

FORUM ARTICLE

## BURNING AT THE EDGE: INTEGRATING BIOPHYSICAL AND ECO-CULTURAL FIRE PROCESSES IN CANADA'S PARKS AND PROTECTED AREAS

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### ABSTRACT

Currently, high intensity, large-area lightning fires that burn during droughts dominate Canada's fire regimes. However, studies from several disciplines clearly show that humans historically ignited burns within this matrix of large fires. Two approaches for fire research and management have arisen from this pattern: a "large-fire biophysical paradigm" related to lightning-ignited fires, and an "eco-cultural paradigm" related to human-caused burning. Working at the edge between biophysically driven fires and eco-cultural burns, and their associated management and research paradigms, presents unique challenges to land managers. We proceed by describing fire frequency trends across Canada, and how an interaction between changing climatic and cultural factors may provide better causal explanations for observed patterns than either group of factors alone. We then describe four case histories of fire restoration into Canadian landscapes moving through evolution, or deliberate intent, towards increasing emphasis on an eco-cultural paradigm. We show that use of cultural burns maintains this facet of the long-term regime while providing greater capacity for larger, higher intensity fires to occur with fewer negative ecological and socio-economic implications. Key lessons learned by practitioners restoring fire to landscapes include: 1) fire is only one process in ecosystems that also include other complex interactions, and thus restoration of fire alone could have unintended consequences in some ecosystems; 2) recognizing long-term human roles of not only fire managers, but also hunters and gatherers is critical in restoration programs; and 3) this diversity of past, present, and future ecological and cultural interactions with fire can link managers to a broad constituency of stakeholders. Bringing this variety of people and interests into the decision-making processes is a necessary pre-requisite to successful fire management at the edge.

**Keywords:** anthropogenic fire, boreal forests, Canada, fire management, fire regimes, lightning fire

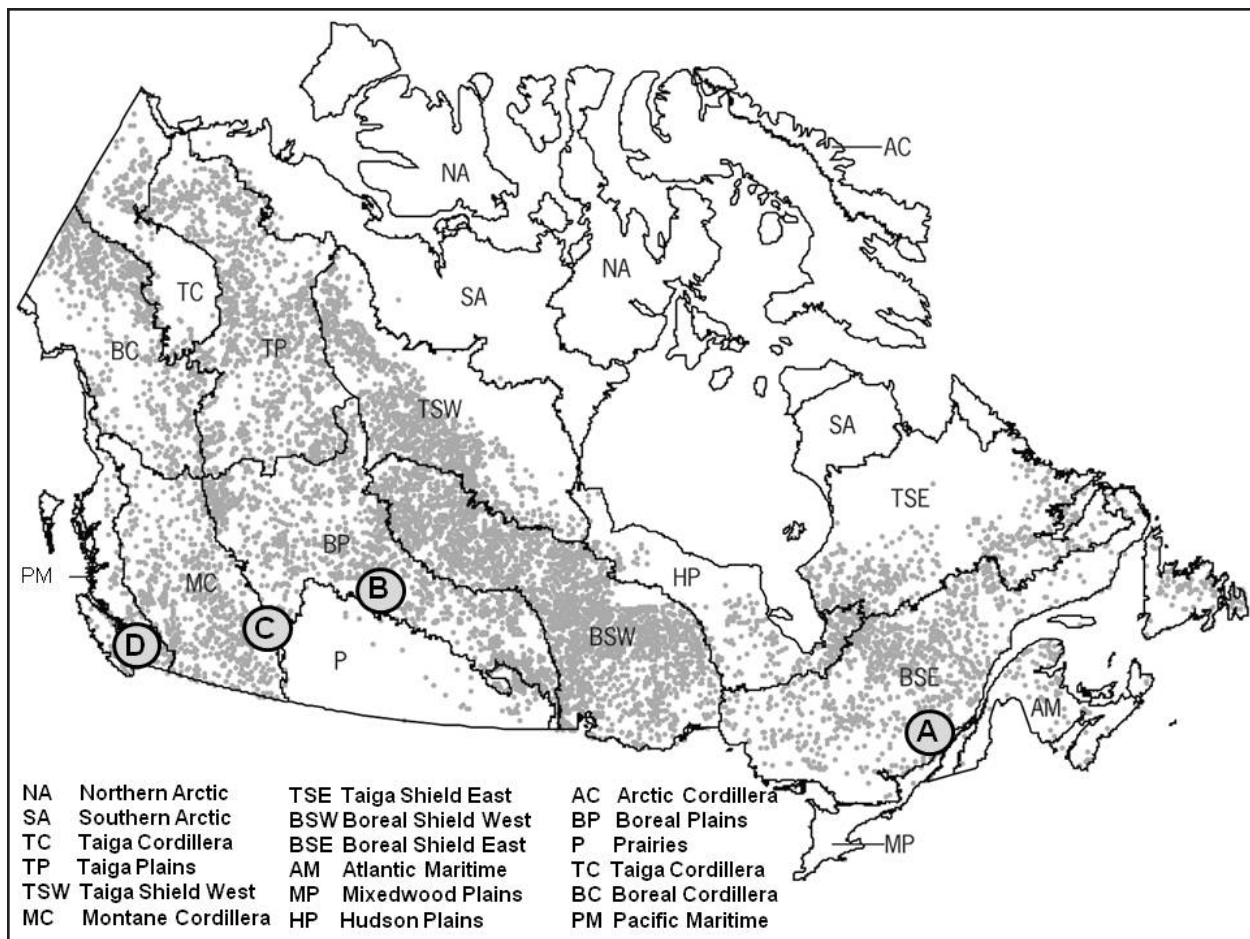
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## INTRODUCTION

*Cultural edges may be more difficult for us to understand than ecological edges.* (Turner et al. 2003)

Wildland fire is a dominant ecological process across Canada. Fire plays a critical role in maintaining characteristic vegetation com-

munities within Canadian ecozones (Figure 1), including the grasslands of the Prairies, subalpine and dry interior forests of the Montane Cordillera, mixed conifer and deciduous forests of the Boreal Plains and Shield, and the eastern hardwood and pine forests of the Mixedwood Plains in southeastern Canada and the Atlantic Maritime ecozones (Stocks et al. 2003, Pyne 2007). Although fire suppression



**Figure 1.** Canadian ecozones (Canadian Ecological Stratification Working Group 1995) and distribution of fires (>200 ha, 1959 to 1997) from the Canadian Large Fire Database (Stocks et al. 2003). Also shown are locations for La Mauricie National Park (A), Prince Albert National Park (B), Banff National Park (C), and Cowichan Garry Oak Preserve and Gulf Islands National Park Reserve (D).

is the primary land management objective in most of Canada, an average of over 2 million hectares burned annually from 1959 through 1997, with up to 7 million hectares burning in major fire years. During this period, burn area was dominated by large fires (>200 ha). Although these burns represented only 3% of the total number of fires, they burned 97% of the area (Stocks *et al.* 2003).

