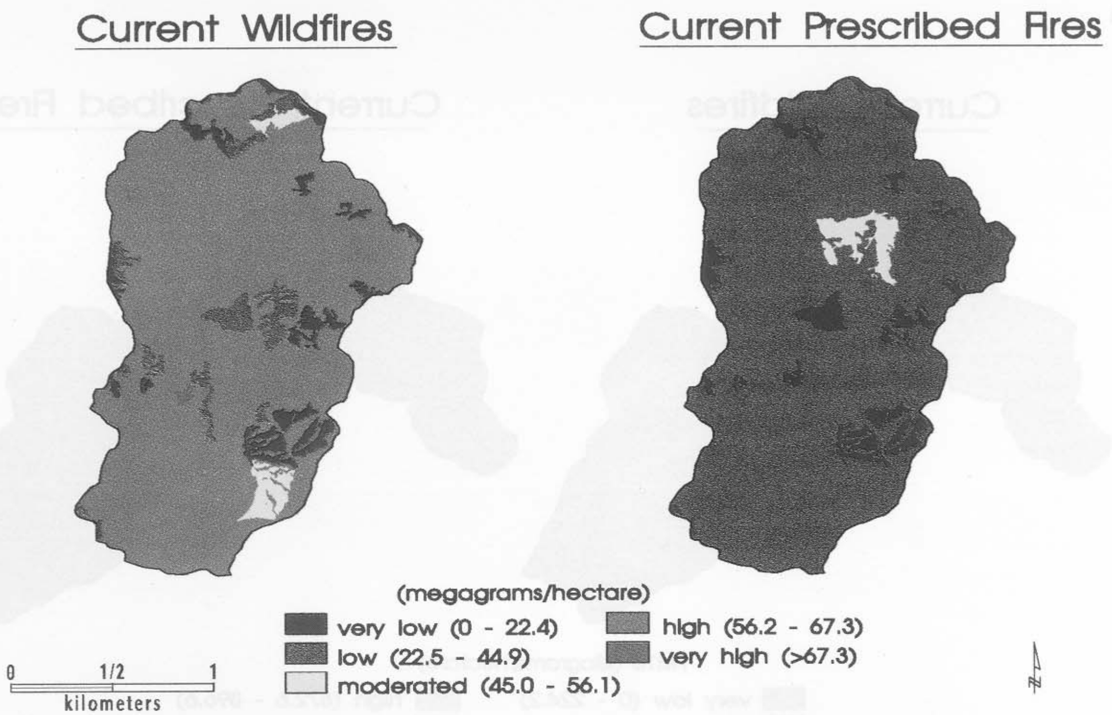

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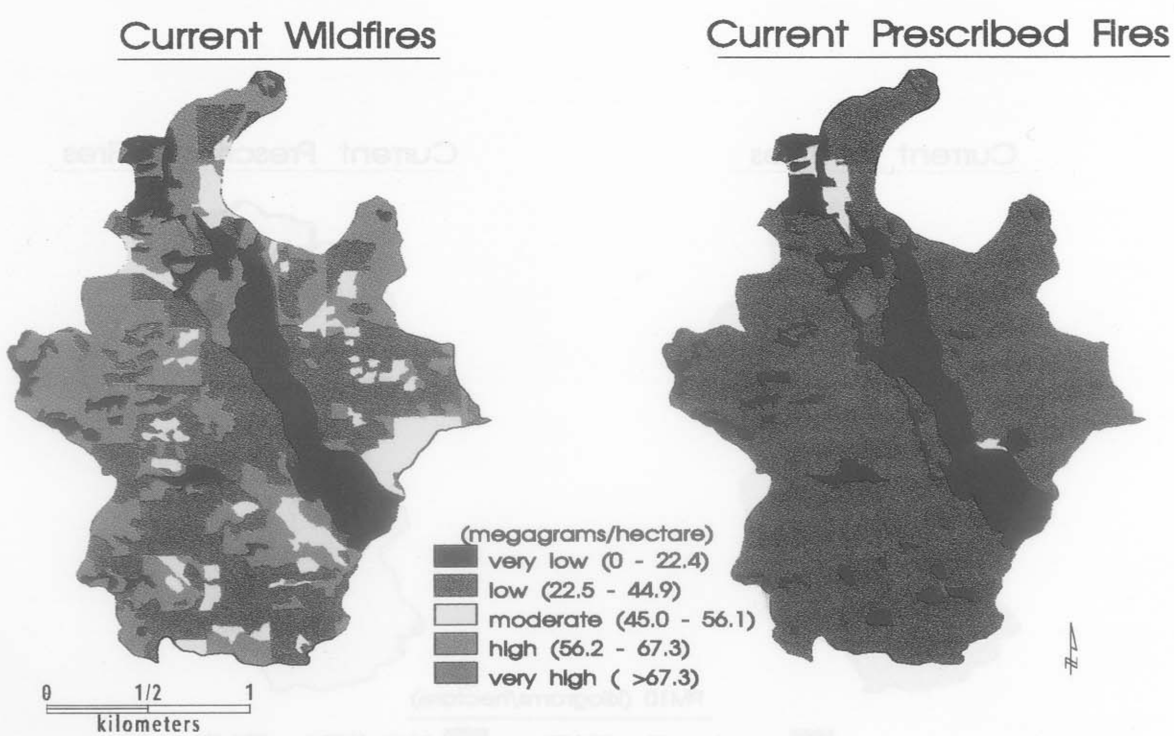
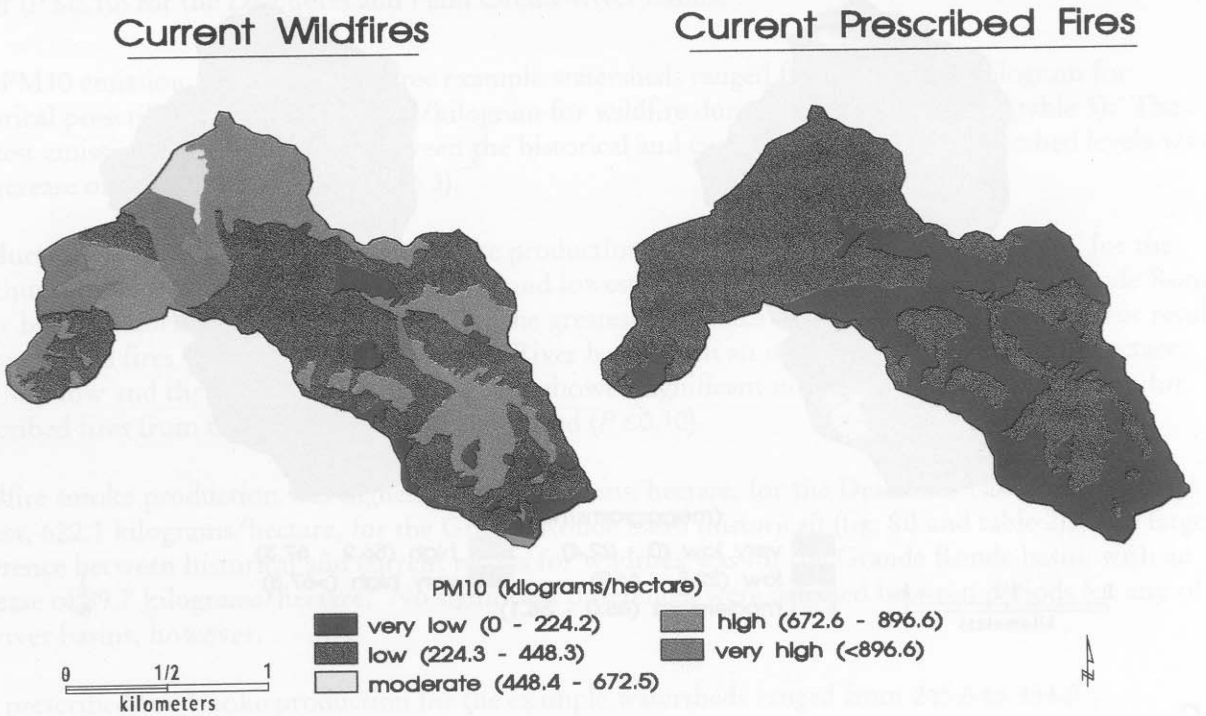


Figure 15—Current maps of fuel consumption for wildfire and prescribed fire: (A) Grande Ronde River basin sample watershed 35 (Eagle Cap Wilderness, Oregon), (B) Grande Ronde River basin sample watershed 55 (Wenaha-Tucanon Wilderness, Oregon), and (C) Yakima River basin sample watershed 30 (Washington).

