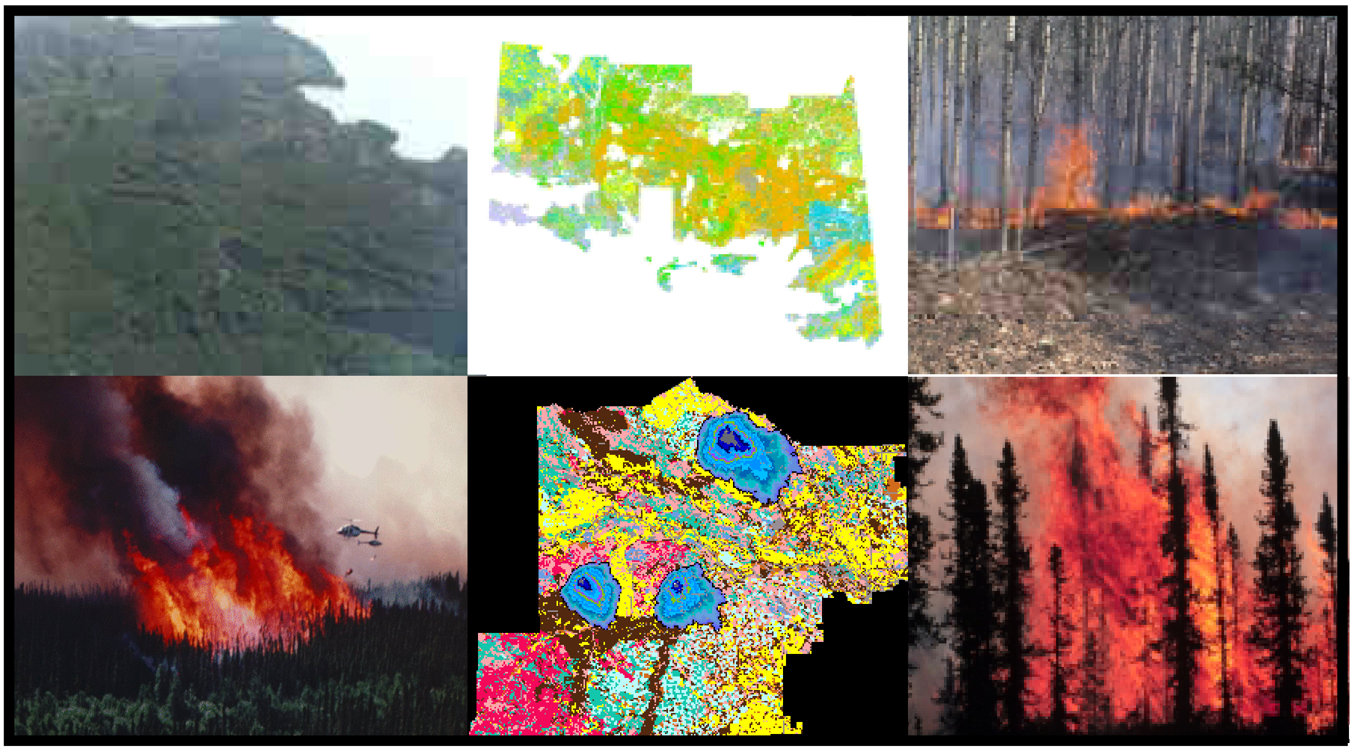
CLIMATE CHANGE IN THE PRAIRIE PROVINCES: ASSESSING LANDSCAPE FIRE BEHAVIOR POTENTIAL AND EVALUATING FUEL TREATMENT AS AN ADAPTATION STRATEGY



A Report for the
Prairie Adaptation Research Cooperative (PARC)
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PREFACE

This report has been prepared as part of a Collaborative Research Agreement between the Prairie Adaptation Research Cooperative (PARC) and the Canadian Forestry Service (CFS), Northern Forestry Centre. The PARC is funded by the Government of Canada's Climate Change Action Fund and it has been created to support and bring together the work of universities, private organizations, and federal and provincial departments on adaptations to climate change in the Prairie provinces. Climate change studies are at the forefront of research priorities at the CFS and thus this opportunity to collaborate with PARC and other partners to enhance our knowledge of forest fire aspects and issues as related to climate change was most welcomed.

This report provides a description of two studies. The first is an assessment of present and future landscape-level wildfire behavior potential in central Saskatchewan. This study is aimed at evaluating the potential impact of climate change on fire behavior characteristics, fire effects, and suppression capability and providing fire managers with procedures and tools to forecast long-term potential changes in the fire environment. Along with the scientific results and their implications for fire and forest management, this first section includes a detailed description of the methodology and the technical requirements because we felt that providing the reader with a knowledge of the intricacies and assumptions used in creating fire behavior potential maps was important. At the end of section one in Appendix I, several maps illustrate the changes in fire behavior potential.

The second study is an evaluation of the effectiveness of landscape-level fuels treatment at reducing wildfire size in a forest management agreement area in west central Alberta. It is hoped that this study will contribute to the development of climate change adaptation strategies that can be used by forest companies in response to potential increases in wildfire activity. This section is presented as a preliminary journal article.

CLIMATE CHANGE IN THE PRAIRIE PROVINCES: ASSESSING LANDSCAPE FIRE BEHAVIOR POTENTIAL AND EVALUATING FUEL TREATMENT AS AN ADAPTATION STRATEGY[1]

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SECTION 1

ASSESSING THE IMPACT OF CLIMATE CHANGE ON LANDSCAPE FIRE BEHAVIOR POTENTIAL IN CENTRAL SASKATCHEWAN

1. INTRODUCTION

The average area burned by wildfires in Canada between 1918 and 1986 has been estimated at 1.3 million ha per year with large annual variations that are dependent on the severity of the fire weather conditions (Van Wagner 1988). The area burned is not uniformly distributed over the Canadian boreal forest; Weber and Stocks (1998) observed that a greater proportion of the area burned occurred west of the Ontario-Manitoba border. The 1989 and 1995 fire seasons have demonstrated how the Prairie Provinces can be affected by wildfires with a total area burned of 4.1 and 2.62 million ha, respectively (Canadian Council of Forest Ministers 1997). Studies have shown that this region of Canada is also expected to exhibit the largest increase in fire season severity under future climatic conditions. For example, using daily results from a Global Circulation Model (GCM), Flannigan *et al.* (1998, 2001) have shown that the western portion of the boreal forest could experience an increase in fire frequency and area burned under a 2xCO_2 climate scenario. Recently, the development of Regional Climate Models (RCMs) has allowed researchers to study the impacts of climate change on wildfire activity on a more localised basis. Based on climate scenario data provided by a Canadian Regional Climate Model (CRCM) (Caya *et al.* 1995), Wotton *et al.* (1998) confirmed the possible significant increase in seasonal fire severity in the southern boreal forest of western Canada.

In recent extreme fire seasons (e.g., 1998 in Alberta, 1995 in Saskatchewan) large areas have burned despite unprecedented suppression expenditures demonstrating that it is not economically feasible to eliminate all large wildfires. Simulation analysis has shown that regardless of the level of protection, a small percentage of fires (e.g., 2-3%) are likely to continue to escape initial attack (McAlpine and Hirsch 1999). Such escaped fires generally account for over 95% of the total amount of the area burned by all wildfires. Given the possible increase in fire weather severity, fire and resource managers need to know the impact that it could have on the future fire behavior potential of the landscape. Moreover, due to the critical role played by forest fires in boreal forest dynamics, and in particular in climate change through its positive feedback on the carbon budget (i.e. more fires release more carbon), there is a need to assess wildfire potential.

In their study, Wotton *et al.* (1998) used the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) to compute daily severity ratings to assess fire danger. The FWI System provides relative measures of fire behavior potential in a standard fuel type and on level terrain based on daily noon observations of temperature, relative humidity, wind speed and 24-hour precipitation. In this study, we conducted a quantitative and spatial assessment of changes in potential fire behavior that used the fire weather data provided by the latest run of the CRCM and combined it with fuel types and topography to further characterise the fire environment. As such, the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) is used to evaluate fire behavior potential as measured by head fire intensity (HFI) (Kafka *et al.* 2000). Fire intensity is defined as the rate of energy release per unit time per unit length of fire front (Byram 1959). It provides a quantitative measure of fire behavior potential and it can be related to fire behavior characteristics (Table 1), fire effects and suppression effectiveness. For example, wildfires with HFI values between about 2000 and 10,000 kW/m begin to exhibit crowning which makes them difficult to control. Fires below 2000 kW/m (Fig. 1) can generally be contained by initial attack crews (Hirsch *et al.* 1998) whereas those over 10,000 kW/m (Fig. 2) are usually beyond control by suppression resources. This study assessed potential HFI in a very large area in central Saskatchewan and enabled us to show the spatial variability of the impact of a future climate on the fire behavior potential. Thus, the objectives of this study are: 1) to develop a procedure to assess the fire behavior potential under present and future climatic conditions and 2) to analyse these potential changes and discuss their implications.

Table 1. General fire behavior characteristics based on head fire intensity (from Alexander and DeGroot 1998, Alexander and Lanoville 1989, Stocks and Hartley 1995, Hirsch 1996).

Head Fire Intensity class (kW/m)	General Fire Behavior Description
0-9	Smoldering or subsurface fires with little or no visible flame
10-499	Slow moving surface fires with relatively low flames
500-1999	Moderately fast spreading fires with low and high flames. Isolated torching may occur if ladder fuels present
2000-3999	Fast spreading, high intensity surface fires or intermittent crown fires with short range spotting
4000-9999	Very fast spreading intermittent crown fires with flames extending above the canopy and short to medium range spotting
10,000-29,999	Continuous crown fires with extremely fast spread rates. Fire whirls, towering convection column and medium to long range spotting possible
> 30,000	Continuous crown fires with extremely fast spread rates and long range spotting. Conflagration or blow-up type behavior possible

Fig. 1. Low intensity surface fire.

Fig. 2. High intensity crown fire.

2. METHODS

2.1. Study area

The study area is located in central Saskatchewan and covers 13.5 million ha (Fig. 3). Long, cold winters and short, cool summers characterise the climate of the study area (Phillips 1990).

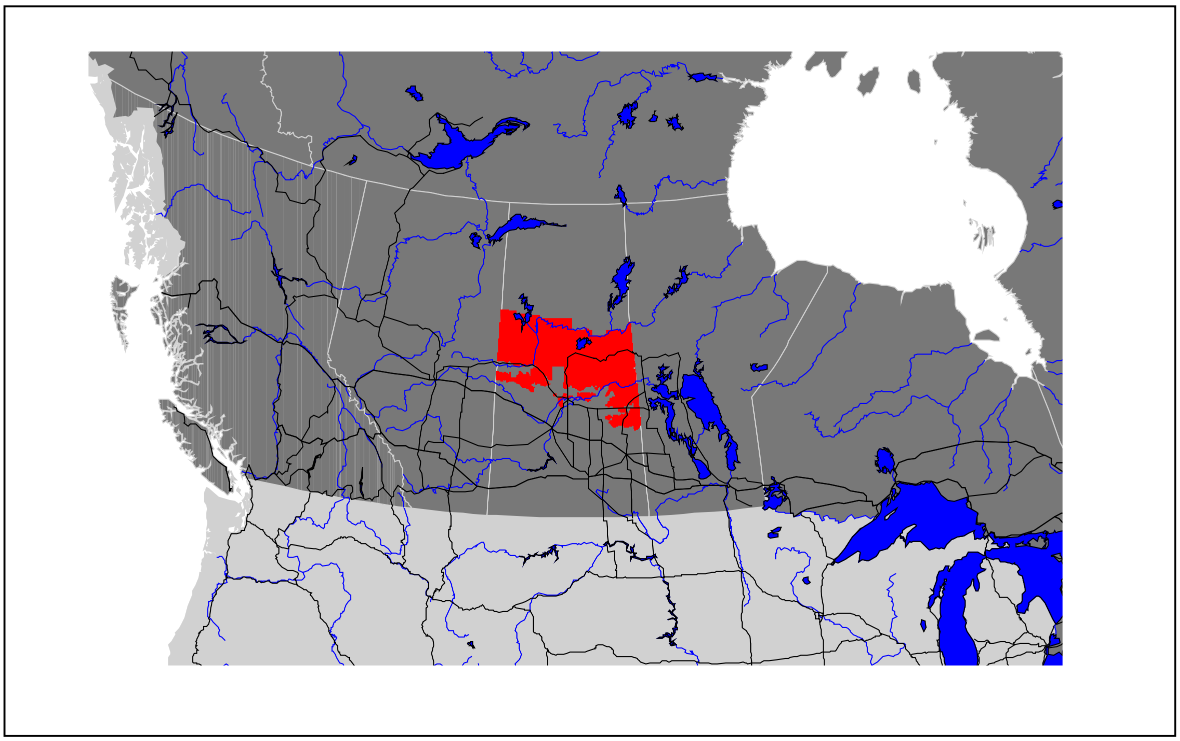

Fig. 3. Study area in central Saskatchewan.

Saskatchewan experiences large daily and annual fluctuations in temperature. Throughout the year, it records the highest number of hours with sunshine in Canada with approximately 2500 hours a year. The La Ronge A weather station (55°09'N, 105°16'W), located approximately in the middle of the study area, reports a range in daily mean temperatures of –20.9°C for the month of January to 16.9°C for the month of July and a yearly average of 1300°-day above 5°C

(Environment Canada 1993). Total yearly precipitation amounts are relatively low (about 500 mm), mostly occurring as rain. According to Rowe's forest regions (1972), most of the study area is located in the Mixedwood region whereas the northern part lies in the Northern Coniferous and Upper Churchill sections. The topography within the Mixedwood region consists mainly of rolling morainic deposits on uplands and smoother glacio-lacustrine deposits on lowlands (Rowe 1972). In contrast, the Northern Coniferous region lies on the Precambrian Shield and is characterized by rocky ridges, poorly drained depressions and numerous lakes. The Upper Churchill is an area of low relief with sandy plains and poorly drained areas. Average elevation is about 400 m, generally increasing from northeast to southwest.

Most of the common boreal forest tree species are present in the Mixedwood region. Trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.) are the dominant deciduous species while white spruce (*Picea glauca* (Moench) Voss) and balsam fir (*Abies balsamea* (L.) Mill.) are usually the most common coniferous species. In the Northern Coniferous section black spruce (*Picea mariana* (Mill.) B.S.P.) is the dominant species with jack pine (*Pinus banksiana* Lamb) occurring on uplands and sandy plains and tamarack (*Larix laricina* (Du Roi) K. Koch) present on lowlands. Fig. 4 shows the FBP System fuel types for the study area at a 100 m resolution. It is important to note that the fuel types on the map do not necessarily represent the actual vegetation because the classification into FBP System fuel types is based on the structure of a stand and its potential fire behavior rather than just the actual species present (see description in Table 2). For example, a jack pine stand with a spruce understory is best represented by the boreal spruce (C-2) fuel type rather than the mature jack

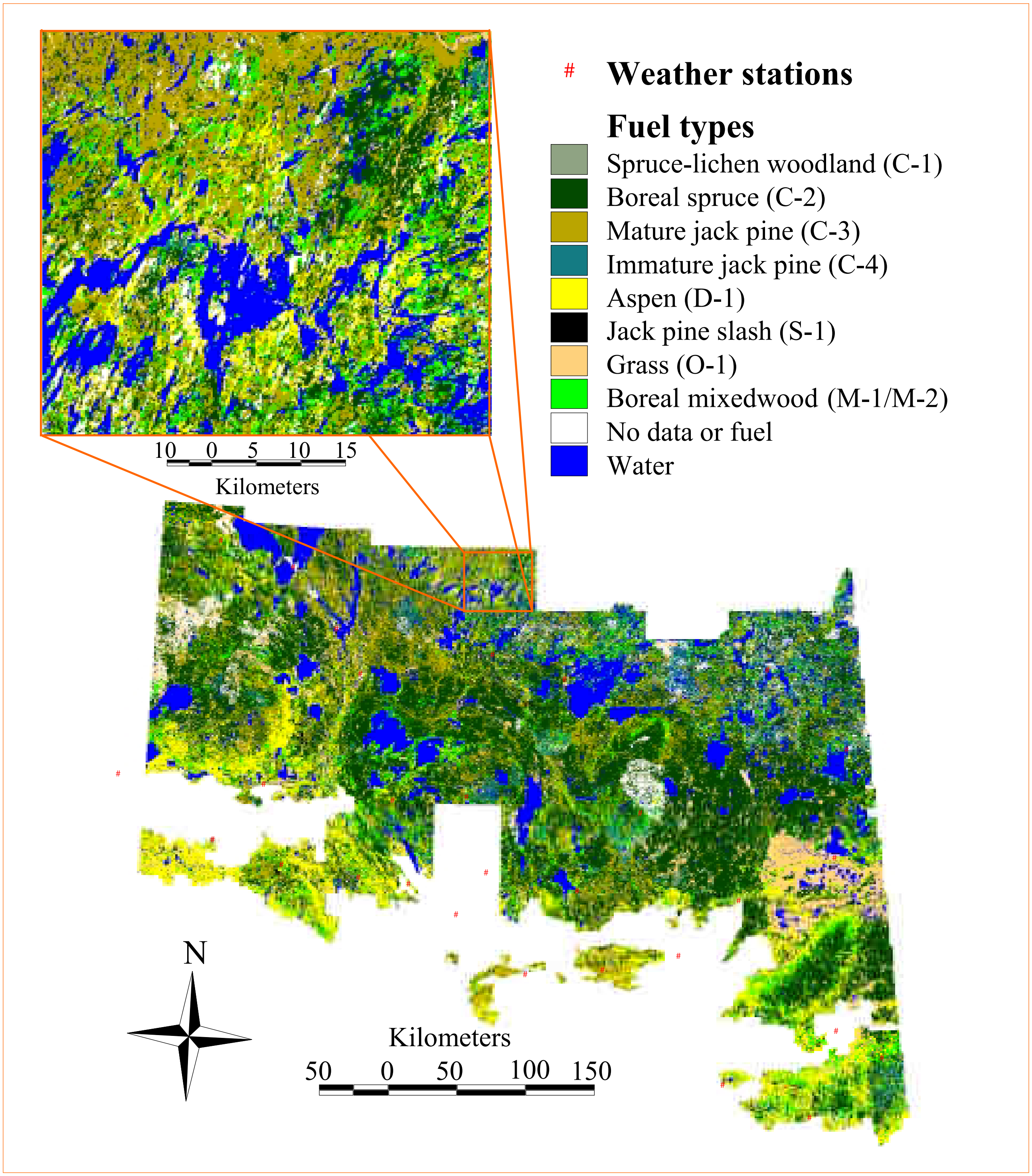

Fig. 4. Canadian Forest Fire Behavior Prediction System fuel types for the study area.

Table 2. The Canadian Forest Fire Behavior Prediction (FBP) System fuel types commonly found in Saskatchewan and their key characteristics (adapted from Forestry Canada Fire Danger Group 1992 and Hirsch 1996).

Name	Designation	Key Characteristics
Spruce-Lichen Woodland	C-1	Open stands with trees in dense clumps Black spruce branches extending to the forest floor Continuous reindeer lichen on forest floor
Boreal Spruce	C-2	Moderately well stocked Black spruce tree crowns extending to or near the ground Labrador tea is a dominant ground cover Deep organic layer
Mature Jack or Lodgepole Pine	C-3	Fully stocked (1000-2000 stems/ha) mature trees Live crown is well above the surface fuels Herbs and shrubs are sparse
Immature Jack or Lodgepole Pine	C-4	Pure, dense stands (10000-30000 stems/ha) of immature trees Continuous vertical and horizontal fuel continuity Large quantity of standing dead understory Heavy dead and down fuel loading
Leafless Aspen	D-1	Pure, semi-mature moderately well stocked stands Ladder fuels absent Well developed shrub layer Continuous leaf litter
Boreal Mixedwood – leafless	M-1	Moderately well stocked stands of boreal coniferous and deciduous species Conifer crowns may extend to or near the ground Moderate shrub and herb layer Coniferous/deciduous composition influences fire behavior
Boreal Mixedwood – green	M-2	
Jack or Lodgepole Pine Slash	S-1	Continuous slash from mature jack or lodgepole pine stands Slash is usually 1-2 years old retaining up to 50% of its foliage
Grass	O-1a/b	Continuous grass: matted (O-1a) or standing (O-1b) Fuel loading can vary and percent cured influences fire behavior

pine (C-3) fuel type because the ladder fuel structure of the stand makes it easier for a surface fire to become a crown fire. Most of the study area is classified to the boreal spruce (C-2) fuel type (Table 3).

Table 3. Area covered by the Fire Behavior Potential System fuel types in the study area.

Fuel type	Area (ha)	% area
Spruce-lichen Woodland (C-1)	2068	0.02
Boreal Spruce (C-2)	5,075,379	37.50
Mature Jack Pine (C-3)	1,590,844	11.75
Immature Jack Pine (C-4)	253,768	1.87
Aspen (D-1)	1,648,258	12.18
Jack Pine Slash (S-1)	123,729	0.91
Grass (O-1)	1,391,052	10.28
Boreal Mixedwood (M-1/M-2)	1,224,017	9.04
Non-fuel	478,437	3.53
Water	1,747,516	12.91
Total	13,535,068	100.00

The fire regime in the study area is characterized by frequent small fires and infrequent large and intense crown fires that account for most of the area burned. Fire suppression is occurring over the entire study area to protect communities, timber, and other forest resources. The study area lies south of one of the most fire active zones in Canada (Fig. 5), where generally wildfires have been allowed to burn freely. Stocks *et al.* (2001, submitted) calculated a very short fire return interval for northern Saskatchewan.

2.2. Overview of methods

Head fire intensity (HFI) usually provides a useful measure of landscape fire behavior potential because it is based on rate of spread and fuel consumption. To evaluate fire behavior potential, HFI maps were built for the study area using the equations found in the Canadian Forest Fire

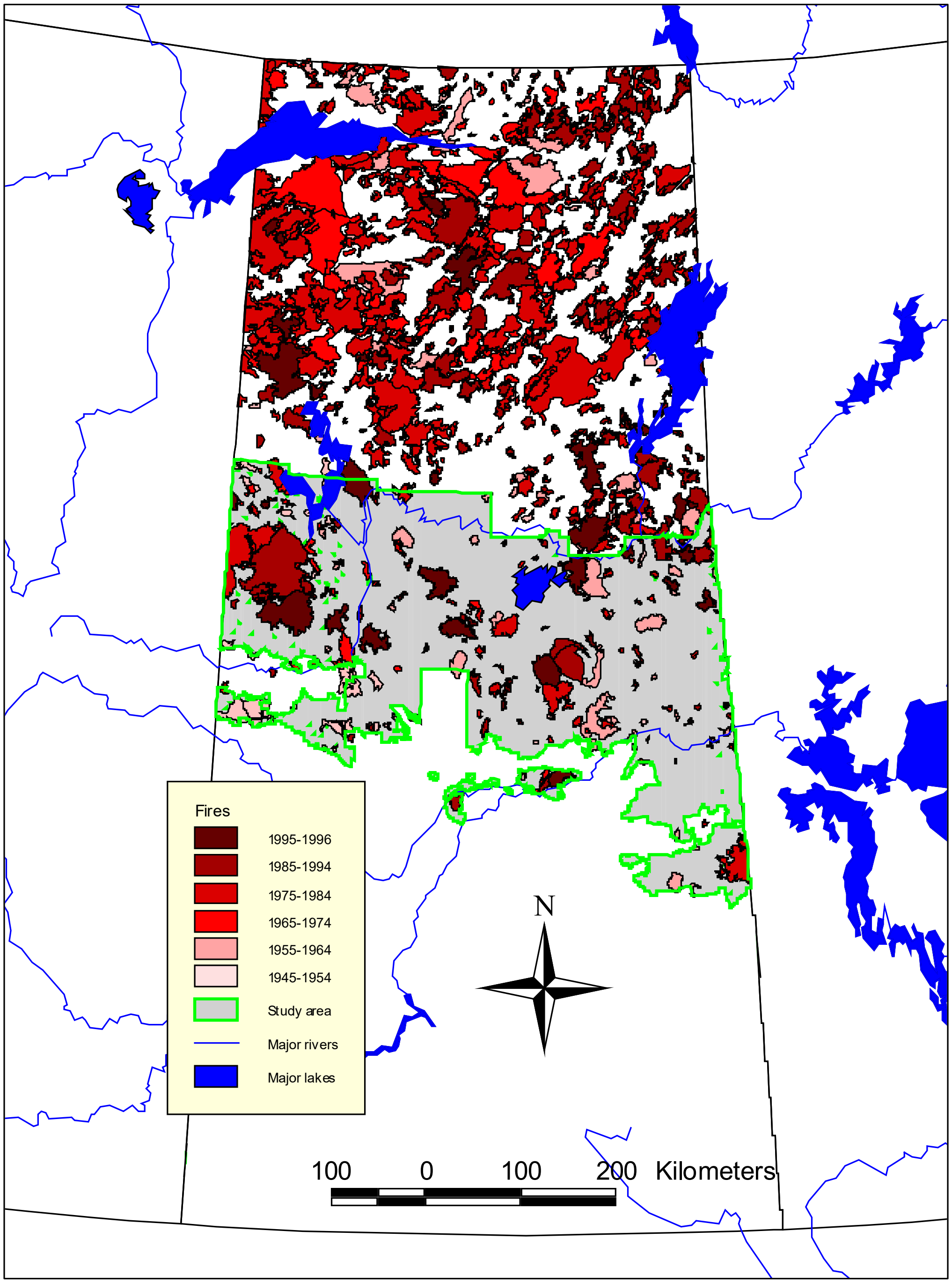

Fig. 5. Large fires (> 1000 ha) in Saskatchewan in the period 1945-1996.

Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). This procedure required fuels, weather, and topographic data.

Fuels data consisted of a FBP System fuel type map at 100 m resolution that already existed but which was initially built from existing vegetation inventory data[2] (the year of the inventory varies among various parts of the study area). No attempt was made to simulate vegetation change in the future because the primary intent of the study was to assess of the effect of climate on the fire behavior potential. Thus, a static fuel type map was used in current and future fire behavior potential assessments.

Fire weather data included daily observations of wind speed (WS) and wind direction (WD) as well as the Fine Fuel Moisture Code (FFMC) and Buildup Index (BUI). The FFMC and BUI are components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). To characterise the current climate conditions, a set of 10 years of fire weather data from 29 stations in and around the study area was used (Fig. 6). For base and future simulated conditions, 169 grid points from the CRCM data set were used to determine the fire weather for periods between 1975-1985, 2041-2049 and 2080-2089 (without 2084) (Fig. 6). These periods, hereafter referred to as scenarios, correspond to $1xCO_2$ (base), $2xCO_2$, and $3xCO_2$ environments, respectively. The analysis also investigated if various periods of the fire season are influenced differently by climate change. Three seasonal time periods were analyzed: 1) full (May to August), 2) spring (May), and 3) summer (June to August). The fire season was initially set from May 1 to

[2] This data was provided by the Prince Albert Forest Fire Management Branch of Saskatchewan Environment and Resources Management (SERM).

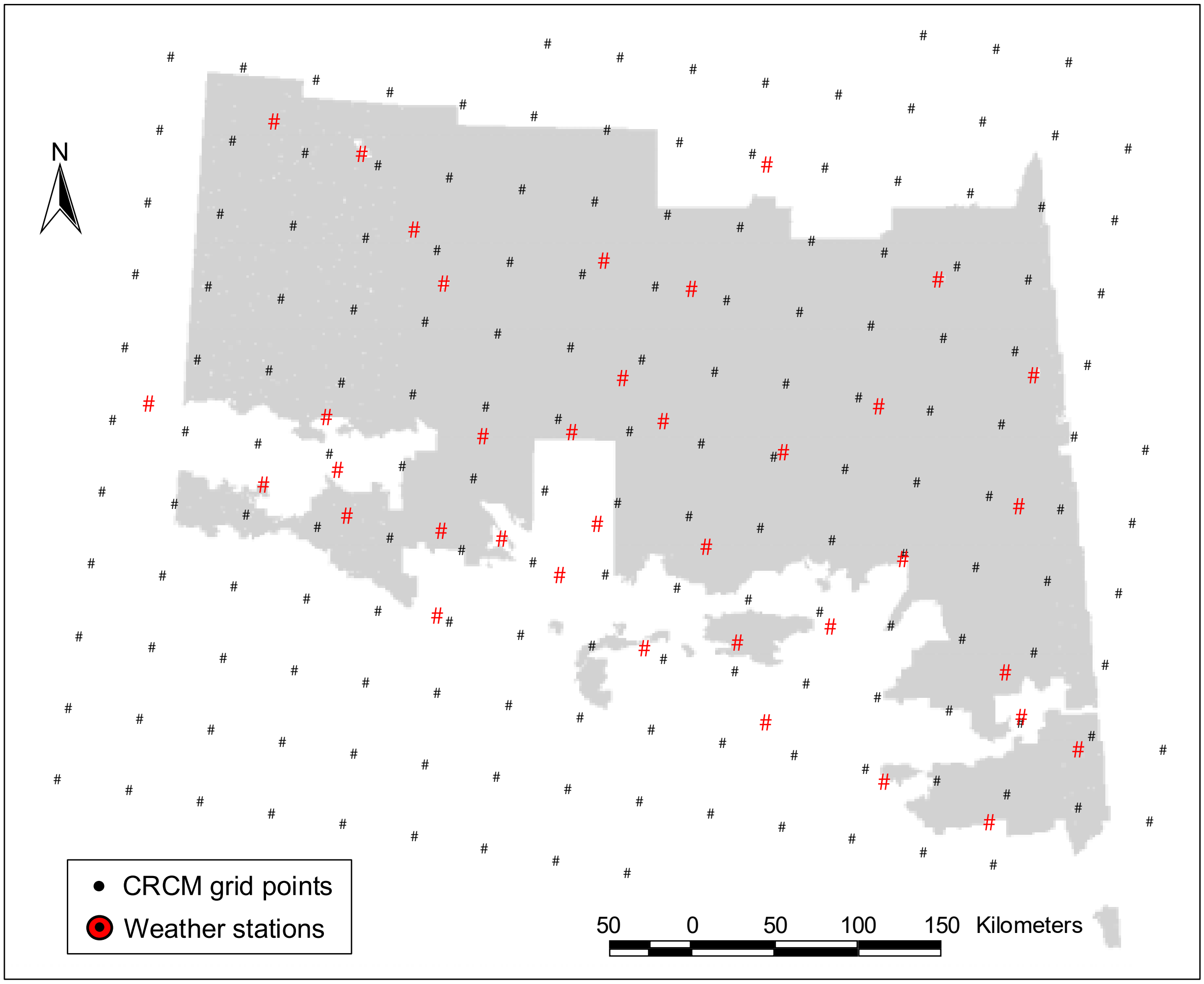

Fig. 6. Weather stations and Canadian Regional Climate Model (CRCM) grid points used in the analysis.

September 30 and the fall season (September) was to be analyzed as well, but preliminary analysis of the CRCM data showed a considerable lack of correlation with historical data in September. Therefore, this month was excluded from the analysis. For each period of the fire season and each climate scenario, percentile values (80th and 95th) of WS, FFMC, and BUI were calculated at each weather station and CRCM grid point. Percentile values are useful because they indicate the frequency at which a certain set of weather conditions are likely to occur. Dominant WD was used in the analysis for all stations and grid points. Thus, the study focused on three levels of analysis, totalizing 24 different sets of conditions: scenarios (4), periods (3) and percentiles (2).

A digital elevation model (DEM) at a 100 m resolution was used to obtain elevation, percent slope and aspect. The use of this resolution to cover the study area for the DEM and FBP System fuel types created a very large number of pixels to process (~13 M) but provided an excellent level of detail for observing fire behavior potential in smaller sections of the study area.

With fuels, fire weather and topographic data, the ArcView GIS-based Spatial Fire Management System (sFMS) (Lee *et al.* 1997, Englefield *et al.* 2000), which includes all of the FBP System calculations, was used to calculate HFI values spatially over the landscape (Kafka *et al.* 2000). A comparison of the current, base and future HFI maps was then conducted to determine the changes in landscape fire behavior potential due to a changing climate. The following sections describe the preparation of the historical and CRCM weather data, the percentile computation (see Fig. 7 for an overview of the steps required), the use of sFMS, and the type of analysis that was conducted.

2.3. Historical weather data

The historical data consisted of recorded weather variables and computed fire weather indexes at several weather stations. A total of 29 weather stations (23 Saskatchewan Forestry (SF) stations and 6 Environment Canada (EC) stations) with a 10-year record of historical weather data (i.e., 1990 to 1999) were selected to cover the study area.

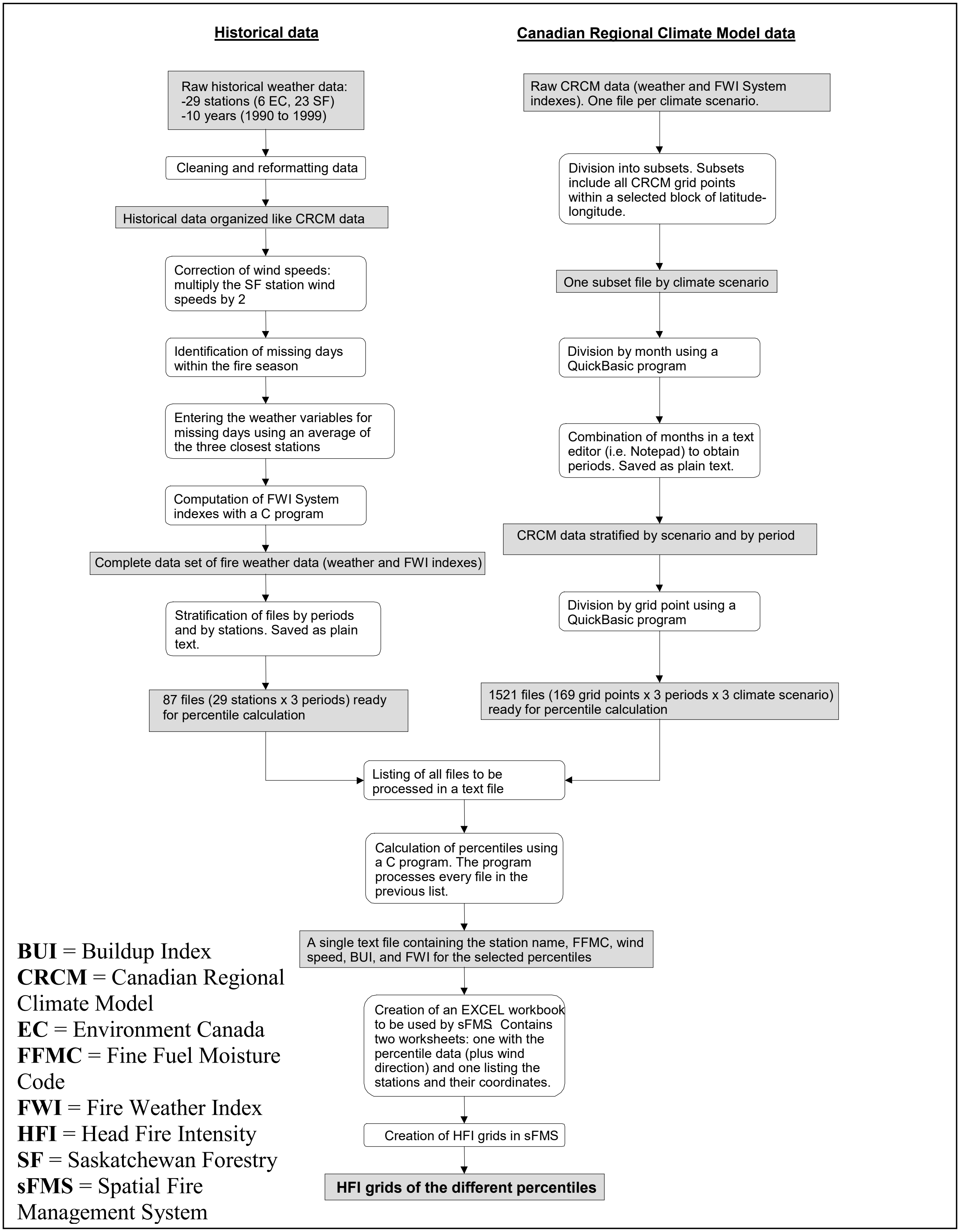

Fig. 7. Flow chart describing the steps required for the weather data processing.

A few weather stations had an incomplete historical weather data set for the 10-year period. That is, for some stations, weather observations and/or fire danger indexes were missing for single days or for more extended periods of the fire season. When weather observations were missing in the middle of the fire season, mean values were obtained from the closest three weather stations and FWI System indexes were recalculated. When only the FWI System indexes were missing in the middle of the fire season, they were simply recalculated using the station's weather observations. When weather observations were missing at the beginning of the fire season, it was assumed that the fire season had not started and thus these periods were not used in the analysis. Finally, when only the FWI System indexes were missing at the beginning of the fire season, they were recalculated to May 1st only if the weather seemed appropriate for an earlier start of the fire season. In theory, stations should be started 3 days after the snow has left the ground or after 3 consecutive days with temperatures exceeding 12°C (Turner and Lawson 1978). For the weather stations that we used, a fire season start on May 1st seemed to be the predominant rule.

Preliminary analysis of the weather data revealed that wind speeds at SF stations were consistently lower than those at EC stations due in large part to local variations in exposure. Given that the CRCM simulations were based on data from EC stations, the observed wind speed values at SF stations had to be modified to correct the discrepancies and to create a more consistent data set. A correction factor of two (i.e., doubling of SF station wind speeds) was applied based on Silversides (1978) who compared winds speeds at forest and airport weather stations in British Columbia. All FWI System indexes were recalculated for the SF stations with the modified wind speed values. Once the historical data were cleaned and modifications applied, they were divided according to the three selected periods of the fire season.