The current regime of large, high-intensity fire is thus understandably the focus of Canadian forest fire researchers and managers. The prevailing “large fire, biophysical paradigm” centers attention on lightning strikes that currently ignite the majority of these burns (e.g., Nash and Johnson 1996), the weather, fuel and topographic factors that favor fire growth (e.g., Stocks *et al.* 2004), and rapid initial attack through technology (lightning detection, use of aircraft, etc.) that can be used to suppress these fires while they are still small (e.g., Martell and Sun 2008). If suppression fails, intensive forest management (logging, thinning) near communities, combined with engineered-building solutions (concrete, fire-proof roofs, etc.), are used to minimize risks to human health and infrastructure from high-intensity infernos (Johnson and Miyanishi 2001, Canadian Wildland Fire Strategy Task Group 2005). From our experience, contemporary researchers and managers working on the basis of the biophysical paradigm tend to conceptualize that lightning ignitions have long burned the majority of the area in many Canadian ecozones (for argument, say >75%), and for various reasons do not believe that human ignitions could have substantially contributed to historic fire regimes in most areas (e.g., Johnson *et al.* 1998, Bergeron *et al.* 2004a).

However important the biophysical role of fire is today, anthropological and historical research throughout Canada shows that, in the past, human attention focused more on an ecological and cultural importance of fire (Pyne 2007). For more than ten millennia, First Nations of indigenous peoples have occupied al-

most all areas of Canada, with population density highest in more southern areas (McMillan 1995). Studies clearly show that humans set low intensity fires that burned over the long term within the larger matrix of fires (Lewis and Ferguson 1988, Turner 1999). Historically, at least in some areas, human use, not suppression, of fire was more significant. Fire was an easily available tool that could be routinely used for purposes ranging from altering wildlife habitat, to improving berry crops, to warfare (Boyd 1999, Stewart 2002). People living on the land understood fire’s role intimately, and because it was their most powerful tool to change landscapes, integrated this understanding into daily decisions for survival. This “eco-cultural paradigm” for fire management may have prevailed because of human’s interaction with large, lightning or human-caused burns. Consider that pre-emptive dormant season burning could reduce the risk of more intense fires later unfavorably altering habitats important to people (Lewis 1980, Lewis and Ferguson 1988). It is important to note, however, that data are lacking for many areas in Canada, and there is still uncertainty and controversy about the magnitude of the eco-cultural use of fire by First Nations, Metis, and early white settlers. Thus, current researchers or managers working with fire based upon an eco-cultural paradigm usually conceptualize that ignitions by humans historically burned only a minor portion of most ecosystems (say <25% of the area burned during past temporal periods), and that this burning was in dormant seasons with relatively low intensity (e.g., Lewis and Ferguson 1988, Johnson-Gottesfeld 1994, Turner 1999). In this respect, both the biophysical and eco-cultural perspectives are currently complementary. However, as we will discuss, there is increasing realization that burning by humans occurred also during dryer conditions, and burned much larger areas (Pyne 2007).

In our opinion, three important trends are increasing the relative importance of the eco-

cultural versus biophysical fire management paradigms in Canada. First, the area within the country dedicated to parks and the participation of First Nations in land management is consistently increasing (Parks Canada Agency 2000). Historically, the solution to unwanted fires was to remove First Nations, transform the landscape with roads, logging, plowing, and settlements, and then implement aggressive fire suppression (Binnema and Niemi 2006, Pyne 2007). The trend to establish more parks, often with First Nations' management or co-management, has made this approach to fire increasingly unworkable. A second trend, as studies reviewed later in this paper demonstrate, is a general decline in Canadian burn area in the southern half of the country (Stocks *et al.* 2003). Thirdly, as a result of the above trends, restoration of long-term fire regimes is becoming a critical part of land management, particularly in parks and protected areas. For example, as of the year 2000, Canada's National Parks Act requires that managers give priority to restoring or maintaining "ecological integrity," which is defined as "a condition that is determined to be characteristic of its natural region and likely to persist, including biotic and abiotic communities, rates of change, and supporting processes." This definition purposely does not differentiate between characteristic conditions that were culturally versus biophysically driven (Parks Canada Agency 2000).

Working at the edge, between biophysically driven fires and eco-cultural burns and their associated management and research paradigms, presents unique challenges to land managers. In this paper, we argue that restoring fire to Canada's parks and protected areas might be more successful by reducing focus on the large biophysically driven fires that currently burn most of the area, and increasing emphasis on the long-term role of eco-cultural fire within the matrix of larger fires. We proceed by giving a brief overview of Canadian fire regimes, then describe spatial and tempo-

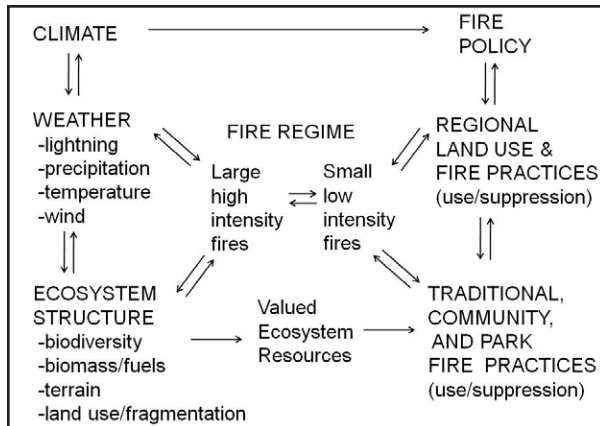
ral fire frequency trends across the country. We critique explanations for declining burn area that arise from changing biophysical or cultural groups of factors alone, and then provide a preliminary conceptual model of how an interaction between these factors may provide a better causal mechanism. We then describe four case histories of fire restoration into Canadian landscapes moving through evolution, or deliberate intent, towards increased consideration of long-term, eco-cultural factors. We summarize lessons learned from these case histories, and conclude with thoughts on how park managers can eventually integrate fire's various biophysical and eco-cultural dimensions.

## CANADIAN FIRE REGIMES THEN AND NOW

Patterns of weather, fuels, topography, and ignition (timing and location) are all key factors that, over time, determine fire regime characteristics such as frequency, seasonality, and severity (Pyne *et al.* 1996). In many landscapes, fire regime characteristics can also be influenced by cultural values that dictate human practices such as land use, suppression and use of fire, and regional and national fire policies. Chapin *et al.* (2003) developed a conceptual model of these interactions, which we have modified (Figure 2).