A



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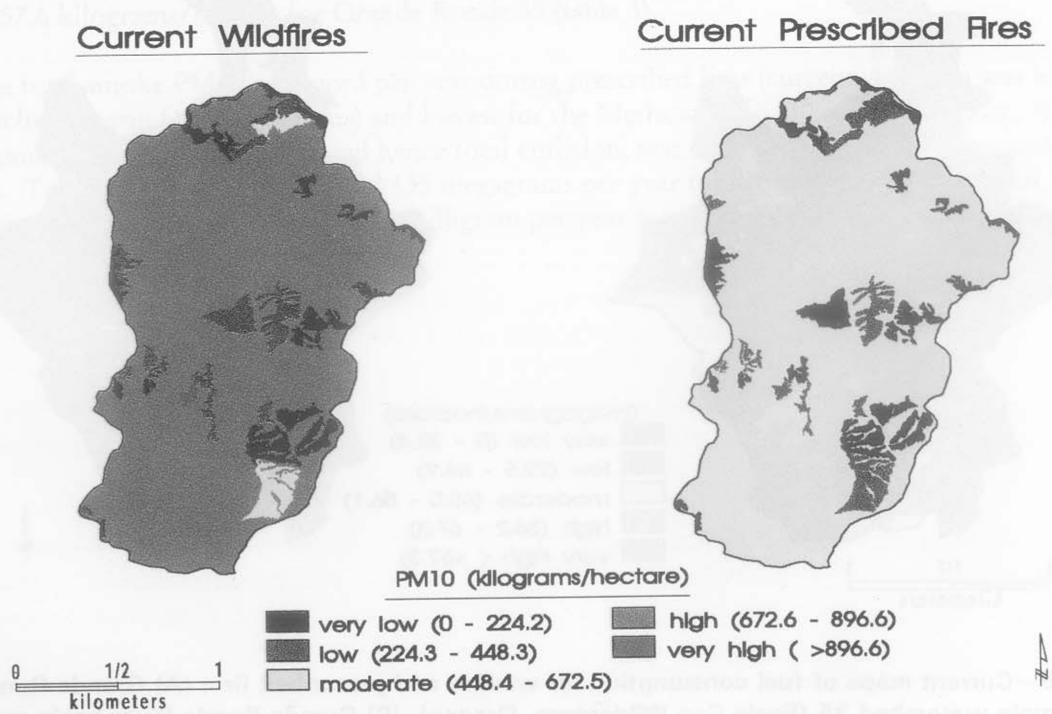