2.4. Canadian Regional Climate Model weather data

The actual data points of the CRCM (Caya and Laprise 1999) weather are a network of grid points (treated like weather stations in our study) located approximately 45 km apart (i.e., 15 seconds in latitude and longitude) (Fig. 8). The CRCM has a much higher resolution than other general circulation models (GCMs) and it is, therefore, more appropriate for the size of our study area and for the treatment of daily meteorological records. As opposed to the historical data, the

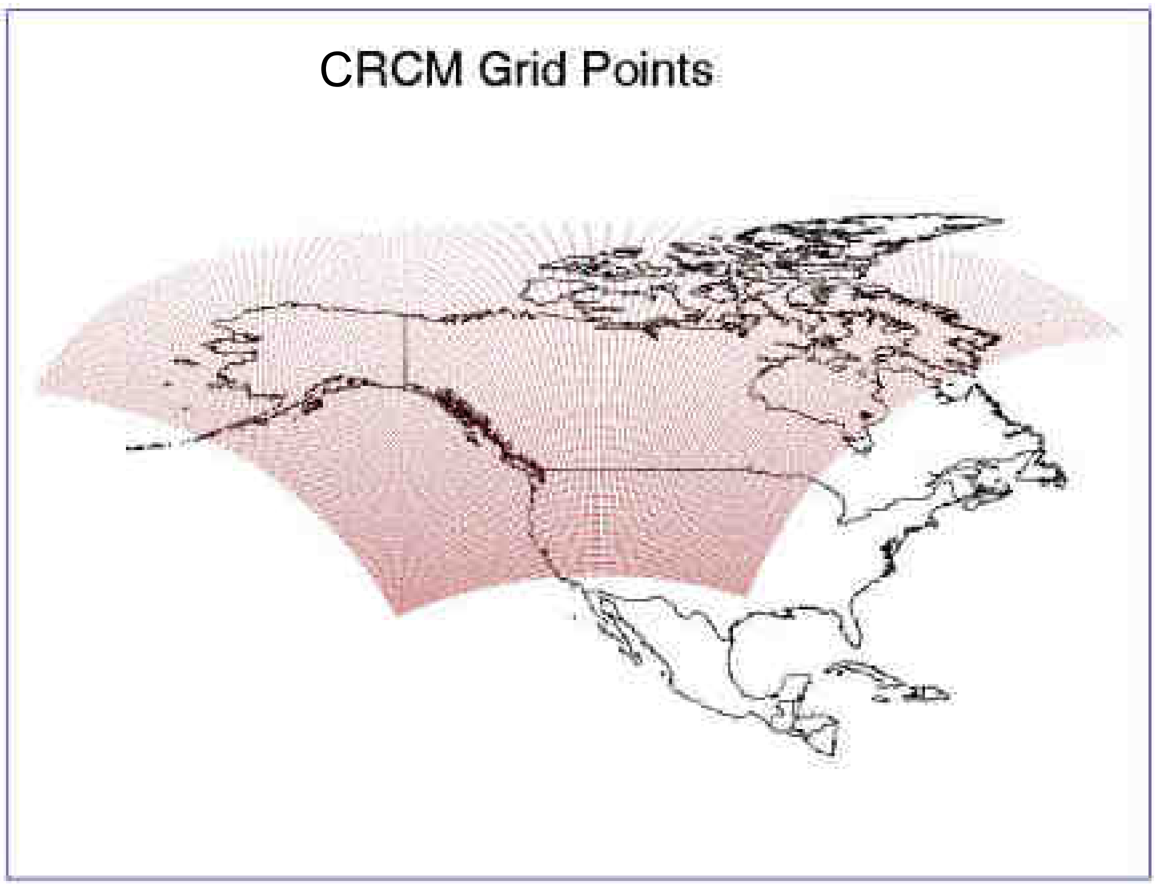

Fig. 8. Distribution of the Canadian Regional Climate Model grid points.

CRCM data is not observed but simulated. The CRCM data are weather outputs from 1xCO_2, 2xCO_2, and 3xCO_2 scenarios, corresponding to CO_2 levels of 437, 827, and 1255 ppm, respectively. The scenarios are based on a greenhouse gas and aerosol transient simulation (Boer *et al.* 2000) with a time step of 15 minutes although most variables are recorded at 6-hour intervals (Caya and Laprise 1999).

Based on a comparison of the CRCM 1xCO_2 scenario and approximately 200 EC weather stations located across the portion of Canada covered by the simulations, various corrections were applied to the original fire weather data before computing FWI System indexes (M. Wotton, unpublished results). Among other discrepancies, the main problems associated with the CRCM data consisted in the wind speeds values being too high and the occurrence of small rain events being too frequent. The main corrections that were applied were: 1) solar noon temperature was approximated by subtracting 2°C from the daily maximum temperature, 2) relative humidity was obtained with the maximum temperature and the previous night's estimate of the minimum temperature used as dew point, 3) wind speeds were divided by the ratio of mean wind speeds from EC historical record and CRCM 1xCO_2 scenario between May and August in the 1975-1985 period, 4) precipitation was corrected by subtracting 1.5 mm from CRCM daily rainfall amounts and 5) the fire season start date was based on a 3-day mean temperature exceeding 3.5°C.

The CRCM data were arranged in three very large files for each of the three CO_2 scenarios and were manipulated using a series of programs (Fig. 7). First, the integral CRCM data files were divided in order to obtain the required subset for the study area. This was done querying the database based on latitude and longitude; a total of 169 grid points covered the study area. The files were then divided according to the selected scenario periods to allow for the computation of percentile values. Finally, files were further subdivided for each grid point to obtain one grid point file for each of the three fire season periods and for the three CO_2 scenarios. This resulted in a total of 1521 files.

2.5. Fire weather and danger percentile calculations

Kafka *et al.* (2000) describe two methods for calculating spatial fire behavior potential using climatological data (Fig. 9). The more accurate of these two methods is the "daily" method that

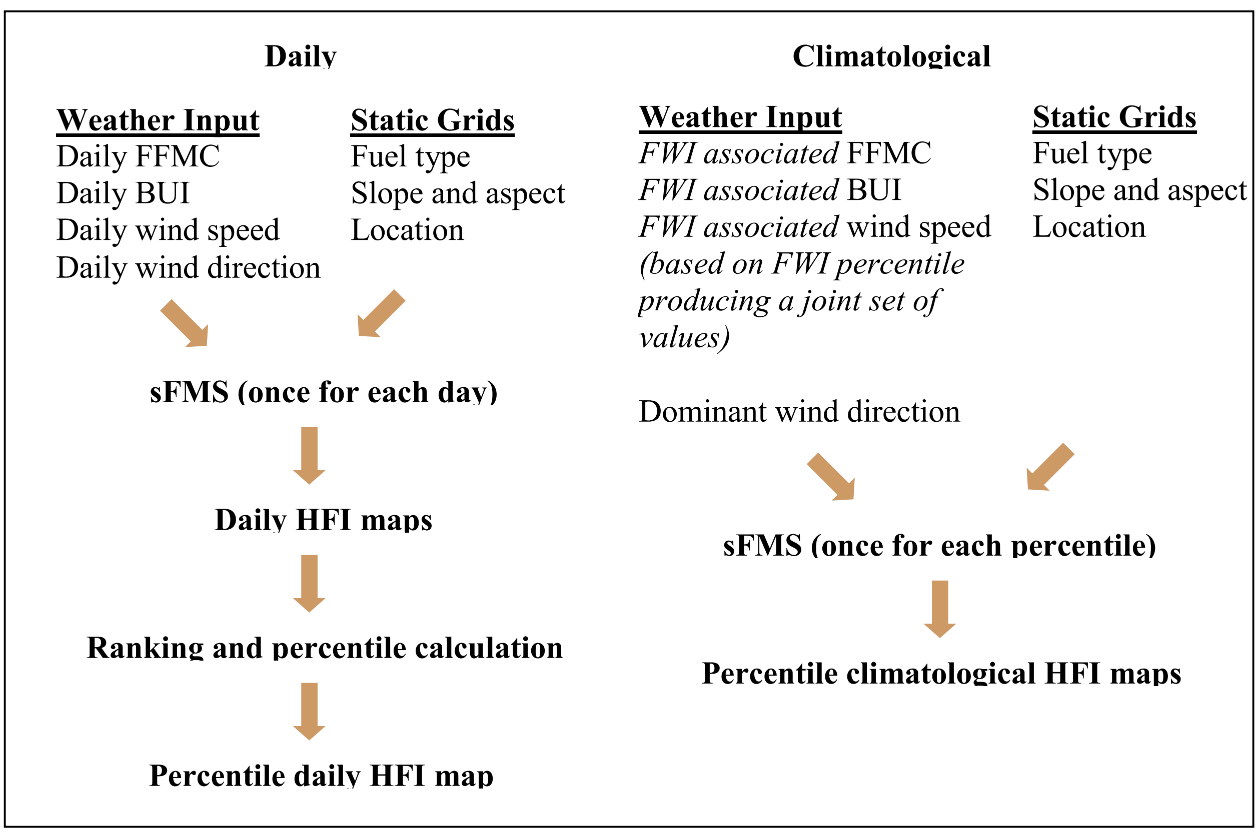

Fig. 9. The daily and climatological method for creating percentile head fire intensity maps with the Spatial Fire Management System (sFMS) (adapted from Kafka *et al.* 2000).

requires creating daily HFI maps using the weather observations at each weather station before calculating the HFI percentile value at every pixel. This method is computationally intensive and was not feasible for our study because of the size of the study area and resolution used. The second method, the "climatological" percentile method, was used in this study. This method consists of obtaining a decadal frequency of extreme fire weather and danger conditions (i.e., FFMC, BUI and WS) at each station (e.g., 80th and 95th percentile in this study). These three values are then used with the dominant wind direction to create the percentile HFI map. Wind direction is not included in the CRCM data and, therefore, the dominant wind direction (i.e., west) as based on the historical record was used in all conditions.

To avoid overestimation of the fire weather and danger conditions (Kafka *et al.* 2000) and to obtain a percentile that is consistent at all weather stations or grid points, the percentile values for the FFMC, BUI, and WS were obtained simultaneously, as opposed to independently. Although there are other ways by which to calculate joint probabilities, we selected FFMC, BUI, and WS values based on the day that corresponded to a specific FWI percentile (i.e., the use of FWI provides a relative measure of the fire danger). That is, the database was ranked from the highest to the lowest FWI value (e.g., Table 4) and the day that corresponded to the FWI percentile position was selected, providing a set of FWI associated FFMC, BUI and WS values. These values specify a certain frequency of conditions for each fire season period within each scenario and for each station or grid point. A few programs were used to execute these procedures and to create a single text file containing all values for all conditions.

Table 4. The 10 days with the most extreme fire danger conditions (i.e., based on the Fire Weather Index (FWI)) from 1990-1999 at the La Ronge weather station (55°09'N, 105°16'W).

Rank	Year	Month	Day	FFMC	BUI	WS	FWI
1	1995	May	29	95.2	84.7	31	72.1
2	1998	August	6	92.7	107.5	33	69.2
3	1995	May	31	94	95.5	31	69.1
4	1998	July	13	88.9	128.9	41	67.9
5	1994	May	7	92.6	30.7	48	63
6	1998	July	14	90.7	132.7	33	62.8
7	1998	August	31	90.6	69.6	41	61.1
8	1998	August	4	92.9	97.9	28	58.2
9	1998	June	9	91.1	95.4	32	55.8
10	1994	August	24	89.3	84.3	37	52.1

2.6. Use of Spatial Fire Management System

Once the FFMC, BUI, and WS values have been determined for each weather station or grid points, they are stored in a file and used by sFMS to build FWI and FBP System outputs (e.g., fuel consumption, rate of spread, HFI). Although other formats can be used in sFMS, in our study an Excel workbook was created with two required worksheets: one with a list of weather station or grid points and their coordinate location; the other with the same weather stations or grid points, dates, and percentile values. Because sFMS was initially designed to create daily maps of FWI System and FBP System outputs for use in operational fire management activities, each set of percentile values was treated as a day. Additionally, date is used with latitude and longitude to create a grid of the foliar moisture content (FMC) which varies throughout the fire season. In our analysis, because each percentile was represented as a day, we created one FMC grid for each fire season period and forced sFMS to use that grid (i.e., sFMS automatically uses a grid that is already built for a particular date).

Before running the analyses, many parameters had to be set or selected in sFMS. The spatial resolution of analyses was set at 100 m in order to achieve the best level of detail possible. Moreover, interpolation between weather stations or grid points was carried out using the inverse distance weighted function method (set to the power of 2) (Flannigan and Wotton 1989). In order to determine the number of stations of influence, a fixed search distance was obtained from equation 1 (Stephens and Stitt 1970, Flannigan and Wotton 1989):

$$R = 1.6(a/n)^{1/2} \tag{1}$$

where R is the radius of influence, a is the area and n is the number of stations. The calculated search distances for weather stations and CRCM grid points were 110 km and 68 km, respectively.

Although topography is not a significant factor in Saskatchewan, the effect of elevation on temperature and the combined effect of slope and wind speed on fire behavior was taken into account using the sFMS elevation adjustment. Finally, the following "fuel type" settings were selected: 1) no green-up and matted grass for the spring period, 2) green-up and standing grass for the summer and full season periods, 3) grass fuel load set to 0.3 kg/m^2, 4) 90%, 55%, and 65% grass curing for spring, summer and full season, respectively, and 5) fuel M-1/M-2 set to a 50% conifer content.

2.7. Data analysis

Various analyses of the fire weather parameters and FWI System indexes were conducted to compare SF and EC weather stations, and CRCM grid points. Histograms, time series and box plots were produced for several weather stations and grid points and key parameters were plotted spatially over the study area.

Comparisons of fire behavior potential were conducted for the historical, $1xCO_2$, $2xCO_2$, and $3xCO_2$ scenarios for each period of the fire season. In order to limit the number of maps, most of the analyses focused on the 80th and 95th percentiles of the full fire season, although other percentiles were also assessed. These two percentiles were useful in observing a gradient in the frequency of weather and spatial variation in HFI. Our analysis was divided into two parts: spatial and non-spatial. Spatial analysis consisted of describing and comparing the HFI maps, whereas the results of the non-spatial analysis were presented as tables and graphs.

As described in the previous section, HFI maps of historical and simulated weather (CRCM) were created for the three selected periods. Qualitative and quantitative assessments of fire behavior potential were made using the HFI maps. As a first step in the analysis, historical maps were analyzed and compared to $1xCO_2$ maps to determine how the two types of data differed spatially and seasonally. The primary objective of this comparison was to outline the differences between the recorded and simulated weather data and to assess the validity of the CRCM data.

The HFI maps produced with the three climate change scenarios were compared in terms of 1) absolute change, 2) proportional change, and 3) fire suppression class change. Absolute change maps were created by subtracting the HFI value in a cell on one map from the value of the same cell on another map. Similarly, proportional change was simply the ratio of HFI values. Finally, fire suppression class change represented the number of HFI class changes (higher or lower) at each pixel between two maps.

Tables and graphs were also used to describe the HFI maps. Percentages of area covered by each HFI class among all conditions were presented in tables. Distributions of the frequency of HFI values were also graphed in 1000 kW/m classes for all pixels in each conditions. The same type of distributions were obtained in 100 kW/m classes for pixels representing the most common FBP System fuel types C-2, C-3, and M-2, for the $1xCO_2$ and $2xCO_2$ scenarios in the full season period at the 80^{th} percentile.

3. **RESULTS**

The results section of this report first presents the assessment of the fire behavior potential of the historical data. Then, comparisons are made between the historical and $1xCO_2$ scenario, the $1xCO_2$ and $2xCO_2$ scenario, and the $2xCO_2$ and $3xCO_2$ scenario. In each of these sub-sections, fire behavior potential is initially described in terms of general trends, and then in terms of spatial patterns. Figures and tables referred to in the next sections are found at the end of the text.

3.1. Assessing the current fire behavior potential with historical climate data

Analysis of the HFI maps derived from the historical (1990-99) fire weather and danger allowed us to evaluate the current fire behavior potential throughout the study area in all fire seasons. Results for the 80^{th} and 95^{th} percentiles are shown in Tables 5 and 6. For the full season period there are no cells in the 0-9 kW/m HFI class. In fact, no area was found in this HFI class across all conditions except in the $1xCO_2$ scenario for the spring period at the 80^{th} percentile. In the 80^{th} percentile full season period HFI map, about 15% of the area is included in each of the 4 HFI classes comprising the 10 to 9999 kW/m range, with the rest of the area (i.e., 38%) in the 10,000-29,999 kW/m class. As in all conditions at the 80^{th} percentile, virtually no area is present in the 30,000 kW/m class. Still at the same percentile, compared to the full season period, the spring has very little area (0.14%) in the 10-499 kW/m class but slightly more area (2-6%) in all of the other HFI classes; whereas the summer season compared to the full season has an increase in percent area found in the 4000-9999 kW/m class at the expense of the 10,000-29,999 kW/m class and in the 10-499 kW/m class at the expense of the 500-3999 kW/m classes.

The same general trends between periods of the fire season occur at the 95^{th} percentile; however, the increase in area found in higher HFI classes is evident. In all periods, results indicate that a significant portion of the study area has HFI values above 30,000 kW/m and most of the area (i.e., approximately two-thirds) is above 10,000 kW/m. The distribution of HFI values at the 80^{th}

percentile shows clearly that most of the area is under approximately 18,000 kW/m whereas at the 95th percentile, it is more equally distributed with most HFI values under about 43,000 kW/m (Fig. 9).

To ease the interpretation of the spatial trends as illustrated by the HFI maps, we divided the study area into 4 general regions: 1) the northern section of the study area (i.e., an 80-100 km wide zone that follows the northern limit of the study area) which is characterized by C-2, C-3, and M-1/M-2 fuel types, 2) the central section which is mainly composed of the C-2 fuel type, 3) the southwest section which has an significant D-1 fuel type component, and 4) the southeast section which combines several fuel types, including the O-1 fuel type in the northern part (refer back to Fig. 4).

The central section is the one that shows the highest fire behavior potential in all seasons both at the 80th percentile, where HFI values are generally in the 10,000-29,999 kW/m class, and at the 95th percentile, where most HFI exceed 30,000 kW/m (Maps 1-6).

At the 80th percentile, the northern section shows HFI values ranging between 2000-10,000 kW/m for the spring period, 2000-30,000 kW/m for the summer period, and 500-30,000 kW/m for the full season period. Among these three periods, the eastern part of this section is generally composed of lower HFI values for the full season, whereas lower HFI values occur in the western part in the spring period. At the 95th percentile, compared to other periods, the spring HFI map shows slightly higher values in the eastern part and lower values in the western part of the northern section.

The southwest section generally has a very low fire behavior potential (i.e., HFI values between 10-499 kW/m) for the full season and summer periods at both percentiles. Relative to these time periods, the spring has a higher fire behavior potential with HFI values generally between 2000-10,000 kW/m.

Finally, the southeastern section of the study area has a wide range of HFI values, with lower values found in the northern part of this section. The fire behavior potential at both percentiles is highest in the spring period. The highest HFI values in this section are in the 10,000-29,999 kW/m class at the 80th percentile and 30,000+ kW/m class at the 95th percentile.

3.2. Comparing the historical and 1xCO_2 scenario

In general, the fire behavior potential of the 1xCO_2 scenario is lower than the historical scenario, especially for the spring period (Table 5 and 6; Fig. 9). The summer and full period 1xCO_2 scenario HFI maps are more consistent with the historical maps in terms of area covered in the lower HFI classes. At the 80th percentile, the 1xCO_2 scenario has more area in the 4000-9999 kW/m class than the historical scenario, but the opposite is true for the 10,000-29,999 kW/m HFI class. At the 95th percentile, the main difference occurs in the 30,000+ kW/m HFI class where the area with this type of fire behavior potential in the 1xCO_2 scenario is very low (1% and 2%, for full and summer period, respectively) compared to historical scenario (30% and 23%, for full and summer period, respectively).

The spring season 1xCO_2 scenario shows significantly lower HFI values when compared to the historical maps. At the 80th and 95th percentile, the 1xCO_2 scenario has 72% and 38% of the area under 2000 kW/m whereas the historical scenario has only 20% and 3%. These major differences are reversed in higher HFI classes where 1% and 10% of the area is above 10,000 kW/m in the 1xCO_2 scenario HFI maps versus 42% and 71% for the historical scenario. Fig. 9 shows how the distribution of HFI values is in better agreement at the 80th percentile compared to the 95th percentile.

The lower HFI values in the 1xCO_2 scenario are also evident from a spatial point of view (Maps 7-12 and 25-26). The 1xCO_2 scenario HFI maps that are more consistent with the results from the historical scenario in terms of HFI values and pattern are the summer and full season HFI maps at the 80th percentile. At the 95th percentile, the summer and full season seem to be constantly one HFI class lower in the 1xCO_2 scenario as compared to the historical scenario. Differences are more pronounced at the 95th percentile than at the 80th percentile but the spatial pattern is similar. The largest HFI differences between the historical and 1xCO_2 scenario occur in the central and northern section of the study area. In a few scattered spots, and particularly in the southeast section of study area, HFI values are higher in the 1xCO_2 scenario (Maps 25-26). Finally, the spring HFI maps are very different for both percentiles with very low values in the 1xCO_2 scenario.

3.3. Comparing the $1xCO_2$ and $2xCO_2$ scenario

The increases in HFI between the $1xCO_2$ and the $2xCO_2$ are significant (Table 5and 6; Fig. 9). At the 80th percentile in the spring, the area covered by values exceeding 2000 kW/m increases by 19 percentage points. At the same percentile in the summer and full period, the area in the 10-499, 500-1999, and 4000-9999 kW/m classes decrease while there is a major increase in the 10,000-29,999 kW/m class (i.e., 28 to 48% and 16 to 46%) from a $1xCO_2$ to a $2xCO_2$ scenario.

At the 95th percentile, important differences also occur in the highest HFI classes for the summer and full season, where the area in the 10,000+ kW/m classes increases by 12 and 8 percentage points, respectively. In the spring, the area covered by values exceeding 4000+ kW/m increases by 5 percentage points. The distribution shows clearly how at the 80th percentile, the $2xCO_2$ scenario has more area covered by HFI values between 15,000-20,000 kW/m and some area in the 20,000-28,000 kW/m range (compared to practically none in $1xCO_2$) (Fig. 9). It also indicates more area covered by HFI values between 25,000-30,000 kW/m and some area in the 30,000-38,000 kW/m range (compared to practically none in $1xCO_2$) at the 95th percentile.

In general, comparing the $1xCO_2$ scenario and the $2xCO_2$ climate scenario in 95th percentile conditions, most of the HFI values in northern section shift to above 4000 kW/m in the summer and full season periods (at the 80th percentile, they shift to above 2000 kW/m) (Maps 13-18 and 27-32). In the same periods, the central section of the study area does not change significantly but almost all HFI values are above 10,000 kW/m in the $2xCO_2$ scenario. Compared to other periods, the spring period at both percentiles shows that increases do not appear to be very significant as most of the areas remain in the same HFI class.

Although it is not shown on the HFI maps except in a southeast section which become included in the +30,000 kW/m class at the 95^{th} percentile, the highest HFI increases also occur in the central section of study area as demonstrated by the absolute change map at both percentile (Maps 27-28). However, the HFI proportional change maps for the full period reveal a different perspective of changes in $2xCO_2$ scenario (Maps 29-30). These maps show that proportionally, there is a general gradient from south to north; the northern section of the study area has the highest proportional increases in fire behavior potential (i.e., in most areas, HFI values are at least doubling, even at the 80^{th} percentile). The HFI class change maps show similar results as the entire northern section shifts to a higher HFI class at the 80^{th} percentile. Other areas have no class changes. At the 95^{th} percentile, some areas in the northern section increase by two HFI classes whereas the southeast section of the study area generally increases by one class.

3.4. Comparing the $2xCO_2$ and $3xCO_2$ scenario

The analysis of future fire behavior potential based on the CRCM revealed very little difference between the $2xCO_2$ and $3xCO_2$, especially at the 80^{th} percentile (Table 5 and 6; Fig. 9). The area in each HFI class does not vary by more than two percentage points between the $2xCO_2$ and $3xCO_2$ scenario in the summer and full period. Differences are slightly higher in the spring period (up to 6 percentage points) but there is no clear trend towards more area in higher HFI values.

Some increases in fire behavior potential occur at the 95th percentile but they are not major. In the full period, approximately 4% of the area is shifted from the 10,000-29,000 kW/m class to the 30,0000+ class. In the spring, a minor percentage of the area changes from the 10-499 to the 500-1999 kW/m class and from the 2000-3999 to the 4000-9999 kW/m class. Finally in the summer, there are slight changes from the 10-499 to 500-1999 kW/m class and from the 10,000-29,999 to 30,000+ kW/m class. The distribution also shows the general similarity between the 2xCO_2 and 3xCO_2 scenario but it points out the slight increases in area in the highest HFI values (Fig. 9).

All the 2xCO_2 and 3xCO_2 scenario HFI maps are generally similar among the various combinations (Maps 19-24 and 33-38). A few changes appear at the 95th percentile in the summer and full period where zones with 30,000 kW/m seem to cover slightly more area. The absolute and proportional change maps indicate important spatial variations; the northern and southwestern sections increase in fire behavior potential whereas in general, the southeast decreases in fire behavior potential. The central section has both increases and decreases in fire behavior potential. The class change maps show that HFI values do not change significantly as almost no areas shifts in HFI class at both percentiles.

4. DISCUSSION

Central Saskatchewan is a region where fire disturbances play a critical role in the dynamics of the boreal forest. Not only does it lie on the edge of one of the most fire-prone areas in Canada (i.e., northern Saskatchewan), but recent studies have shown that it is one of the areas of the continental boreal forest that will experience the greatest increase in fire severity and fire weather conditions (Wotton *et al.* 1998). This could translate into a longer fire season, shorter fire cycle, greater area burned, and more frequent extreme fire behavior.

Our study area represents the southern boreal forest of Saskatchewan that has been under intensive forest and fire management for last few decades. These activities have influenced the fire regime in the recent past by changing the spatial and temporal distribution of fuels and modifying the dynamics of wildfires. Among other effects, these factors could have had an important impact on the number of human-caused and lightning-caused ignitions, as well as on the spread of large fires. Whatever the direct influence, it is clear that in the last 30 years, there is a definite difference between the fire regime of this region and the one in northern Saskatchewan where fires have been allowed to burn freely (Fig. 5). The human influence on climate is another important change that will affect the dynamics of wildfires in the boreal forest.

Climate has changed in the past and fire regimes have been modified accordingly (Clark 1988, 1990). At present, it seems that climatic changes are occurring faster than in any period in the past. A warmer climate does not necessarily mean more extreme fire weather conditions across all of Canada because of its spatial variability and the influence played by other weather variables such as precipitation, relative humidity and wind. For instance, it seems that the area burned has decreased in Quebec since the 1850's in the warmer period that followed the Little Ice Age (Bergeron 1991, Bergeron *et al.* 2001). On the other hand, it appears that in western Canada, a warmer climate will increase the length and the severity of the fire season (Wotton and Flannigan 1993). However, we still know little about climate and fire dynamics. For example, Bonsal and Lawford (1999) have just recently found a relationship between El Nino and La Nina events and summer extended dry spells on the Canadian Prairies. Increases in lightning (Price and Rind 1994) and changes in climate oscillations, fire ignitions (Flannigan and Wotton 2001) and fire behavior potential are other unknowns associated with climate change. Our study addresses the question of the influence of projected climate change on regional fire behavior potential.

4.1. Current fire behavior potential in central Saskatchewan

Our study confirms that central Saskatchewan is in a part of the boreal forest where high fire behavior potential can be expected frequently throughout the fire season (Maps 1-6). This is due to periodic extreme fire weather events and because a high percentage of the study area is covered by highly flammable coniferous fuel types (Fig. 4). Results indicate that close to 40% of the area has HFIs exceeding 10,000 kW/m in 80th percentile conditions (Table 5). In other words, if a wildfire were to occur, on 20% of the days during the fire season, it would be a continuous crown fire that would be extremely difficult to control on at least 40% of the study area. On 5% of the days, this type of fire behavior could occur over a minimum of two-thirds of the study area, including significant areas that could have wildfires with conflagration type behavior (HFIs exceeding 30,000 kW/m) (Table 6).

The spring season is a particularly severe period for very intense fires in central Saskatchewan since the total area with an HFI above 30,000 kW/m is extensive at the 95th percentile and most of the remaining areas would be able to sustain a moderately fast spreading wildfire (i.e., HFI exceeding 2000 kW/m) (Map 5). Conditions such as this make it very challenging to control any escaped wildfires due to severe weather and fuel conditions (i.e., possible matted and fully cured grass, and leafless deciduous vegetation). Even in 80th percentile conditions in the spring, most of the area could sustain a high intensity continuous crown fire (Map 2). It is only when green-up occurs (summer and full season) that the frequency of extreme fire behavior potential is somewhat reduced (i.e., except in the central section of the study area), thus improving the potential effectiveness of suppression (Maps 1-6). The reduction in fire behavior potential is associated with the aspen, mixedwood, and grass fuel types that become less flammable after green-up. The central section is by far the one that has the highest fire behavior potential in all periods due to a large portion of the area composed of the highly flammable boreal spruce fuel type. The results also indicate that in the northern section, 80th percentile fire weather conditions lead to areas with potential HFI values in the 2000-10,000 kW/m range. It is in this range that fires move faster and begin to crown. Thus, in this section, some wildfires occurring under these conditions could be difficult to control, others could possibly be held under control with an extensive use of suppression resources.

The fire behavior potential conveyed by the historical data is very high and results have shown that it is overestimated because of the wind correction that was applied to SF stations. In fact, this correction was effective in increasing the winds to a similar level on average for the full fire season as compared to the EC stations (Figs.10-12) but it also produced several extremely high daily wind values. In turn, this resulted in some extreme FWI values as shown by the distribution and outliers in Fig.12. It is thus at the 95th percentile that the overestimation is most prominent because extreme values had more influence. To improve the consistency of the spatial patterns, the historical HFI maps could have been created with SF stations data only (but differences with

CRCM data would have been more pronounced because the model is based on EC weather station data). Note that SF stations have to be used for spatial fire behavior potential analysis because there are not enough EC stations to cover such a large area.

There is also a minor concern with the method used to determine the percentile values because there is considerable variability in the selected FFMC, BUI, and WS for a specific FWI value (Fig. 13). Although this technique ensures that the highest FWI values or fire danger days are ranked before selecting the percentile, the same FWI can have different sets of FFMC, BUI, and WS values. The spatial interpolation between weather stations in sFMS smoothes this effect but it may be responsible for some local variations in HFI values. Using the daily method would solve most of these shortcomings but it could not be applied to such a large area. Nevertheless, despite these constraints, the historical maps provide a good representation of current fire behavior potential in central Saskatchewan.

4.2. Differences in fire behavior potential among the historical and 1xCO_2 scenarios

The comparison of the fire behavior potential derived from historical and 1xCO_2 climate scenarios was conducted to better understand the CRCM weather data and the changes predicted by the model in the future. Our historical results are based on the period between 1990-1999 whereas the base 1xCO_2 represents the decade between 1975-1985. In general, the 1xCO_2 HFI maps show a lower fire behavior potential than the historical HFI maps in all periods at the 80th and 95th percentile (Maps 1-12 and 25-26). This is largely due to the wind speed overestimation mentioned earlier. The difference between historical and 1xCO_2 maps could also be explained by the fact that the historical data may have already been partially affected by climate change due to higher concentrations of CO_2 in the atmosphere in the 1990's (Fig. 10); differences between the observed and modeled weather indicate that although the CRCM 1xCO2 scenario has, on average, higher mean temperature and lower relative humidities, there is more rainfall, especially in the spring period (Figs. 11 and 12). Another reason for discrepancies is that the weather generated by the CRCM is less variable than the observed weather data, thereby, underestimating extreme conditions (Fig. 10).

Although important differences occur, some periods and/or percentiles conditions are in better agreement between the two scenarios. This is the case in lower HFI classes for the fire behavior potential maps produced with data from the summer and full season periods. Differences are more pronounced, yet acceptable, at a higher fire behavior potential. For example in the full fire season period, the 1xCO2 scenario maps have less area in the 10,000+ kW/m classes than the historical, both at the 80th (29%vs 38%) and 95th percentile (51% vs 67%) (Tables 5 and 6). Due to the overestimation effect, the differences are emphasized at the 95th percentile where the 1xCO_2 summer and full season period HFI maps very rarely exceed 30,000 kW/m compared to 30% and 23% of the area, respectively, that are above this value in the historical maps.

The summer and full season 1xCO2 scenario maps expose the same spatial trends as the historical but only seem to be consistently one HFI class lower in the 95th percentile. The 80th percentile reduces the effect of extremes and synchronizes the results better, and that especially in the south. Nevertheless, extreme fire behavior potential conditions still occur frequently in the

$1xCO_2$ scenario with large areas above 10,000 kW/m at the 95th percentile and above 4000 kW/m at the 80th percentile.

One major discrepancy in the $1xCO_2$ scenario is the spring period. The HFI maps for this scenario in the spring period display very low HFI values that are not only markedly lower than historical values but also lower than the summer and full season $1xCO_2$ scenario maps. Therefore, this period is inconsistent with the current seasonal trend in which the spring tends to display the highest fire behavior potential. As mentioned above, these very low values are a direct result of excessive spring rainfall amounts generated by the CRCM (Fig. 11). Moreover, another explanation is that the differences are emphasized due to the fact this period of the fire season is very short and, thus, percentiles are obtained from a low number of days.

There are also a few areas, especially in the extreme southeast, where lower HFI values are found in the $1xCO_2$ scenario. This effect is a result of different spatial weather patterns but it might also be explained by the variation among weather stations introduced by the joint percentile calculation.

This comparison is not the main purpose of our study but it does indicate that the true current fire behavior potential may lie somewhere in between the historical and $1xCO_2$ scenario HFI maps. It also shows the unreliability of the spring data generated by the CRCM for fire weather analysis.

4.3. Fire behavior potential in a $2xCO_2$ scenario

This study indicates significant increases in fire behavior potential over the entire study area with a doubling of CO_2. For example, results show that during the full fire season period, on 20% of the days (80^{th} percentile), 48% of the total area or more could sustain a high intensity crown fire. This is a 3-fold increase compared to the $1xCO_2$ scenario. If the frequency of extreme wildfire events increases in the future as predicted by these results, it could significantly reduce the effectiveness of suppression in central Saskatchewan and, in turn, increase the area burned by large wildfires. It could also have an impact on the availability of a sufficient timber supply. These important increases in fire behavior potential are clearly shown by the distribution of HFI values at the 80^{th} and 95^{th} percentile; in the $2xCO_2$ scenario, there are significant areas where potential HFI is 20,000-28,000 and 30,000-38,000 kW/m, respectively (Fig. 9). These types of intensities are extremely rare in the $1xCO_2$ scenario. Thus, if the fuel types are similar in the future, the CRCM predicts that a $2xCO_2$ environment will produce more extreme fire weather and cause an increase in the potential for fast spreading, high intensity wildfires.

The northern section of the study area is particularly at risk in terms of future increases of fire behavior potential (Map 7-18 and 27-32). At the 95^{th} percentile, a vast majority of cells have HFI values above 4000 kW/m whereas at the 80^{th} percentile they usually exceed 2000 kW/m. The north section has the highest proportional increases in fire behavior potential with practically the entire section experiencing at least a doubling in HFI. This is due not only to the possibility that fire weather severity increases faster in the north section of the study area, but also to the fact that the fire behavior potential of jack pine fuel type, which has a higher height to live crown base, increases sharply when intermittent crowning occurs (Fig. 15). It seems that this crowning threshold is overcome in both the 80th and 95th percentile in the 2xCO_2 scenario, which significantly increases the fire threat posed by this section. The same effect could have played a role in the high proportional increases in mixedwoods at the 80th percentile. This higher frequency of more extreme fire behavior along with the remoteness of the northern section could result in more wildfires burning out of control in a 2xCO_2 environment.

Although it is not shown on the HFI maps, except in a southern part which becomes included in the 30,000+ kW/m class, the central section of the study area has the highest absolute increases in fire behavior potential. This is due in part because of the southwest to northeast decrease in the severity of conditions (Fig. 14) and because the boreal spruce fuel type, which is very flammable, is very abundant in this section. In contrast to the north section, the ladder fuel structure of the boreal spruce fuel type in the central section renders a surface fire more prone to crowning. This explains the high fire behavior potential at both percentiles in the 1xCO_2 environment and the subsequent lesser proportional increases in a 2xCO_2 environment. The threshold between intermittent and crown fires occurs at lower percentile conditions than the ones that were used (Fig. 15). Thus, this situation is different from the dynamics in the north section (i.e, there would not likely be more fires in the critical 2000-10,000 kW/m class because they would just occur in lower percentile conditions) but not less critical because an extreme fire behavior potential would likely present itself much more frequently.

The southeast section of the study area has a similar trend to the central section in terms of fire behavior potential increases, except the grass area to the north, which varies more according to the period of the season than to change in fire weather conditions associated with climate change (i.e., the grass fuel type is thus more dependent on its state).

In general, the northeast section shows the lowest increases and accounts for most of the decreases in fire behavior potential that occur in the study area (especially in 95th percentile conditions). The large deciduous component found in this section reduces the effect of more extreme weather conditions associated with climate change because this fuel type does not seem to respond with increases in HFI once green-up has occurred. Noteworthy is that spring conditions could make the aspen fuel type more prone to be influenced by climate change although this is not shown by the HFI maps due to the questionable quality of the projected data in this period.

4.4. Fire behavior potential in a 3xCO_2 scenario

One of the unexpected results of the analysis was the overall similarity between the 2xCO_2 and 3xCO_2 scenario (Map 13-24, Map 33-38), indicating that the important increases from 1xCO_2 to 2xCO_2 seem to level off. Indeed, in 80th percentile conditions, the net change of pixels from one HFI class to another is low (Table 5). However, at the 95th percentile, the 3xCO_2 scenario suggests a slight increase in the percentage of the study area in the highest HFI classes (Table 6).

The main difference between these two scenarios is the spatial pattern. Some areas have significant decreases in fire behavior potential (particularly at the 95th percentile in the central region) whereas other areas show important increases. An important point to notice is that the

HFIs in the northern section of the study area continue to increase (proportional change is relatively high) indicating a further reduction in suppression capability (Maps 33-36).

4.5. Implications for the dynamics of the boreal forest and sustainable forest management

Forest fires are an important agent of change in the boreal forest and their periodic occurrence maintains ecosystem health, structure and integrity. The importance of wildfires in ecosystem processes and function is generally accepted but our knowledge of the role of wildfires in the dynamics of the boreal forest (fire effects, biodiversity, species succession) and global cycles (e.g. carbon) is still limited. Predicting the impact of climate change on the dynamics of the boreal forest is very difficult due to the lack of knowledge of the effect of changes in disturbance regime. For example, we still speculate on the longer-term impact of fire suppression on area burned. It has been suggested that changes in the fire regime may have a greater impact on vegetation than the direct effects of climate change (Weber and Stocks 1997). Flannigan and Wotton (2001) further proposed that more frequent wildfires could hasten vegetation change through species migration.

In our study, an increase in area that can sustain a high fire behavior potential at any time implies potentially more extreme fire events, more area burned, and a shorter fire cycle. The increase in intensity of some fires would likely be translated into higher rates of spread and more erratic behavior (further increasing area burn) rather than a significant increase in fuel consumption (i.e., HFI is based on rate of spread and fuel consumption). However, a few wildfires in a higher

CO_2 level environment could consume more fuel by burning more deeply into organic layer and soil and cause regeneration problems. However, it is likely that the main changes will be associated with a shorter fire cycle in combination with the higher temperatures and a lower moisture regime. Due to the different adaptations to fire of boreal species, these changes could possibly result in a change in species composition (e.g., Bergeron and Dansereau 1993) and produce a northern shift in the limit between the grasslands, open parklands and southern edge of the boreal forest in Saskatchewan.