### *Spatial Variation of Fire Weather and Behavior*

No country-wide fire regime map is available for Canada. Thus, for a coarse scale analysis of Canadian fire regimes, we focus on the cumulative effect of weather variables (wind, rainfall, and temperature patterns), as integrated through the Canadian Forest Fire Weather Index (FWI), to predict fire occurrence and behavior (Stocks *et al.* 1989). The simplest model for interpreting the broad geography of Canadian fire assumes, at least in the past, that

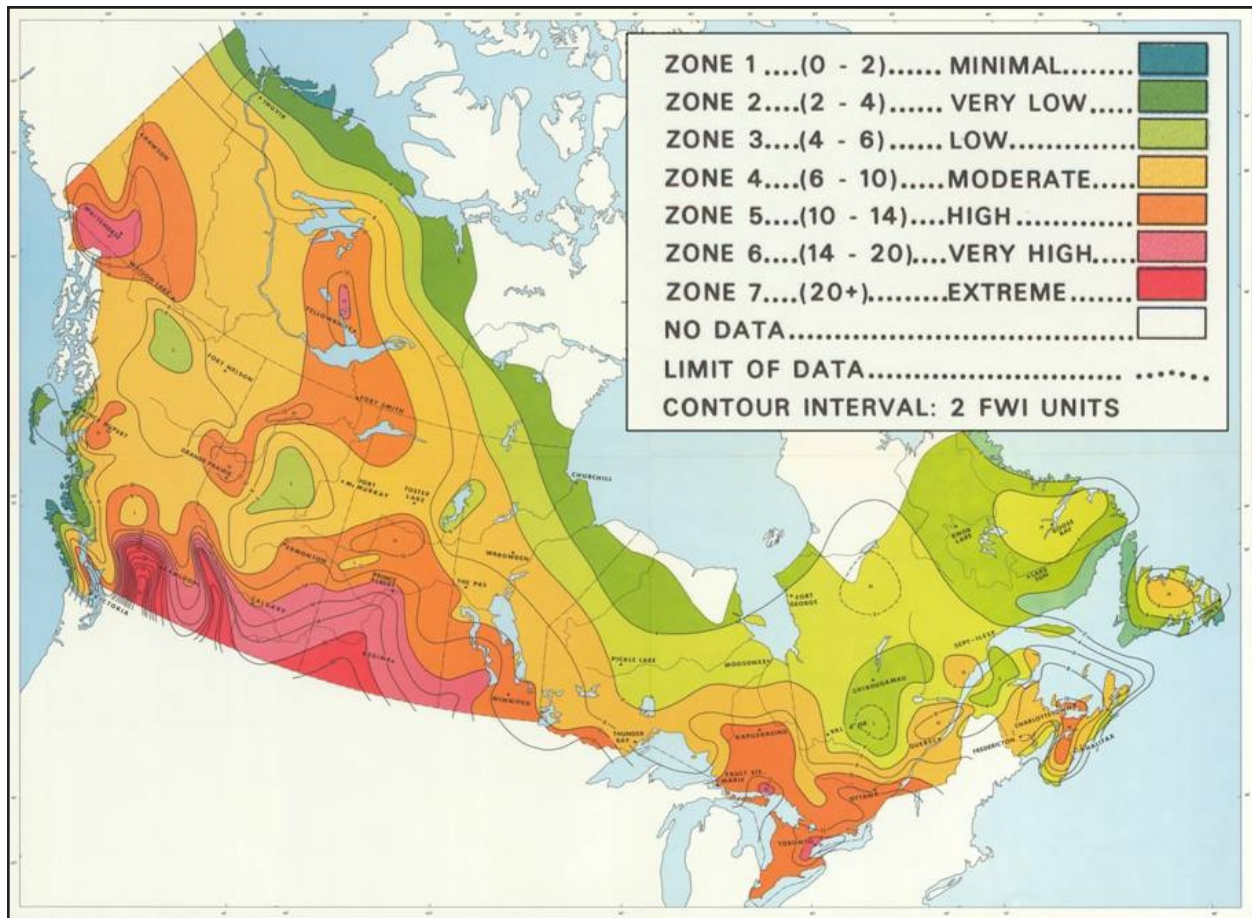


**Figure 2.** A conceptual model of the interaction between biophysical and cultural factors influencing fire regimes (modified from Chapin *et al.* 2003).

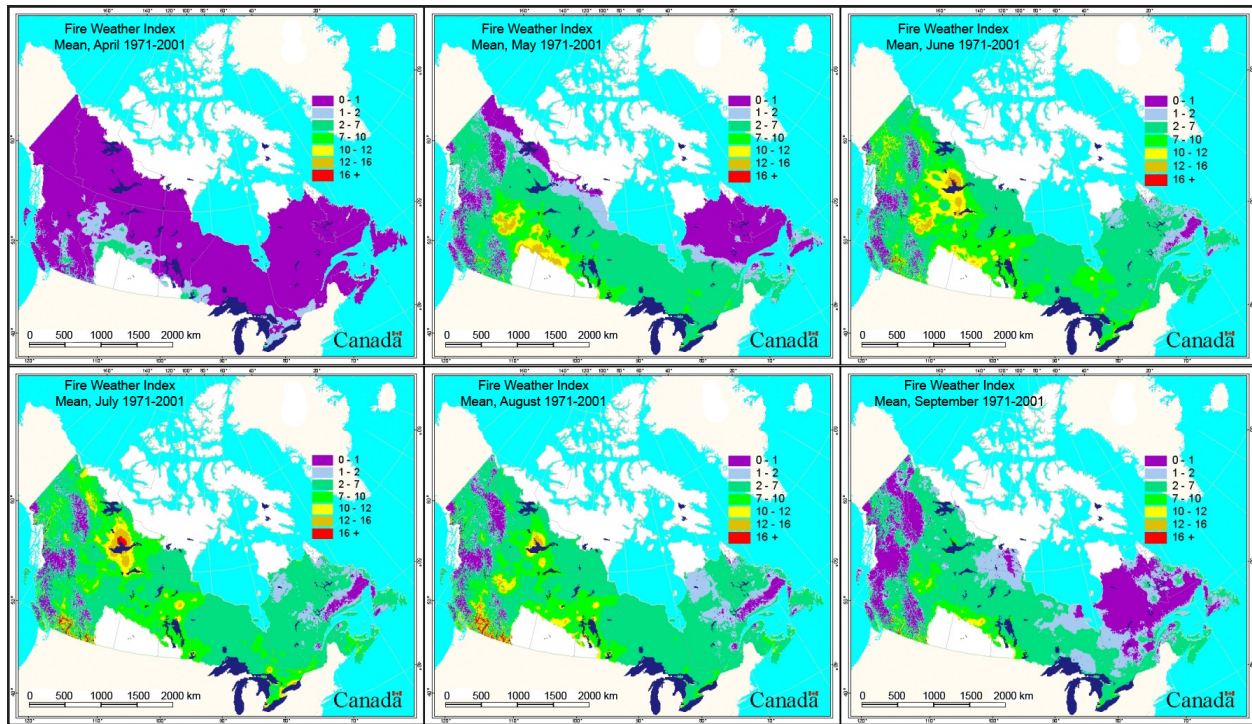
ignition and fuels were not limiting (Krawchuck *et al.* 2009). Lightning and human caused fires were relatively common, and the

resulting burn area was mostly related to weather patterns (Bergeron *et al.* 2004a, Girardin 2007, Lepofsky and Lertzman 2008). In a later section, we will further discuss the assumption of ignition limitation.