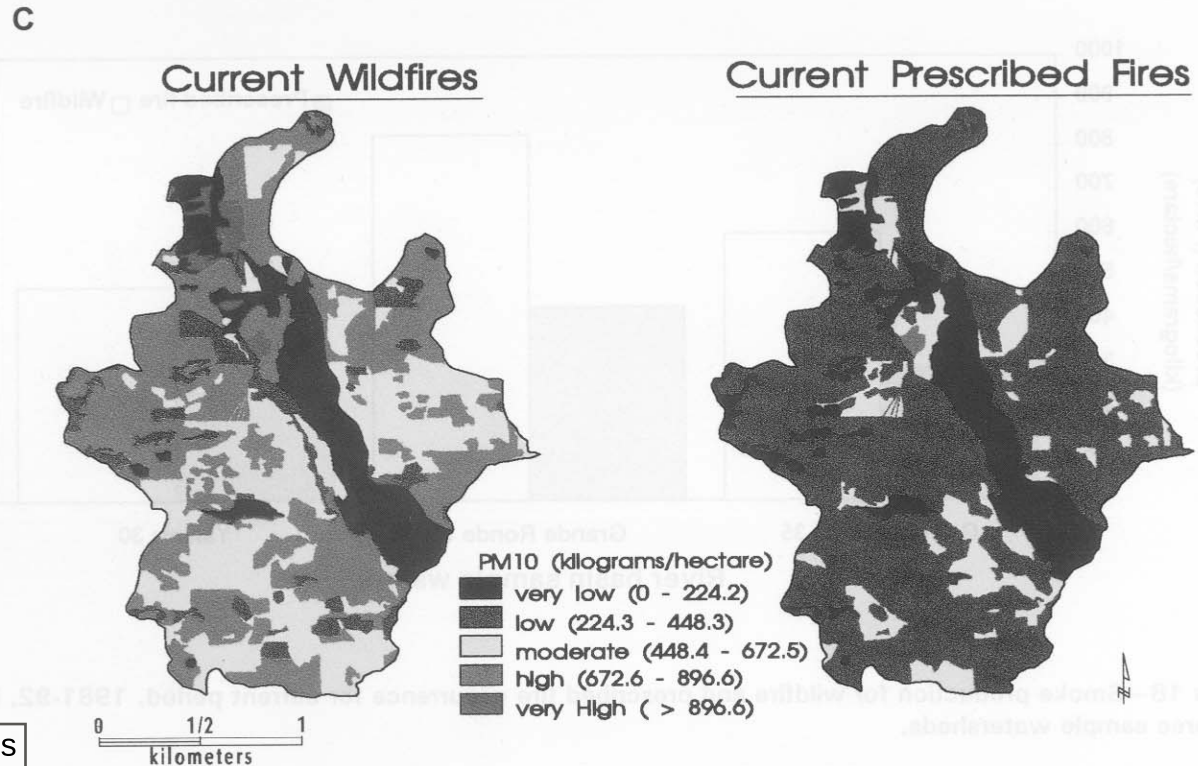

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Figure 16—Historical and current maps of wildfire smoke production: (A) Grande Ronde River basin sample watershed 35 (Eagle Cap Wilderness, Oregon), (B) Grande Ronde River basin sample watershed 55 (Wenaha-Tucanon Wilderness, Oregon), and (C) Yakima River basin sample watershed 30 (Washington).

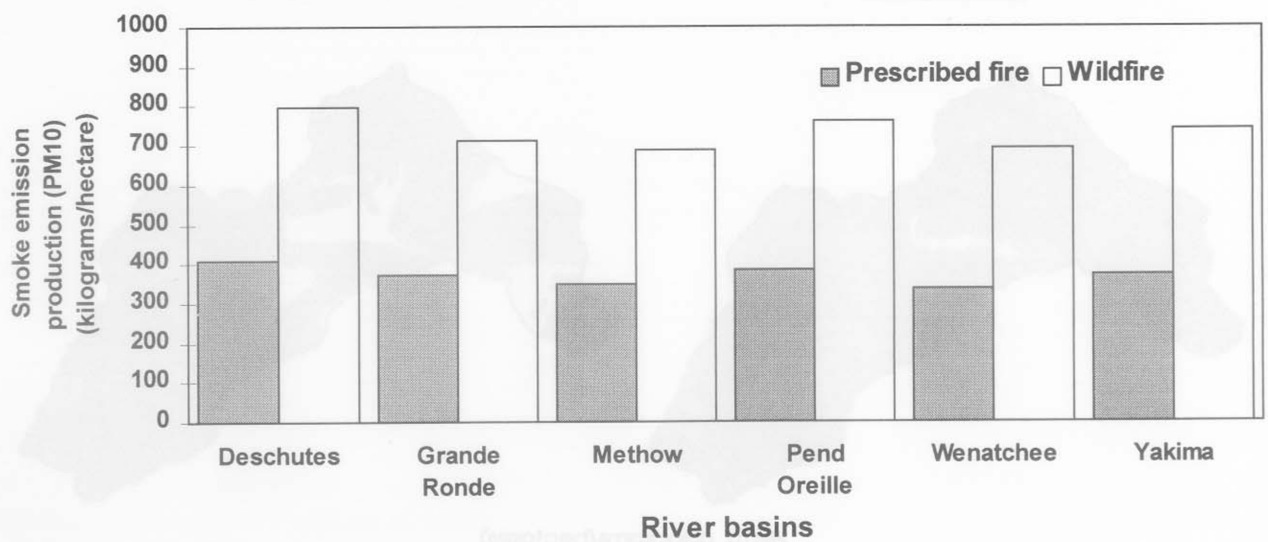

Figure 17—Smoke emissions production for wildfire and prescribed fire occurrence for current period, 1981-92, in the six river basins.