The socio-economic impact of higher fire behavior potential in the future may be critical in central Saskatchewan. It could mean both an increase in expenditures for suppression and a decrease in the timber supply available to forest companies. Due to these added constraints, it could be very difficult to practice sustainable forest management without resorting to some type of adaptation measures or strategies. One possible alternative is the inclusion of strategic fuel treatments in forest planning to reduce the spread of large fires (SECTION II). This strategy involves the creation of fuel barriers (aspen and mixedwoods fuel types) that account for a lower fire behavior potential. Our study has shown that even in future more extreme weather conditions, these fuel types are relatively stable and would rarely be conducive to high intensity wildfires. However, note that fire behavior potential represents just one of the four components of an assessment of wildfire threat (others include ignition potential, suppression capability, and values-at-risk). Essentially, the predicted significant increases in the fire behavior potential component stress the importance of integrating fire and forest management (Hirsch *et al.* 2001) in order to harmonize decisions and policies and achieve an optimization of adaptation efforts towards climate change.

4.6. Conducting fire behavior potential assessments to measure the effect of climate change

An important step that this study has not addressed is to link the higher fire behavior potential to area burned. This could have been achieved through a compilation of weather conditions under which significant daily area burned are recorded in the study area. Moreover, our study did not take into account the possible feedbacks that could be associated with climate change in the boreal forest because it used static fuel types. The need to model forest succession and disturbance over time is very challenging but essential to allow to form a more accurate picture of the impact of climate change in the boreal forest dynamics.

Conducting this type of fire behavior potential study requires a considerable amount of work to manipulate and prepare the weather data before any analysis. The processing time is also to consider in this type of assessment. For example, a 733-MHz computer ran for approximately 2.5 hours for each of the HFI maps that were created in our study. At this rate it would have been impossible to produce the percentile HFI maps in a timely manner with the more accurate daily method at the maximum resolution.

5. CONCLUSION

Although central Saskatchewan already represents an area of high fire behavior potential, significant increases are predicted over the entire study area with climate change (2xCO_2), except in deciduous fuel type when green-up occurs. The north section of the study area has the highest proportional increases whereas the central section has the highest absolute increases. Most important changes occur during a doubling of CO_2 concentrations in the atmosphere and seem to stabilize in a $3xCO_2$ environment despite large regional spatial variations. In these weather conditions, the north section once again shows significant proportional increases. These increases in fire behavior potential could considerably reduce suppression capability and lead to greater area burned by wildfires. This, in turn, could have major social, economical and ecological impacts in Saskatchewan.

Climate change could represent an important challenge to the sustainability of the forest industry in this area of the boreal forest. Adaptation strategies such as fire-smart forest management or more generally, the integration of fire and forest management could be essential if the predicted increases in fire behavior potential occur in the future.

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Table 5. Percentage of the study area in each head fire intensity class in each fire season period and climate scenario in 80th percentile conditions.

		Percentage of area in each head fire intensity class (kW/m)						
Scenario	**Season**	0-9	10-499	500-1999	2000-3999	4000-9999	10,000-29,999	30,000+
Historical	Full	0	15.09	16.22	14.75	15.47	38.25	0.22
1xCO_2	Full	0	17.92	20.53	8.49	24.49	27.88	0.69
2xCO_2	Full	0	14.35	12.70	9.09	14.57	48.20	1.09
3xCO_2	Full	0	14.52	12.02	9.12	14.26	48.99	1.09
Historical	Spring	0	0.14	19.58	20.02	18.10	41.50	0.66
1xCO_2	Spring	0.04	32.34	39.73	19.45	7.79	0.65	0
2xCO_2	Spring	0	21.99	31.23	25.93	19.93	0.92	0
3xCO_2	Spring	0	24.46	25.34	29.97	19.20	1.03	0
Historical	Summer	0	26.21	8.78	12.30	23.12	29.50	0.10
1xCO_2	Summer	0	31.17	11.24	11.59	29.88	15.89	0.23
2xCO_2	Summer	0	26.43	2.97	10.68	12.67	46.27	0.98
3xCO_2	Summer	0	26.26	3.45	11.32	10.99	47.02	0.95

Table 6. Percentage of the study area in each head fire intensity class in each fire season period and climate scenario in 95th percentile conditions.

		Percentage of area in each head fire intensity class (kW/m)						
Scenario	**Season**	0-9	10-499	500-1999	2000-3999	4000-9999	10,000-29,999	30,000+
Historical	Full	0	13.60	10.72	2.22	6.37	37.53	29.56
$1xCO_2$	Full	0	14.38	14.74	5.17	15.11	49.17	1.44
$2xCO_2$	Full	0	14.19	12.25	0.62	13.74	51.19	8.01
$3xCO_2$	Full	0	14.21	12.27	0.26	13.55	47.00	12.71
Historical	Spring	0	0	3.45	12.03	13.70	30.83	39.99
$1xCO_2$	Spring	0	9.13	28.75	16.95	35.22	9.82	0.12
$2xCO_2$	Spring	0	6.27	28.71	13.86	40.52	10.30	0.34
$3xCO_2$	Spring	0	2.89	32.38	11.71	43.31	9.50	0.21
Historical	Summer	0	18.92	7.55	0.23	8.27	41.62	23.41
$1xCO_2$	Summer	0	26.31	3.57	6.58	15.60	46.18	1.75
$2xCO_2$	Summer	0	25.74	0.74	0.80	12.81	53.64	6.28
$3xCO_2$	Summer	0	23.17	3.30	0.55	15.26	46.52	11.19

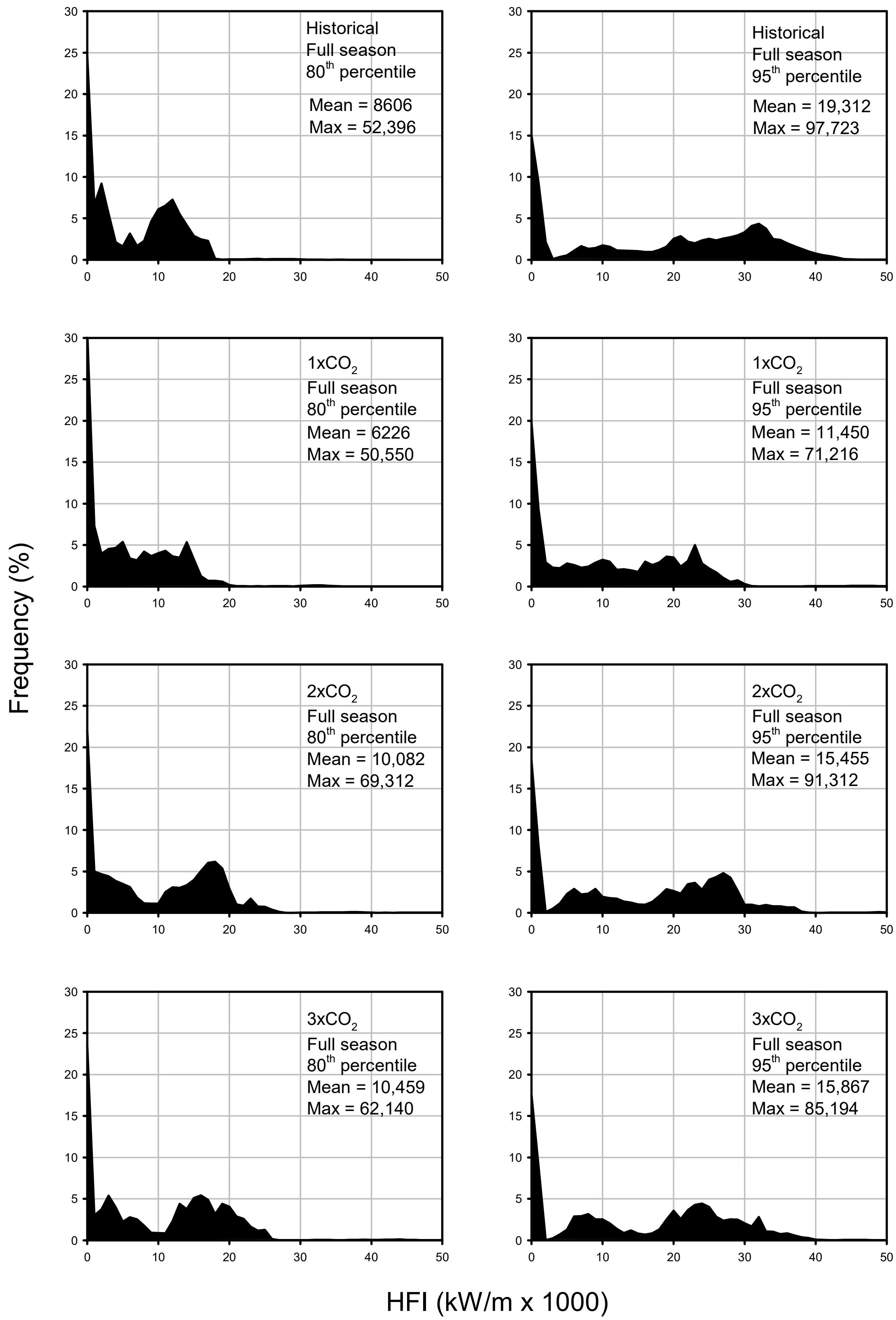


Fig. 10. Distribution of head fire intensity (HFI) values in 1000 kW/m classes with mean and maximum values for the full season period in all scenarios at the 80th and 95th percentile.

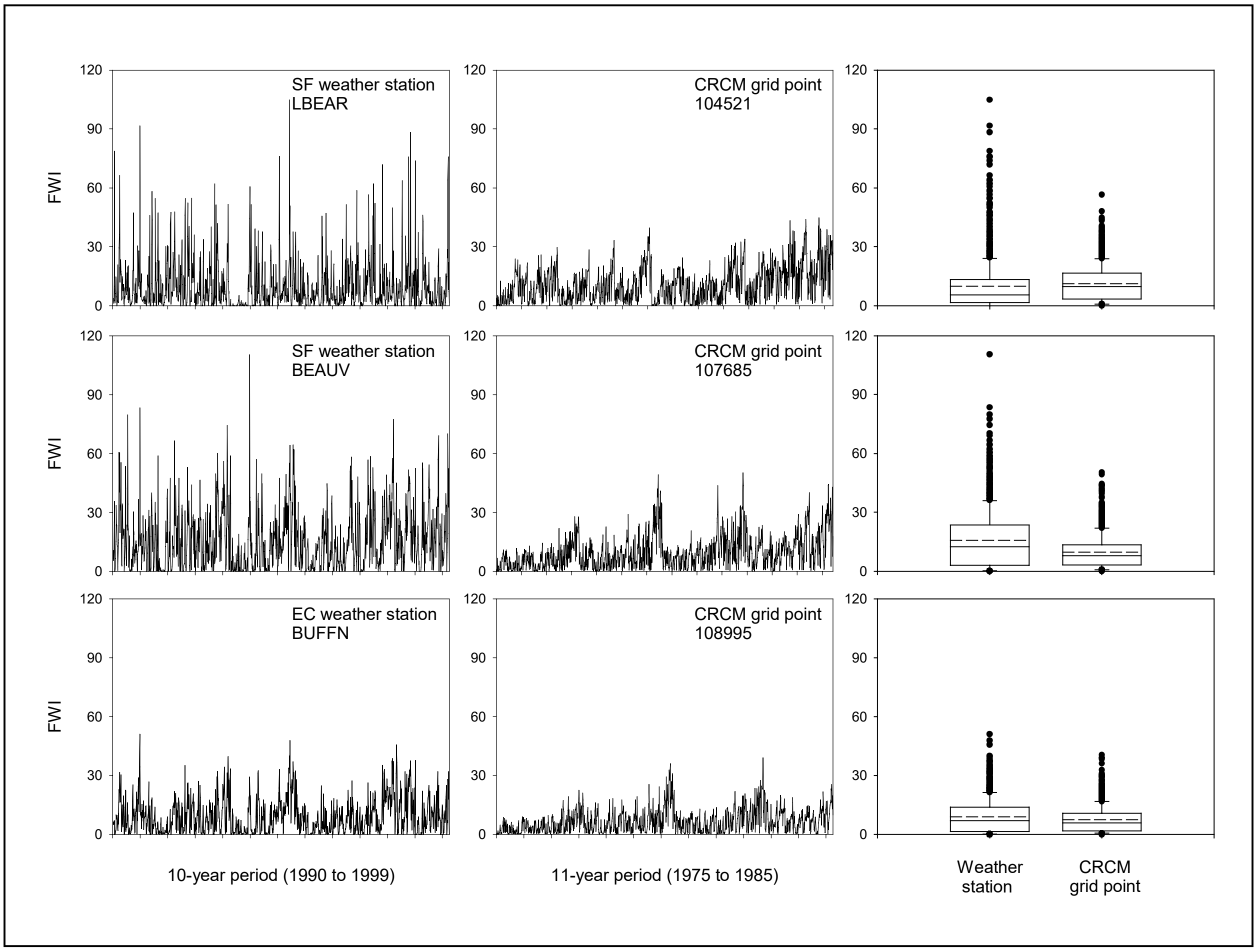


Fig. 11. Time series and box plots illustrating the variability of the Fire Weather Index (FWI) values for Environment Canada (EC) stations (N=6), Saskatchewan Forestry (SF) stations (N=6) and the Canadian Regional Climate Model (CRCM) 1xCO_2 scenario grid points (N=6). The nearest Saskatchewan Forestry stations and Canadian Regional Climate Model grid points to Environment Canada stations were selected. Points represent outliers that exceed the 10^{th} and 90^{th} percentiles.

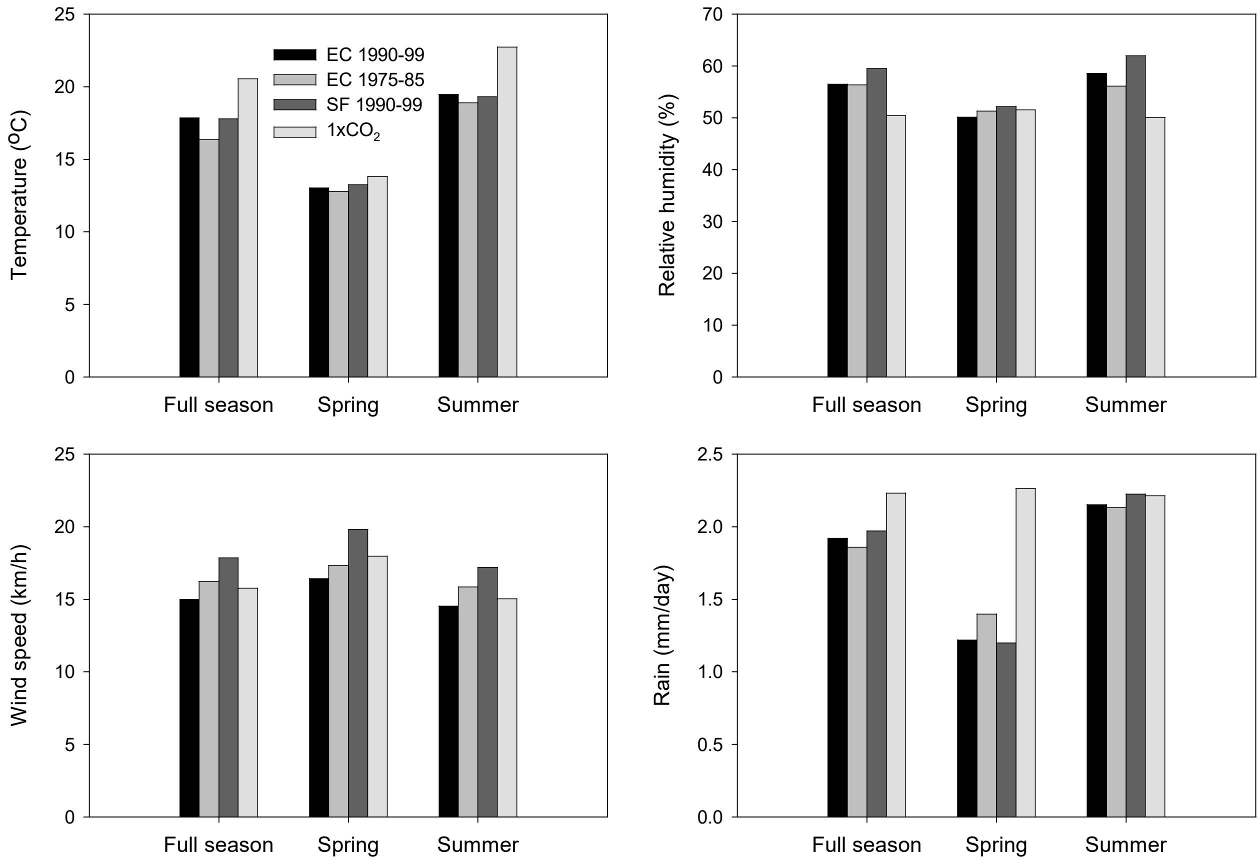


Fig. 12. Comparison of weather data observations for Environment Canada (EC) stations from1990 to 1999 (N=6), Environment Canada stations from 1975 to 1985 (N=13), Saskatchewan Forestry (SF) stations (N=6), and the Canadian Regional Climate Model (CRCM) $1xCO_2$ scenario grid points (N=6). The nearest Saskatchewan Forestry stations and Canadian Regional Climate Model $1xCO_2$ scenario grid points to Environment Canada stations from 1990 to 1999 were selected. Environment Canada stations from 1975 to 1985 are inside or close to the study area.

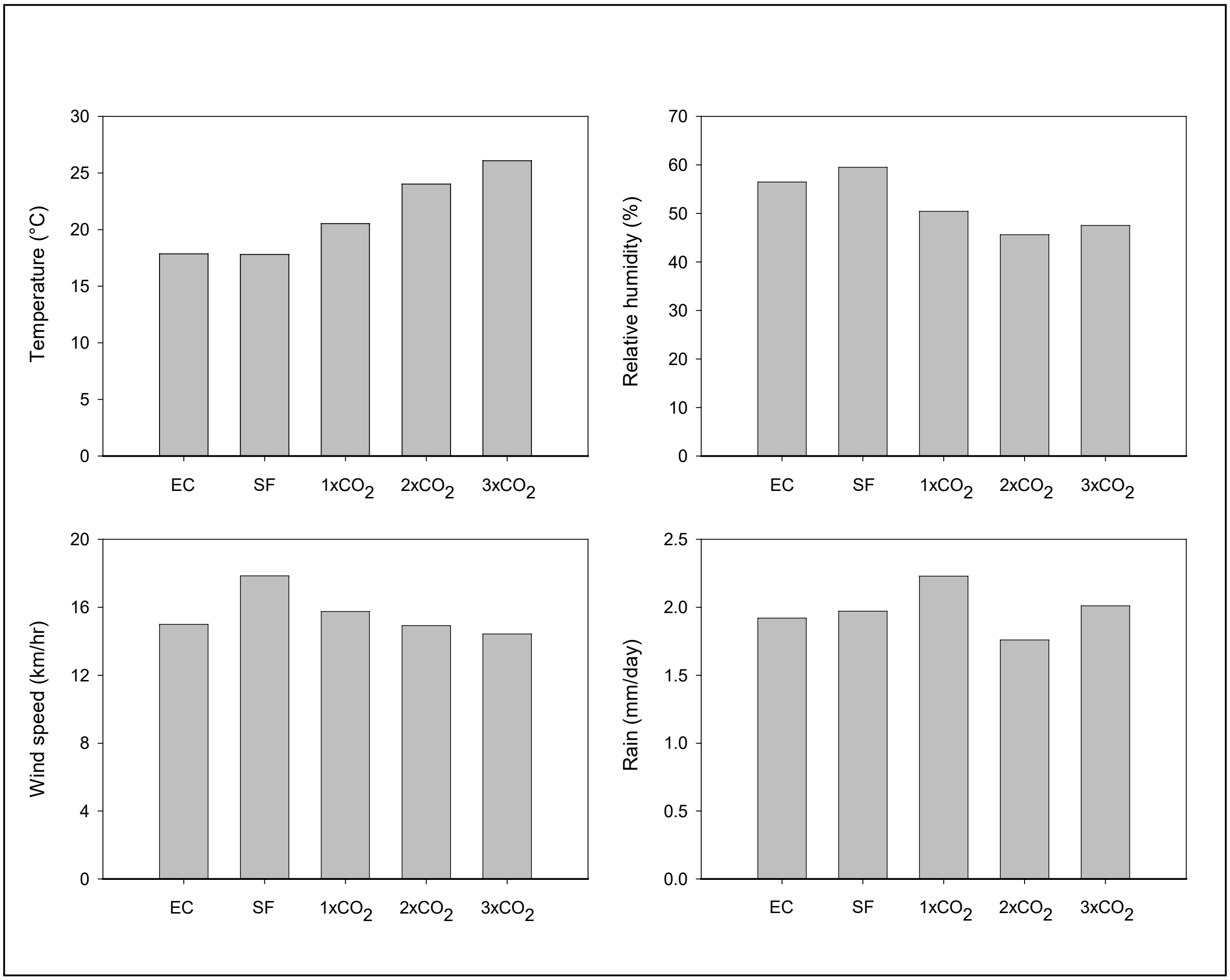


Fig. 13. Average weather data observations for Environment Canada (EC) stations (N=6), Saskatchewan Forestry (SF) stations (N=6) and the three Canadian Regional Climate Model (CRCM) scenario grid points (N=6) for the full fire season. The nearest Saskatchewan Forestry stations and Canadian Regional Climate Model scenario grid points to Environment Canada stations were selected.

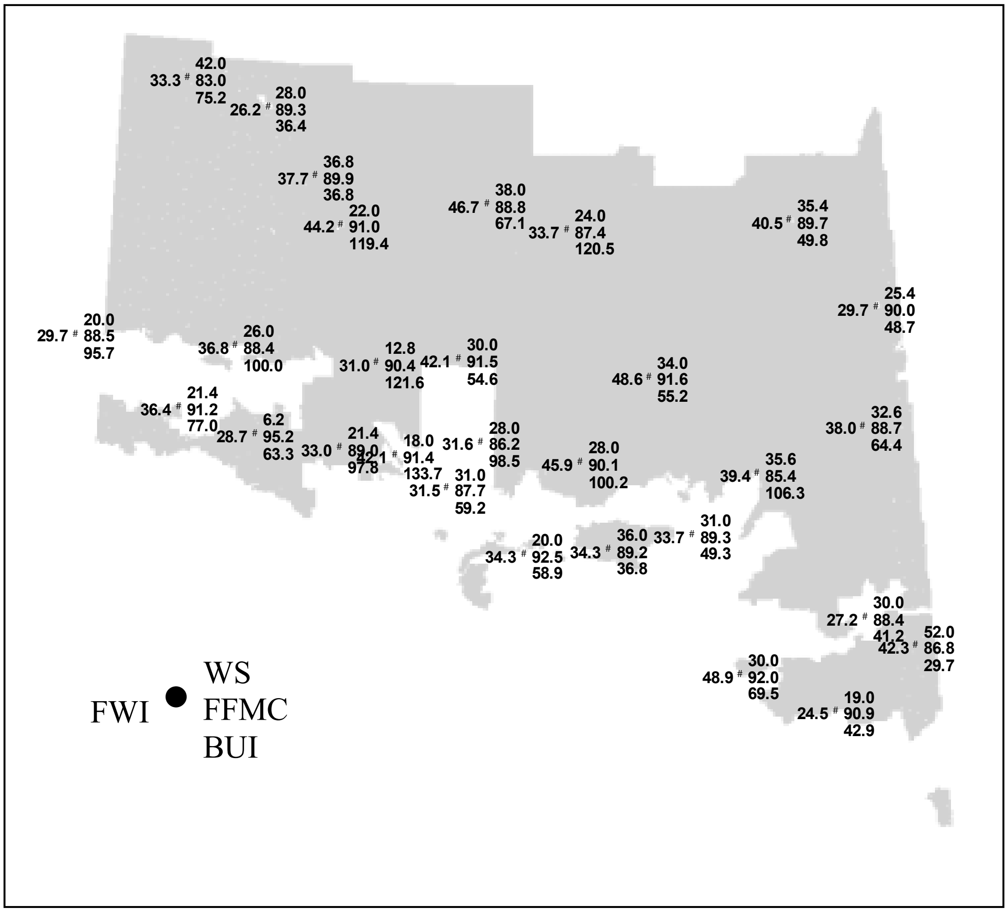


Fig. 14. Fire Weather Index (FWI) values and their corresponding Fine Fuel Moisture Code (FFMC), Buildup Index (BUI), and wind speed (WS) values for each weather station at the 95th percentile.

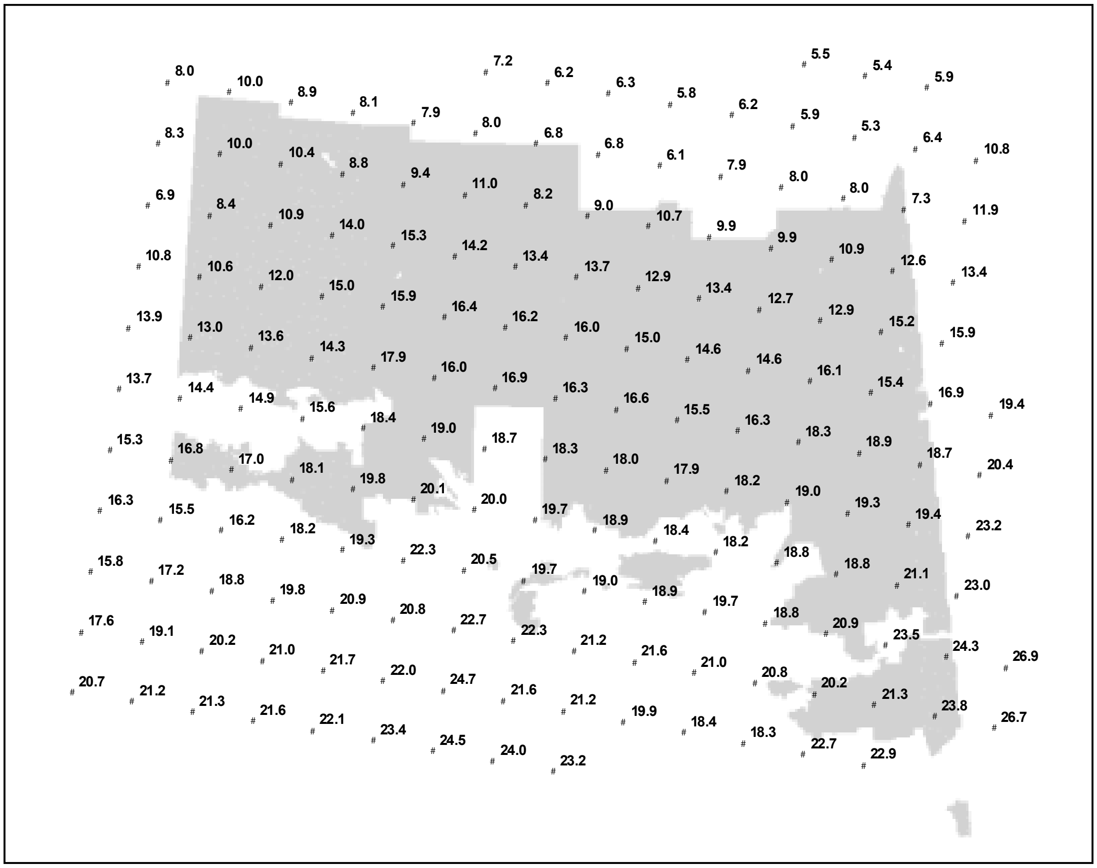


Fig. 15. Fire Weather Index (FWI) values at each Canadian Regional Climate Model (CRCM) grid point for the full fire season period 1xCO_2 scenario at the 95th percentile.

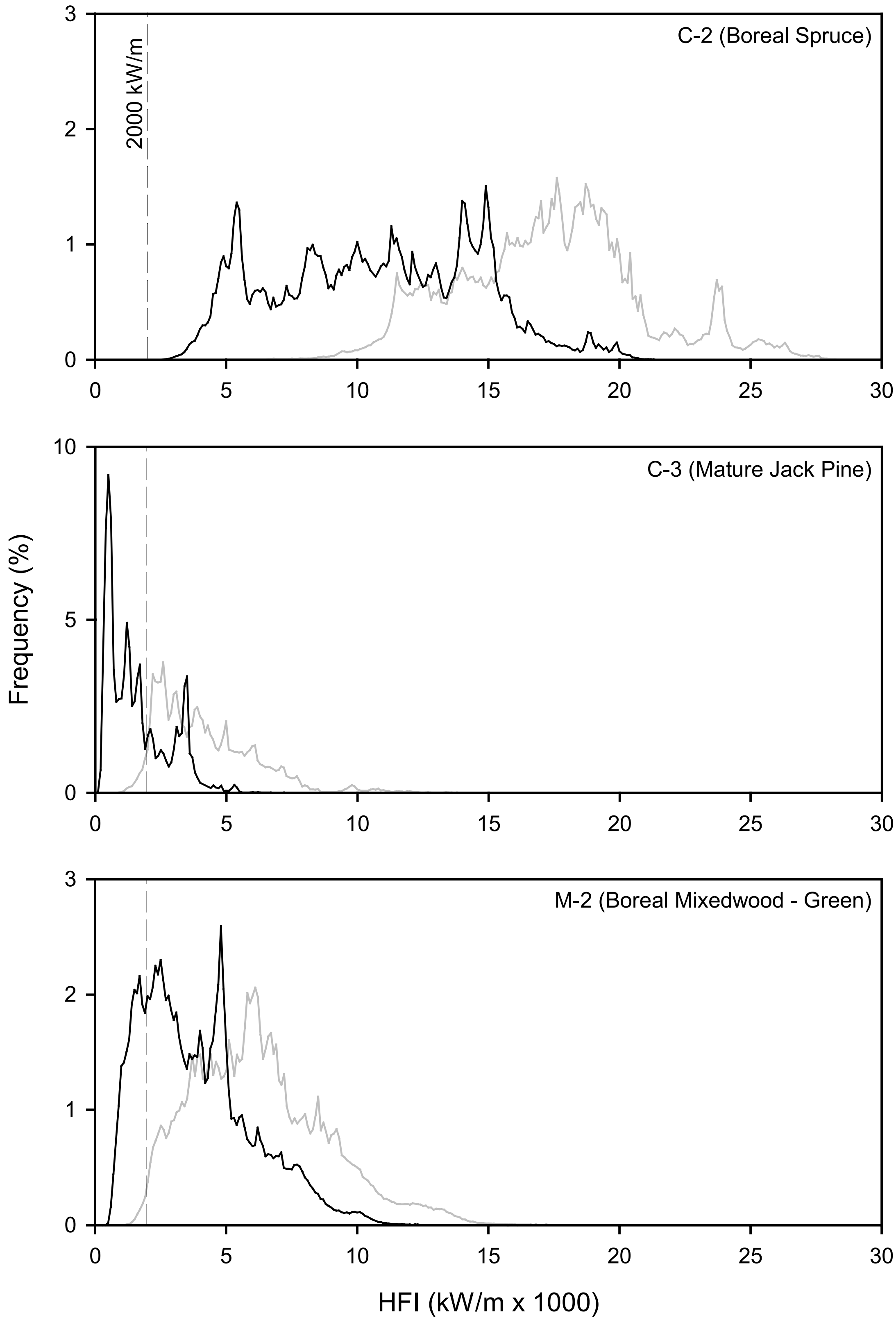
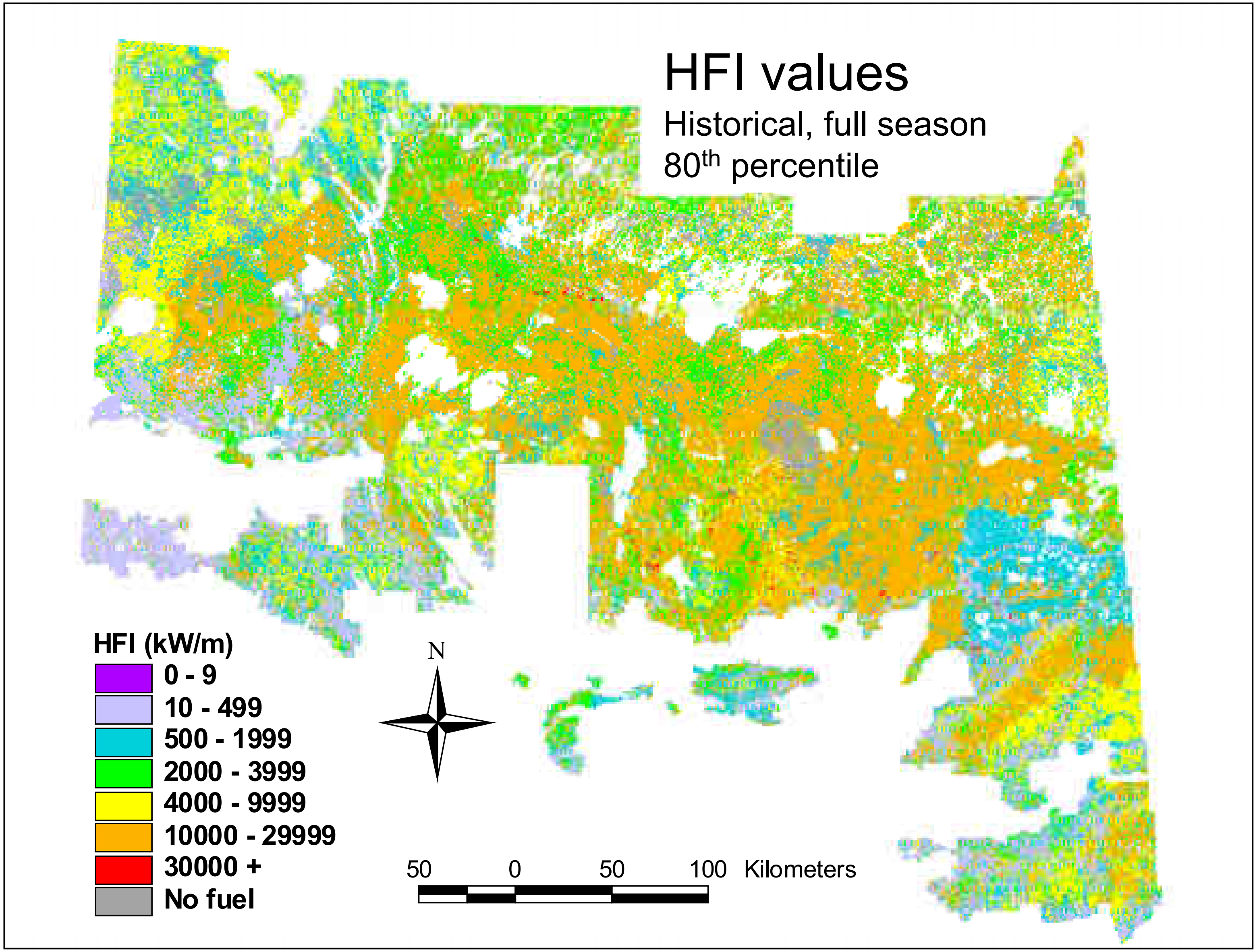
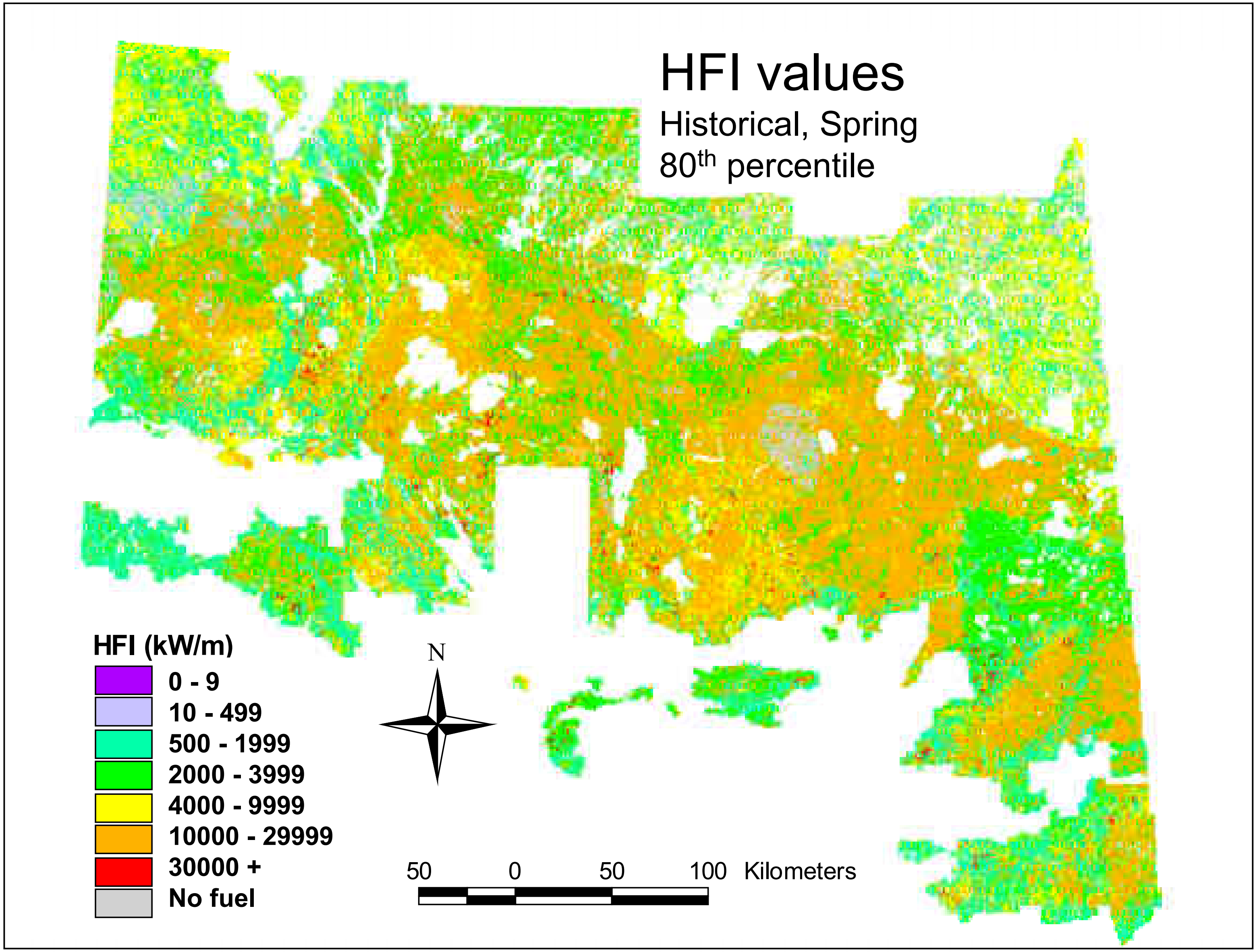


Fig. 16. Distribution of head fire intensity (HFI) values in 100 kW/m classes for the C-2, C-3, and M-2 fuel types in the 1xCO_2 (black) and 2xCO_2 (gray) climate scenarios for the full season at the 80th percentile. Note the different scale in the y-axis for the C-3 fuel type.