We use two country-wide spatial models (Simard 1973, Canadian Forest Service 2010) to show spatial and temporal patterns of the FWI. There is a similar pattern visible in both spatial models (Figures 3 and 4). The mean FWI decreases from south to north, with nodes of weather favorable to fire activity in the southern Montane Cordillera, the southern Prairies, the Mixedwood Plains in the Great Lakes area of south-central Canada, and the south-central Atlantic Maritime ecozones. The peak of burning conditions varies by month across the country (Figure 4). The Prairies and southern Boreal Plains have highest fire weath-



**Figure 3.** Fire weather zones of Canada (from Simard 1973) calculated from mean fire weather index values for the months June, July, and August for 364 weather stations for the period 1957 to 1966.



**Figure 4.** Mean Fire Weather Index values for Canada calculated for the months April through September from several hundred weather stations for the period 1971 to 2001 (Canadian Forest Service 2010). Fire weather was not monitored for the majority of the Prairie ecozone and for northern Canada due to low fire occurrence.

er indices in April and May; the Boreal, Taiga, and Mixedwood Plains in June and July; and the Montane Cordillera and Pacific Maritime ecozones during August. By September, most of the country is cooling, but areas of higher fire weather index values still occur in the southern Montane Cordillera, the southwestern Prairies, and the Mixedwood Plains in eastern Canada. Simard's (1973) analysis also provides distributions of the FWI by zone (Table 1). His analysis clearly shows that for the majority of areas, most of the days when burning will occur will have low to moderate intensity fire. His analysis is based on June-to-August data only, when conditions are driest. Inclusion of data from April, May, and October (Figure 4) would further increase the number of days of low to moderate fire intensity potential, particularly in southern areas.

#### Long-Term Temporal Variation of Fire Frequency by Fire Weather Zones

We extended reviews of fire history studies for Canada's boreal forest ecozones (Bergeron *et al.* 2004a, Zhang and Chen 2007) to include other areas of Canada, and categorized fire history studies by the Simard (1973) FWI zones (Table 2). In most cases, these studies used dendrochronology to determine either the time-since-fire (in high-severity regimes) or fire intervals (in low-severity regimes). From this information, either the fire cycle (years required to burn an area equivalent to the study area), or the mean fire interval (years) can be estimated. In landscapes with periodic random fire occurrence that is consistent over time and space, these estimates of fire frequency will be equivalent (Johnson and Van Wagner 1985, Johnson and Gutsell 1994). In cool and moist areas, researchers used soil charcoal evidence (e.g., Hallett *et al.* 2003) to evaluate fire fre-

**Table 1.** Percent of days by potential fire behavior for fire weather index (FWI) zones of Canada (from Simard 1973).

Zone (FWI map color code)	Mean FWI	Percent days by fire behavior and map fire zone							
		No fire	Light Smoldering surface	Moderate surface	Hot surface	Torching	Crown fire	Conflagration	
1- Minimal (blue green)	0-2	65	34	1					
2- Very low (dark green)	2-4	40	50	7	3				
3- Low (light green)	4-6	31	44	15	5	4	1		
4- Moderate (yellow)	6-10	20	40	20	10	7	2	1	
5- High (orange)	10-14	15	40	10	15	10	7	2	1
6- Very high (light red)	14-20	5	30	10	20	15	15	3	2
7- Extreme (red)	20+		25	7	10	13	20	15	10

quency. For studies listed in Table 2 that describe fire cycles or intervals over multiple time periods, the earliest period likely provides the best estimate of long-term conditions before alterations caused by contemporary cultural and land use change (e.g., McMillan 1995). As one would expect, the past fire frequency broadly follows the FWI zones. Historically long fire cycles (>400 yr), often estimated from stand age or soil charcoal analysis, occurred in cooler and wetter areas such as along Canada's coastline. Shorter fire intervals (<50 yr) occurred in the areas with the highest FWI values, such as the southwestern Montane Cordillera, and the Prairies.

Multiple time-period evaluations have nearly always found longer fire cycles or fire intervals in the past, particularly in the southern parts of the country. Surprisingly, the greatest decreases in fire activity occurred in the high to extreme fire weather zones (Figure 3), for example on the eastern slope of the Rocky Mountains within the Montane Cordillera (Van Wagner *et al.* 2006). However, a trend of decreasing area burned in recent de-

cadecades has also occurred in the very low to moderate fire weather zones, such as in the Boreal Shield East ecozone in central Quebec and Ontario (Bergeron *et al.* 2001). Many studies show that this change in fire regime can be detected in two sequential periods: an early decline that occurred around 1750 to 1850, depending on the location; and a second, more dramatic, decrease in fire activity in the early to mid 1900s (e.g., Masters 1990, Bergeron *et al.* 2001, Van Wagner *et al.* 2006). In contrast, several fire history studies for the Boreal Plains West, and northern Boreal Shield West ecozones reported little change in fire frequency over time, regardless of fire weather zone (e.g., Johnson 1979, Bothwell *et al.* 2004).

This spatio-temporal pattern is also well demonstrated by an analysis of Canada's large fire database (Stocks *et al.* 2003; Figure 5). This map shows that for the period 1959 to 1997, very little area burned in four ecozones where, historically, it had had the highest frequency (Table 2): the southern Montane Cordillera, the Prairies, the Mixedwood Plains in

**Table 2.** Selected fire history studies for areas within fire weather index (FWI) zones of Canada (see Figure 3). Where detailed fire history studies are unavailable, research from areas in adjacent United States was used. If researchers assigned climate change as a primary factor causal to a fire frequency change at the end of a period, this is indicated by an asterisk.