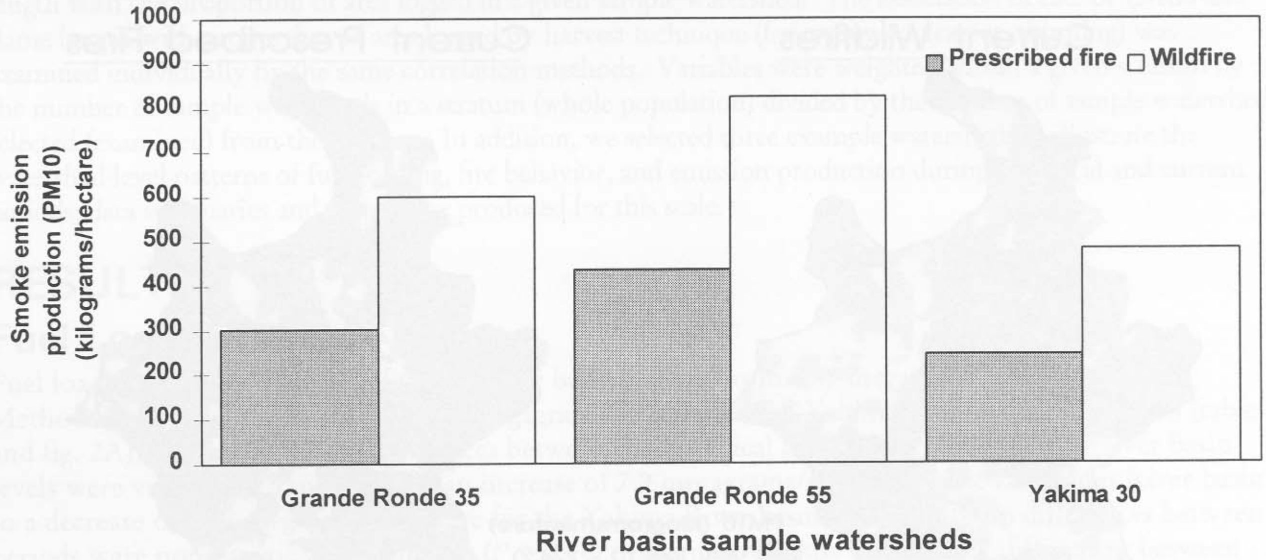

Figure 18—Smoke production for wildfire and prescribed fire occurrence for current period, 1981-92, in the three sample watersheds.

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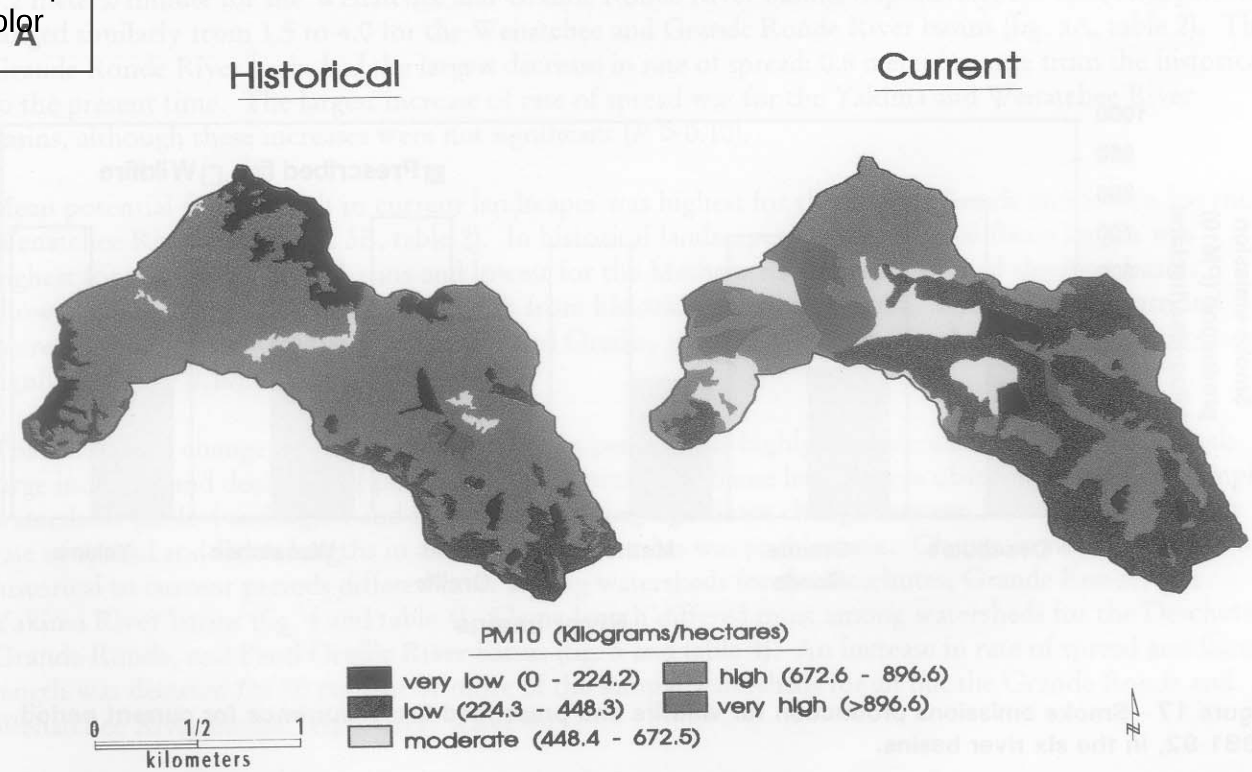