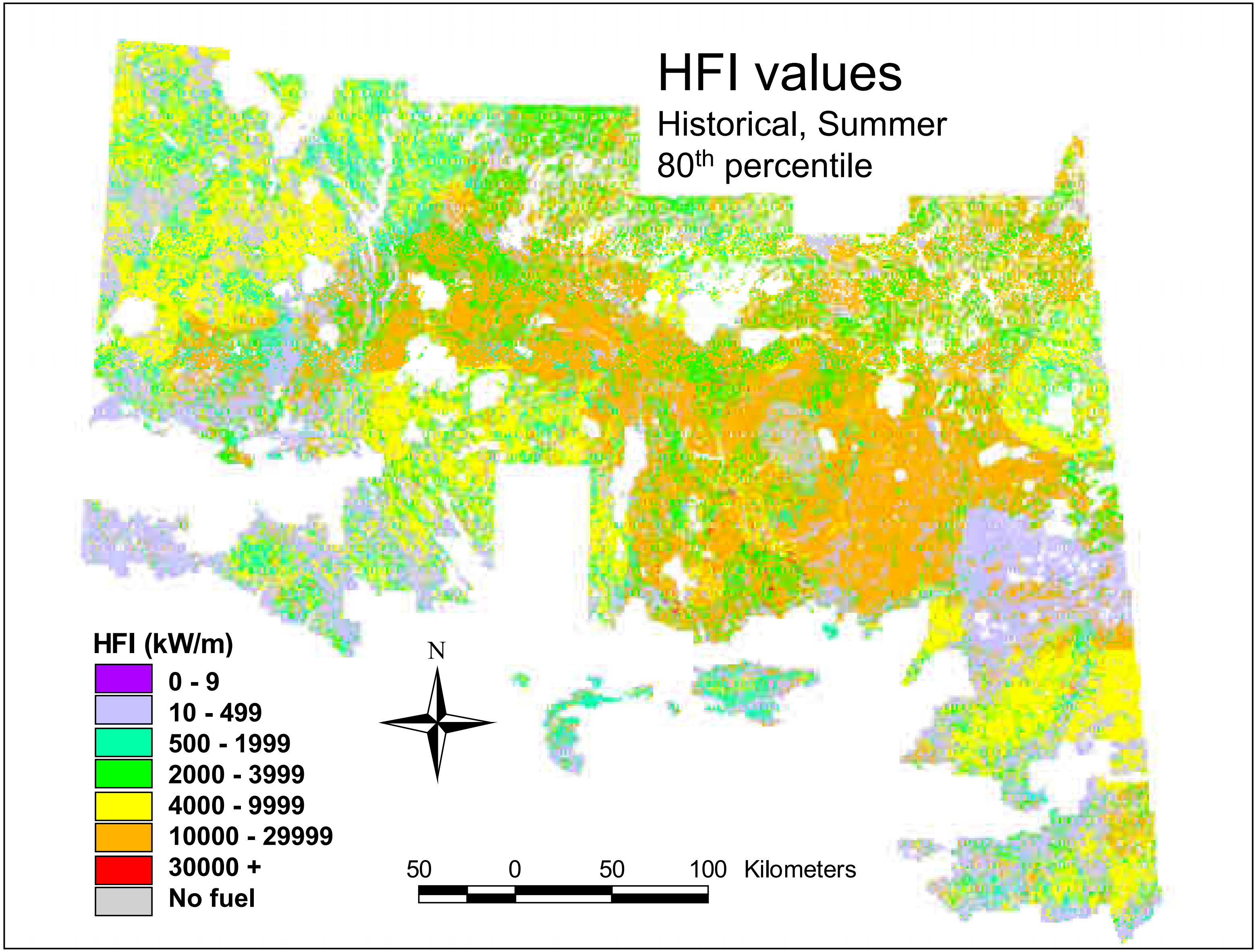
6. APPENDIX I



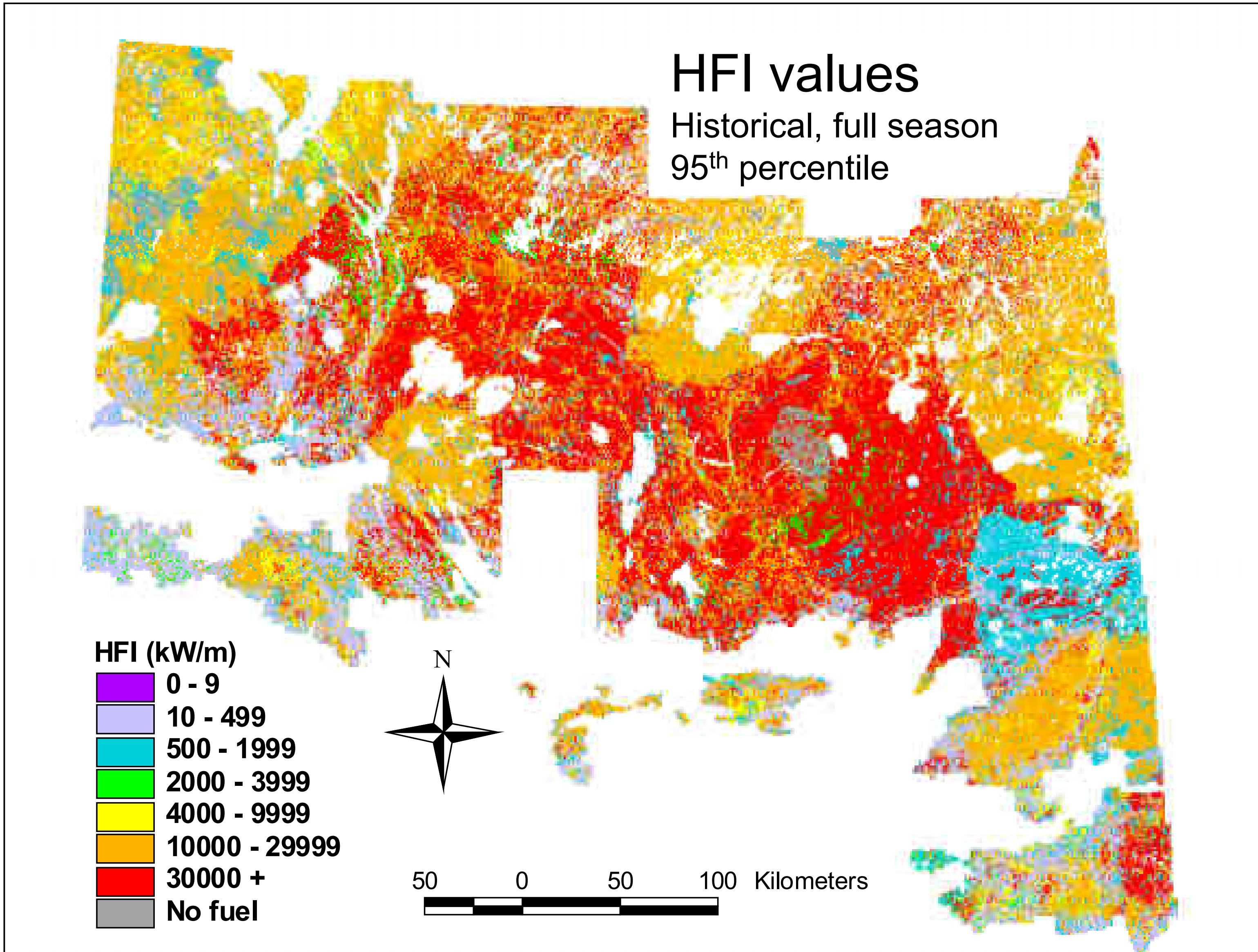
Map 1. Head fire intensity (HFI) in the historical scenario.



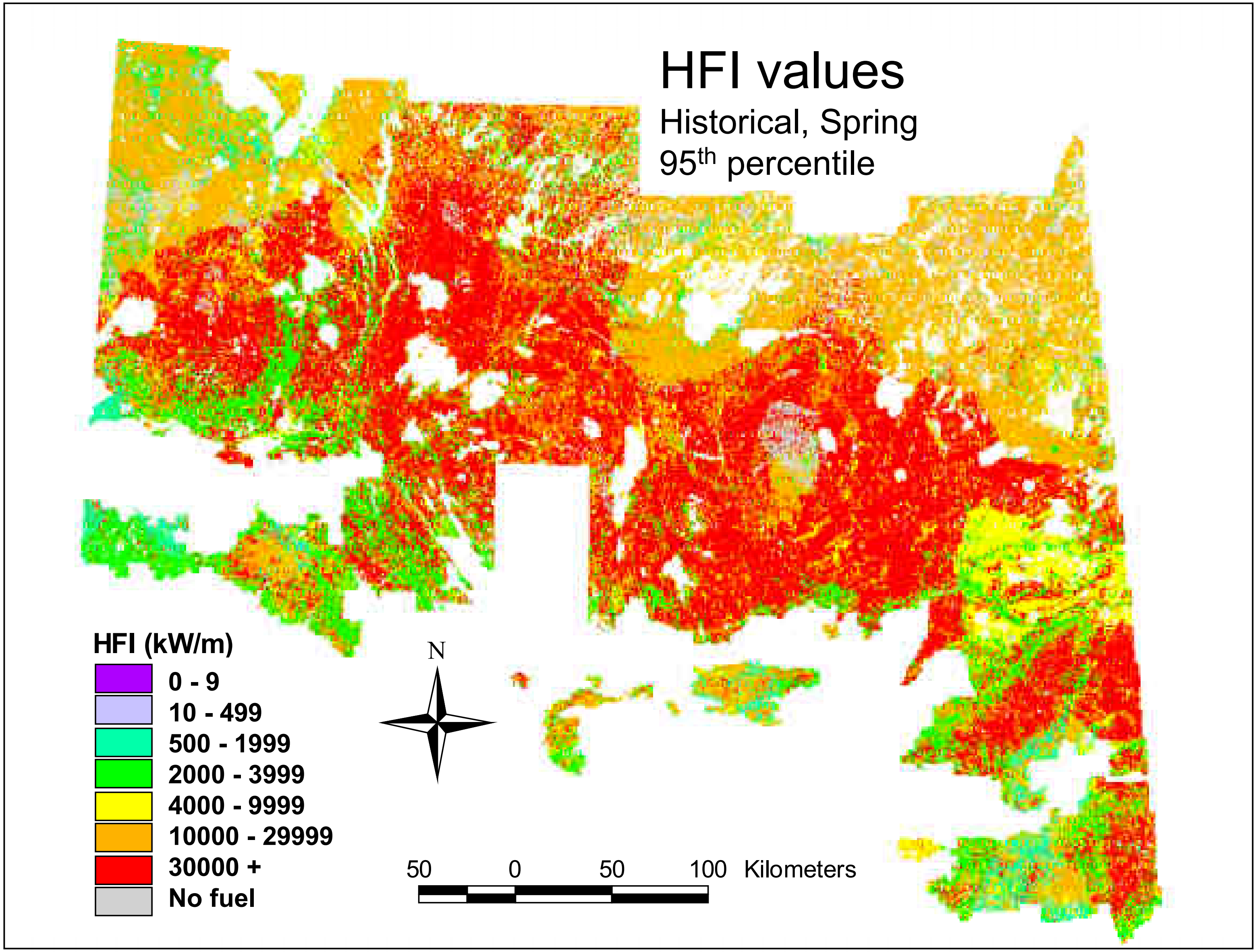
Map 2. Head fire intensity (HFI) in the historical scenario.



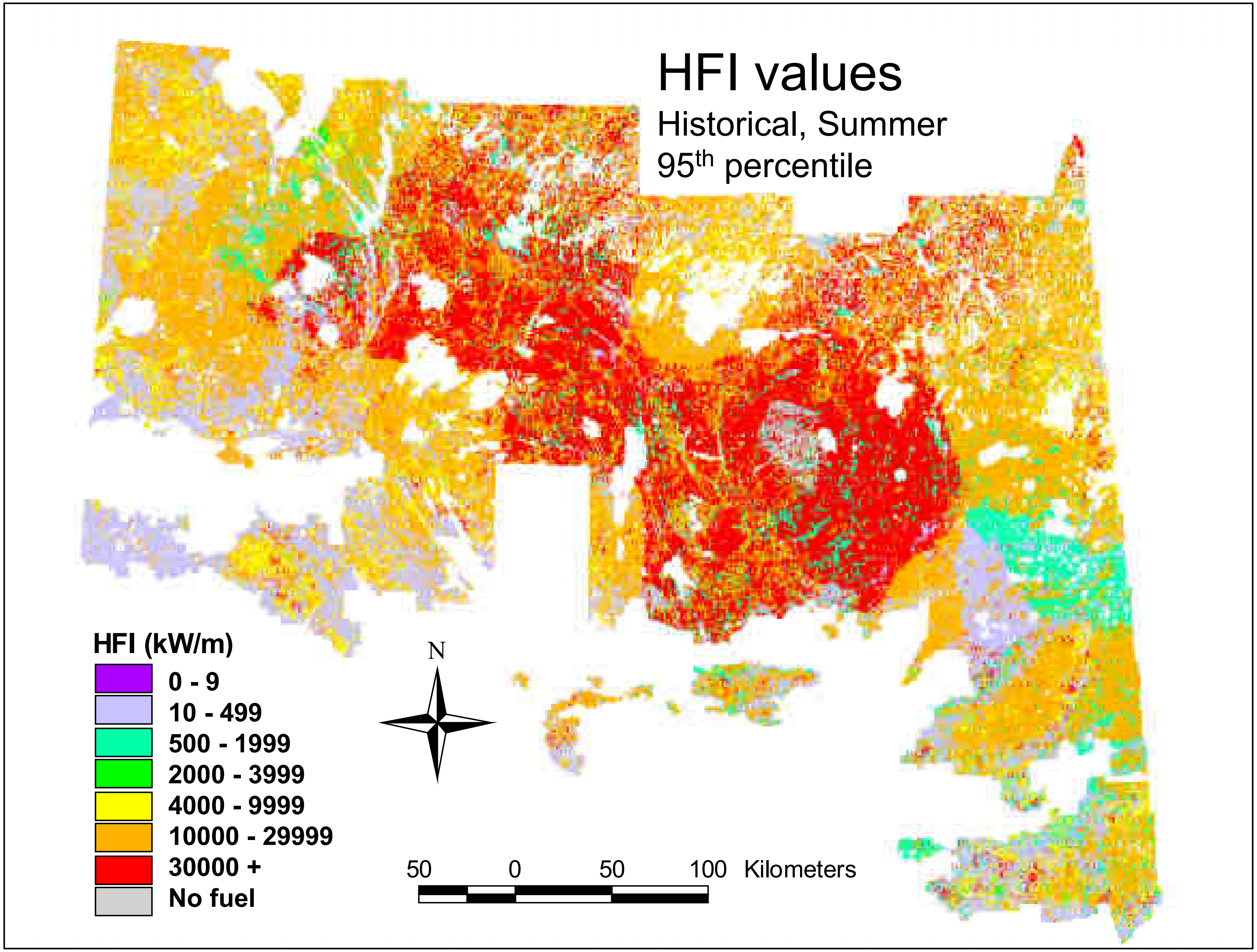
Map 3. Head fire intensity (HFI) in the historical scenario.



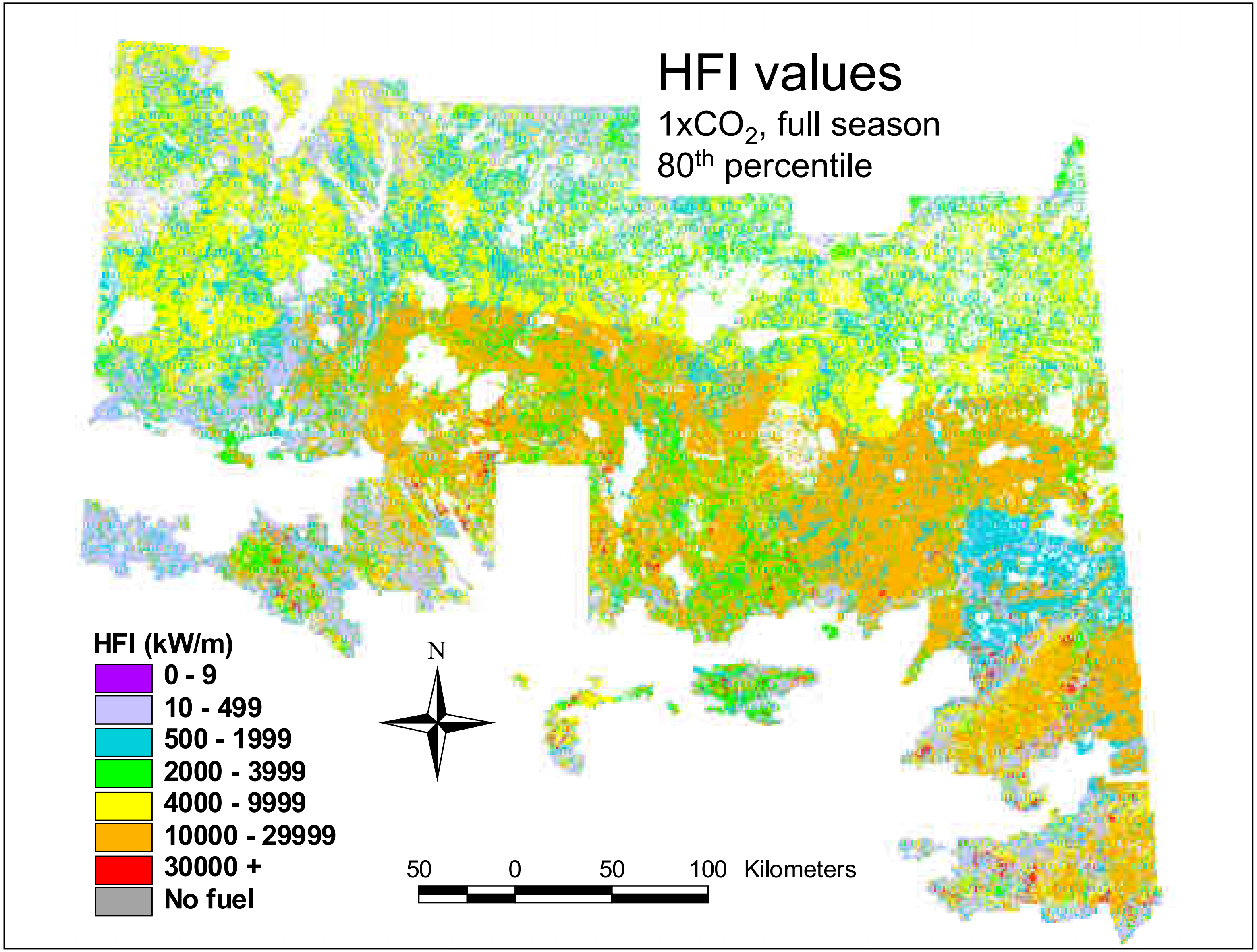
Map 4. Head fire intensity (HFI) in the historical scenario.



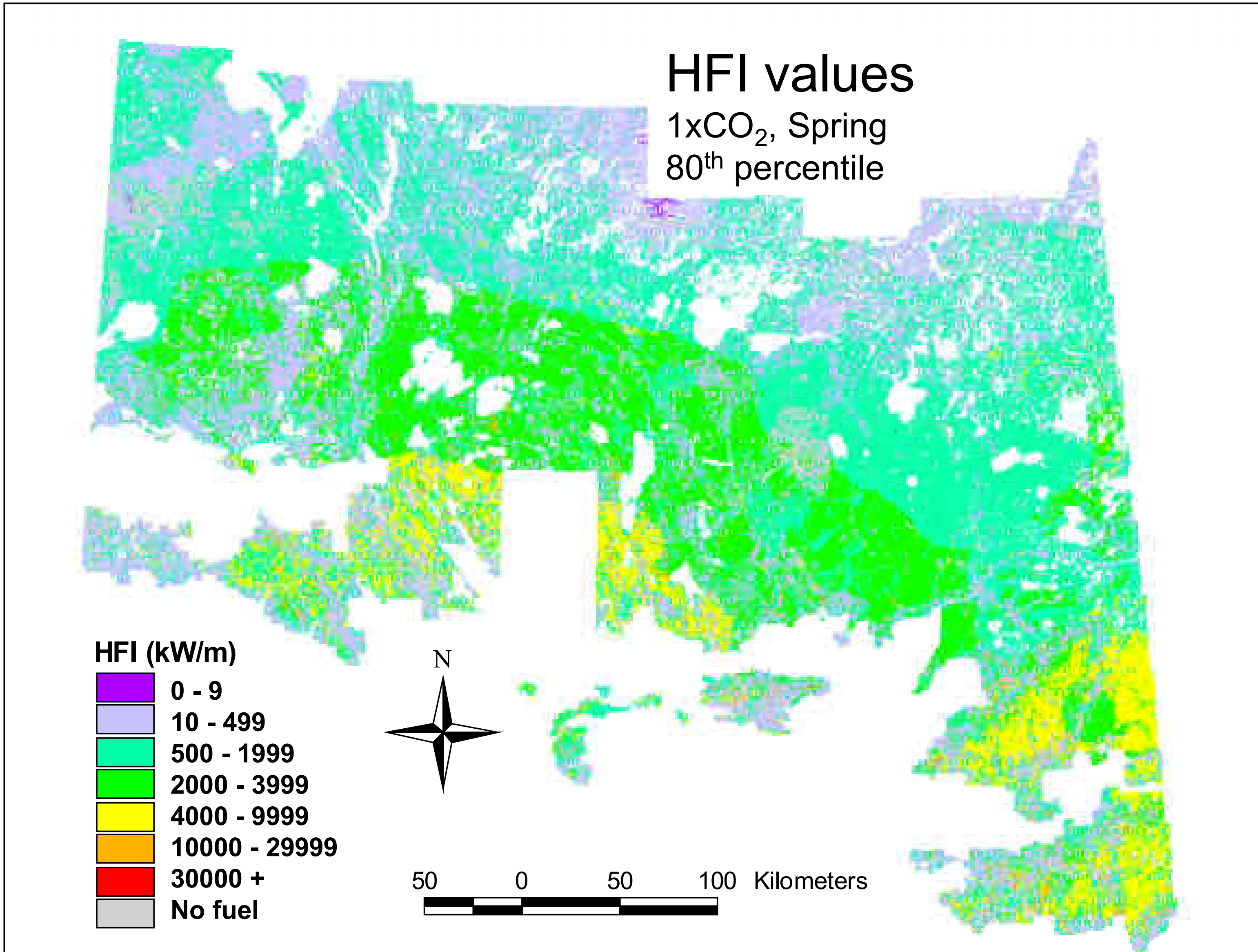
Map 5. Head fire intensity (HFI) in the historical scenario.



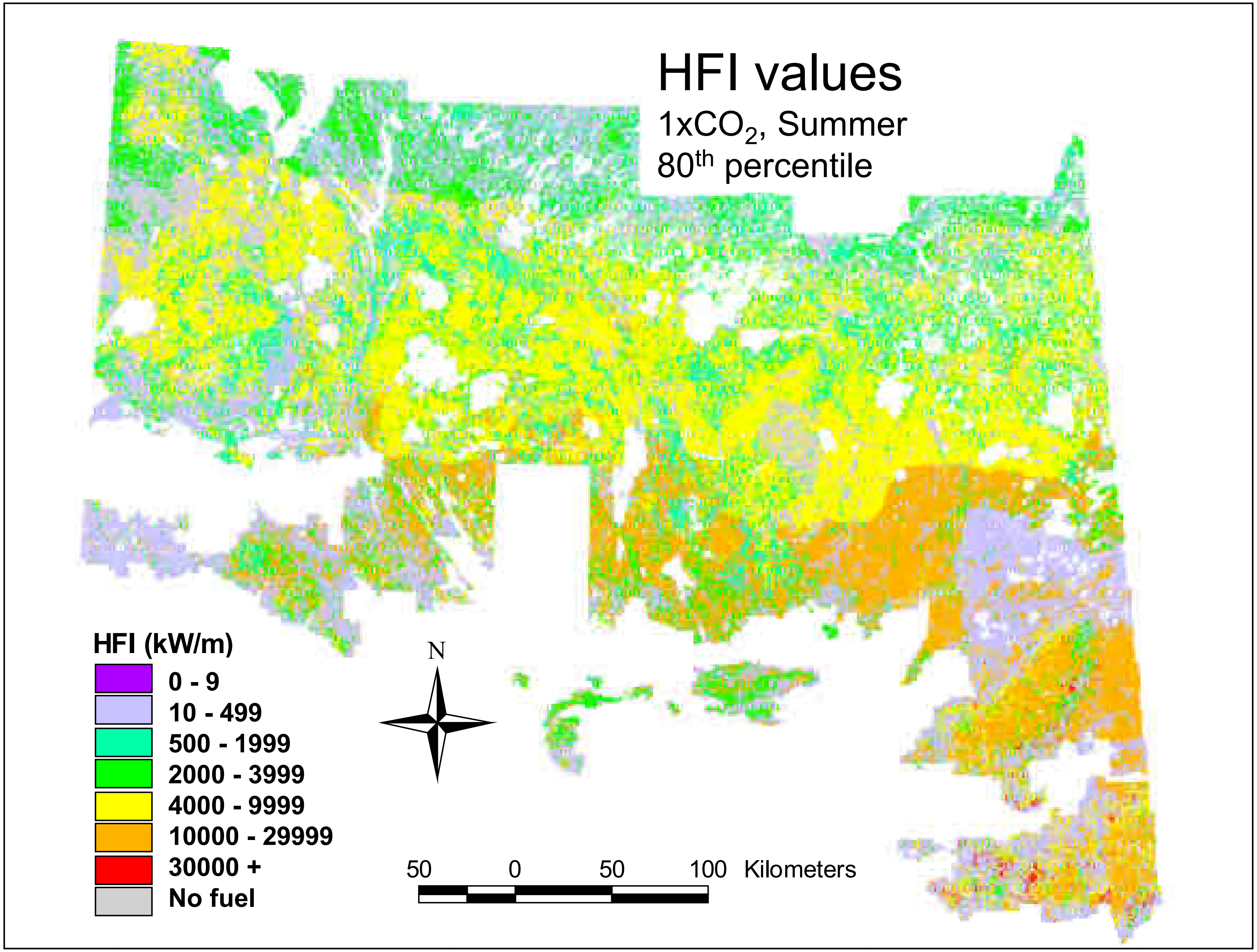
Map 6. Head fire intensity (HFI) in the historical scenario.



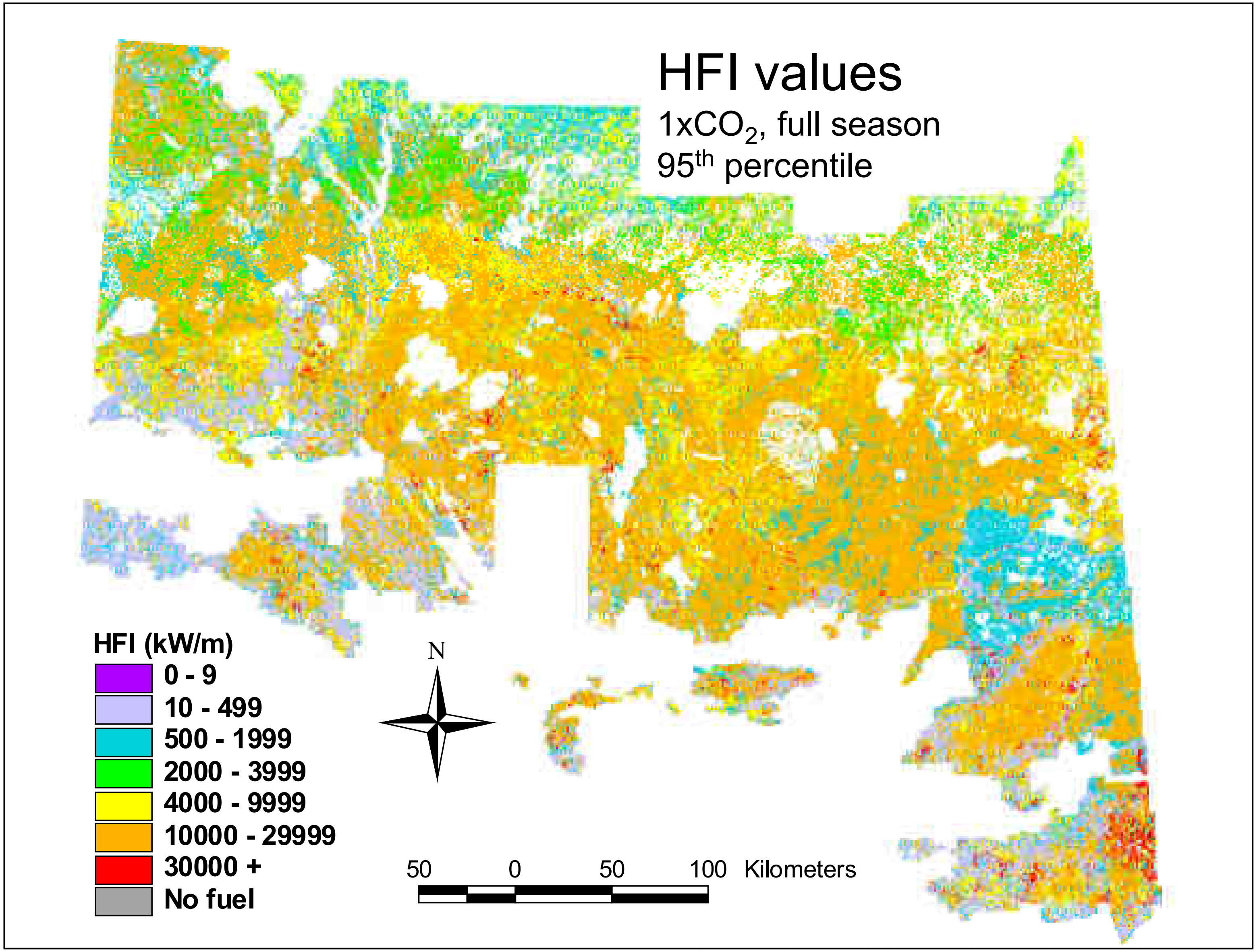
Map 7. Head fire intensity (HFI) in the $1xCO_2$ scenario.



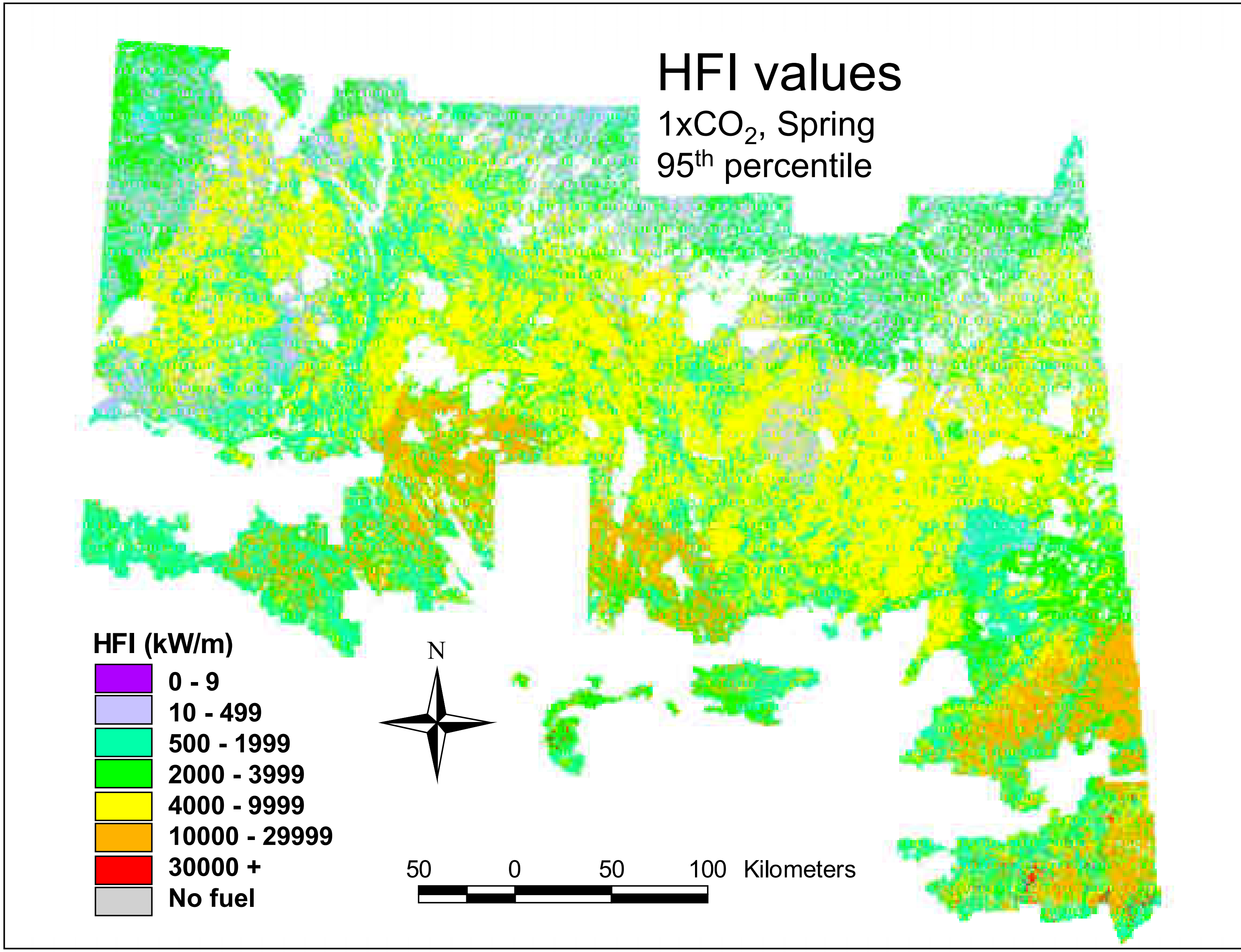
Map 8. Head fire intensity (HFI) in the $1xCO_2$ scenario.



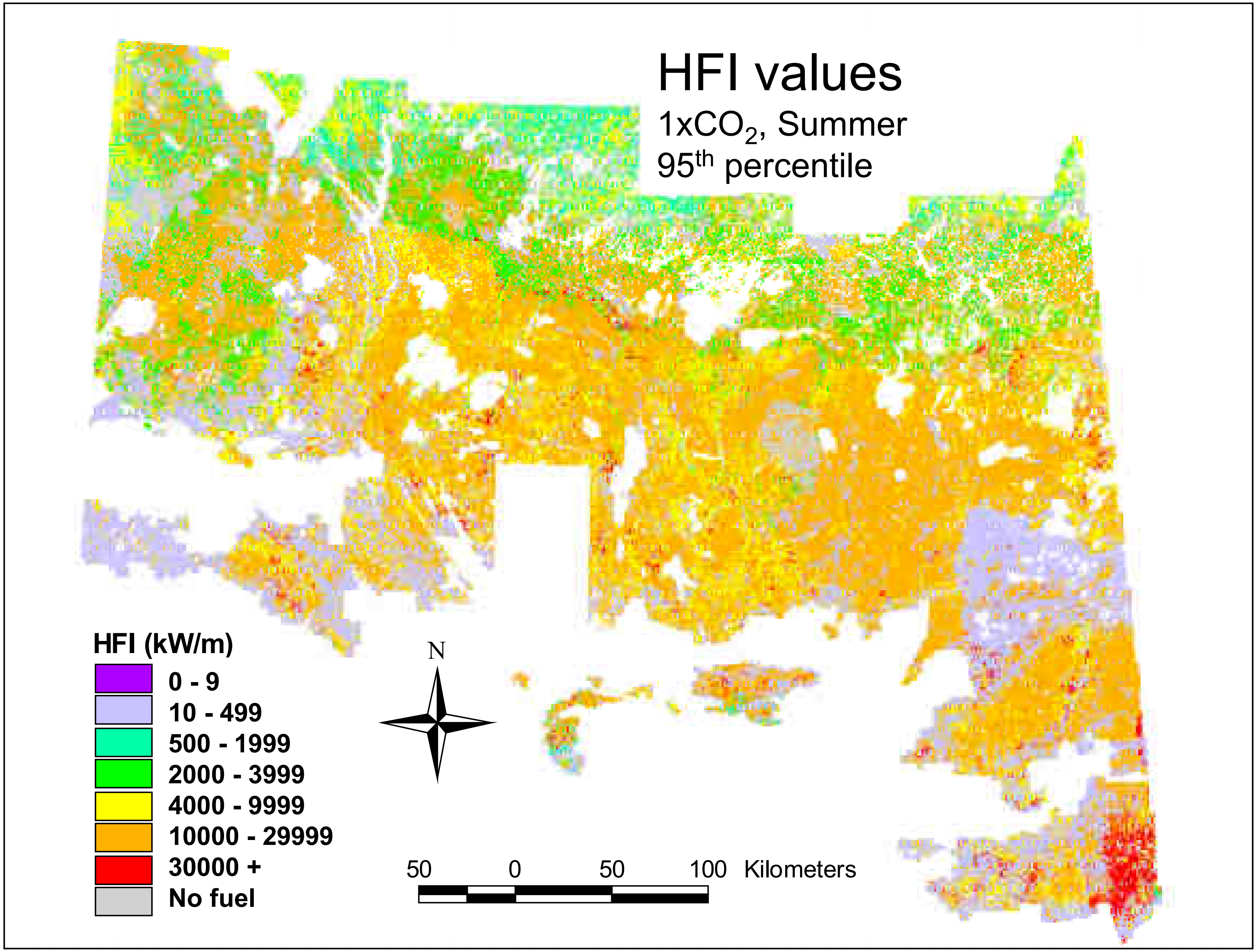
Map 9. Head fire intensity (HFI) in the 1xCO_2 scenario.