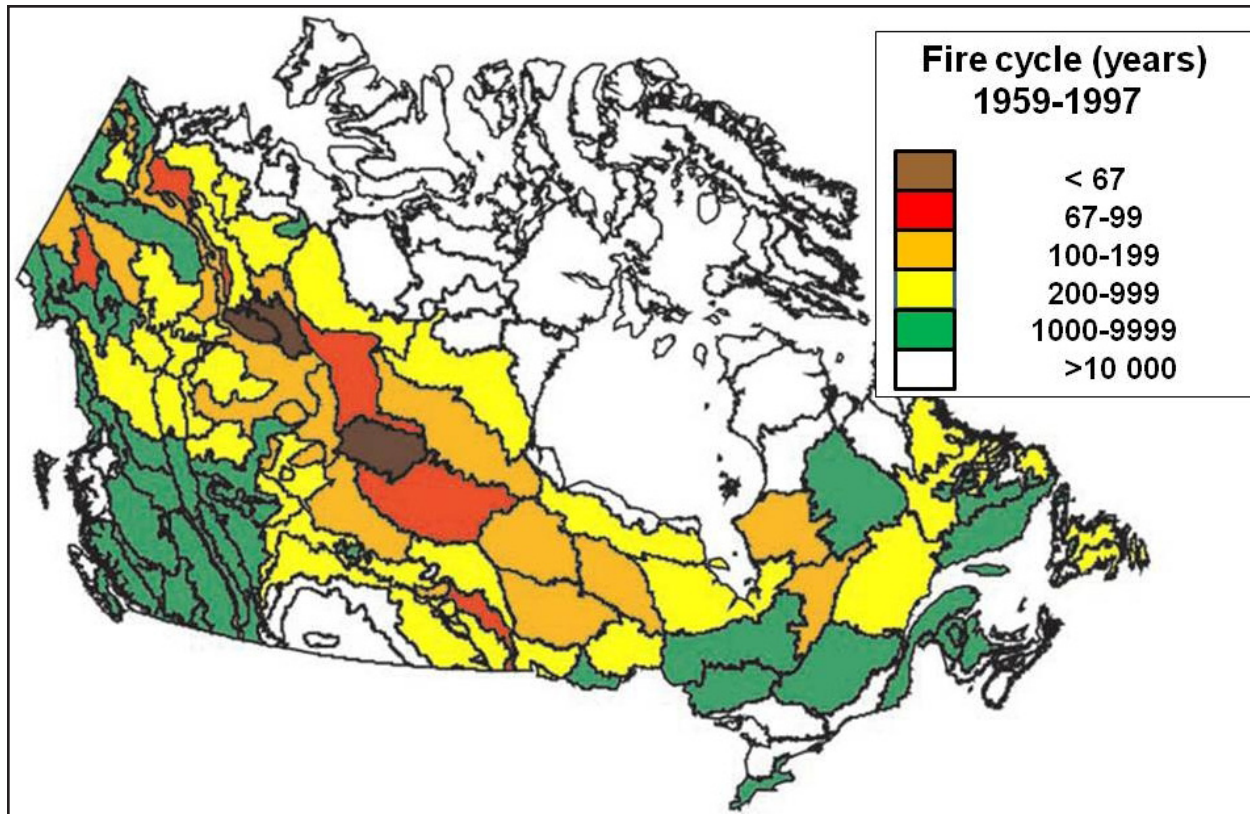
FWI zone	Ecozone <sup>a</sup> -vegetation cover <sup>b</sup>	Reference	Estimated mean fire interval or fire cycle <sup>b</sup> in years (time period, year AD)			Potential causal covariates analyzed <sup>c</sup>		
			Early period	Middle period	Late period			
Minimal	PM-conifer	Lertzman <i>et al.</i> 2002 Gavin <i>et al.</i> 2003	>1000 (<2000)			TE, FT, C		
	PM-conifer	Daniels and Gray 2006	>500			LU		
	MC-conifer	Hawkes 1997, Kopra and Feller 2007	>500 (<1940)			TE, RC		
	PM-conifer	Hallett <i>et al.</i> 2003	174-272 (800-2000)			RC, C		
Very low	TP-boreal conifer	Johnson 1979	102 (<1975)			RC		
	BSE-conifer	Bergeron <i>et al.</i> 2001	69* (<1850)	123* (1850-1920)	273 (1920-1999)	C, RC		
	BSE-conifer	Bouchard <i>et al.</i> 2008	>500 (1800-2000)			RC		
Low	TP-boreal conifer	Johnson 1979	70 (<1975)			RC		
	BSE-conifer	Bergeron <i>et al.</i> 2001	86* (1850-1920)			195 (1920-1999)	C, RC	
	BSE-conifer	Le Goff <i>et al.</i> 2007	99* (1720-1940)			282 (1940-1998)	C, RC	
	BSE-conifer	Lauzon <i>et al.</i> 2007	89* (1600-1850)			176 (1850-2003)	IW, IT	
	BSE-conifer	Bouchard <i>et al.</i> 2008	250 (1800-2000)				RC	
Moderate	MC-conifer	Van Wagner 1978	50 (1680-1915)			>80 (1915-1960)	LU	
	TP-boreal conifer	Johnson 1979	50 (<1975)				RC	
	MC-conifer	Johnson <i>et al.</i> 1990	80* (1520-1760)			110 (1760-1988)	TE, LU	
	BSE-conifer	Bergeron <i>et al.</i> 2001	131* (<1850)	234* (1850-1920)	521 (1920-1999)	C, RC		
	BSE-conifer	Bergeron <i>et al.</i> 2001	83* (<1850)	146* (1850-1920)	325 (1920-1999)	C, RC		
	BSE-mixedwood	Lefort 2003, Bergeron <i>et al.</i> 2004b	83* (<1850)	111* (1850-1920)	326 (1920-1990)	C, FT, IW, RC, IT, FT, LU, LF		
	BC-conifer	Bothwell <i>et al.</i> 2004	28 (1813-1974)				RC	
	TP-boreal conifer	Bothwell <i>et al.</i> 2004	27 (1765-1977)				RC	
High	BSW-mixedwood	Heinselmann 1973, Van Wagner 1978	47 (1542-1911)			1000 (1911-1970)	IW, FT, IT, S, FS, LU	
	AM-mixedwood	Wein and Moore 1977				>650 (1920-1975)	FT, IT, S, RC	
	MC-conifer	Tande 1979	74 (1675-1913)			Few fires (1913-1975)	TE, FT	
	TP-boreal conifer	Johnson 1979	37 (<1975)				RC	
	BP-conifer	Larsen 1997	25-49 (1750-1859)			59-89 (1860-1989)	FT	
	BP-conifer	Weir <i>et al.</i> 2000	15* (<1890)	75* (1890-1945)	1745 (1945-1996)	RC, LU		
	MP-mixedwood	Dey and Guyette 2000, Cwyner 1977	29 (1643-1814)	6 (1814-1954)	Few fires	RC, IT, TK, LU		
	BP-mixedwood	Tardif 2004	35 (1700-1880)	278 (1900-1960)	>15 000 (1960-2002)	C, LU, FS		
Very high	MC-conifer grassland	Tande 1979	21* (1675-1913)			Few fires (1913-1975)	TE, FT	
	MC-conifer	Masters 1990	60* (1508-1778)			130* (1778-1928)	>2700 (1928-1988)	TE
	MC-conifer	Johnson and Larsen 1991	50* (1600-1730)			90 (1730-1990)	TE	
	BP-mixedwood	Weir <i>et al.</i> 2000	25* (1795-1945)			645 (1945-1996)	FT, LU, IT	
	MC-conifer westslope	Van Wagner <i>et al.</i> 2006	99 (1332-1840)			352 (1841-1999)	RC, C, LF	
	MC-conifer eastslope	Van Wagner <i>et al.</i> 2006, and others	72 (1285-1760)	174 (1760-1940)	6855 (1941-1999)	RC, C, IW, TE, IT, FS, LU, TK, LF		
Extreme	MC-conifer grass	Heyerdahl <i>et al.</i> 2006	37 (1700-1860)			Few fires (1860-2005)	LU, C, TE	
	MC-conifer	Gray <i>et al.</i> 2004	19 (1694-1883)			>115 (1884-1998)	TE	
	MC-conifer grass	Heyerdahl <i>et al.</i> 2005	16 (1750-1950)			Few fires (1950-2004)	TE, S	
	MC-conifer grass	Daniels <i>et al.</i> 2009	10-26 (1509-1944)			Few fires (1944-2006)	C, LU	
	P-conifer grass	Fisher <i>et al.</i> 1987	27 (1600-1770)	14 (1770-1900)	42 (1900-1987)	LU, FS		
	P-conifer grass	Brown and Seig 1999	10-12 (1564-1912)			Few fires (1912-1996)	S, LU, RC	

<sup>a</sup> See Figure 1.