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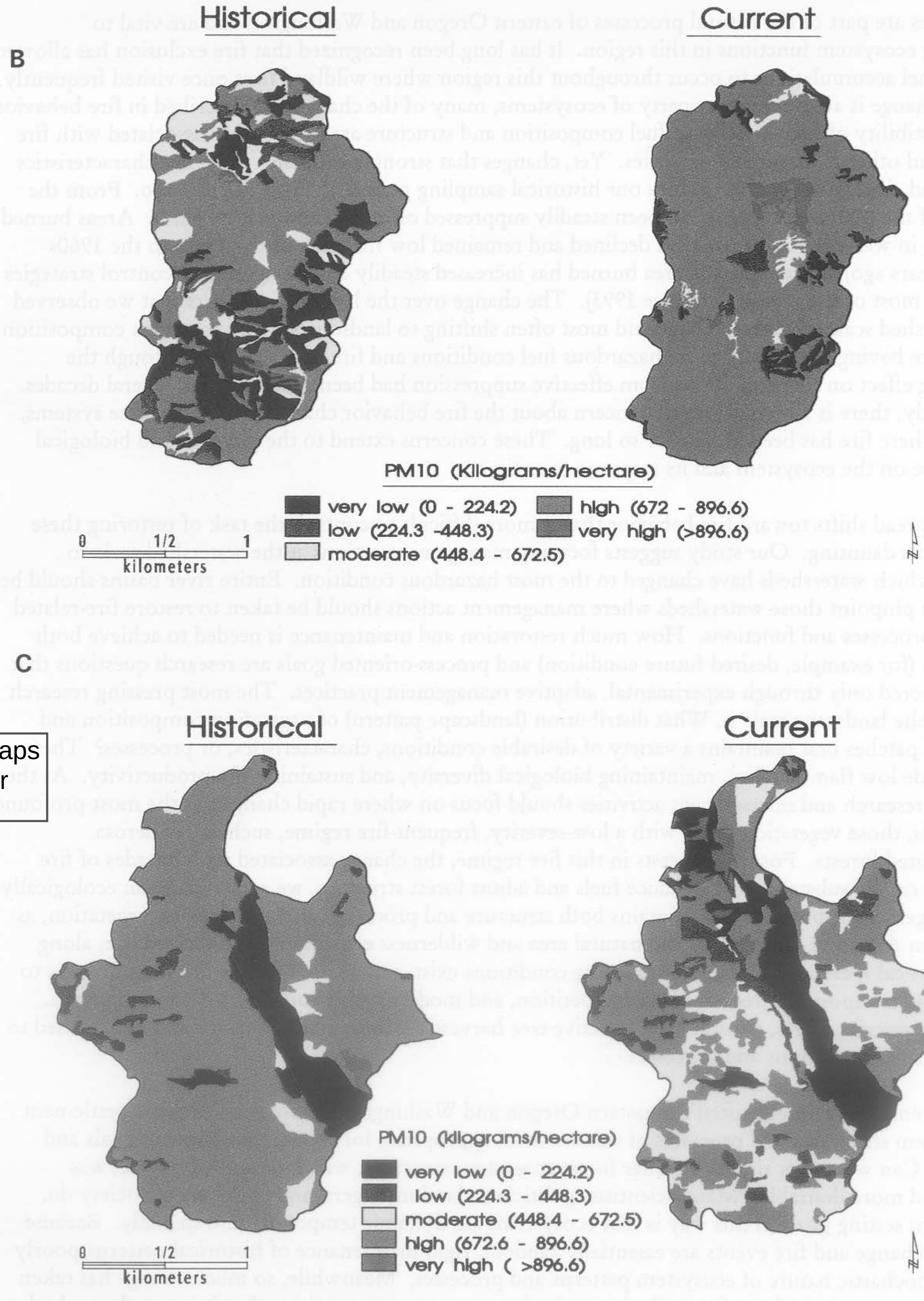

Figure 19—Current maps of smoke emissions production for wildfire and prescribed fire: (A) Grande Ronde River basin, sample watershed 35 (Eagle Cap Wilderness, Oregon); (B) Grande Ronde River basin, sample watershed 55 (Wenaha-Tucanon Wilderness, Oregon); and (C) Yakima River basin, sample watershed 30 (Washington).