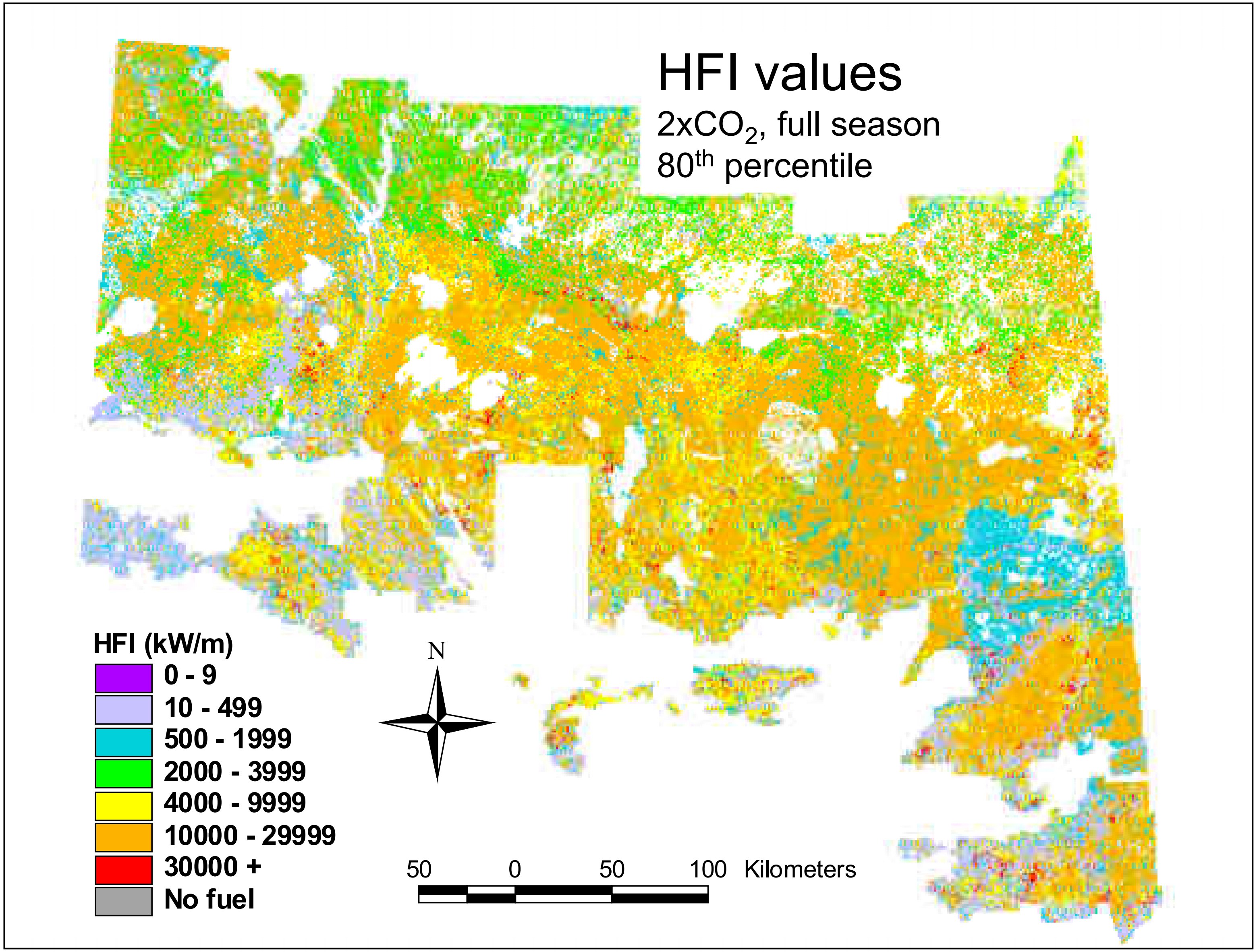
Map 10. Head fire intensity (HFI) in the $1xCO_2$ scenario.



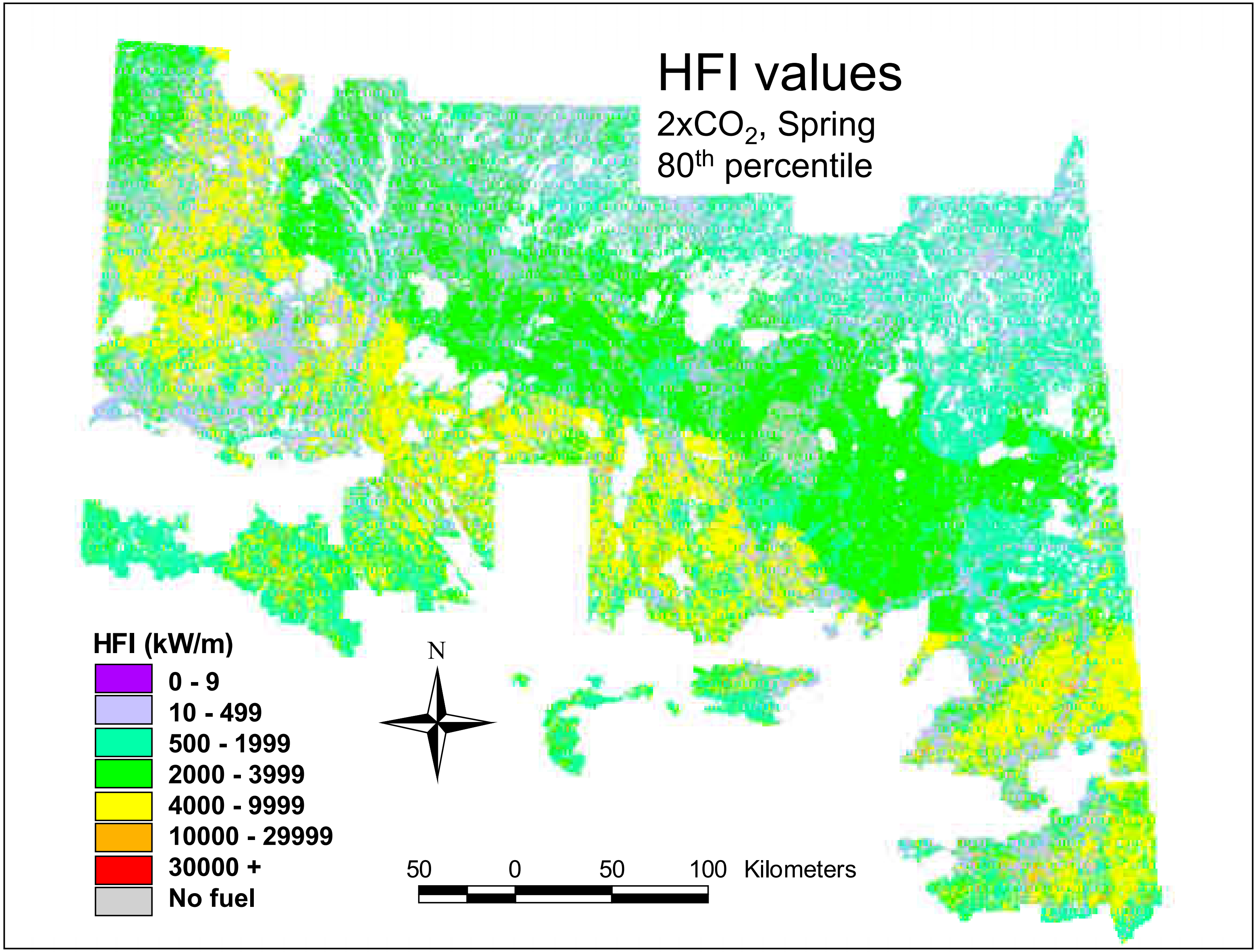
Map 11. Head fire intensity (HFI) in the $1xCO_2$ scenario.



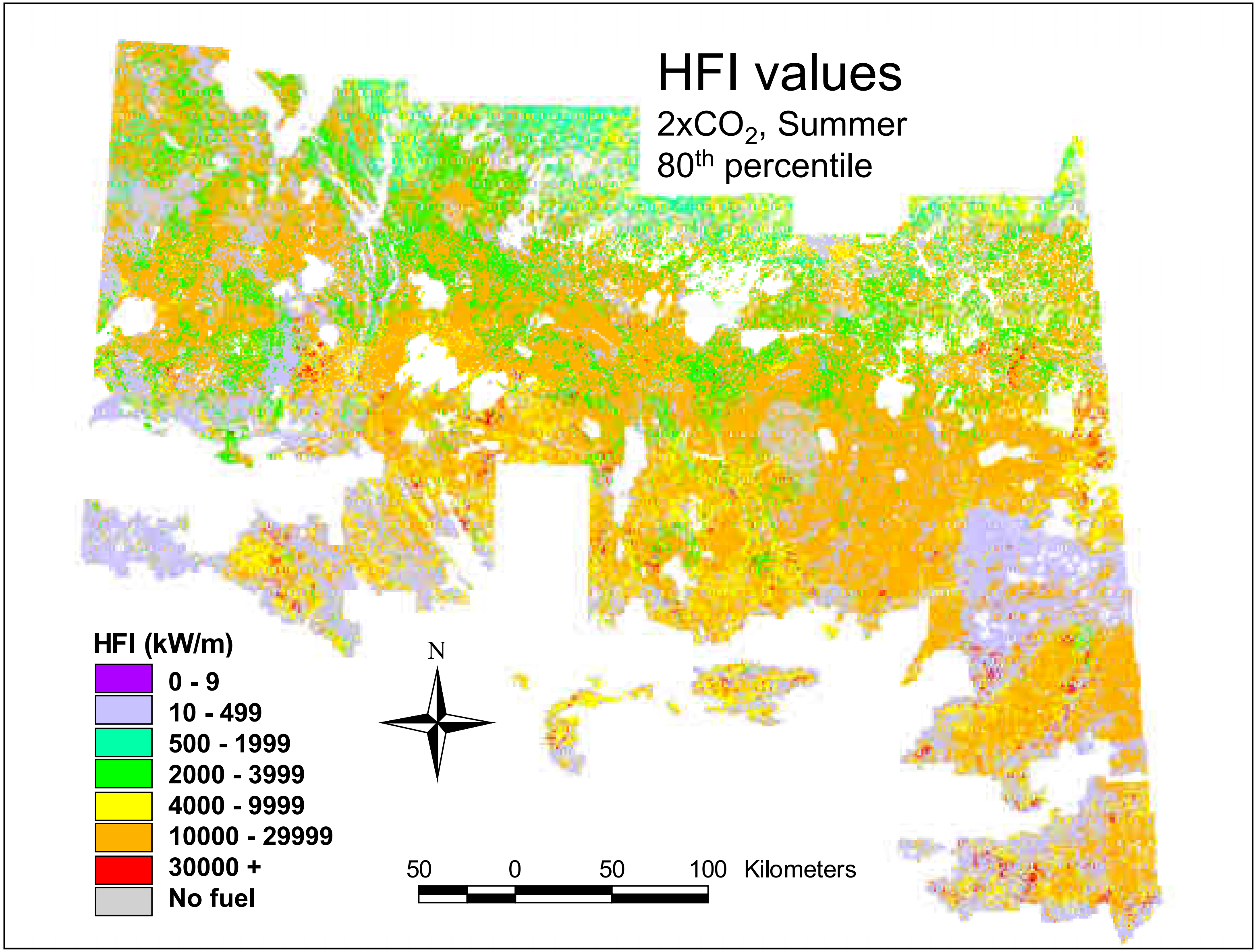
Map 12. Head fire intensity (HFI) in the 1xCO_2 scenario.



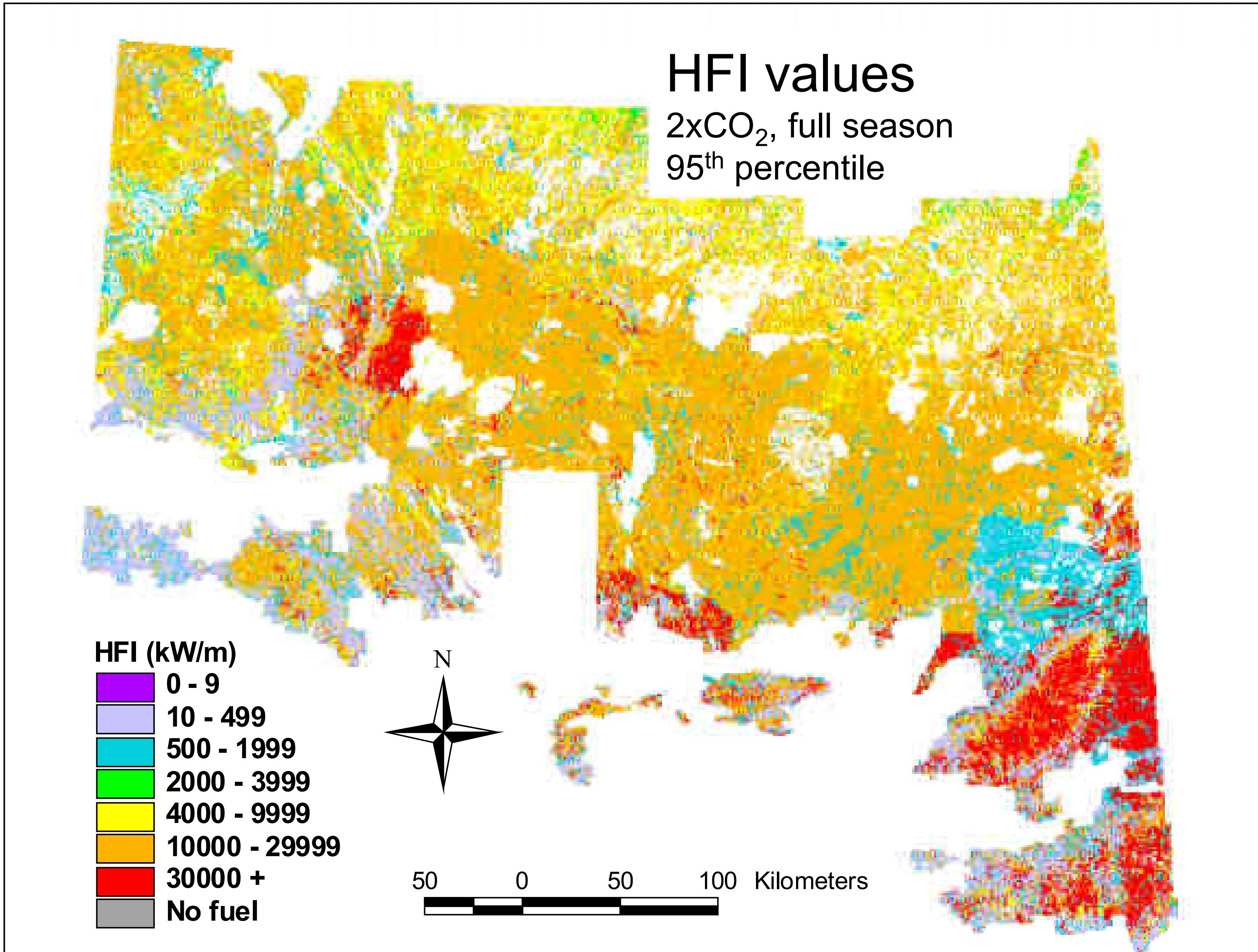
Map 13. Head fire intensity (HFI) in the $2xCO_2$ scenario.



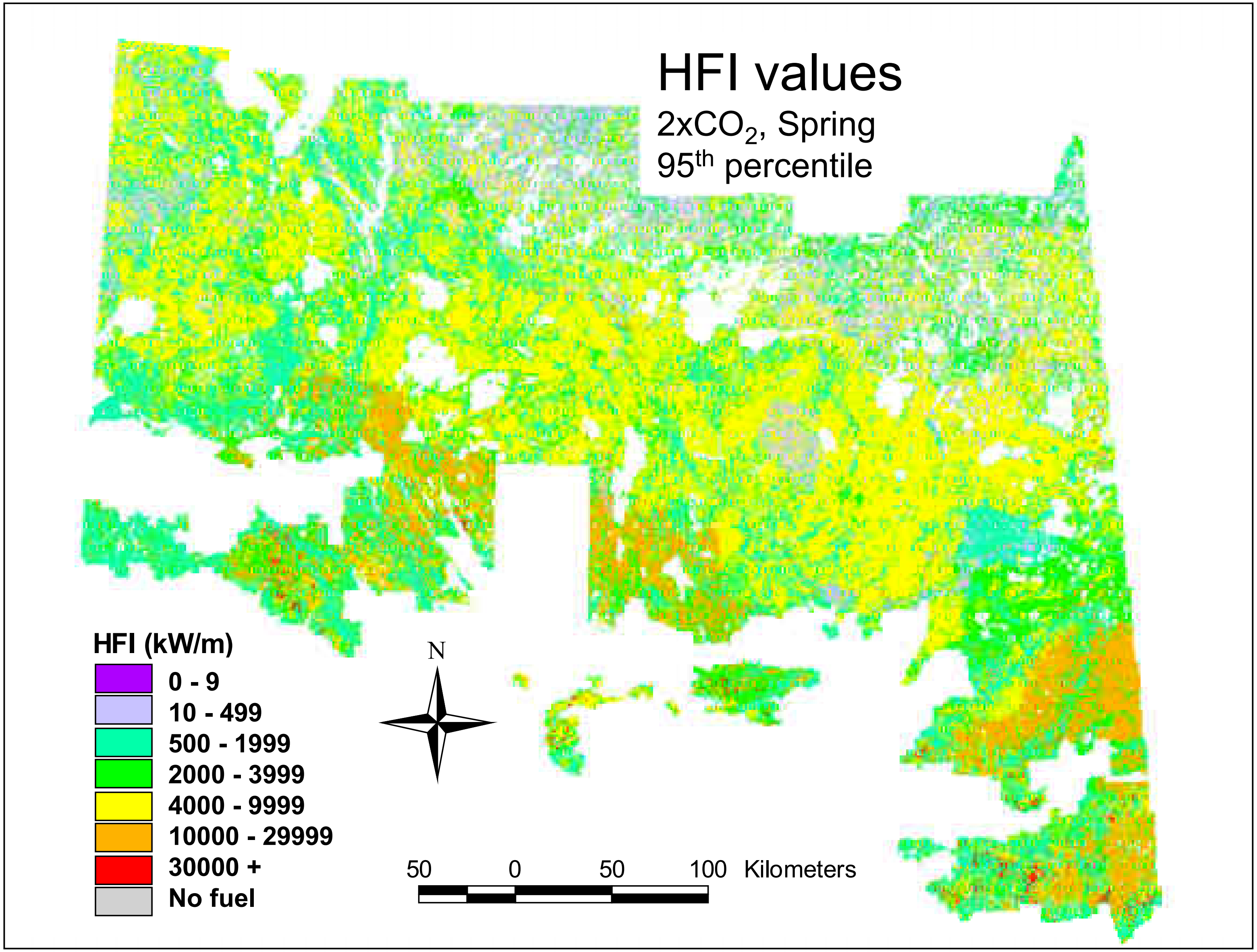
Map 14. Head fire intensity (HFI) in the $2xCO_2$ scenario.



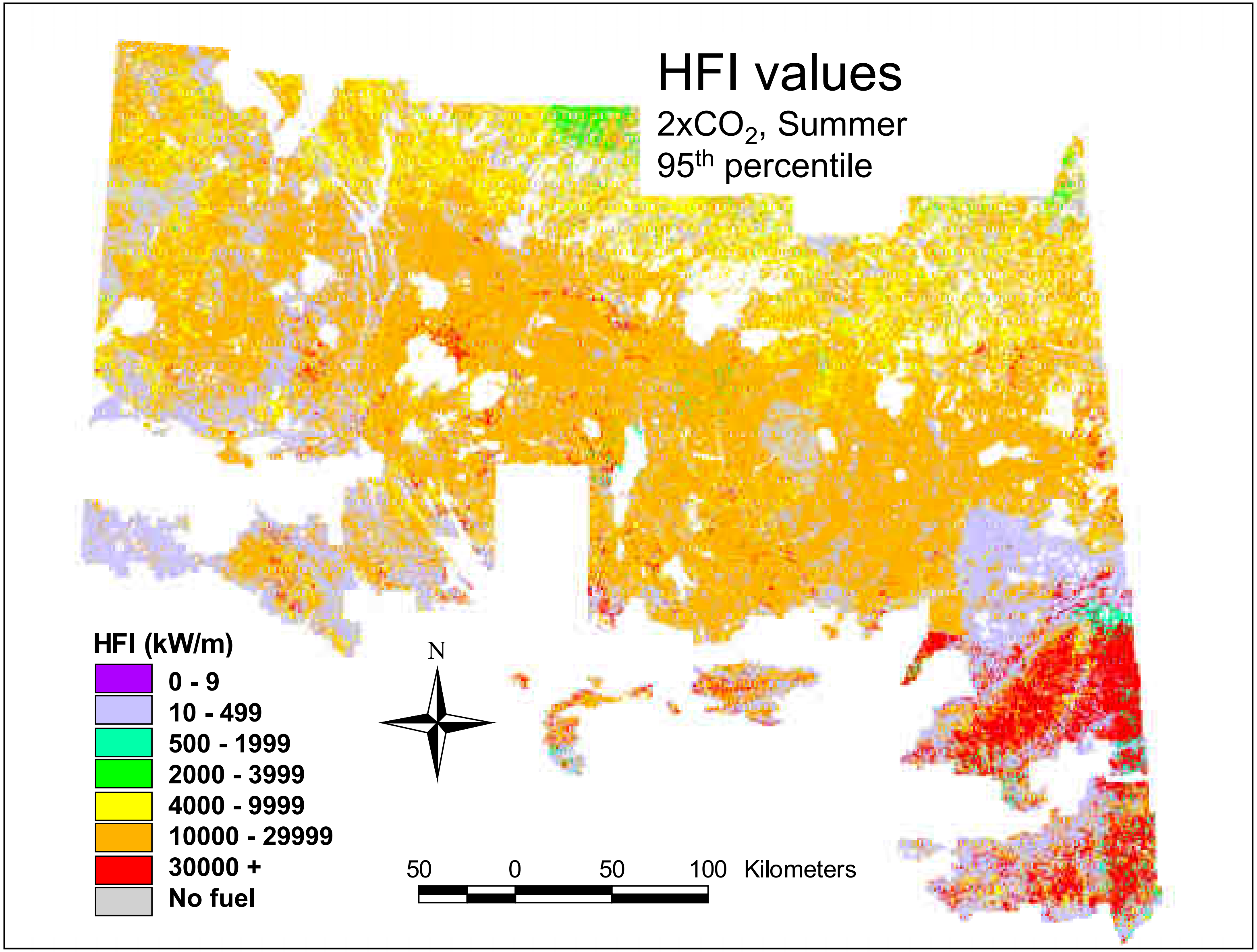
Map 15. Head fire intensity (HFI) in the $2xCO_2$ scenario.



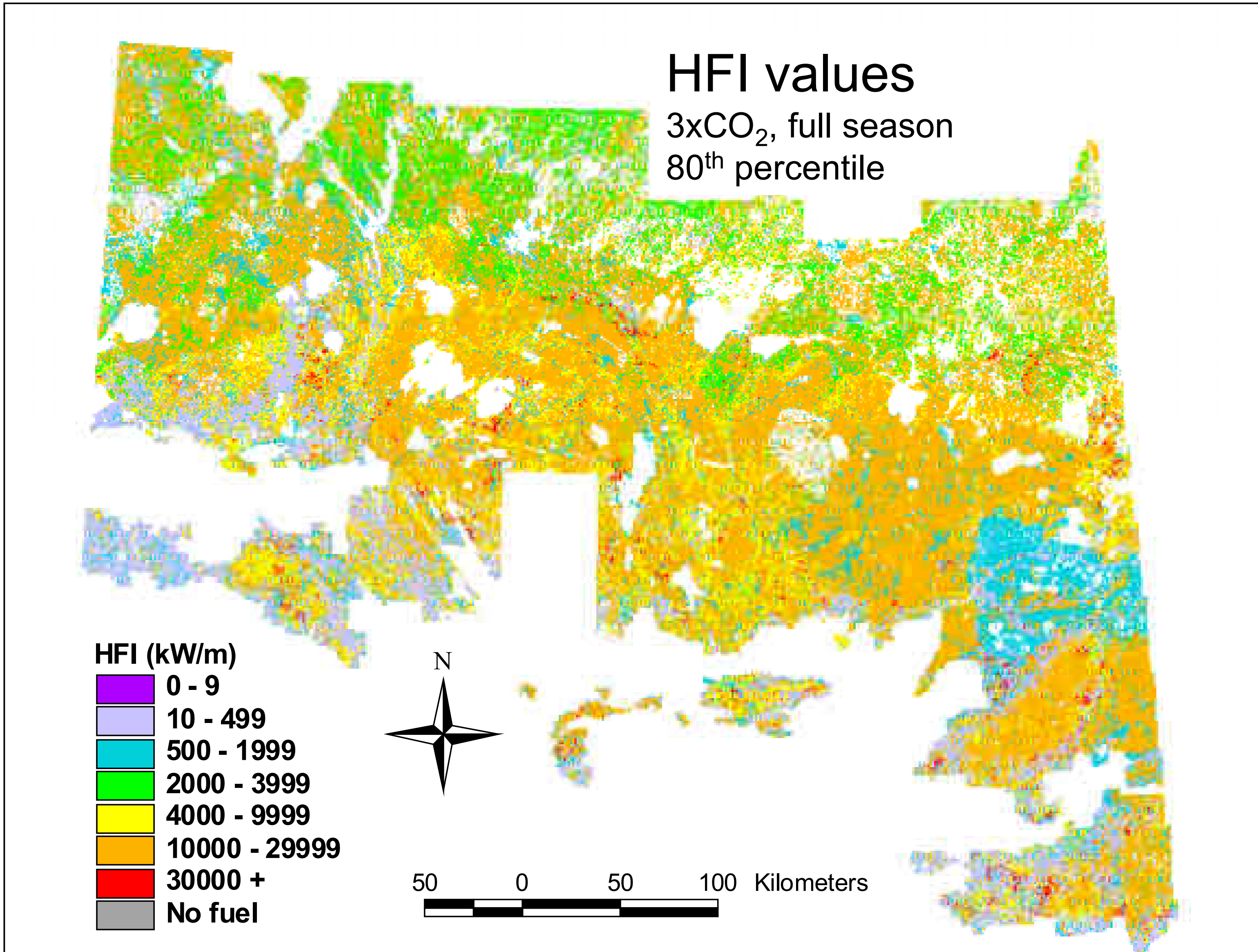
Map 16. Head fire intensity (HFI) in the 2xCO_2 scenario.



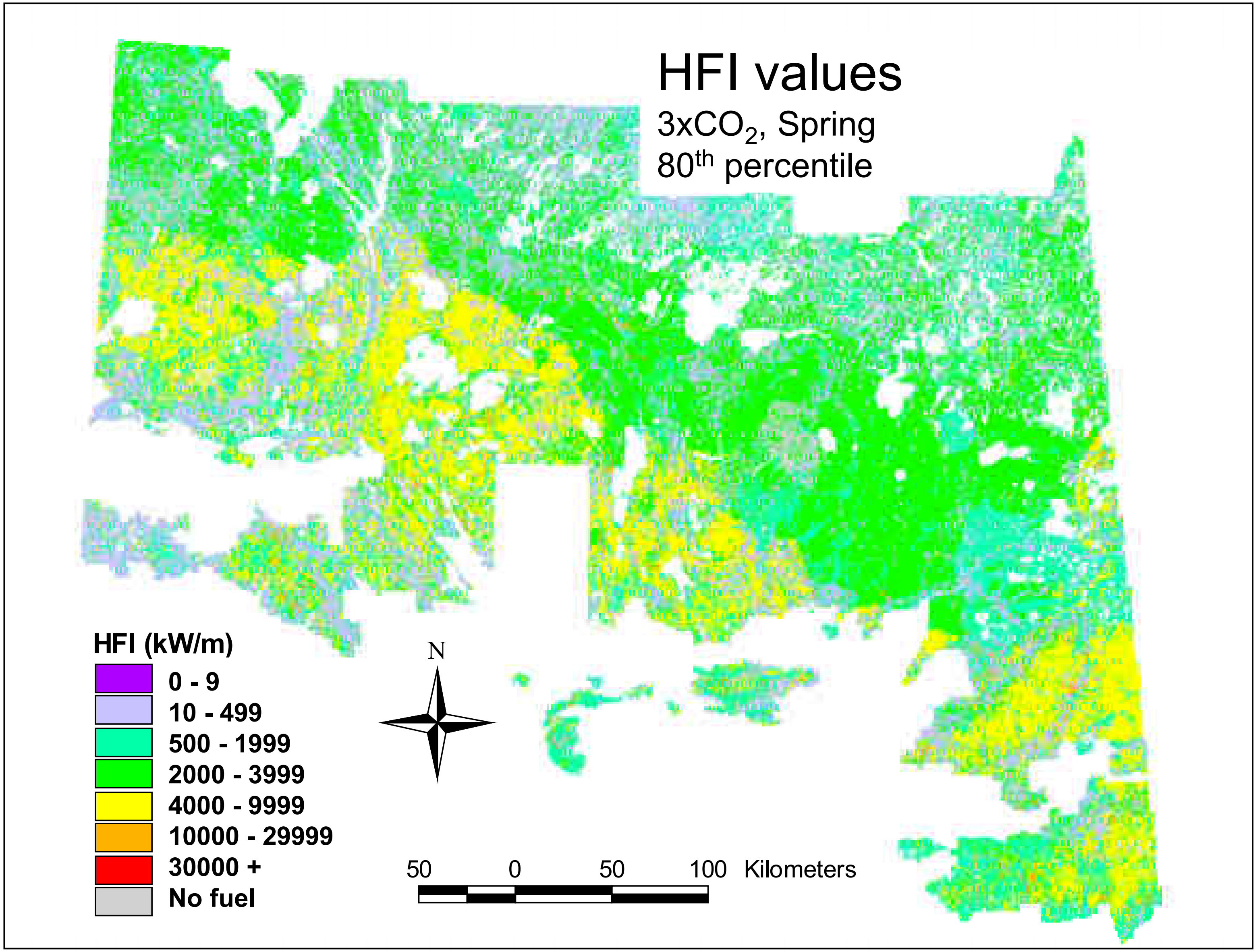
Map 17. Head fire intensity (HFI) in the $2xCO_2$ scenario.



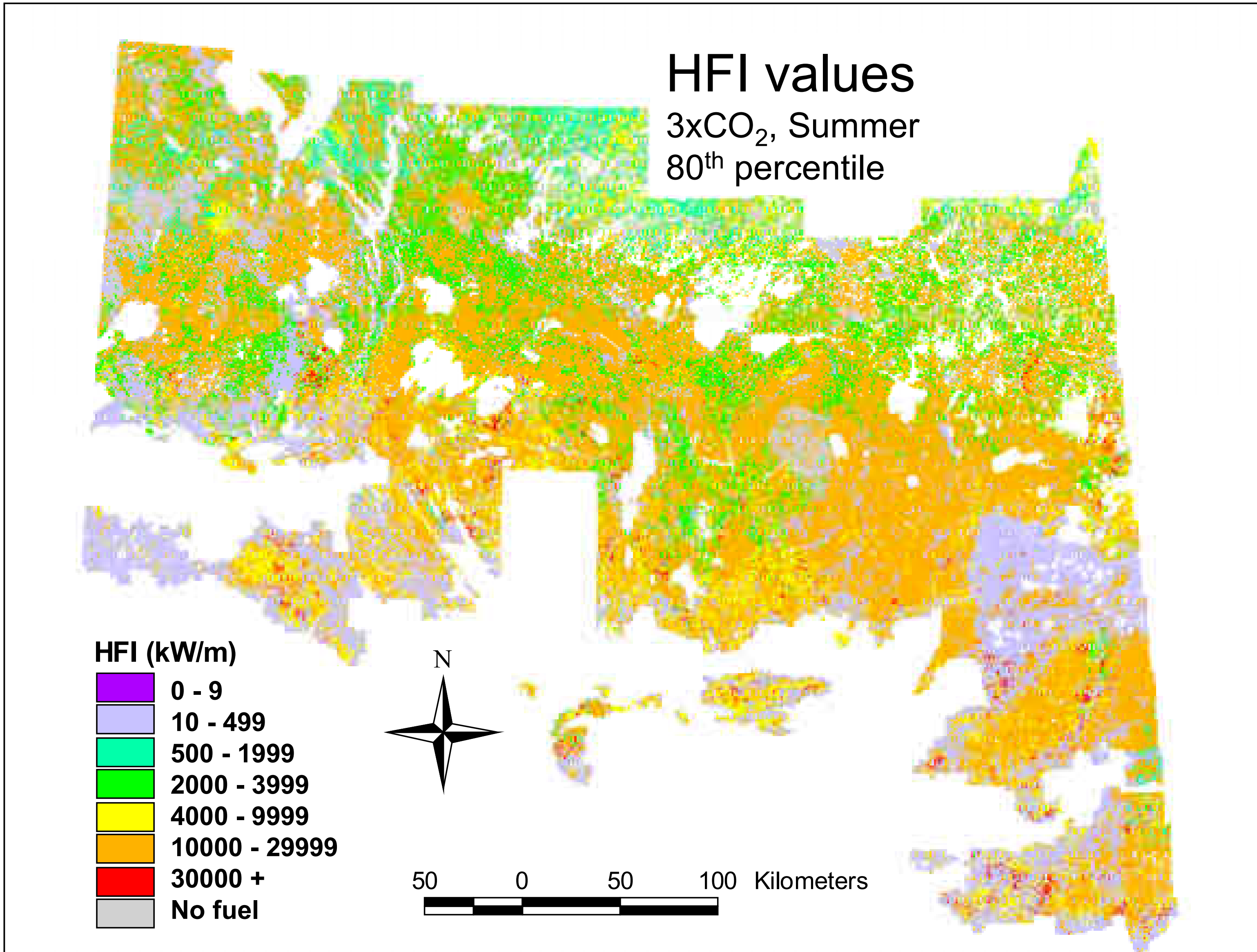
Map 18. Head fire intensity (HFI) in the $2xCO_2$ scenario.



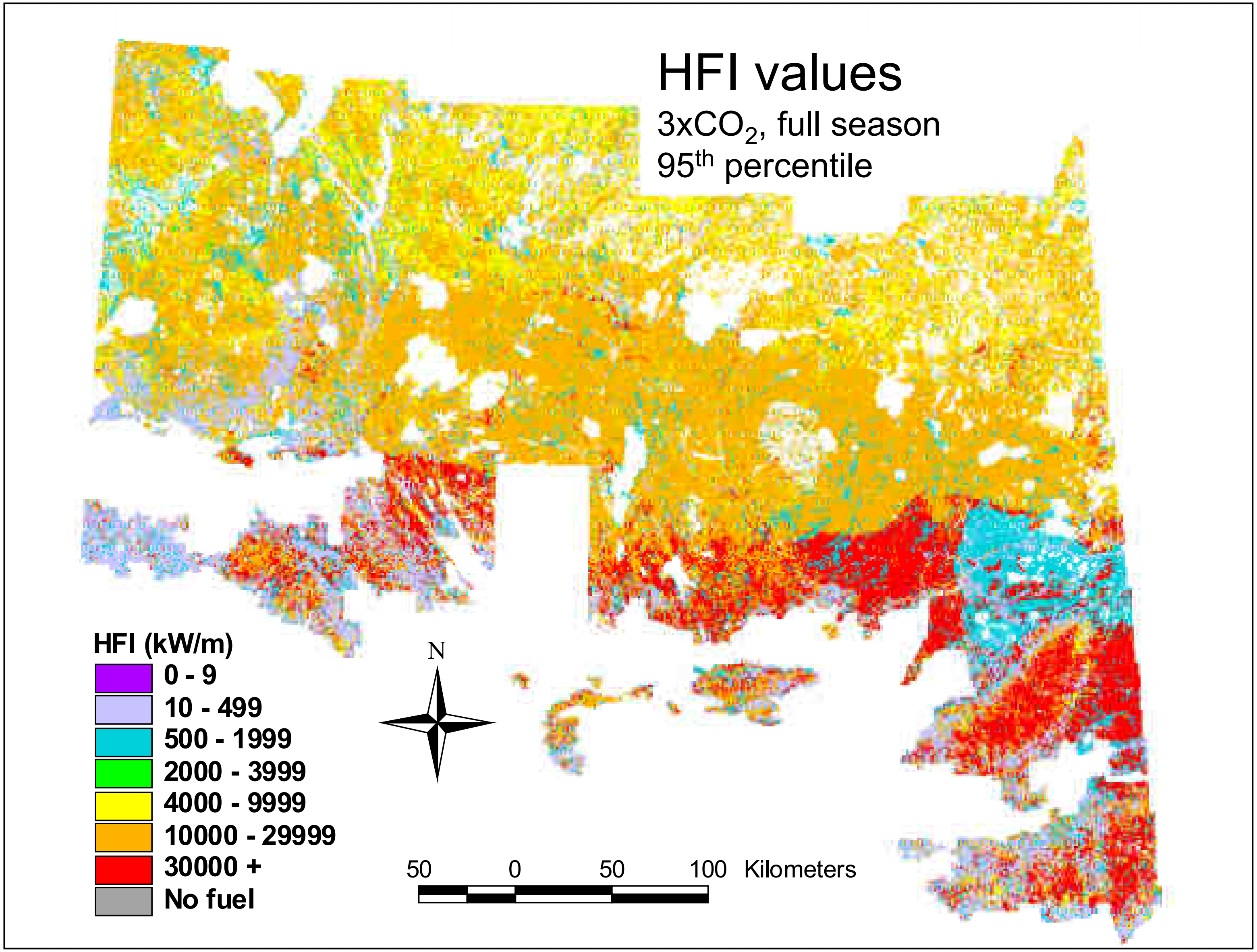
Map 19. Head fire intensity (HFI) in the $3xCO_2$ scenario.