<sup>b</sup> As defined by Johnson and Van Wagner (1985), the mean fire interval is the average time between known dates of fires across a point, whereas the fire cycle is the time required to burn an area equal to the study area.

<sup>c</sup> Covariates are coded as proxy climate data, usually derived from tree-ring studies (C), fire suppression (FS), fuel or vegetation type (FT), ignition type (IT), instrumental weather data (IW), lightning frequency (LF), land-use changes (LU), regional comparisons between areas (RC), local topography effects (TE), seasonality (S), and First Nations' occupation patterns and traditional knowledge (TK).





**Figure 5.** Fire cycles for ecoregions mapped within ecozones (Canadian Ecological Stratification Working Group 1995) for the period 1959 to 1997, from the Canadian Large Fire Database (modified from Stocks *et al.* 2003).

south-central Canada, and the Atlantic Maritime. However, similar to the dendrochronology studies, the large fire database records large burn areas still occurring in a broad belt across the centre of the country in the western Boreal and Taiga ecozones, reaching across western Ontario, Manitoba, Saskatchewan and Alberta, and the southern Northwest Territories.

Interestingly, very few of the studies summarized in Table 2 reported an increase in burn area associated with what is commonly called settlement periods—the time of transition from land occupation by First Nations to more recent land uses. The dates for this period vary by area as European influence moved west and north across the country over the last few centuries (McMillan 1995). The failure to detect a period of high fire frequency associated with this migration is remarkable because of the many reports of anthropogenic burning during

the early years of mining, agriculture, railroad operation, and forestry is certainly well documented (e.g., Wein and Moore 1977, White 1985, Weir and Johnson 1998, Bergeron *et al.* 2004b, Lauzon *et al.* 2007, Pyne 2007). In Canada, this prolific level of burning by humans eventually stimulated a major government response including establishment of the Dominion and provincial forest reserves and management organizations, as well as technological developments in pumps, engine spark arrestors, and eventually aircraft (Pyne 2007). Although this amount of burn area may have captured the interest of the governments of the day, it is likely not detected in fire history studies because it was relatively similar or, in some cases, actually less than the burn area in previous times (Table 2).

## DRIVERS OF FIRE FREQUENCY CHANGE

Understanding the magnitude and causes of changes in fire frequency is critical for researchers and land managers in evaluating actions that could be taken if fire frequency is to be modified. Table 2 lists potential causal factors that researchers have evaluated for interpreting spatial or temporal variations in fire frequency. Although there is little debate that land-use changes and fire suppression have been primary factors causing burn area decline in several southern ecozones (e.g., Prairies, Mixedwood Plains, and Atlantic Maritime; Figure 1), for the large area of Canada that has forest cover and is lightly human-occupied, this question is stimulating research and debate (e.g., Johnson *et al.* 1998, Ter-Mikaelian *et al.* 2009, Girardin *et al.* 2009). We first critique two general explanations for reduced burn area that are often evaluated independently (Table 2): climatic change (based upon a biophysical paradigm), and changing human land use patterns (an eco-cultural paradigm). We then provide an explanation based upon an interaction effect between biophysical and eco-cultural factors.

### *Biophysical versus Eco-Cultural Factors: a Difficult Dichotomy*

Long-term, directional climate change is the primary explanation currently advanced under a biophysical paradigm for sustained, reduced fire activity observed for many areas of Canada, particularly for changes occurring prior to the year 1900, and for boreal forest ecozones (Table 2). Large burn areas in Canada usually occur during droughts resulting from stable, high pressure systems in the upper atmosphere that block the west to east movements across the country of rainfall-bearing storms (Skinner *et al.* 2002). Numerous studies (reviewed by Macias Fauria and Johnson 2008) describe drought conditions resulting

from tele-connections between large-area synoptic patterns. These range from relatively short-term phenomena (several months) of the Arctic Oscillation, to the longer El Niño Southern Oscillation (2 yr to 4 yr periodicity), to the Pacific Decadal Oscillation (20 yr to 40 yr). These patterns in turn fluctuate within the century-scale Dansgaard-Oeschger cycles that influence climatic anomalies such as the Medieval Warming Period or Little Ice Age (Bond *et al.* 1997). All of these climatic cycles may, in turn, be altered by directional anthropogenic global warming with potentially significant implications for Canadian fire frequency (e.g., Flannigan and Van Wagner 1991; Flannigan *et al.* 1998, 2005).

Despite the continued emphasis by many biophysical researchers on changing climate as a causal factor for increasing fire cycles or mean fire intervals (Table 2), there is, as of yet, no strong evidence for continuous, directional climatic change that could explain the magnitude and consistency of the decline in burn area observed in several Canadian ecozones. Under the key assumption that lightning, not humans, caused most Canadian burn area over the long-term (Johnson and Larsen 1990, Bergeron *et al.* 2001), climate-based explanations for changing fire frequency propose that historic burning mainly occurred during the peak period of lightning occurrence from late May through August (Nash and Johnson 1996). Several researchers (Masters 1990, Johnson and Larsen 1991, Bergeron and Archambault 1993, Le Goff *et al.* 2007) suggest that weather conditions since the beginning or end of the Little Ice Age (various years proposed by different authors; Table 2) may have reduced the frequency of days when large fires could occur during this summer lightning period. Support for this hypothesis is difficult to evaluate for western Canada because most studies did not actually analyze climate or instrumental weather covariate datasets (e.g., Johnson *et al.* 1990, Masters 1990, Johnson and Larsen 1991, Weir *et al.* 2000; Table 2). For the Boreal Shield

East ecozone, Bergeron and Archambault (1993) correlated a climate-proxy dataset developed from a single set of tree rings to explain a fire frequency decline that occurred about 1850, and the results from this limited dataset were, in turn, extrapolated to several other areas (Bergeron *et al.* 2001, Bergeron *et al.* 2004b). Other approaches using instrumental weather records in eastern Canada unfortunately did not include large datasets across transition times when fire frequency declined (e.g., Lefort *et al.* 2003, Girardin *et al.* 2004, Lauzon *et al.* 2007). Few of the above studies listed in Table 2 quantified and evaluated covariates related to cultural factors (e.g., First Nations population, number and location of fires by ignition source, land use practices, etc.).