CONCLUSIONS AND RECOMMENDATIONS

Periodic fires are part of the natural processes of eastern Oregon and Washington and are vital to maintaining ecosystem functions in this region, It has long been recognized that fire exclusion has allowed unnatural fuel accumulations to occur throughout this region where wildland fires once visited frequently. Although change is an inherent property of ecosystems, many of the changes we described in fire behavior and combustibility of fuels relative to fuel composition and structure are presumably associated with fire exclusion and other management activities. Yet, changes that strongly influence these fire characteristics probably had already taken place before our historical sampling period of 35 to **50** years ago. From the early part of the 20th century, fire has been steadily suppressed on public and private lands. Areas burned by wildfires in western North America declined and remained low from about the **1920s** to the 1960s (about 35 years ago); since then, the area burned has increased steadily despite aggressive control strategies throughout most of the region (see Agee 1993). The change over the last 35 to **50** years that we observed at the watershed scale seems to be large and most often shifting to landscapes with vegetation composition and structure having potentially more hazardous fuel conditions and fire behavior, even though the potential lag effect on fuel conditions from effective suppression had been underway for several decades. Consequently, there is a high degree of concern about the fire behavior characteristics for these systems, especially where fire has been absent for so long. These concerns extend to the physical and biological effects of fire on the ecosystem and its response over time.

With widespread shifts toward fire behavior that is more difficult to control, the task of restoring these systems seems daunting. Our study suggests focusing management actions at the watershed scale to determine which watersheds have changed to the most hazardous condition. Entire river basins should be evaluated to pinpoint those watersheds where management actions should be taken to restore fire-related ecosystem processes and functions. How much restoration and maintenance is needed to achieve both conditional- (for example, desired future condition) and process-oriented goals are research questions that can be answered only through experimental, adaptive management practices. The most pressing research question at the landscape scale is, What distribution (landscape pattern) of vegetation composition and structure of patches best maintains a variety of desirable conditions, characteristics, or processes? These might include low flammability, maintaining biological diversity, and sustaining site productivity. At the stand scale, research and management activities should focus on where rapid change has the most profound effect; that is, those vegetation types with a low-severity, frequent-fire regime, such as ponderosa pine-dominated forests. For these forests in this fire regime, the change associated with decades of fire suppression can be substantial. To reduce fuels and adjust forest structure, we recommend an ecologically based management approach that maintains both structure and process goals for managing vegetation, as adapted from Agee and Huff (1986), for natural area and wilderness ecosystems. Prescribed fire, along with mechanical measures if hazardous burning conditions exist, can be used for restoration purposes to regulate stand composition, reduce plant competition, and modify fuels to achieve a desired structure. Over time, prescribed fires, natural fires, selective tree harvesting, or combinations thereof can be used to maintain desired conditions and processes.

Many different fire regimes existed for eastern Oregon and Washington before pre-European settlement. Are ecosystem structures and processes of this era most appropriate for setting management goals and objectives? Can we accept that this earlier forest ecosystem structure, which depended on fire, was healthier and more desirable? Many scientists, politicians, land managers, and members of society do. The pitfall in setting goals in this way is that ecosystems are dynamic temporally and spatially. Because ecosystems change and fire events are essentially random, rigid maintenance of historical patterns poorly reflect the stochastic nature of ecosystem patterns and processes. Meanwhile, so much change has taken place in some ecosystems from fire exclusion and other management activities, that it is not clear whether restoration actions can bring these systems back to some desired "historical state." Additional research is essential to increase our knowledge about fire dynamics relative to ecosystem change.

Prescribed fires and prescribed natural fires (lightning-caused fires controlled to meet predetermined management prescriptions) are recommended ways to restore fire-related ecosystem processes and functions. Clearly, the most significant constraint to achieving this is the effect of smoke. Most prescribed fires have the potential to degrade ambient air, impair visibility, and expose the public to various concentrations of smoke. These negative effects of prescribed fire contradict current state and national air quality regulations. Scientists and managers will need to describe-and the public will need to understand-the tradeoffs among increased prescribed fires, wildfires, ecosystem health, visibility degradation, and the public health problems resulting from exposure to smoke.

One of the most important tradeoffs to consider is the substantial increase in smoke production from wildfires versus prescribed fires. Wildfires occur when fuels are dry, fuel consumption is greater, and the fuels are consumed during the less efficient smoldering stage, which nets about twice as much PM10 when compared to a prescribed fire. If prescribed fire can be used to restore or maintain fire-adapted ecosystems, yet reduce the potential of wildfire, PM10 production from landscape burning could be reduced considerably. In addition, prescribed fires are planned in advance, and four mitigation techniques are available to further reduce air quality impacts. Managed ignitions can be planned for situations when (1) smoke will disperse quickly, (2) smoke will avoid sensitive airsheds, (3) less fuel will be consumed more efficiently and produce less smoke, and (4) fuels have been removed or reduced, thereby eliminating the need to burn. In cases where specific objectives are to be met, some of these mitigation techniques may not be employed to the fullest extent possible.