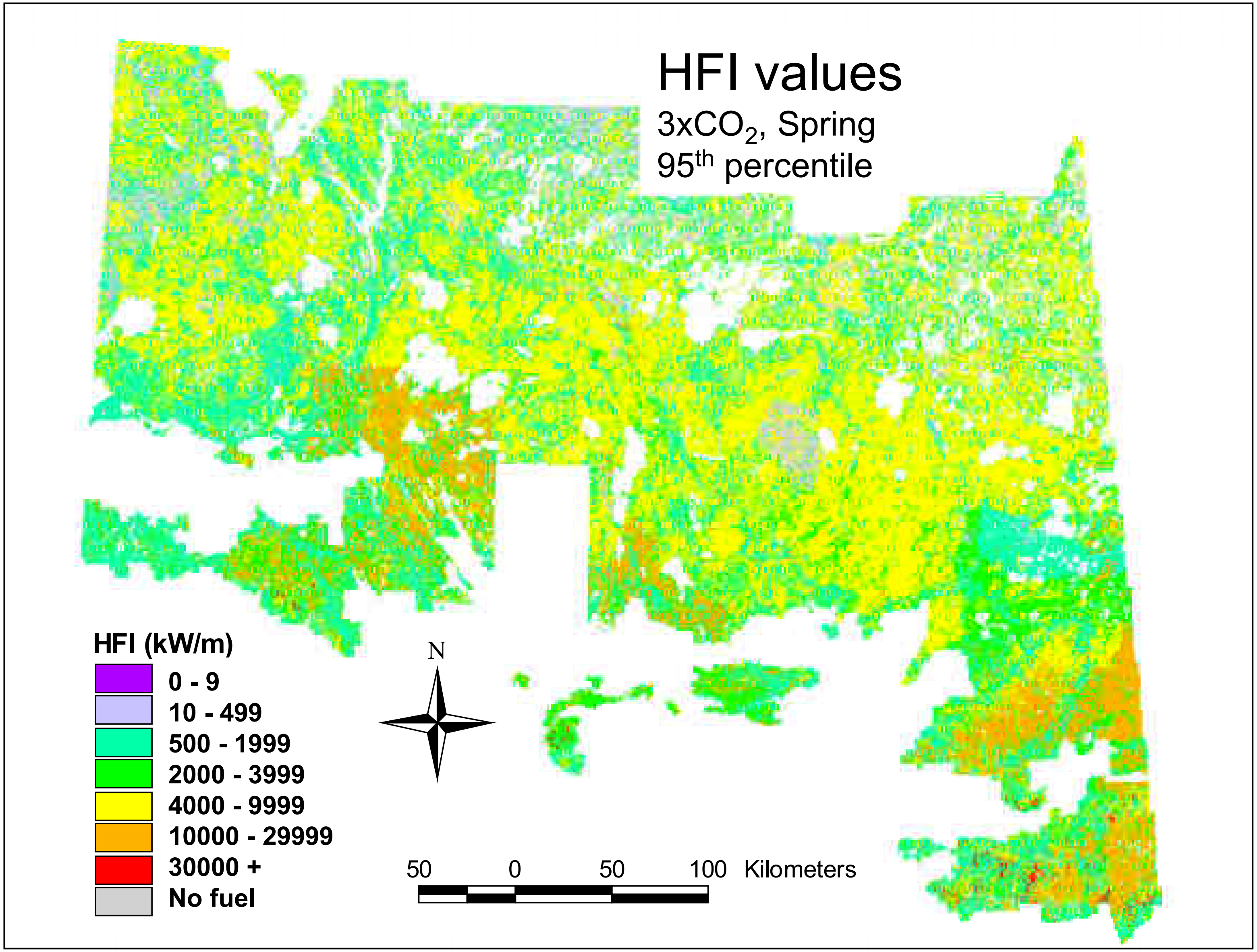
Map 20. Head fire intensity (HFI) in the $3xCO_2$ scenario.



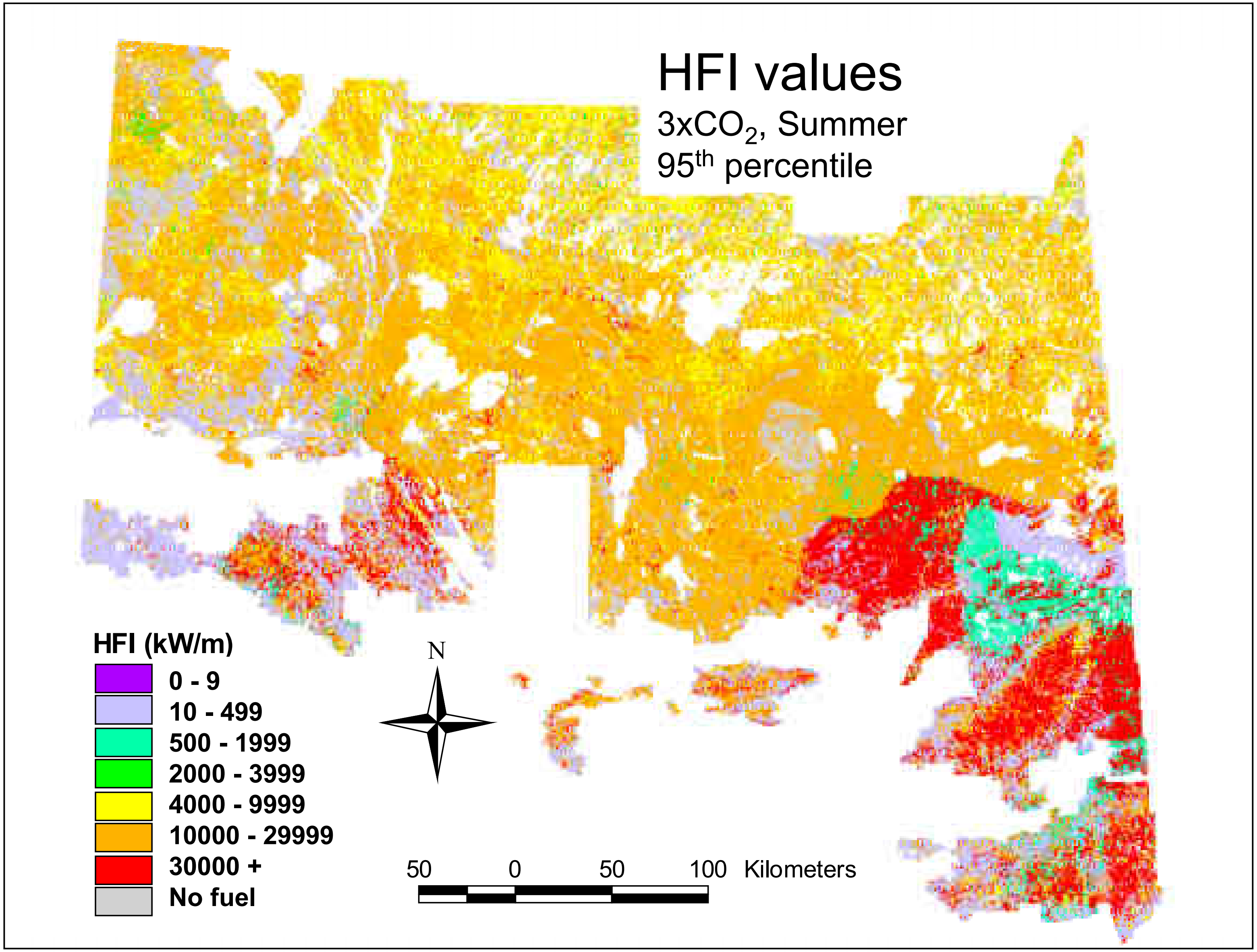
Map 21. Head fire intensity (HFI) in the $3xCO_2$ scenario.



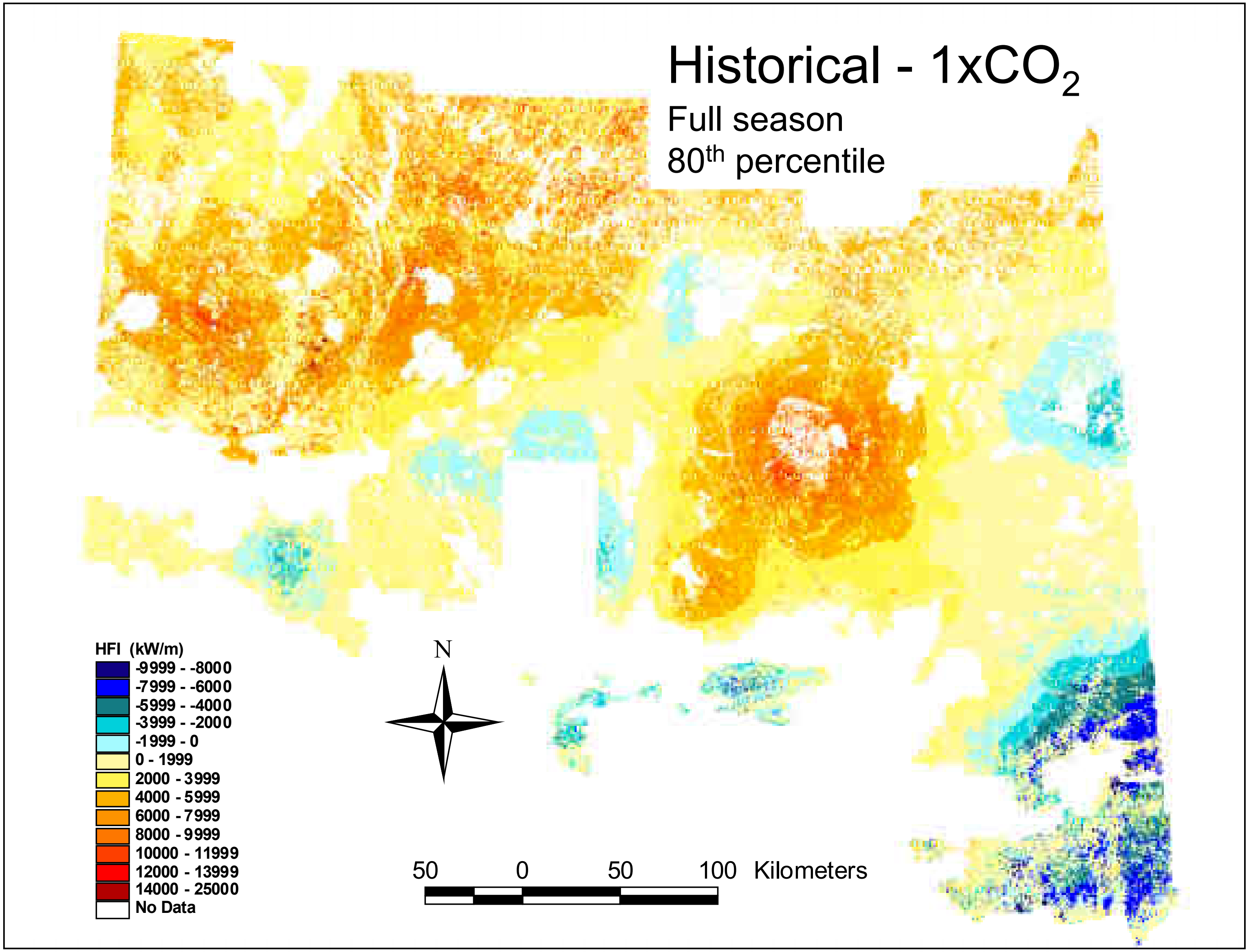
Map 22. Head fire intensity (HFI) in the $3xCO_2$ scenario.



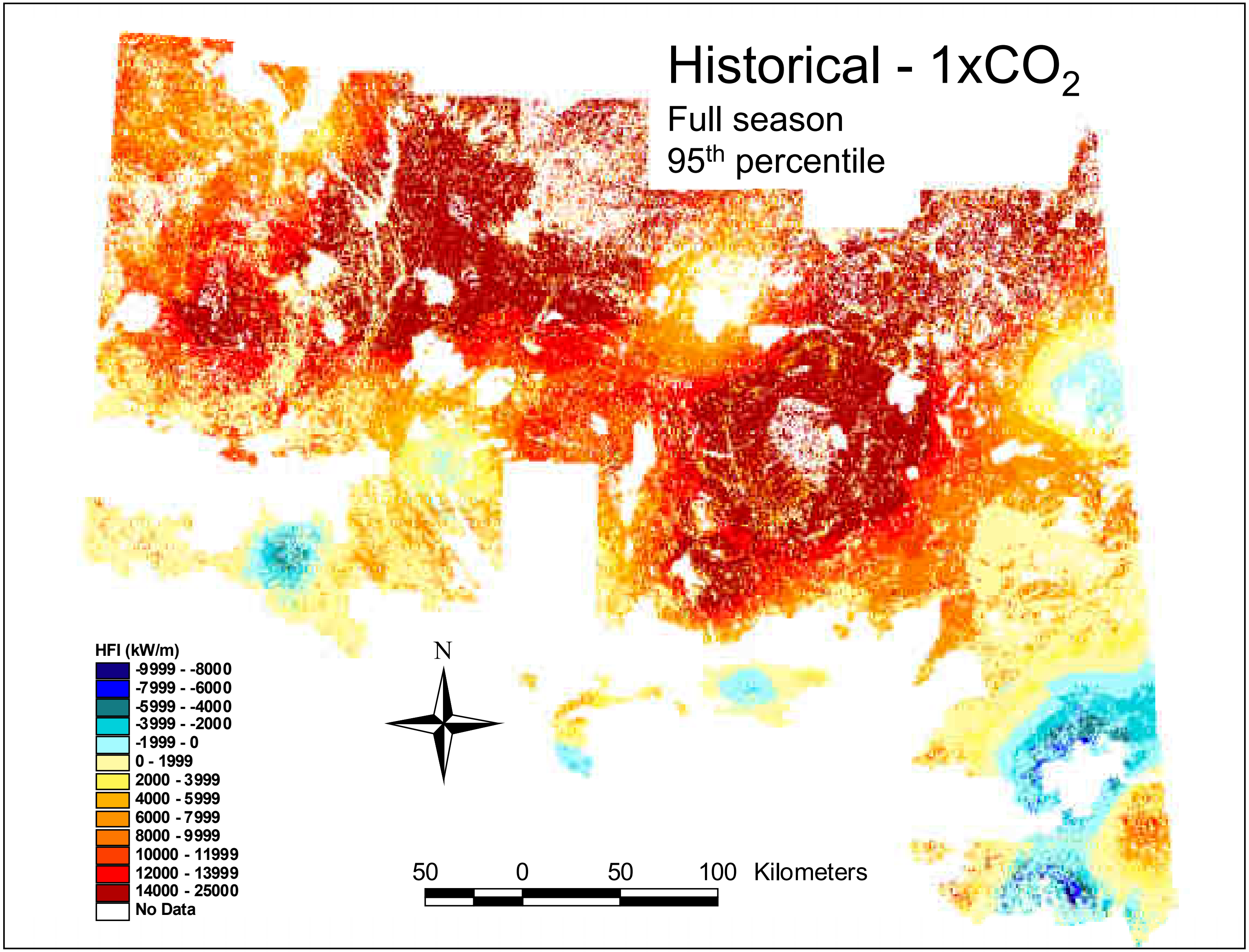
Map 23. Head fire intensity (HFI) in the 3xCO_2 scenario.



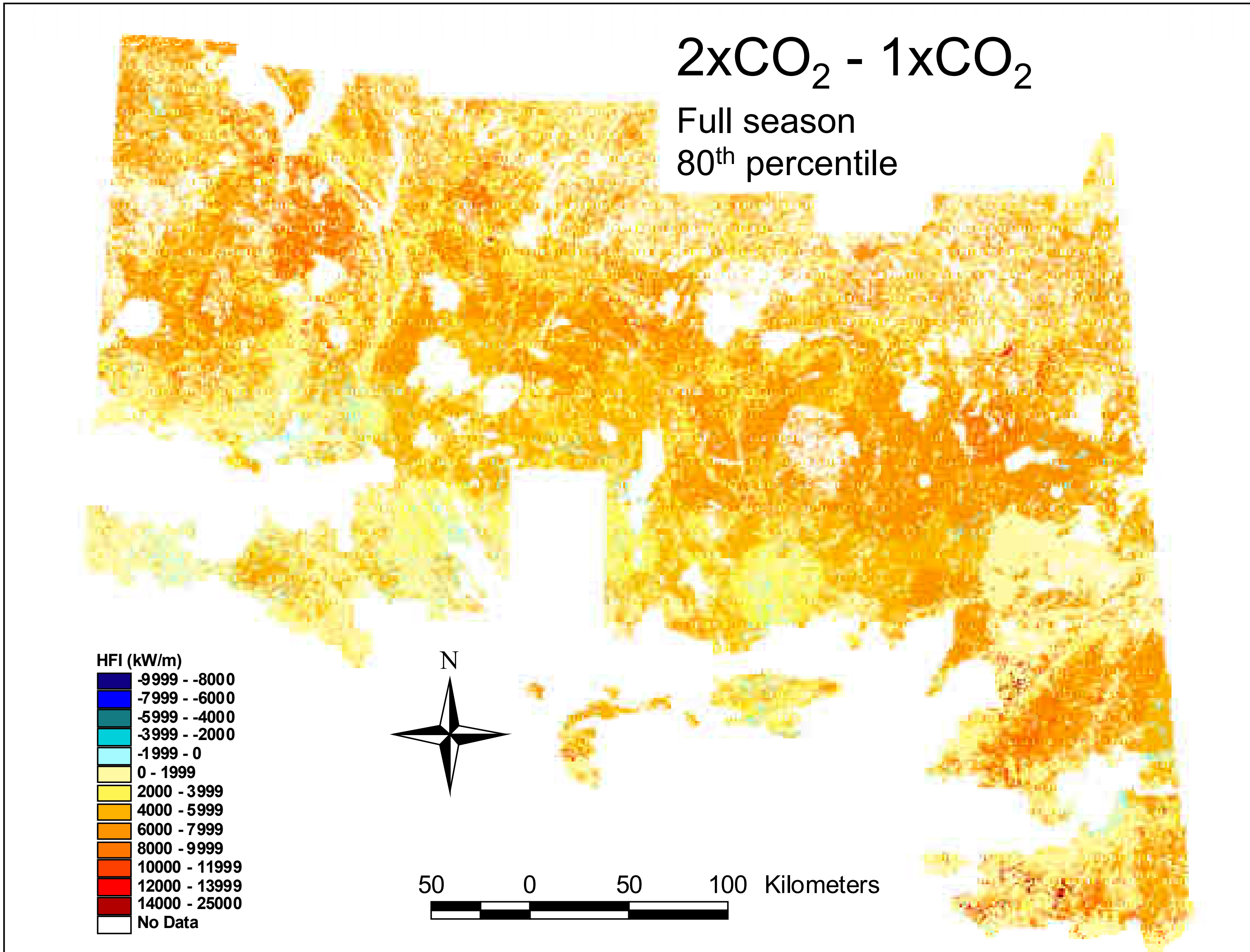
Map 24. Head fire intensity (HFI) in the $3xCO_2$ scenario.



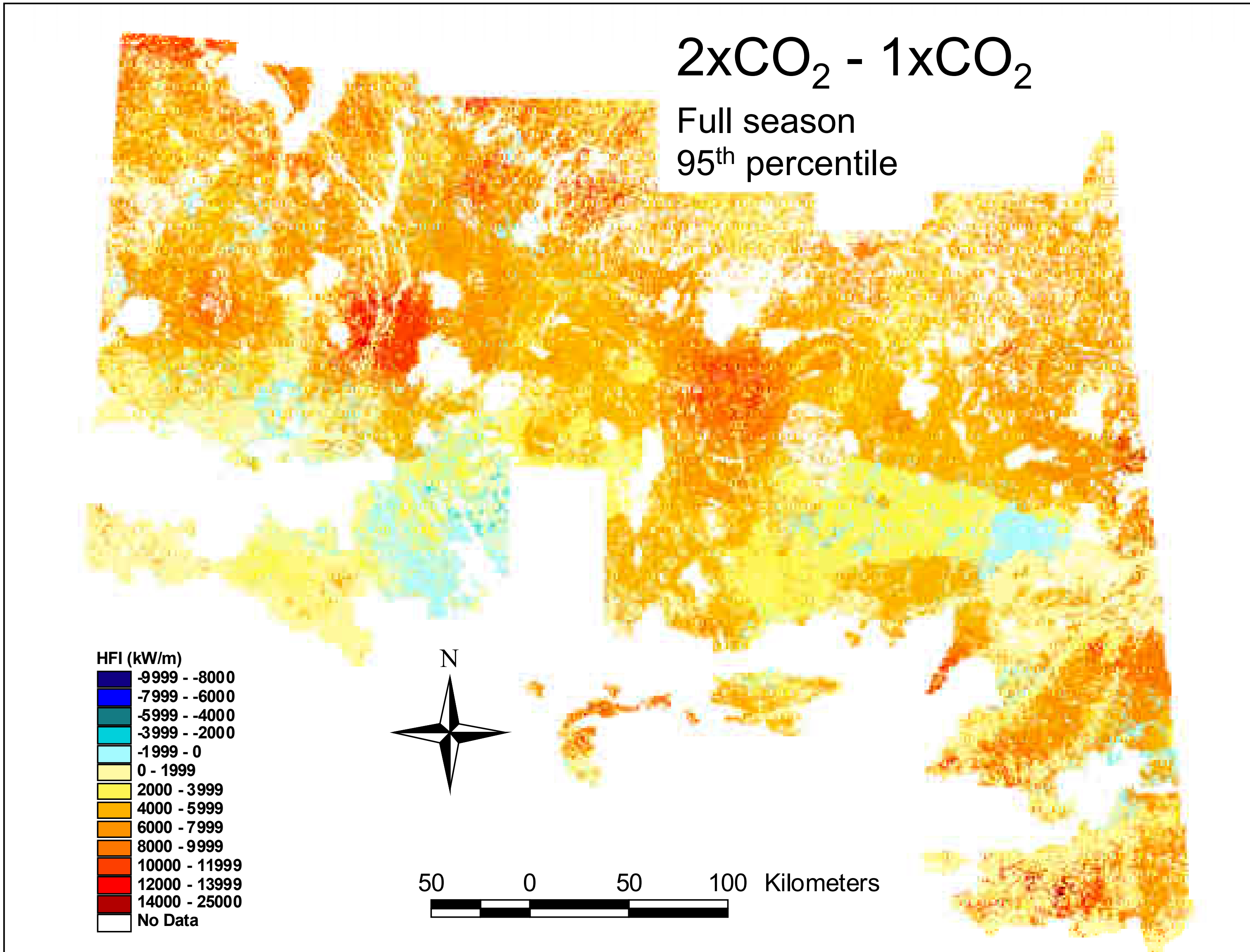
Map 25. Absolute change in head fire intensity (HFI) between the historical and 1xCO_2 scenario.



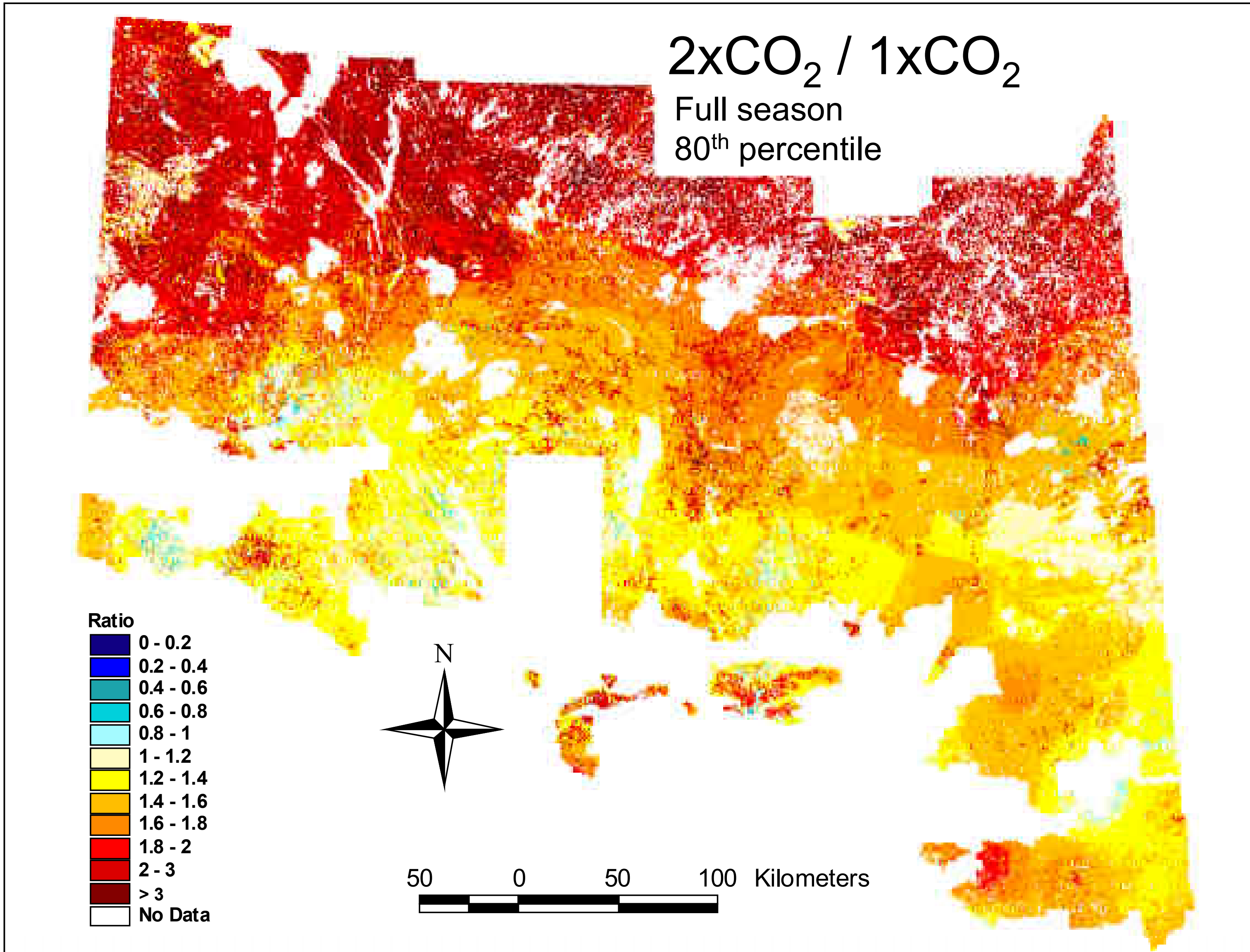
Map 26. Absolute change in head fire intensity (HFI) between the historical and $1xCO_2$ scenario.



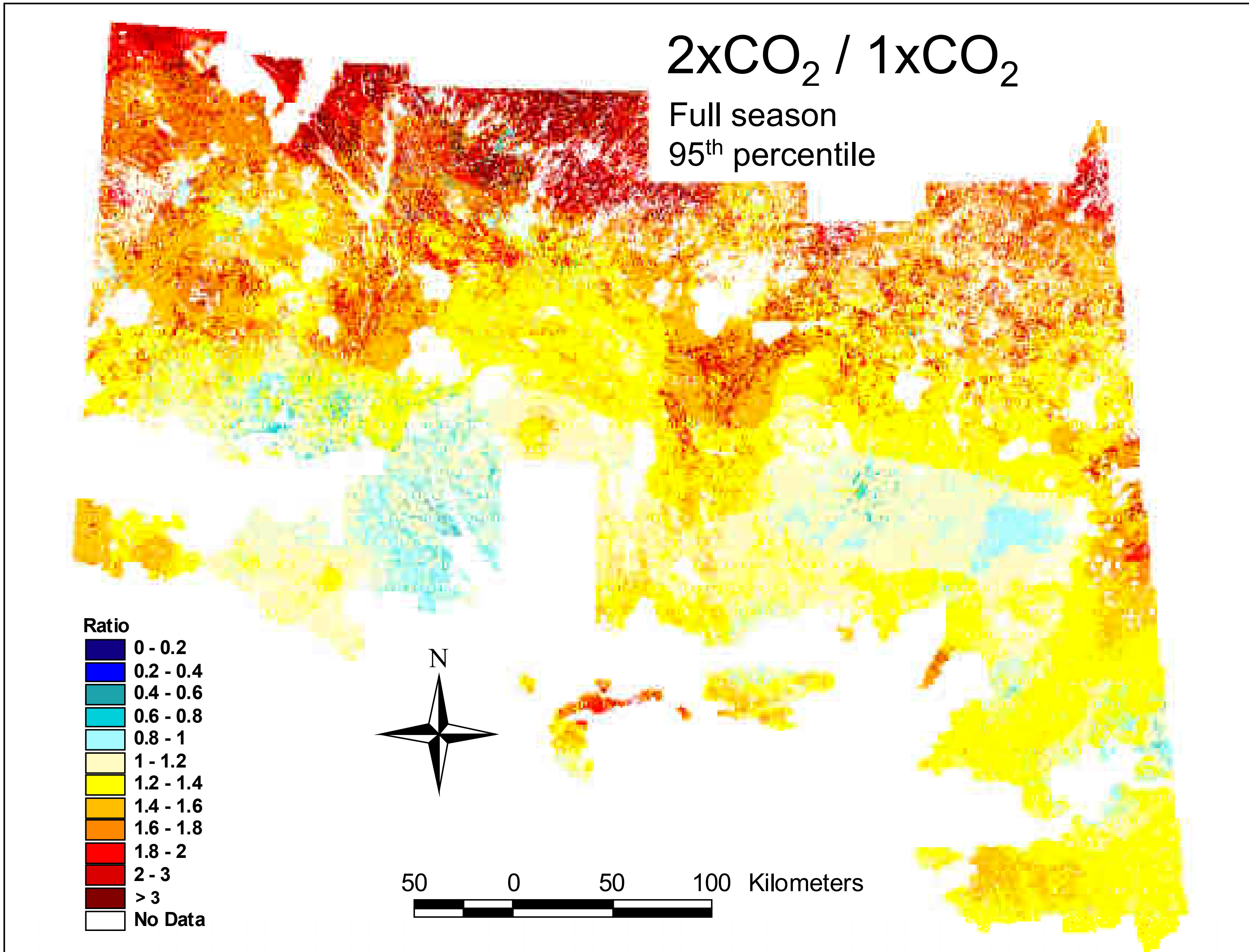
Map 27. Absolute change in head fire intensity (HFI) between the $2xCO_2$ and $1xCO_2$ scenario.



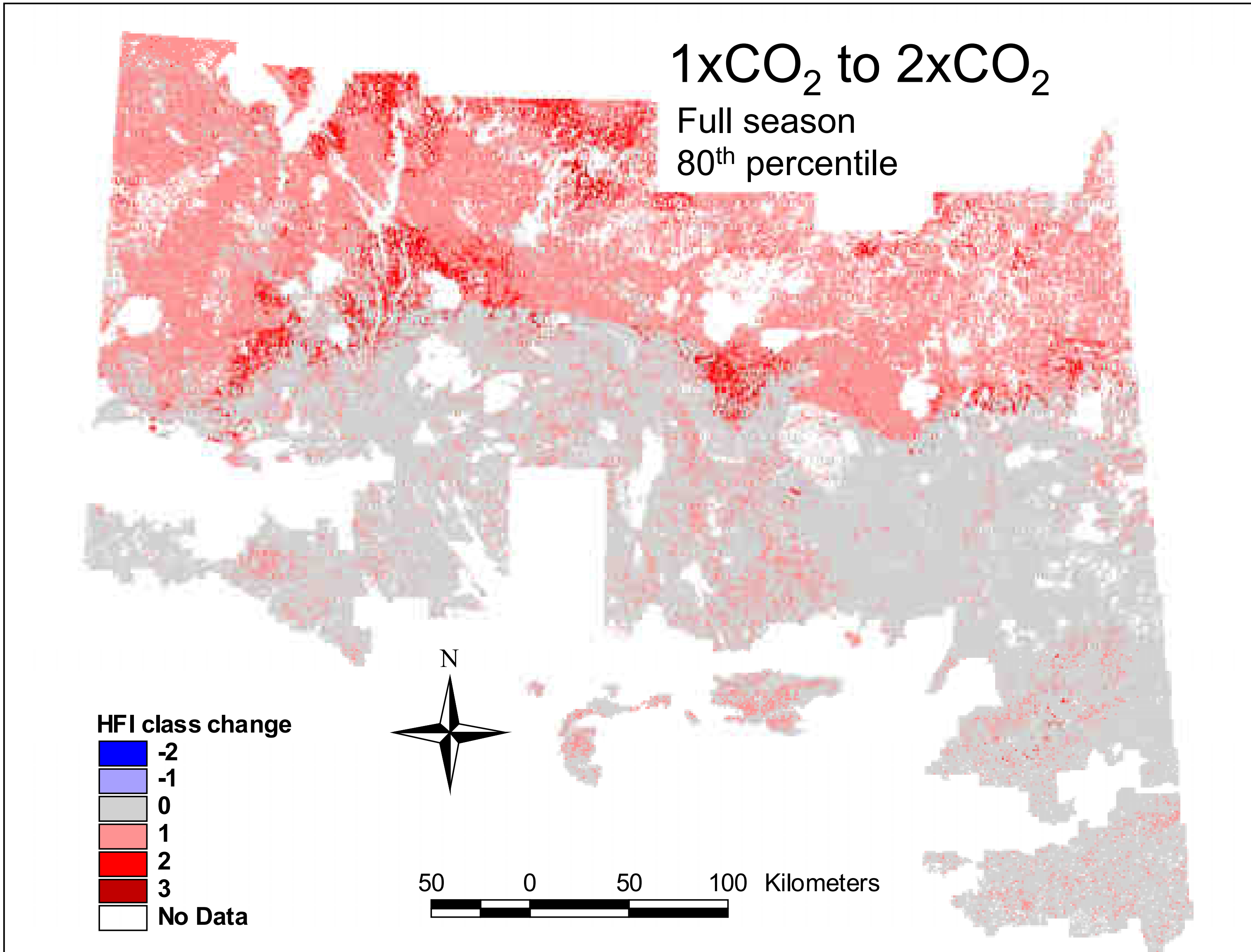
Map 28. Absolute change in head fire intensity (HFI) between the $2xCO_2$ and $1xCO_2$ scenario.



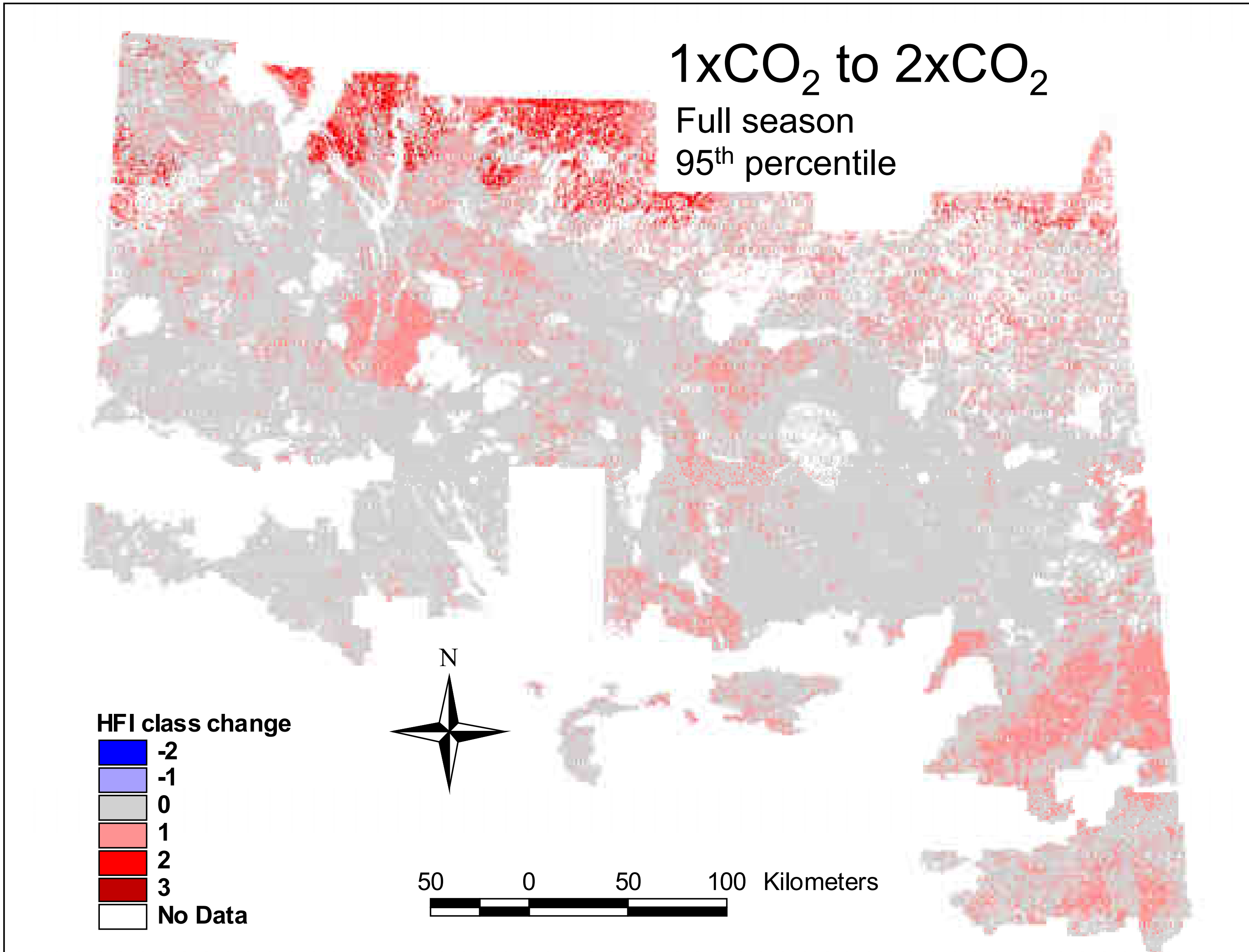
Map 29. Proportional change in head fire intensity (HFI) between the $2xCO_2$ and $1xCO_2$ scenario.



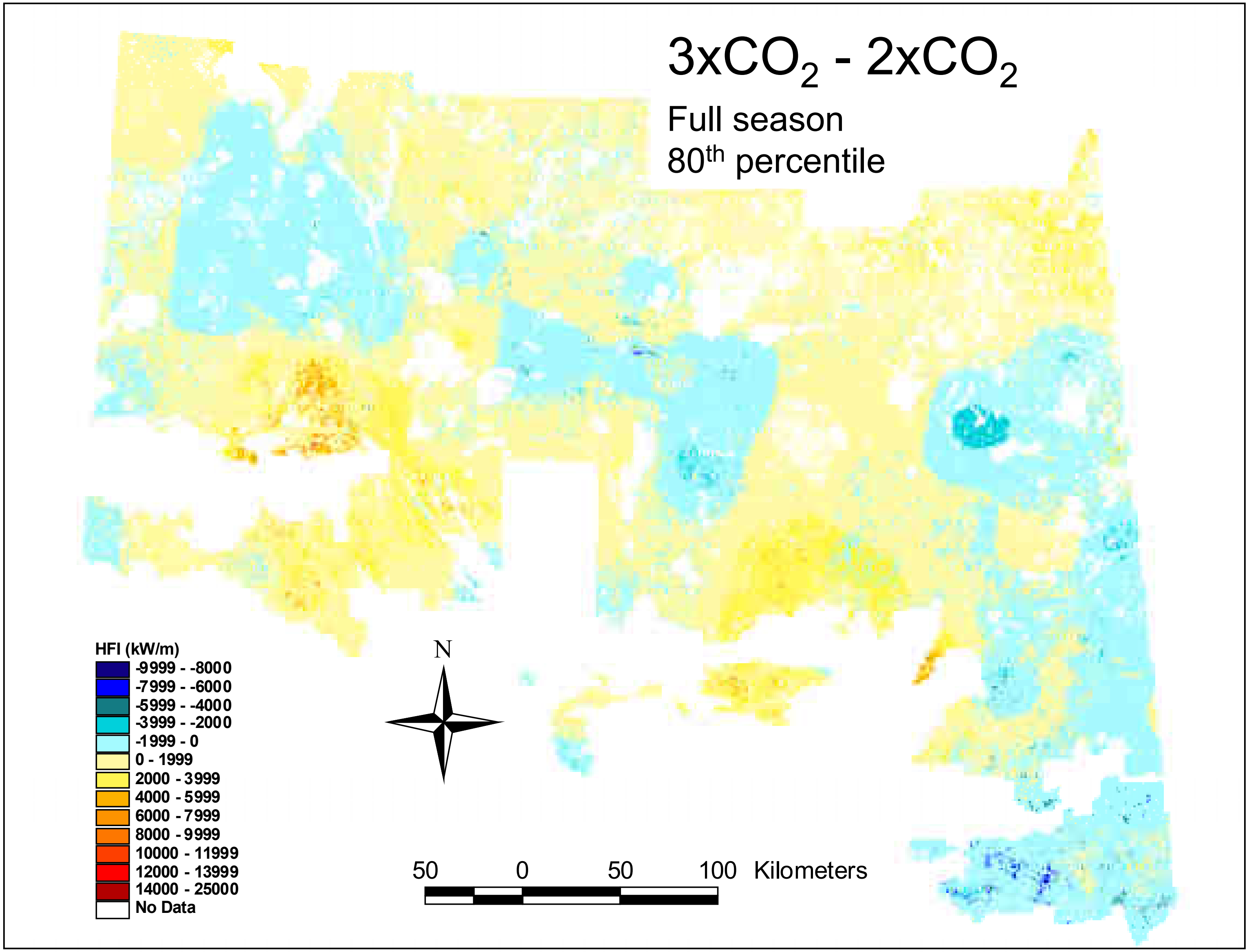
Map 30. Proportional change in head fire intensity (HFI) between the $2xCO_2$ and $1xCO_2$ scenario.