More recently, a large dataset of tree-ring width chronologies from across the country have been evaluated to develop multi-century, proxy-weather data, including the FWI's mean monthly Drought Code. Based on recent burn area (Stocks *et al.* 2003), Girardin (2007) and Girardin and Sauchyn (2008) have extrapolated these data to derive an expected annual area burned for the past two centuries. This analysis shows that for the period 1781 to 1982, the weather conditions favoring large burn area was oscillatory with a mode of 26.7 yr. In order of magnitude, the three periods of predicted lowest annual area burn were 1796 to 1815, 1945 to 1969, and 1878 to 1906. Four periods of predicted highest annual area burned were 1781 to 1795, 1837 to 1849, 1907 to 1944, and most recently, 1970 to 1982 (Girardin 2007). There is spatial heterogeneity in area burned within North American ecozones within periods of years (Girardin and Sauchyn 2008), and at a circumboreal level for the actual spatio-temporal periodicity of the cycles themselves (Girardin *et al.* 2009). On the basis of correlation analysis, Girardin (2007: Table 3) shows that for Canadian ecozones in which fire activity remains high (e.g., Taiga Plains, Taiga Shield, Boreal Shield West; Figures 1 and 5),

the current observed burn area (1920 to 2005) has a reasonably strong relationship ( $r = 0.45$  to  $0.87$ ) with North American land temperature records. However, burn area correlation to temperature is weaker ( $r = -0.17$  to  $0.47$ ) for the ecozones in which fire frequency has declined (e.g., Montane Cordillera, Prairies, Boreal Shield East). This suggests that other factors are influencing burn area in these ecozones. Similar results were obtained when instrumental weather records were used to calculate century-long monthly precipitation and FWI datasets for Banff National Park in the Montane Cordillera (White 1985, Fuenekes and Van Wagner 1995). Analysis of these data showed that the frequency of drought varies over time, but not in a directional manner. Burn area was historically dominated by human sources, has consistently declined over the decades, and has become increasingly unresponsive to weather periods favorable to fire ignition and growth. Historically, drought years consistently resulted in large fires; recently, they have not (White 1985, Van Wagner *et al.* 2006).

Significantly, over the whole country, the ecozones with the lowest fire frequency in the past 50 yr (Figure 5; Stocks *et al.* 2003) compared to long-term fire frequency (Table 2) are southern areas (e.g., Montane Cordillera and the northern edge of Plains ecozones). Although some of these areas may have experienced an increase in precipitation in the last century compared to other ecozones due to heterogeneity in climatic fluctuations across the northern hemisphere (Girardin *et al.* 2009), they currently have the most days of any Canadian regions during which FWI conditions are high (Figures 3 and 4; Table 1). The long-term decrease in burn areas in these ecozones is thus likely due to other factors interacting with climatic variation.

Alternately, the eco-cultural paradigm posits that changes in cultural practices can explain a portion of the reduced burn area. Historic First Nations' occupation (McMillan

1995) and use of fire has been extensively documented for virtually all Canadian ecozones (Figure 1) including the Mixedwood Plains near the Great Lakes (Day 1953, Loope and Anderton 1998, Dey and Guyette 2000), the Boreal Plains (Lewis 1980, Lewis and Ferguson 1988), the Prairies of west-central Canada (Nelson and England 1971, Pyne 2007), the Montane Cordillera (Johnson-Gottsfeld 1994, Barrett and Arno 1999, White *et al.* 2001, Lepofsky and Lertzman 2008), and drier areas of the Pacific Maritime ecozone (Turner 1999, Beckwith 2004, Bjorkman and Vellend 2010). Cultural fire use likely declined dramatically beginning as early as the 1500s in eastern Canada as long-term human use patterns changed due to disease-driven population declines, tribal movements, education programs, resettlement on reserves, and a myriad of other cultural changes that have altered First Nations' land use practices (McMillan 1995, Turner *et al.* 2003, Pyne 2007). For example, the smallpox epidemic in the 1780s in western North America (Boyd 1999, Binnema 2001) is coincident with several studies that show an initial decline in fire frequencies around this time (Table 2; Van Wagner *et al.* 2006). Recent cultural changes including fire prevention and suppression (Stocks *et al.* 2003, Cumming 2005, Martell and Sun 2008) are also likely important contributing factors to a second and more severe inflection in fire frequency that occurred in mid-1900s across much of southern Canada (Table 2, Figure 5). This recent reduction in burn area is also partially due to land use change that alters fuel abundance or continuity (Weir *et al.* 2000, Krawchuk *et al.* 2009). For example, grazing by domestic stock may reduce herbaceous biomass and hence potential for burning (Heyerdahl *et al.* 2006). Obviously, in the Prairie and Mixedwood Plains ecozones (Figure 1), replacing large areas of native plant communities with agricultural crops has reduced fire potential (Weir *et al.* 2000).

However, current anthropological research and traditional knowledge rarely explain the

large decline in burning observed in several ecozones. As critiques on the magnitude of eco-cultural burning have noted (Vale 2002, Barrett *et al.* 2005, Baker 2009), historical or traditional ecosystem knowledge research infrequently provides detailed descriptions of aboriginal peoples burning the large areas that would explain early-era, high fire occurrence across broad regions. We also observe that many studies report people carefully burning limited areas near travel routes, villages, or important plant gathering areas (e.g., Lewis and Ferguson 1988, Turner 1999, Beckwith 2004); but even if small fires were often intended, it is unclear to us how fire spread was limited if weather favorable for high intensity fires occurred after the burns were lit. Even today, with application of technology and human resources, prescribed burns in northern forests and shrublands routinely develop high intensities that are difficult to control, and cross control lines. Similarly, researchers (e.g., Johnson *et al.* 1998, Bridge *et al.* 2005) argue that due to high fire intensities, there is insufficient evidence that modern fire suppression programs have demonstrably reduced burn area in several ecozones, even in southern portions of Canada. However, their research is generally not supported by fire history data showing fire frequency declines in the 1900s (Table 2). In addition, they did not evaluate the cumulative effects of modern efforts to prevent human fire occurrence, nor the effects of rapid initial actions to prevent small lightning fires from becoming large (Cumming 2005, Martell and Sun 2008).