Wildfires are not planned; therefore, there is little opportunity to employ mitigation techniques except to suppress the fire as quickly as possible. The smoke generated will be directed and concentrated according to the prevailing wind and atmospheric stability. This will often occur during the summer months when fuel moisture is low, fuel consumption and smoke production are high, and stable atmospheric conditions may persist. Wildfire does have one advantage over prescribed fire: it might not occur. Will the public be willing to accept smoke from prescribed fires spread over a period of years or find it preferable to gamble that a catastrophic wildfire, which sends out large amounts and greater concentrations of smoke in a few months, will not occur?

It is commonly noted that if we do not prescribe burn now, wildfire may soon do the job in a much less acceptable way, from both ecosystem and air quality standpoints. This premise will not be accepted by society and cannot be used as an excuse for not providing quality information about potential impacts of prescribed burning for forest health. The public has previously chosen to bear the costs associated with clean air. Will the public rate air quality values higher than forest health values by choosing to accept wildfire in place of managed fire? Probably yes, unless (1) a strategic plan is developed to address all regulatory requirements such as guidelines for prevention of significant deterioration, visibility, emissions reduction, and health risks associated with prescribed fire; (2) the public understands the tradeoffs; (3) the public regulatory agencies are involved with fire-management planning; and (4) a strong research program is provided.

The assessment of vegetation related to fire behavior and air quality provided in this report is a cursory look at 35 to 50 years of change across the landscapes of eastern Oregon and eastern Washington. This paper has only touched the surface on what must be done to produce a comprehensive fire hazard and air quality tradeoff analysis that society deserves and will require. The structure and methods for completing the comprehensive tradeoff analysis have been formulated through this study, however, and further work could begin immediately and move ahead quickly.

There are several areas of this study that could be improved on to better understand fire and air quality implications. First, interested public citizens, politicians, land managers, and regulators will need to be identified and their informational needs assessed. Second, additional aerial interpretive data should be collected to improve the historical baseline information for fuel loading, area burned, and emissions produced. This should include information on understanding presettlement fire regimes and related forest structure, composition, and patterns. Third, estimates of potential fire behavior, emissions, and air quality impacts from a mix of future prescribed fire and wildfire scenarios will need to be made. Finally, an information system needs to be designed and implemented to enable society and policymakers to make informed choices about the appropriate role of prescribed fire in restoring or maintaining fire-adapted ecosystems.

Fire is an essential component in the dynamics and sustainability of many ecosystems in eastern Oregon and eastern Washington. Fire is not a tool that should be used for all sites or situations. It is, however, a tool that should be available and understood during design of a management strategy for certain ecosystems. Proper application of fire, in harmony with other management techniques, often may be the best option for meeting specific objectives while creating the fewest adverse effects.

ACKNOWLEDGMENTS

Our thanks go to the photo-interpreting teams from the Wenatchee, Okanogan, Colville, Wallowa-Whitman, Umatilla, and Deschutes National Forests who mapped and attributed the vegetation and physical features of the sample watersheds used in this study. Pete Ohlson and Don Spurbeck located and acquired historical photograph coverage of the sample watersheds from the National Archives and managed the photo-interpreting teams. Tom Anderson, Randy Gray, Craig Miller, and John Beebe provided much assistance with digitizing and analyzing map data in GIS and developing graphics. Tim Max gave important statistical advice on study design and data analyses. We thank Steve Garmen, Colin Hardy, Charles Philpot, and Brad Smith for their review of drafts of this manuscript.

English Equivalents

When you know:	Multiply by:	To find:
Megagrams per hectare	0.446	tons per acre (fuel loading and consumption)
Grams per kilogram	2.003	pounds per ton (emission factor)
Kilograms per hectare	0.892	pounds per acre (smoke production)
Meters	3.281	feet

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We compared the potential tire behavior and smoke production of historical and current periods based on vegetative conditions in 49 5100- to 13 500-ha watersheds in six river basins of eastern Oregon and Washington. Vegetation compositions, structure, patterns were attributed and mapped from aerial photographs of 1932 to 1959 (historical) and 1981 to 1992 (current). Vegetation with homogeneous composition and structure were delineated as patches. Because of the high variability we observed in fuel or vegetative conditions, we recommend an extensive characterization of these conditions before large-scale restoration and maintenance of fire-related processes are undertaken.

Keywords: Fire, fire behavior, smoke production, air quality, eastern Oregon, eastern Washington, forest health, fuel loadings, historical landscapes, vegetation structure.

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