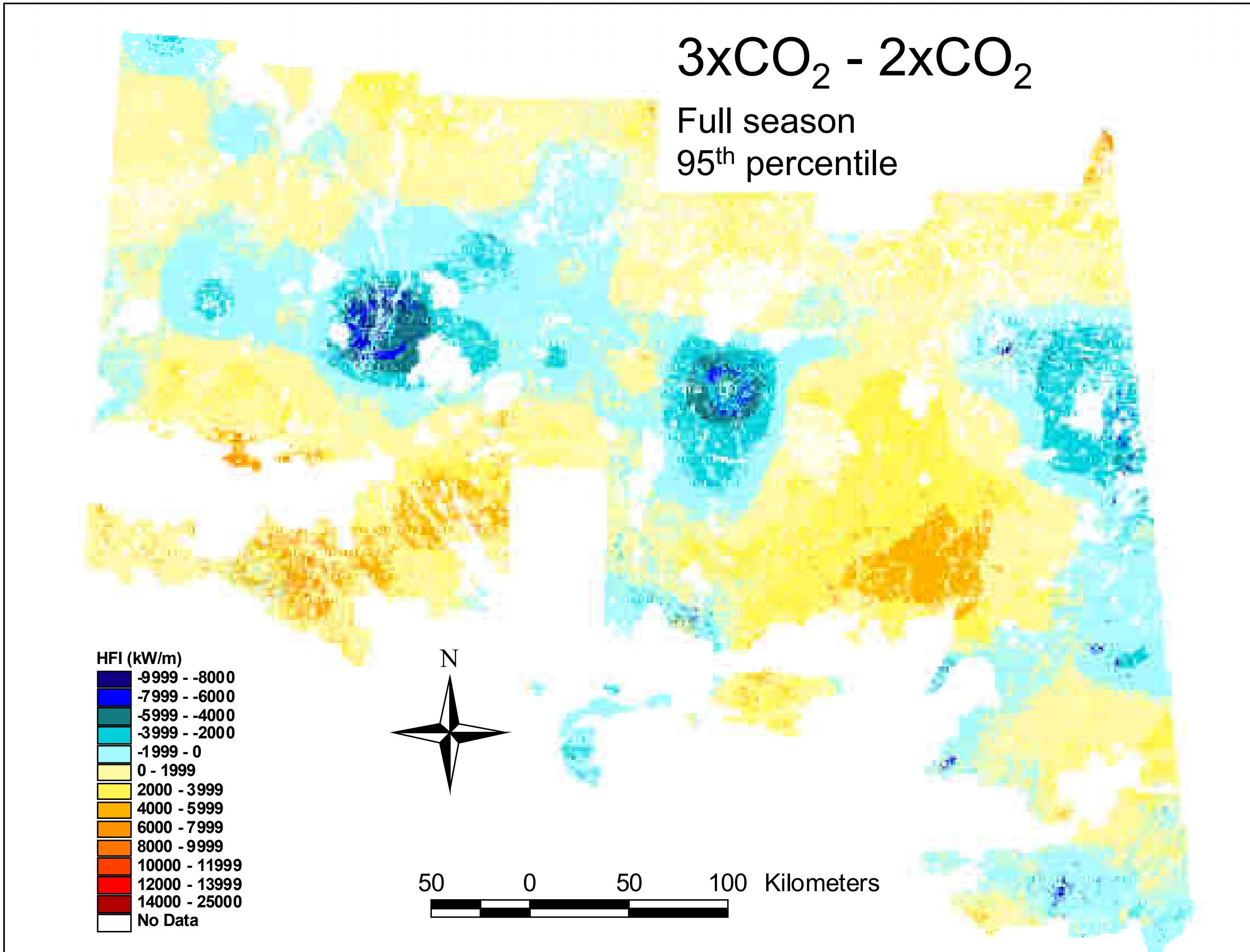
Map 31. Change in head fire intensity (HFI) class from the $1xCO_2$ to the $2xCO_2$ scenario.



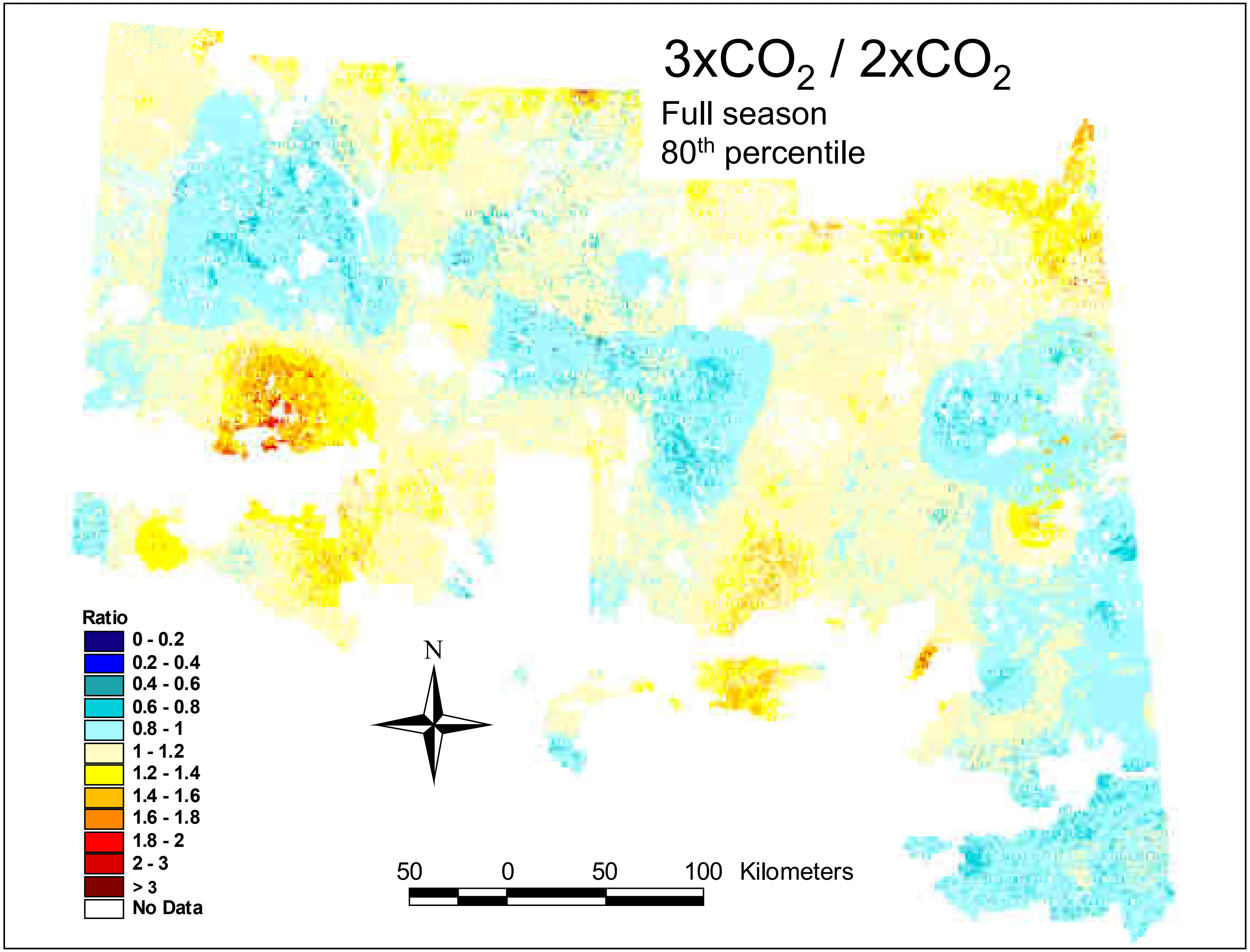
Map 32. Change in head fire intensity (HFI) class from the $1xCO_2$ to the $2xCO_2$ scenario.



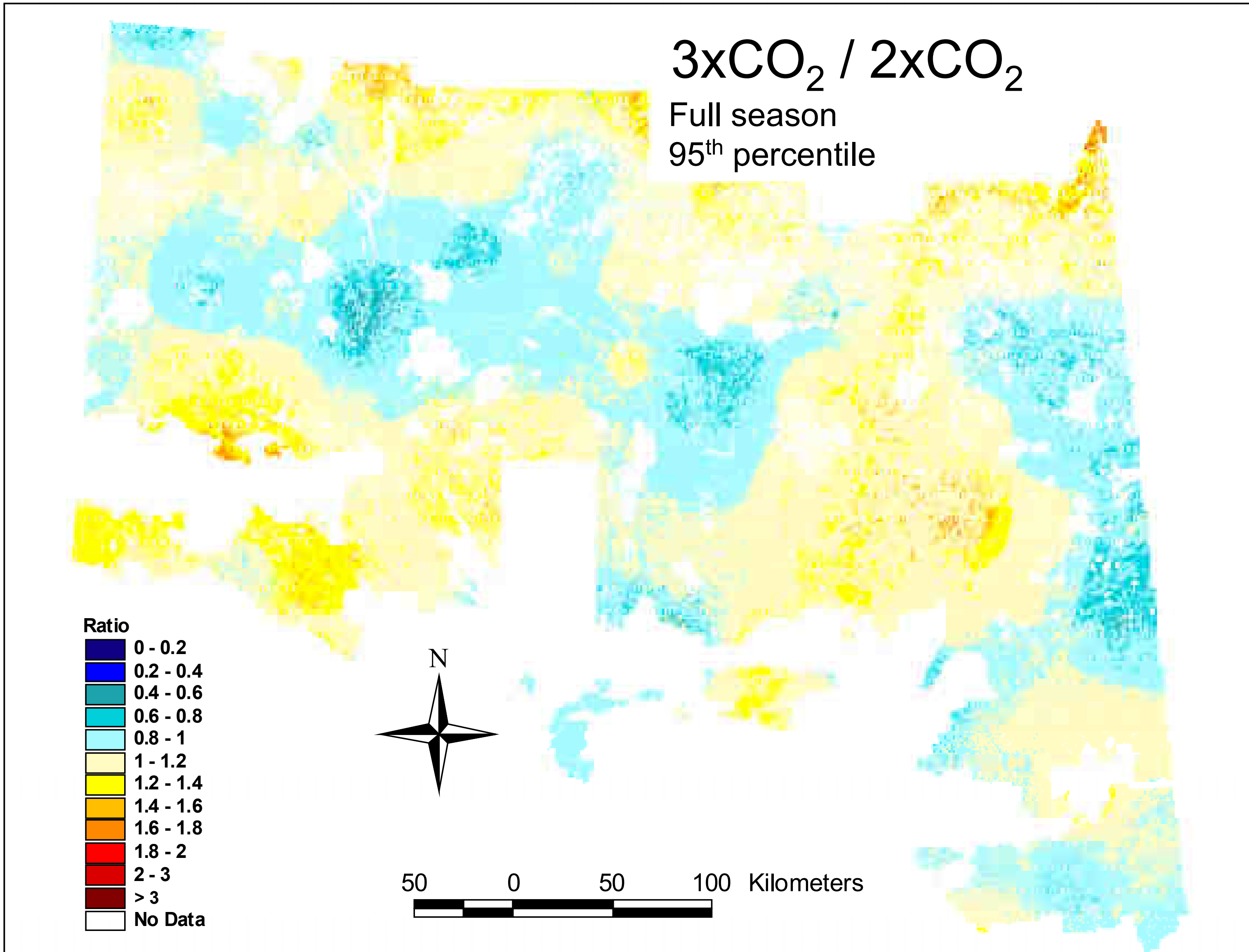
Map 33. Absolute change in head fire intensity (HFI) between the $3xCO_2$ and $2xCO_2$ scenario.



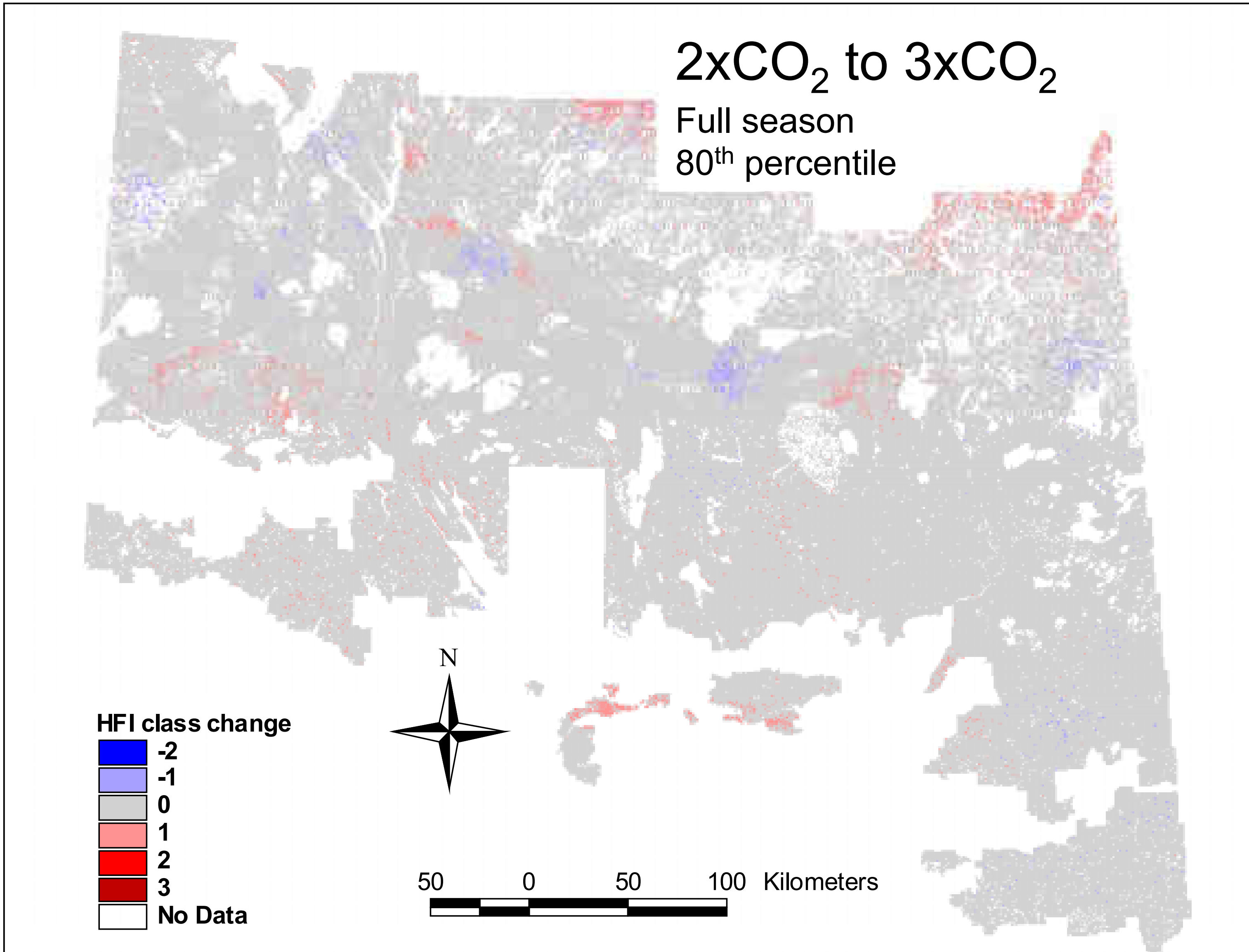
Map 34. Absolute change in head fire intensity (HFI) between the $3xCO_2$ and $2xCO_2$ scenario.



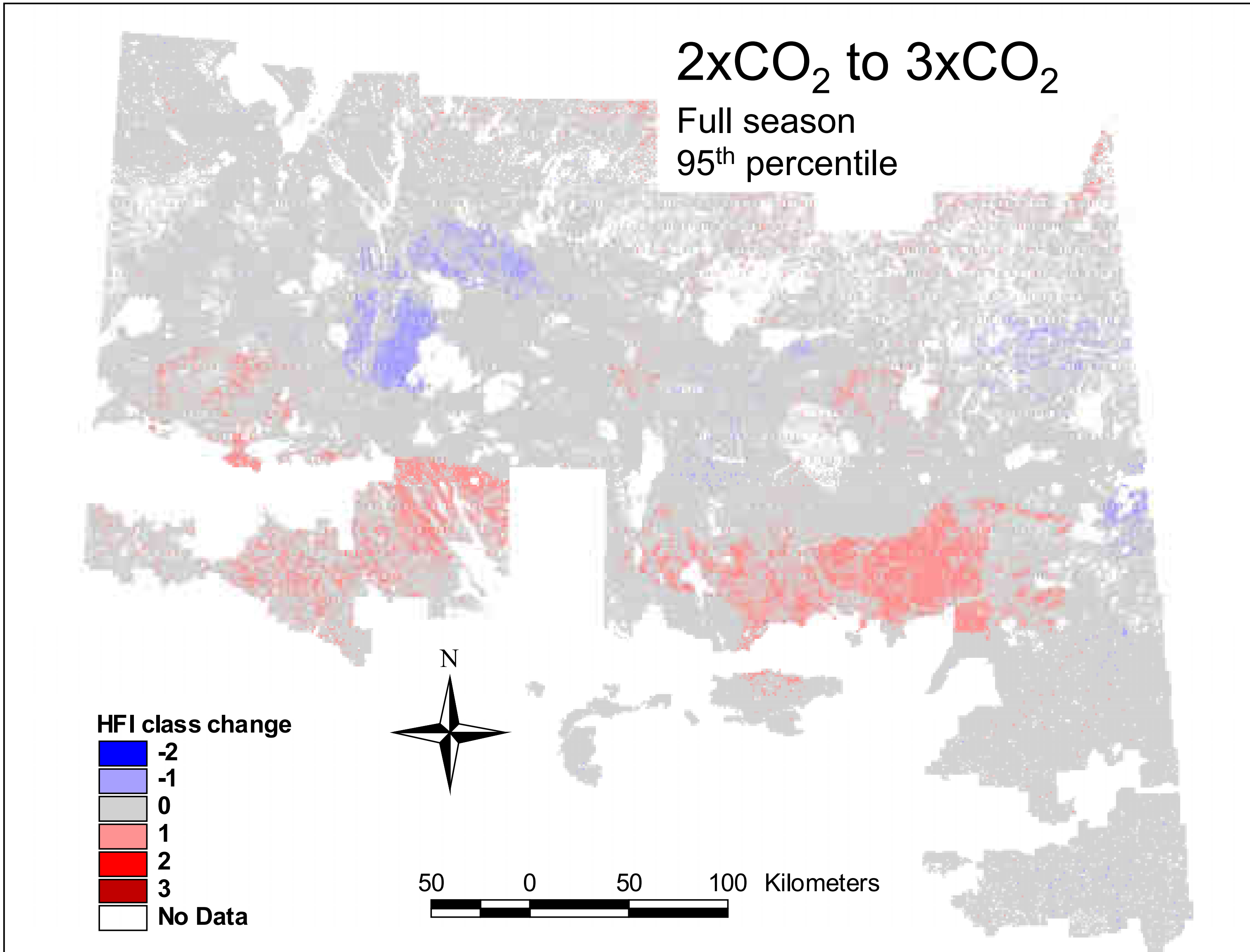
Map 35. Proportional change in head fire intensity (HFI) between the $3xCO_2$ and $2xCO_2$ scenario.



Map 36. Proportional change in head fire intensity (HFI) between the $3xCO_2$ and $2xCO_2$ scenario.



Map 37. Change in head fire intensity (HFI) class from the $2xCO_2$ to the $3xCO_2$ scenario.



Map 38. Change in head fire intensity (HFI) class from the $2xCO_2$ to the $3xCO_2$ scenario.

USING FOREST MANAGEMENT TECHNIQUES TO ALTER FOREST FUELS AND REDUCE WILDFIRE SIZE: AN EXPLORATORY ANALYSIS[1]

Kelvin Hirsch,[2] Victor Kafka,[2] Bernie Todd,[2] and Cordy Tymstra[3]

ABSTRACT

Over the next few decades a considerable portion of the productive boreal forest will be harvested and there is an excellent opportunity to use forest management activities (e.g., harvesting, regeneration, stand tending) to alter the forest fuels. This paper describes a process for incorporating strategically-located, landscape-level fuel treatments, primarily species conversion, into a long-term forest management plan. Using a mechanistic fire growth model, a comparative analysis of projected landscapes found the fuel treatments could have a considerable impact on fire size and timber supply without adversely affecting biodiversity. Future research needs and the implications for forest management in crown fire-dominated boreal forest ecosystems are discussed.

Keywords: fuels management, fire-smart forest management, forest management planning, timber supply modelling, boreal forest

INTRODUCTION

Fire is an important natural disturbance in boreal forest ecosystems and has significant economic, social, and ecological effects. Over the last two decades there has been an average of about 10,000 fires per year in Canada and the annual area burned has varied between 0.3 million and 7.5 million ha (Canadian Council of Forest Ministers 1997). Most (97%) of the area burned is caused by a small proportion (3%) of all reported wildfires (Weber and Stocks 1998). Although forest managers are increasingly recognising the ecological benefits of fire, in parts of the inhabited and industrial forest limiting the area burned by undesirable wildfires remains a priority.

Traditionally, Canadian fire management agencies have focused on the prevention and suppression of wildfires in an attempt to protect life, property, and natural resources. This has been quite effective in some regions, but it is not possible to eliminate wildfire across all of the boreal forest because fire suppression appears to be approaching its limit of economic effectiveness. This is exemplified by recent fire seasons (e.g., 1998 in Alberta, 1996 in Quebec, 1995 in Ontario) during which large areas have burned despite unprecedented fire suppression expenditures. It is further supported by simulation modelling results for Ontario that showed a small number of wildfires (2-4%) are likely to continue to escape initial attack, and have the potential to become large, due to diminishing marginal returns on suppression investments (McAlpine and Hirsch 1999). This means that to reduce the area burned below current levels it will be necessary to

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[1] Section 2 of a report entitled *Climate Change in the Prairie Provinces: Assessing Landscape Fire Behaviour Potential and Evaluating Fuel Treatment as an Adaptation Strategy* submitted to the Prairie Adaptation Research Cooperative (PARC), May 2001.

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implement a new, proactive approach to fire management that emphasises stand- and landscape-level fuels management in conjunction with fire suppression.

Fuels management is the planned manipulation of forest vegetation to decrease the intensity and rate of spread of a wildfire to improve suppression effectiveness and reduce fire impacts. Pyne et al. (1996) identify three types of fuels management: reduction, conversion, and isolation. These activities have generally been associated with the protection of relatively small, high value areas, such as homes in the wildland-urban interface, but may also have application at the landscape scale (Agee et al. 2000, Weatherspoon and Skinner 1996). Finney (2000) has conducted a theoretical analysis of the shape and pattern of fuel breaks on a landscape to minimise fire spread. In a more applied approach, Sessions et al. (1999) discuss the effect of different management actions, including the creation of fuel breaks, on achieving multiple resource goals in a portion of the Sierra Nevada forest of California. The present study, initiated at the request of a forest company in Alberta, builds upon these works by exploring how landscape-level fuels management can be integrated into a long-term forest management plan in a region of the boreal forest.

Over the next 30-50 years a considerable portion of Canada's productive boreal forest will be harvested, implying there is a tremendous opportunity to use forest management activities (e.g., harvesting, regeneration, stand tending) to alter the forest fuels. Such actions, termed fire-smart forest management, could reduce both the potential for catastrophic wildfires and the risk associated with the use of prescribed fire (Hirsch et al. 2001). This paper provides an analysis of one of many possible fire-smart forest management techniques. It describes a method for incorporating strategically-located, landscape-level fuel treatments into a spatial timber supply model. It also examines the potential effectiveness of these treatments at reducing fire size based on an evaluation conducted with a mechanistic fire growth model and discusses the implications for forest management in intensively managed, crown fire-dominated, boreal forest ecosystems.

STUDY AREA

The study area (Figure 1) is located in west-central Alberta and is comprised of the Forest Management Agreement (FMA) area held by Millar Western Industries (MWI). Millar Western Industries operates both a pulp mill and sawmill in Whitecourt, Alberta and is commited to adaptative and sustainable forest management (Millar Western Forest Products Limited 2000). The MWI FMA is about 300,000 ha in size and consists of four separate but adjacent blocks. The topography of this general area, locally known as the Swan Hills, is characterized by low elevation, rounded hills and plateaus resulting primarily from the last glaciation. Elevation varies from 600 m near the Athabasca River in the southeast portion of the FMA to over 1300 m in the northwest and extreme southwest parts of the study area. Soils are characterized by gray luvisols or related podzolic types (Rowe 1972).

The FMA is located within the Mixedwood (B.18a) and lower Foothills (B.19a) section of the boreal forest (Rowe 1972). It contains 4 natural regions: Upper Foothills, Lower Foothills, Central Mixedwood, and Dry Mixedwood (Strong 1992). Common tree species in this region are lodgepole pine (*Pinus contorta* Dougl. Ex Loud.) or jack pine (*Pinus banksiana* Lamb), trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and black spruce (*Picea mariana* (Mill.) B.S.P.). White spruce (*Picea glauca* (Moench) Voss), white birch (*Betula* *papyrifera* Marsh.), and tamarack (*Larix laricina* (Du Roi) K. Koch) can also be found on specific sites.

The general climate in this region consists of long, cold winters and short, cool summers (Environment Canada 1993). Monthly mean daily temperature can vary from –13 °C in January to 15 °C in July. Precipitation occurs mostly as rain in the summer months and averages about 500 mm per year, but amounts vary spatially due, in part, to topography.

The fire regime in this part of the boreal forest is characterised by frequent, small, low to moderate intensity fires and infrequent, large, high intensity crown fires (Cayford and McRae 1983, Viereck 1983). Between 1961 and 1998 there were 4695 fires and 613,000 ha burned in the Swan Hills region, but there was considerable annual variation in fire activity (Table 1). Sixty-one percent of all fires were human-caused, most of which ignited in April and May, and 39% were lightning fires, generally occurring from June through August. Each category of fire accounted for about half of the total area burned. Only 1.6 % of all fires exceeded 200 ha in size but they have accounted for 97.1% of the total area burned.

Logging has been occurring in this area since the early 1900s; however, intensive timber production has become common only in the last few decades. Recreation (e.g., camping, hunting, fishing) as well as oil and gas exploration and development are the other major land uses in this area. Mixed farming is commonly practiced along on the agriculture-forestry fringe and some grazing does occur in the southeastern portion of the MWI FMA.

ASSESSING THE FIRE ENVIRONMENT

Defining and implementing landscape-level fuels management treatments requires the integration of fire and forest management activities and must be based on a thorough understanding of the fire environment.[4] In this study, historical fire weather/danger, fire incidence, and fire spread data plus a map of current fuel types and a digitial elevation model were used to evaluate fire ignition and behaviour potential over the landscape. Analysis of the fire weather/danger data showed that this area's fire climate is not as severe as some other parts of the boreal forest, but occassionally short periods of extreme fire weather have resulted in major wildfires. For example, the Virginia Hills Fire (May 1998) burned over 163,000 ha and the Lesser Slave Lake Fire (Kiil and Grigel 1969) in May 1968 spread 64 km in a 10 hour period reaching a final size of 162,000 ha. Figure 2 provides a map of fires in this region that have exceeded 200 ha in size since 1931 and shows that most have burned in a southeasterly or northwesterly direction, which is consistent with the dominant wind directions on days with high fire danger.

Wildfire occurrence patterns since 1961 were analyzed using geographic information system (GIS) coverages of fire ignition data (Figure 3). Lightning fires were most frequent in the higher elevation areas near Swan Hills, uncommon in the most southwestern corner of the FMA, and very rare in the aspen dominated southeastern block of the FMA. As expected, human-caused fires were concentrated around communities, roads, recreational areas, and the agriculture-forestry fringe.

[4] Fire environment is defined as the surrounding conditions, influences, and modifying forces of topography, fuel, and fire weather that determine fire behaviour (Canadian Interagency Forest Fire Centre 2000).

Fuels, fire climate, and topographic data were used to evaluate fire behaviour potential over the study area using a procedure described by Kafka et al. (2000). A fuels map (Figure 4) was obtained using a program[5] that converts Alberta Vegetation Inventory (AVI) data into one of 16 Canadian Forest Fire Behaviour Prediction (FBP) System fuel types (Forestry Canada Fire Danger Group 1992). Topographic data consisted of a 100 m by 100 m digital elevation model that permitted the calculation of percent slope. Fire climate data was derived from 10 years (1989-1998) of daily fire weather observations and fire danger indexes for 6 stations in or near the FMA. Independent percentiles (Table 2) were calculated for wind speed and two components of the Canadian Forest Fire Weather Index System (Van Wagner 1987), the Fine Fuel Moisture Code (FFMC), and the Buildup Index (BUI). Using the fuels, topography, and different sets of seasonal fire weather/danger percentiles, head fire intensity (HFI) maps (Figure 5) were produced using the Arc-View based Spatial Fire Management System (Englefield et al. 2000). Analysis of these maps showed that the greatest fire behaviour potential exists during the spring in the southwest corner of the FMA because it is dominated by almost continuous stands of immature lodgepole pine (C-4) and boreal spruce (C-2) fuel types. Aspen and mixedwood stands had considerably lower HFI values and mature pine stands would support crowning only on the most extreme fire danger days. Recent cutblocks and burns can often have a heavy grass fuel loading (e.g., 3-10 t/ha) and even though HFI values for these areas were relatively low, they remain a hazard because the spread potential is very high when the grass is fully cured.

A simple evaluation of fire suppression capability was based on maps of probability of containment (Hirsch et al. 1997) calculated for a range of fire weather/danger conditions and initial attack response times. These maps, along with others showing the distance to permanent water sources and access for heavy equipment, indicated suppression capability was lowest in the extreme southwest and northwest portions of the FMA.

Combining the results of these separate analyses, it was apparent that the southwest portion of the FMA is of considerable concern because it had the highest fire behaviour potential and lowest suppression capability. Interestingly, from a long-term timber supply perspective this area is also of particular importance because it contains a large portion of semi-mature pine that will be the company's primary source of fibre in a few decades. Fortunately, a large number of ignitions have not occurred in this area in the recent past, but the potential for human-caused ignitions does upwind. A high potential for lightning and human-caused ignitions exists near the town of Swan Hills; however, this poses only a minor threat to the FMA because of the prevailing wind direction on high hazard days. There are also numerous human-caused ignitions near Whitecourt but the southeastern section of the FMA is dominated by aspen stands that have a low behaviour potential.

INCORPORATING STRATEGICALLY-LOCATED LANDSCAPE-LEVEL FUEL TREATMENTS INTO A FOREST MANAGEMENT PLANNING MODEL

One of many possible fire-smart forest management techniques is to use fuels management to create areas with reduced fire spread potential in strategically significant locations. The idea of landscape-level fuel treatments is conceptually similar to installing fire doors in a building in order to reduce the possibility of a fire spreading between compartments. The need to consider such treatments arose after an analysis of MWI's initial forest management strategies showed that those

[5] The AVI2FBP program was developed by and is available from the Alberta Sustainable Resource Development, Land and Forest Service, Forest Protection Division, Edmonton, Alberta.

approaches that focused solely on timber production would increase the fire behaviour potential of the landscape over time (Millar Western Forest Products Limited 2000). Given that MWI has a relatively small FMA and a limited wood supply, the company was very concerned about the potential impact of fire on the amount and flow of wood fibre.

The specific type and location of the fuel treatments were determined during a 2-day workshop with planning and timber supply foresters working with MWI. Insights obtained from the fire environment analysis were used extensively in conjunction with the participants' local knowledge of the FMA and values at risk (e.g., current and future timber values, site productivity, important infrastructure, critical wildlife and fisheries habitat, key archaeological sites). Through consensus, the workshop participants identified numerous areas suitable for fuel treatments, especially species conversion and, to a lesser extent, fuel reduction. The result was a spatial forest management plan aimed at creating a landscape consisting of areas with low flammability adjacent to larger compartments of valuable or highly productive conifer stands suitable for intensive management (Figure 6). To be conservative, the fuel treatments were designed to be relatively large (e.g., at least 1 km wide) to minimize the probability of breaching by spotting although it is recognized that smaller treatments could be effective when considered in conjunction with fire suppression action.

For different types of stands within each compartment a specific set of regeneration, stand tending, and succession rules were established emphasizing the establishment of fuel treatments and/or fibre production. These rules were incorporated into Woodstock (Feunekes and Coswell 1997) and Stanley (Remsoft Inc. 1996), the aspatial and spatial timber supply models used by MWI. The timber supply models used locally-derived growth and yield functions, made no allowance for future fire loss (in accordance with the policy in Alberta), and had no adjacency, green-up, or cutblock size constraints. The objective was to maximise fibre production from the FMA in a sustainable manner over a 200-year planning horizon and therefore included harvesting stands within the fuel treatments (Millar Western Forest Product Limited 2000).

ASSESSING THE IMPACT ON FIRE SIZE

To assess the impact of the fuel treatment scenario on fire size, it was compared to a business-as-usual (BAU) forest management scenario,[6] which served as a baseline for all of the MWI analyses (Millar Western Forest Product Limited 2000). For both scenarios, the timber supply models provided a "snap shot" of the vegetation for the FMA every 10 years and this information was converted into FBP System fuel types over the 200 year planning horizon. Initially two different pairs of maps (i.e., fuel treatment versus BAU in 2098 and 2178) for the largest portion of the FMA (200,000 ha) were selected for comparison because the fuel treatments in these time periods were relatively well defined. In addition, a third, hypothetical landscape was created by superimposing the well-established fuel treatments of 2178 on the original 1998 land base. This was done to test the effectiveness of the fuel treatments in isolation of the effects of the timber harvesting rules and objectives. Unfortunately it was not possible to evaluate the whole FMA and the surrounding region due to a lack of accessible fuels data.

[6] The business-as-usual scenario is a two-pass system where cutblocks cannot exceed 50 ha in size and cut over areas must be sufficiently stocked with new trees before the adjacent stand can be harvested.

To test the potential effectiveness of the fuel treatments on fire size, wildfire behaviour was modelled under extreme burning conditions. The point of origin of each fire was determined randomly within a set of 5 km by 5 km grid cells. This resulted in a total of 71 free-burning wildfires being simulated over the landscape for each scenario. This approach was preferred to randomly allocating fire ignitions on the study area as it ensured an even distribution of large fire ignitions thereby providing a more uniform and comprehensive test of the fuel treatments. Fire spread was simulated using an hourly time-step, 8-point cellular fire growth model (Kourtz et al. 1977, Todd 1999). This model incorporates the impact of spotting on the rate of spread through the FBP System equations (Forest Canada Fire Danger Group 1992) but does not model the probability of a spot fire breaching a fuel treatment. Given the size of the treatments (e.g., minimum of 1 km wide) relative to the spotting distances generally observed in the boreal forest, the likelihood of a fire jumping a fuel treatment was considered relatively low. Eight simulations were conducted for each landscape using selected extreme weather conditions for two seasons (spring and summer), two dominant wind directions (NW and SE), and two fire periods (6 hours and 12 hours to represent a 1-day and 2-day fire run, respectively). The fire weather/danger inputs were based on the independently derived 80th percentile values of FFMC (90), BUI (50) and wind speed (15 km/h) for a representative weather station (i.e., Windfall) in the study area.

A quantitative comparison of all 71 fires simulated on the current land base and the hypothetical fuel treatment landscape for the spring time conditions and northwest winds showed a considerable decrease (about 25%) in the average fire size (Figure 7). A paired t-test found this difference to be statistically significant ($p = 0.0056$) at the 95% confidence level. Analysis of the fire size distribution also showed that those fires greater than 20,000 ha in size were eliminated on the fuel treatment landscape while the number of fires less than 5000 ha increased. Similar relative results were obtained for the summer weather conditions, 6-hour fire run period, and for two other replications of the simulations using different random ignition locations.

The fuel treatments can certainly have an impact on the size of individual fires (e.g., Figure 8), but the 25% reduction in the average size of the simulated fires does not necessarily mean there will be an equivalent reduction in area burned on the landscape. This is because the amount of area burned will also depend on other factors including fire occurrence risk, frequency of extreme fire weather conditions, and fire suppression effectiveness. The estimate of the effectiveness of the fuel treatments on fire size in this study is, however, considered to be conservative because the treatments were evaluated in their most flammable state (i.e., in the spring prior to leaf flush) and excluded modelling the impact of fire suppression.

A comparison of the BAU and fuel treatment scenarios in 2098 and 2178 to the 1998 land base showed that when future landscapes are influenced by harvesting they may become more flammable. This is because of the extensive invasion of grass into cutover areas and an increase in the number of immature conifer stands. This finding contradicts a commonly held belief that if you harvest the trees you eliminate the wildfire problem. The significant influence of cured grass on fire spread was evident during the spring fires in 1998 (Herman Stegehuis, personal communication) and was the primary reason for the smaller difference between the BAU and fuel treatment simulation results for the 2178 landscape.

The rules used to include the fuel treatments into the timber supply models were relatively simple but a qualitative assessment of the type and arrangement of fuels every decade identified the need for further refinement. More specifically, in some time periods the fuel treatments were well-established but in other periods they were almost completely eliminated. This was due to the timber supply models' objective of maximising wood volume and the absence of rules to constrain harvesting activities in the treatment areas in any one time period. The lack of green-up and adjacency constraints also contributed to the creation of some large, continuous cut blocks, which may be socially or ecologically undersirable. From a fire suppression perspective, a large cut block can be either positive or negative depending its location and flammability at a particular point in time relative to the surrounding area. In comparison, the BAU approach resulted in many small ($\leq$ 50 ha) cut blocks over the whole landscape that would do little to limit the spread of large fires.

The timber supply analysis conducted by MWI found the fuel treatment scenario caused a moderate (20%) increase in the total annual allowable cut (AAC) in comparison to the BAU case (Millar Western Forest Product Limited 2000). This was due, in part, because MWI was able to offset the increase in aspen and mixedwood production in one location with intensive conifer production in another. The reason the AAC did not rise even more under the fuel treatment scenario was because future fire loss was not included in the AAC calculations (a policy in Alberta); however, the forest managers realize the fuel treatments could reduce the fire behaviour potential of the landscape in some time periods and further increase the AAC.

Millar Western Industries also conducted an evaluation of the impact of the fuel treatments on biodiversity using the Biodiversity Assessment Program (Duinker et al. 2000) and found positive and negative results. The fuel treatment scenario increased the habitat suitability index for many species because of an increase in the amount of deciduous forest. On the other hand, the intensive logging required to maximise fibre production resulted in a considerable reduction in the amount of older aged forest stands, which can have a detrimental impact on some species. Overall the BAP assessments for the fuel treatment scenario were well within the range of all of the forest management strategies tested by MWI (Millar Western Forest Product Limited 2000).

FOREST MANAGEMENT IMPLICATIONS AND FURTHER RESEARCH NEEDS

The results of this study have shown it is possible to incorporate strategically-located, landscape-level fuel treatments into long-term forest management planning. Acknowledging that fuels management may not be possible across the whole boreal forest (Amiro et al. 2001), that in rare instances the treatments may still be quite flammable, and that fuel conversion will take time to develop, the treatments could have a considerable impact on the fire behaviour potential in some industrial forest areas. Converting highly flammable coniferous stands to less flammable deciduous or mixedwood stands will reduce fire spread potential. It will also create predetermined anchor points suitable for direct and indirect attack that could increase large fire suppression effectiveness and reduce the likelihood of catastrophic wildfires. This, in turn, would decrease the risk associated with timber management in fire-dominated forests and the threat of wildfire to people and infrastructure. Once in place, such fuel treatments would also lower the risk associated with prescribed burning making it easier to use fire as a site preparation tool, for the enhancement of biodiversity and forest health, and to reduce forest fuels.

This study has provided a few key insights and also generated a number of questions that require further investigation. 1) Grass management is very important in locations where it aggressively invades cutovers. Forest managers who have been trying to deal with grass from a regeneration perspective must also consider ways to reduce the presence, loading, and spatial dispersion of grass to reduce fire spread potential. 2) Greater benefit would be gained by planning and evaluating fuel treatments on larger landscapes (e.g., regionally) because fires igniting outside an FMA could influence areas within it. 3) There were limitations to the rules used in the timber supply modelling as they resulted in the some fuel treatments being completely harvested in a 10-year time period. These rules could be modified to prevent the periodic elimination of the fuel treatments; however, it may be even more advantageous if the fuel treatments were spatially dynamic through time (i.e., move over the landscape throughout a rotation to protect the constantly changing areas that are of the most value). 4) The fuel treatments are intended to reduce the risk of catastrophic wildfire, not eliminate it, and so a better understanding of the limits of their effectiveness under various fire environment conditions is essential. For example, more information on when deciduous stands may be prone to extreme fire behaviour is needed (e.g., Quintilio et al. 1991). 5) To accurately estimate landscape flammability and potential reduction in area burned resulting from the fuel treatments it is necessary to model the effects on both ignition potential (e.g., Kourtz and Todd 1991) and fire spread in a more rigorous and integrated manner. 6) It is necessary for the timber supply analysis to consider the influence of harvesting and fire simultaneously (e.g., Johnson et al. 1996, Sessions et al. 1996). 7) Further work is needed to evaluate various fire-smart forest management strategies on forest health, biodiversity, and other market and non-market forest amenities. 8) Landscape-level fuels management is a strategy that could be used by forest companies and other land management organisations to adapt to the potential increases in wildfire activity (Grissom et al. 2000) that are projected under a changing climate (Flannigan et al. 1998, Stocks et al. 1998).

CONCLUDING REMARKS

This was an applied research study aimed at exploring ways of integrating fire and forest management in Canada and even though further research is required it has led to a number of new, practical initiatives. For instance, Millar Western Industries has begun incorporating fire concepts into their short-term operational forest management activities and are planning to make fire-related issues a major part of their next detailed forest management plan. The Alberta Land and Forest Service has initiated a landscape fire assessment pilot project that draws upon the techniques described in this study to evaluate fire environment conditions on a regional basis. They, along with the Canadian Forest Service, have also developed and conducted an annual 4-day professional development course on techniques for integrating fire and sustainable forest management.

Implementing sustainable forest management in fire-dominated ecosystems will require balancing the short- and long-term economic, social, and ecological effects of fire. This will be extremely challenging and may require a paradigm shift in both fire management and forest management planning and operations. Creating strategically-located, landscape-level fuels treatments is one possible fire-smart forest management technique; however, over the next few years many other approaches will undoubtedly be discovered, evaluated, and applied by forestry and fire professionals in Canada.

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Table 1. Number of fires and area burned in west-central Alberta (i.e., the area bounded by latitude 53.8° – 55.5°N and longitude 114° – 117°W) between 1961 and 1998.

Year	Number of fires			Area burned		
	Human	Lightning	Total	Human	Lightning	Total
61	117	70	187	10296	17310	27606
62	25	24	49	144	1021	1165
63	50	44	94	160	68	228
64	63	11	74	618	399	1017
65	35	18	53	104	0.4	105
66	76	18	94	878	2	880
67	151	50	201	1972	181	2153
68	149	27	176	231483	86	231569
69	76	53	129	457	255	711
70	89	31	120	514	4	519
71	82	26	108	74	5	80
72	61	47	108	172	30897	31068
73	60	12	72	270	0.4	270
74	54	38	92	452	10178	10630
75	91	11	102	122	1	123
76	89	9	98	967	2	968
77	50	11	61	244	1	245
78	54	32	86	71	13	84
79	59	36	95	159	325	484
80	118	55	173	5069	122	5191
81	107	162	269	846	15565	16410
82	86	135	221	499	2657	3156
83	60	45	105	1861	84	1945
84	91	87	178	924	58	983
85	63	71	134	142	76	218
86	62	24	86	94	436	529
87	133	110	243	1607	824	2431
88	123	25	148	718	4	721
89	69	38	107	3570	8	3578
90	52	101	153	52	290	342
91	79	40	119	407	12	419
92	64	82	146	512	36	548
93	56	22	78	111	6	116
94	50	38	88	273	10	283
95	53	30	83	104	176	280
96	19	7	26	290	0.4	291
97	30	8	38	33	0.3	34
98	97	204	301	51893	213864	265757
Total	2843	1852	4695	318161	294977	613138
Mean	74.8	48.7	123.6	8372.66	7763	16135
Std Dev	32.1	44.1	63.0	38123	34897	56122
Median	64	37	106	430	72	630
Minimum	19	7	26	33.31	0.3	33.57
Maximum	151	204	301	231482.9	213864	265756.8

Table 2. Selected independent percentiles for the wind speed (WS), Fine Fuel Moisture Code (FFMC), and Buildup Index (BUI) at 6 weather stations in the Swan Hills region (based on data for 1989-1998). Data Source: Alberta Sustainable Resource Development.

70th Percentile												
Station	**All season**			**Spring**			**Summer**			**Fall**		
	WS	**FFMC**	**BUI**	**WS**	**FFMC**	**BUI**	**WS**	**FFMC**	**BUI**	**WS**	**FFMC**	**BUI**
EA	14	85	26	14	87	28.75	15	84	25	14	84.9	26.9
W4	12	86	39.7	14	89	42	12	86	40	11	85.9	38
ZU	13	86.2	33	15	88.4	37	14	85	30	11	85.5	34.9
TO	18	84.3	23	19	87	23	18	83	18.35	18	84	24
IM	18	84.8	25	18	86	24	18	81.6	22.1	19	85	28
GM	18	81.3	16	18	85	21	18	78	15	18	82	15
80th Percentile												
EA	17	87	33	18	89	34	17	86.3	31.9	16	87	33.4
W4	13	88	48	15	90	50	14	87.2	51	12	87.1	46
ZU	15	88	41	16	89.8	46	15	87	36	15	87	42
TO	21	86.8	28	22	88.3	29	22	86	22	21	86	30
IM	22	87	30.7	22	87.7	28	22	85	28	22.5	87	34
GM	21	85	21	19	87	24	21	84	19	21	85	21
90th Percentile												
EA	20	89	42.3	21	90	39.5	20	88.6	43.5	19	88	42.9
W4	16	89.3	60.9	18	91.1	60.6	16	89	64	15	89	57
ZU	20	89.9	53	20	91	58	20	89	49	18	88	53
TO	28	88	37	27	89.7	37	28	87.8	26	27	87.4	39
IM	28	88.8	41	29	89	41	27	88	38	29.5	89	43.3
GM	24	87	29	23	88	29	24	87	27	25	87	32
95th Percentile												
EA	23	90	51.6	24	92	48	23	90	53.2	22	90	50.4
W4	18	90.5	72	20	92.5	67.7	18	90	77	18	90	66
ZU	20	90.9	64.1	22	91.5	68	20	90	60	20	89	64.1
TO	33	89.3	44.9	32	91	45	34	89	35	33	88	43.6
IM	33	90	50.8	35	90	48	31	89	46	36	90	57
GM	28	89	36	26	89	33	28	89	34	30	88	42

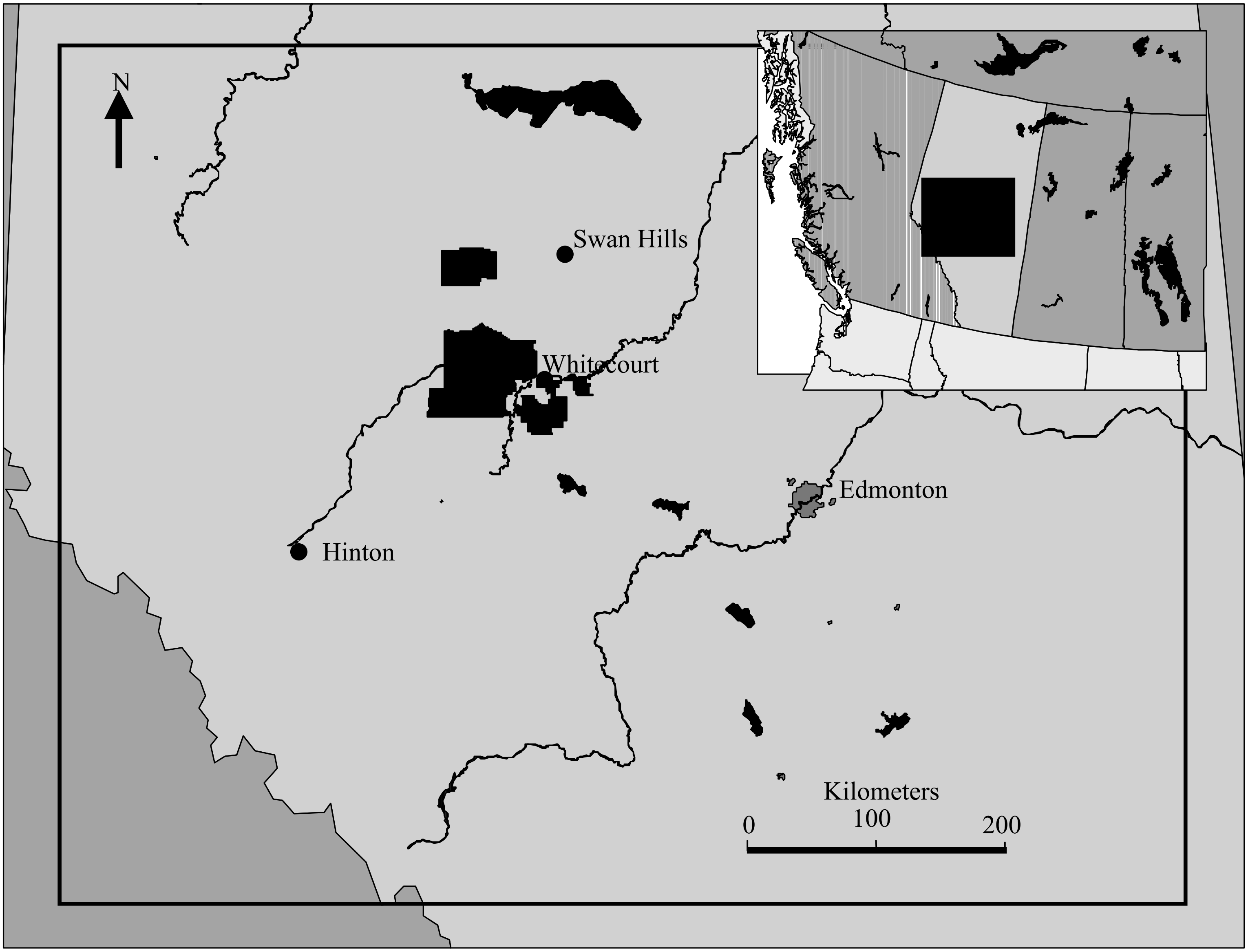

Figure 1. Location of the study area in west-central Alberta.

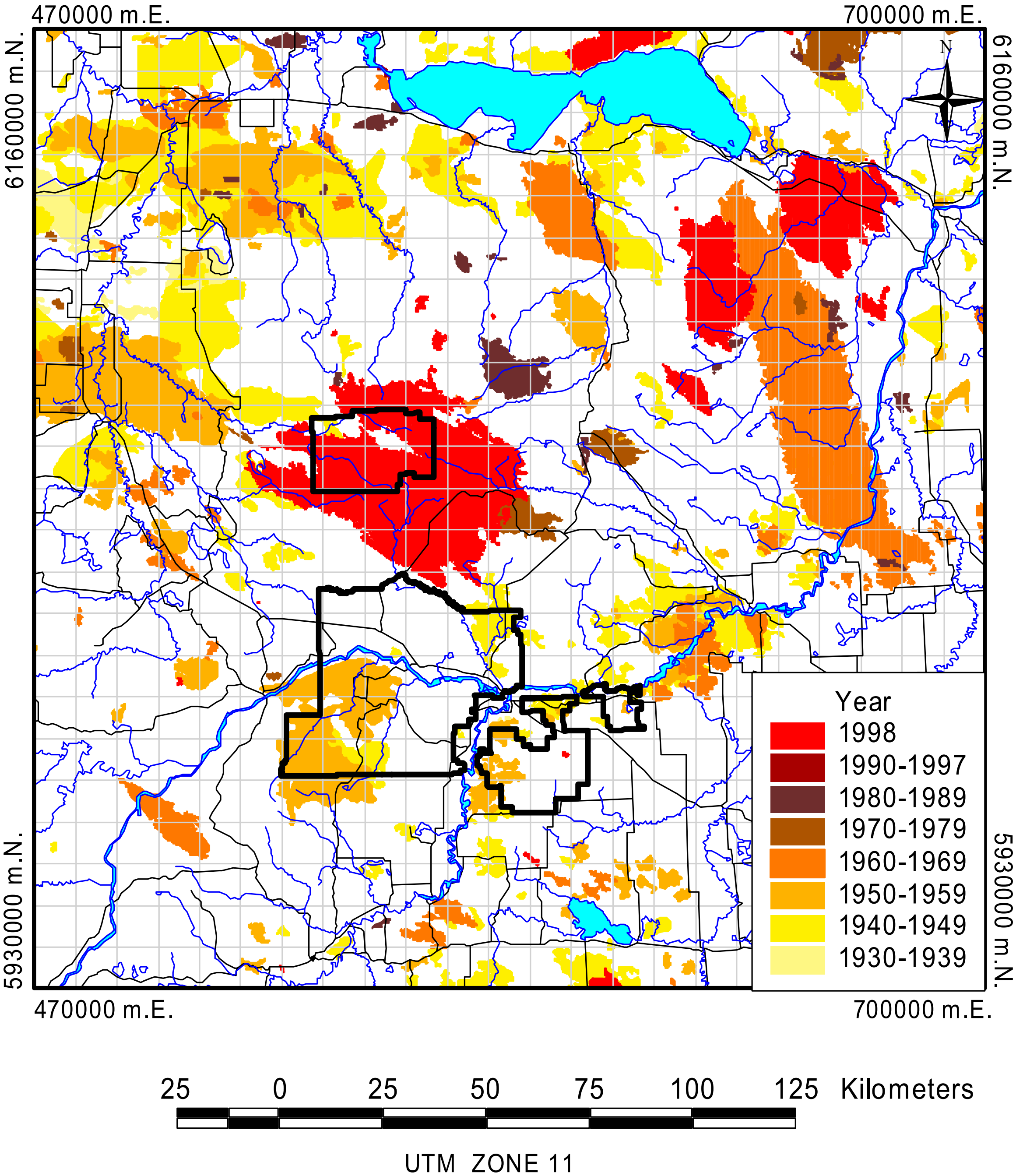

Figure 2. Large fires (greater than 200 ha) in west-central Alberta (1931-1998).
Source data: Alberta Sustainable Resource Development.

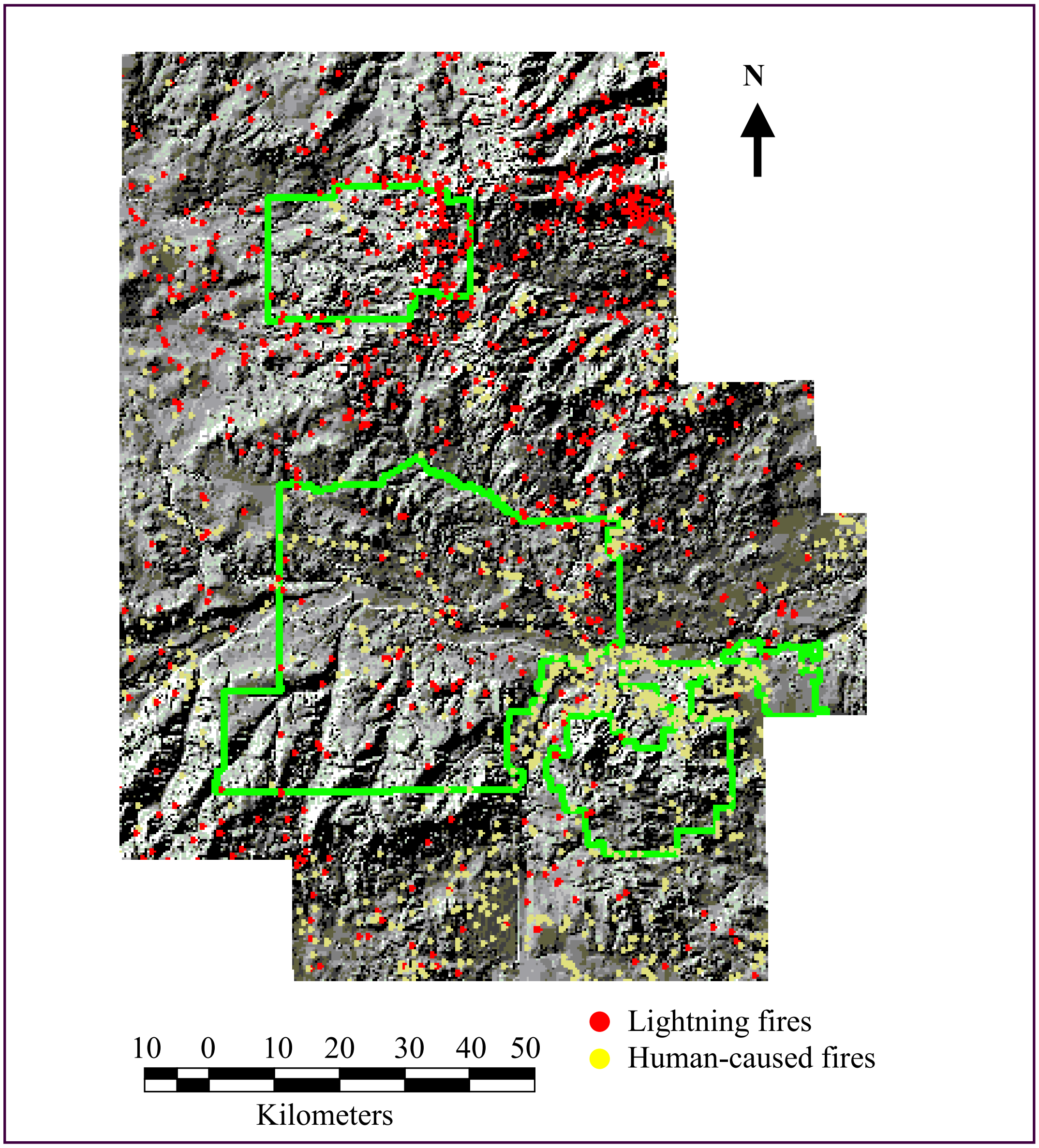

Figure 3. Location of lightning and human-caused fire ignitions in the Swan Hills region between 1961 and 1998. Source Data: Alberta Sustainable Resource Development.

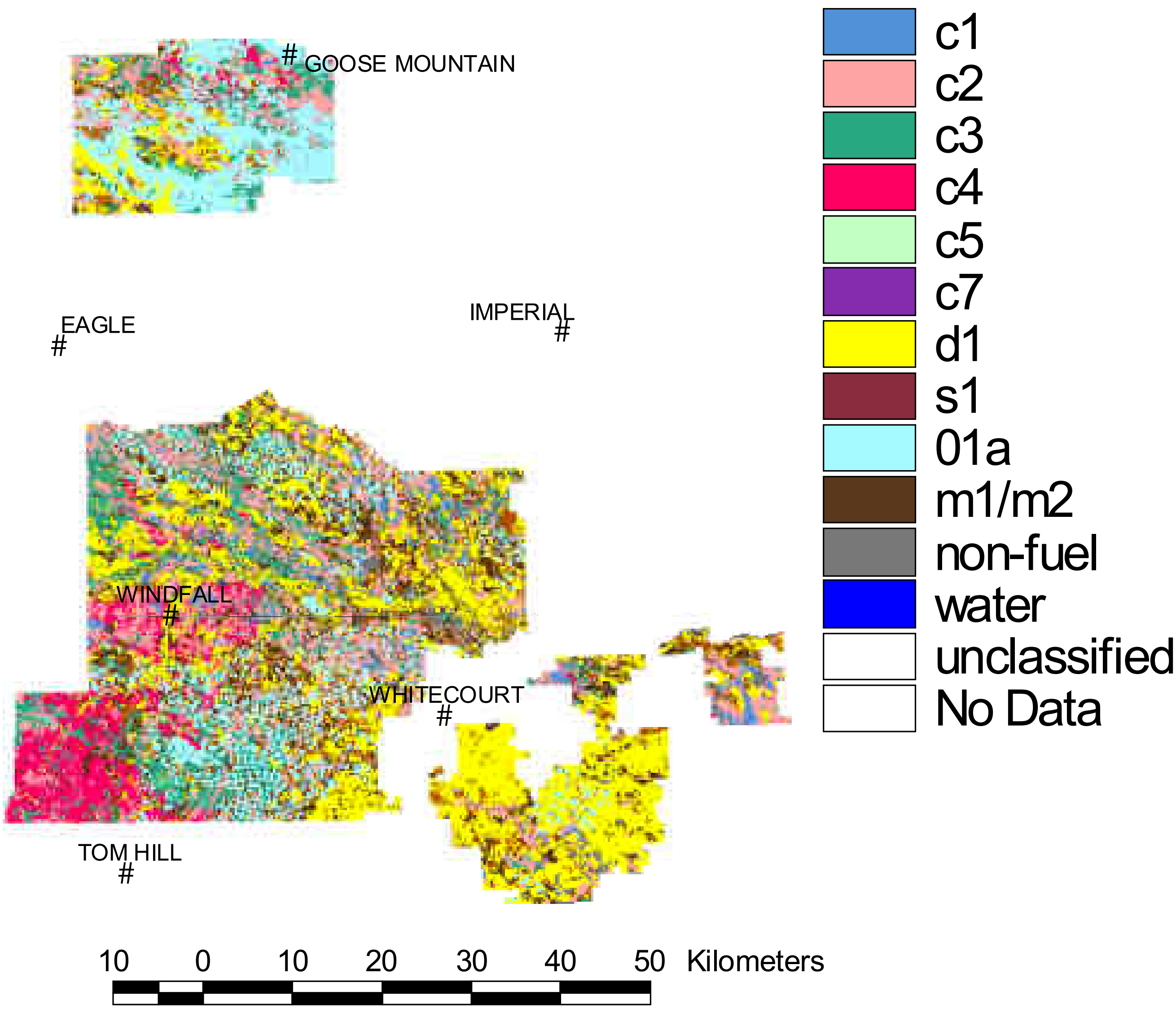

Figure 4. Fuel type map for the Millar Western Forest Management Agreement area.

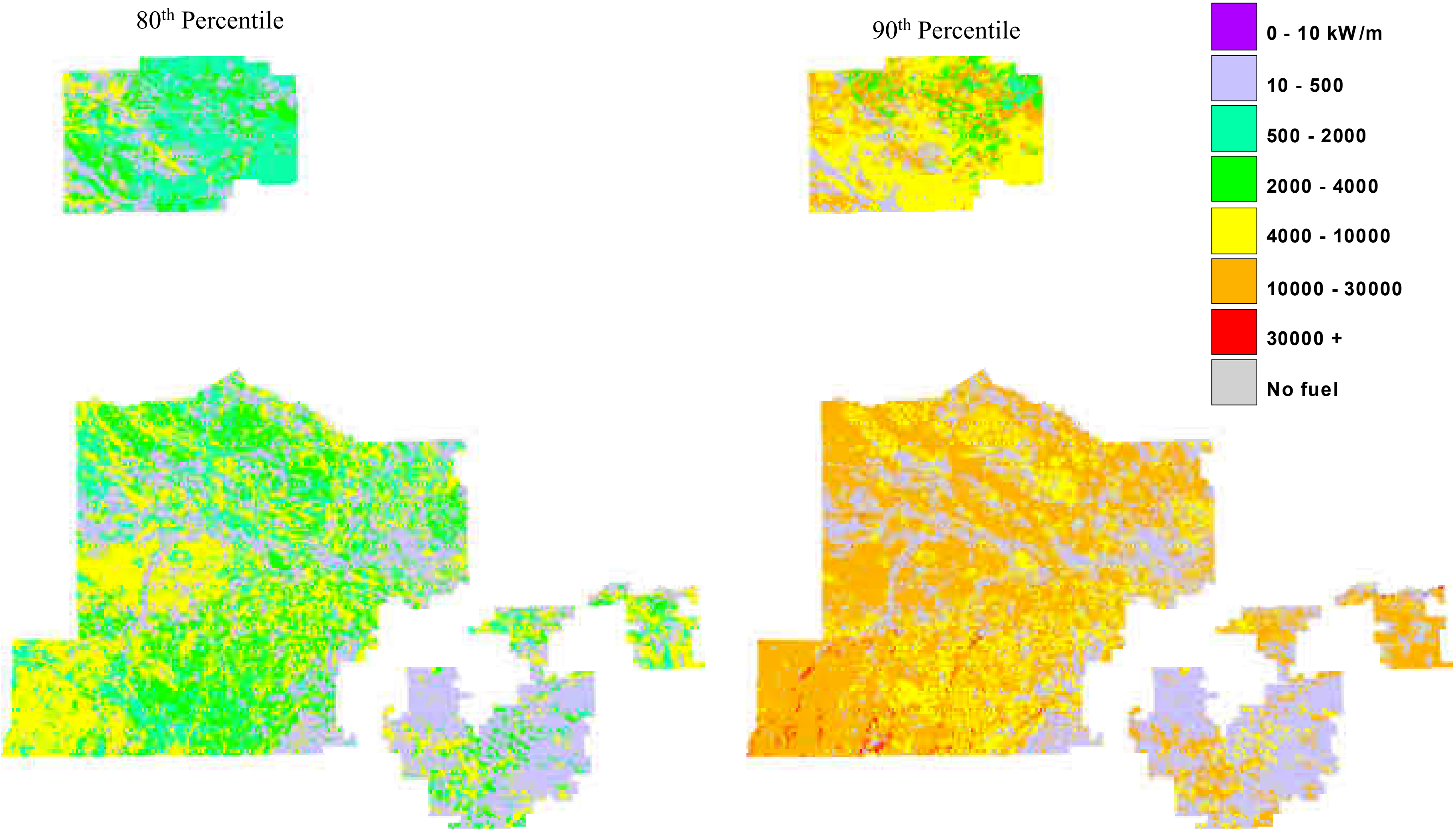

Figure 5. Example of the head fire intensity percentile maps (spring conditions) used to evaluate fire behaviour potential on the Millar Western Industries Forest Management Agreement area.

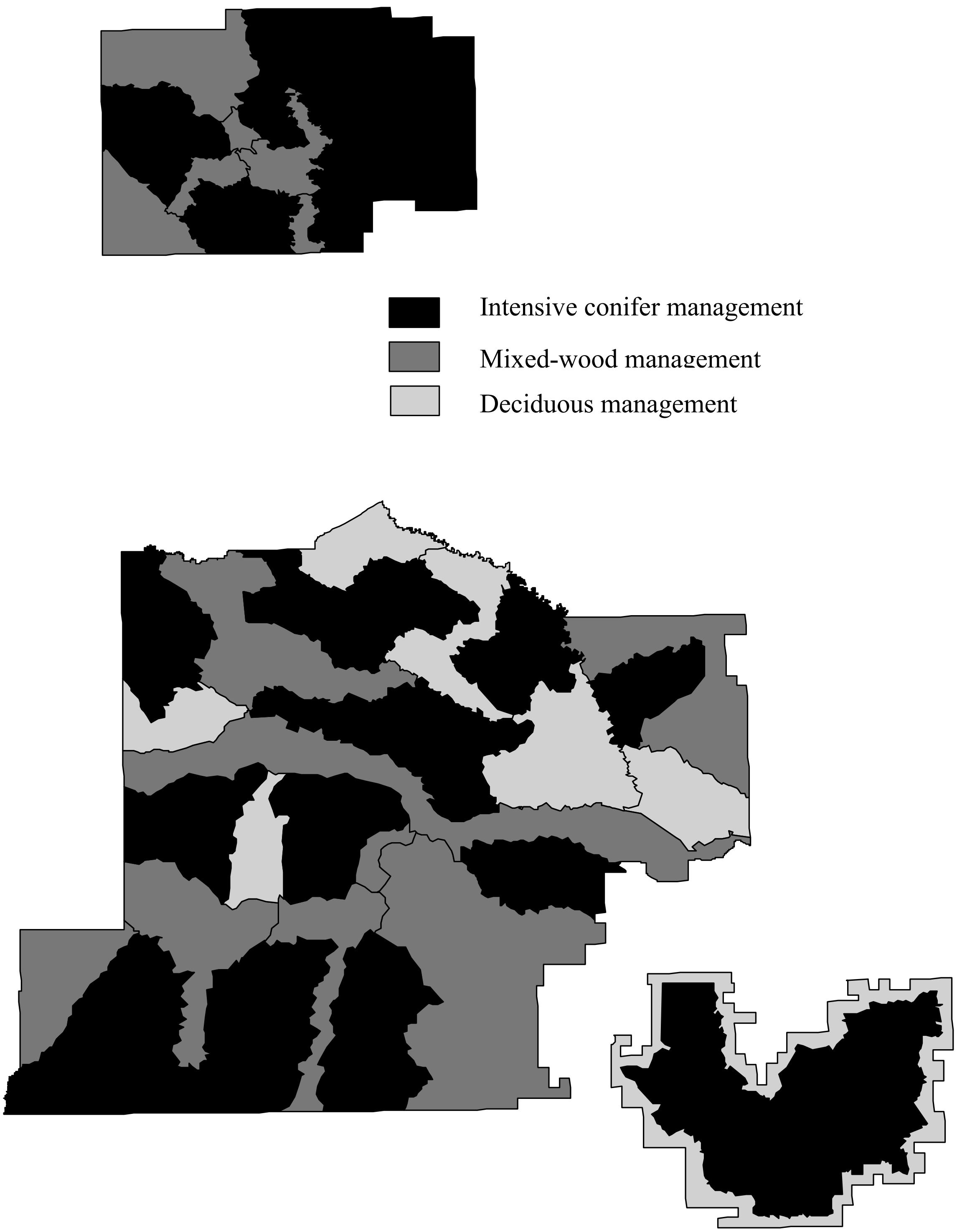

Figure 6. Proposed compartments for landscape-level fuel treatments and intensive conifer management on the Millar Western Industries Forest Management Agreement area.

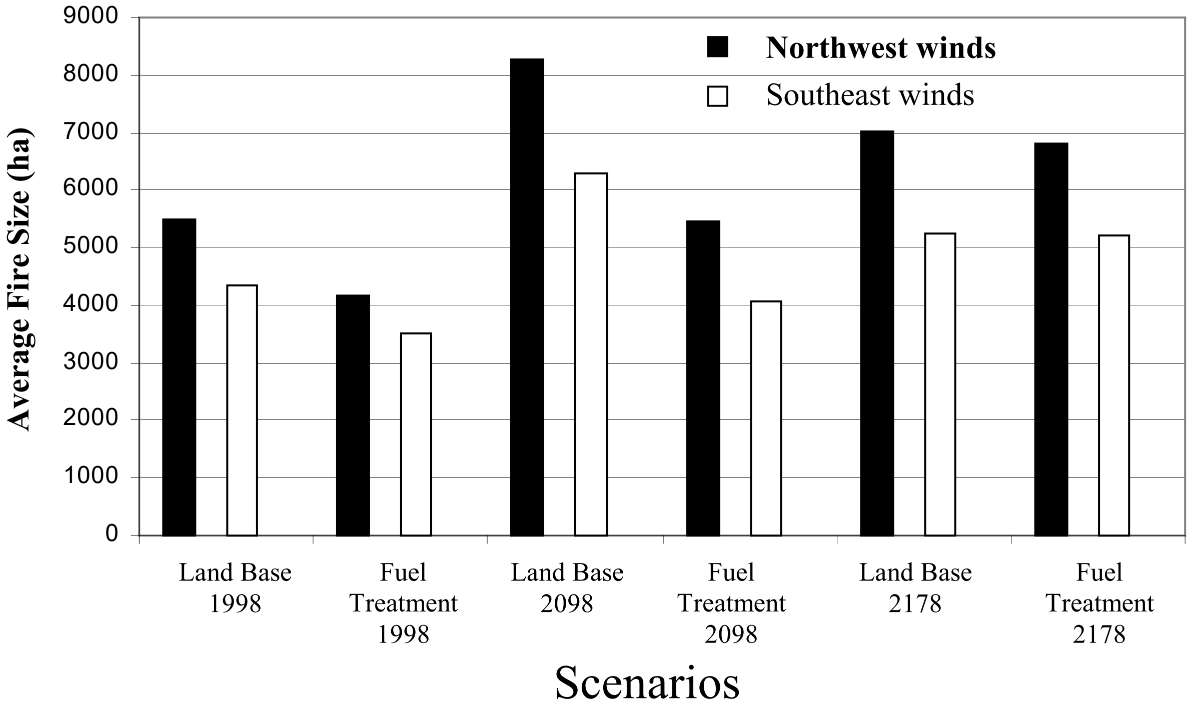

Figure 7. Average size of the simulated fires on the current, hypothetical and projected landscapes for a 12 hour run under spring time conditions

Current Land Base (1998) Hypothetical Fuel Treatment Landscape (1998)

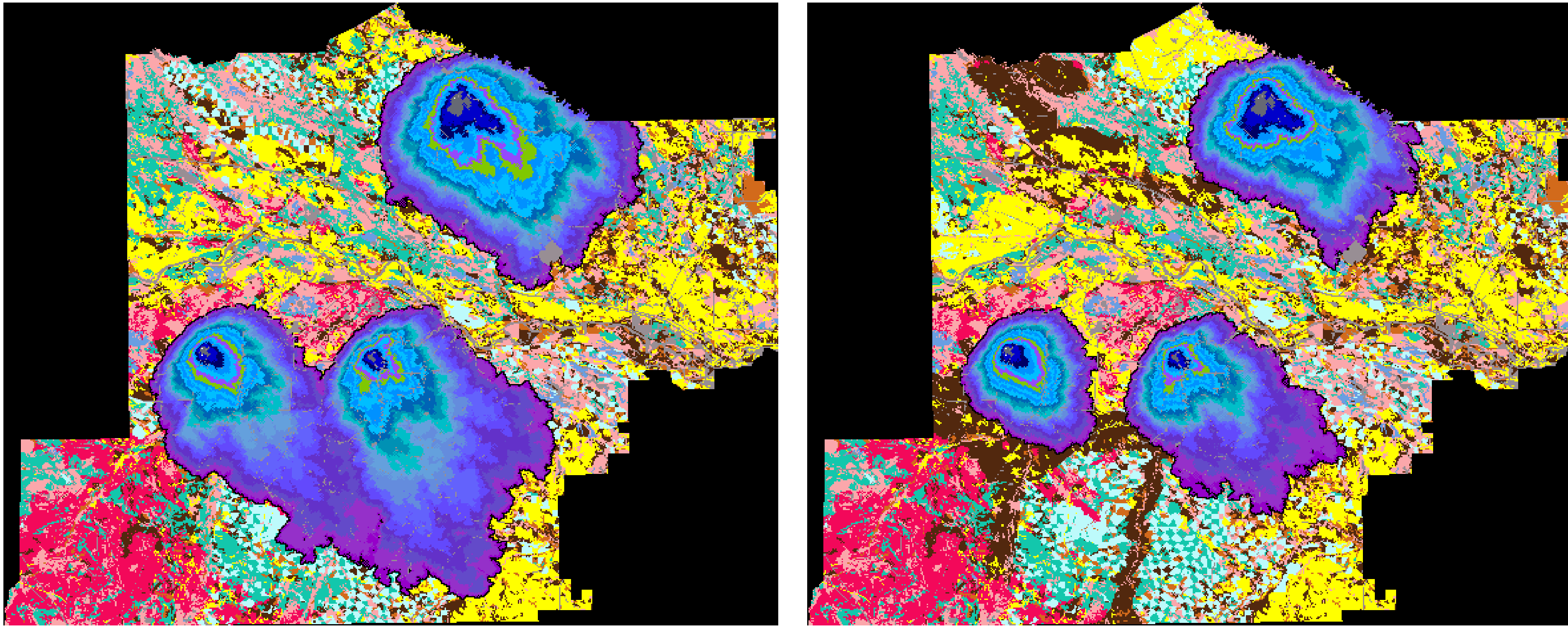

Figure 8. Size of three simulated fires on the current and hypothetical fuel treatment landscape after a 22 hour fire run.