Moreover, the current cultural paradigm of small fires only does not reconcile the fire history evidence. The large area of human-ignited fires known to be associated with the settlement period in many landscapes appears to be similar or less than the area burned in the preceding period of First Nations' land occupation (Table 2; White 1985, Van Wagner *et al.* 2006). To explain this pattern, Weir and Johnson (1998) and Weir *et al.* (2000) provide an innovative argument for an interaction between cli-

matic and cultural ignition factors in their study area in Saskatchewan. They conclude that the pulse of known settlement burning that was observed in the period 1890 to 1945 only maintained the previous era of high burn area that they assume was caused by lightning. This burn area would have been expected to decline due to a climatic change proposed to have occurred at the same time. However, they did not evaluate climate or instrumental weather datasets available for these periods and did not describe potential aboriginal burning patterns prior to settlement (Table 2). Although this type of interaction effect may have occurred for this study area, on a national basis, a more parsimonious explanation is that climate has, in most areas, continued to be cyclic (see Figure 2 in Girardin 2007) and has not caused the long-term decline of fire frequency that was observed for southern wildland areas of the country. As noted above, past widespread settlement burning simply maintained the historic pattern of burn area caused by previous cultural and lightning-ignited fires interacting with climatic variation (White 1985, Van Wagner *et al.* 2006)—although the purpose and timing of this burning likely varied from First Nations' use of fire. Eventually, as the period of settlement fires ended, burn area declined to the consistently low burn area and resulting long fire intervals observed today in many ecozones (Table 2, Figure 5).

To conclude this literature review, research approaches to fire frequency using biophysical or cultural groups of factors independently are imperfect (Lepofsky and Lertzman 2008). As Lertzman *et al.* (1998) observe,

*Hypotheses about the causal mechanisms for temporal variability in fire frequency should be generated from, or substantiated by independent data (e. g., long-term climate studies, or the history of settlement, development, and management in a region).*

Recently, biophysically oriented studies more rigorously analyze climate or instrumental weather data, but cultural variables are usually not evaluated due to the often-made assumptions that people, past or present, only infrequently ignite fires (Johnson and Larsen 1991), or that many areas of Canada were virgin landscapes with low human occupation and few human effects on ecosystems (Bergeron *et al.* 2001). However, research from archaeology, history, anthropology, and traditional knowledge increasingly does not support these viewpoints (McMillan 1995, Pyne 2007). Cultural studies continue to fail to appreciate that, although humans may have favored burning during dormant seasons outside the main summer period of drought (Lewis 1980, Barrett and Arno 1999), their fires could persist on the landscape and eventually grow, similar in pattern to lightning-caused fire (Pyne 2007). In addition, there is increasing evidence that, through carelessness, warfare, or other means, human fires were ignited in locations and time periods in which widespread burning did occur (Boyd 1997, Pyne 2007). To simply summarize, both people and lightning cause fires, and under certain combinations of biophysical conditions, any fire can burn vast areas.

#### *Interactions between Biophysical and Eco-Cultural Factors*

Given that both biophysical and eco-cultural factors (Figure 2) contribute to the spatial and temporal variability in past and present Canadian fire regimes, the key question is how do these interact? Researchers are evaluating this question for numerous areas including the North American boreal forest (Weir *et al.* 2000, Chapin *et al.* 2003, Kasischke and Turetsky 2006), the Eurasian boreal forest (Drobyshev *et al.* 2004, Granström and Niklasson 2008, Farukh *et al.* 2009), cordilleran forests (White 1985, Carcaillet *et al.* 2009), and the earth's biosphere as a whole (Ferretti *et al.* 2005, Lavorel *et al.* 2007, Marlon *et al.* 2008, Kraw-

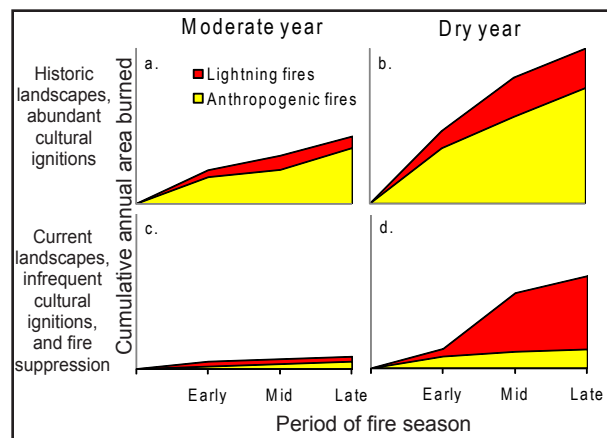
chuk *et al.* 2009). In Canadian boreal forests, Pyne (2007: 31) describes the historic interactions of these two factors as a mosaic of anthropogenic and lightning-driven fire:

*Some hundreds of years ago the boreal belt overall probably had more fires, more spring fires, a finer texture of burns along major routes of travel and patches of habitation, with splotches erupting when those fires broke free. These fires, too, would originate from corridors and seasons of human occupation. What these fires burned, lightning could not. Probably the grand sweep showed a mosaic of larger and smaller tiles; the bigger pieces were far removed from human settlement, with a fine-grained landscape of intricate shards near habitations.*

From our review of these studies, we propose several principles that have significant importance to the application of past and present interaction of biophysical and eco-cultural factors to fire management in Canadian parks and protected areas. First, as noted above, the physics of fire growth are not dependent on the type of ignition, but rather on the interacting physics of weather, terrain, and fuels (Van Wagner 1985). However, for cultural ignitions, human understanding of these interactions can influence burn area to the degree that weather and fire behavior conditions can be predicted. Secondly, although the frequency of past lightning and human ignitions remains difficult to determine (Wierzchowski *et al.* 2002, Barrett *et al.* 2005, Kay 2007), it is clear that past peoples, for social or technological reasons, did not systematically put out fires. Thus, depending on weather, fuels, and topography, human or lightning ignitions could smolder or freely burn on the landscape for days to months (Lawson *et al.* 1997, Pyne 2007: 61-64, Anderson *et al.* 2009, Anderson

2010). This is contrary to most current North American land use practices that successfully suppress many fires when they are smoldering or have low intensities (Cumming 2005, Martell and Son 2008). Moreover, Lewis and Ferguson (1988) documented First Nations' use of fire in areas of forest deadfall with the purposeful expectation that these fires would smolder until dry conditions prevailed. Finally, for most of Canada, we reiterate that periods of extreme fire weather (drought and high winds) are the primary factors causing large burn areas (Amiro *et al.* 2004). However, effects of changes in the frequency of these weather events on burn area cannot be evaluated independently of lightning frequency, cultural factors, or fire management actions that regulate the number of small fires on the landscape that can become large (Lertzman *et al.* 1998).

Based upon these ideas, Figure 6 is a highly simplified conceptual pattern of a long-term fire regime showing the interaction of cultural and lightning ignitions and years with high fire weather index conditions ("dry"), and moder-



**Figure 6.** A conceptual model of annual cumulative burn area as an interaction between ignition source (lightning or cultural) and general fire weather pattern ("moderate" or "dry" year) based upon the fire regime of an eastern slope area of the Montane Cordilleran ecozone (White 1985, Wierzchowski *et al.* 2002, Van Wagner *et al.* 2006). The model assumes that the previous year was a "wet" year with no area burned that would influence the current year's burning pattern.

ate fire weather (“moderate”) conditions. We assume that the previous year was “wet,” leaving no burned areas on the landscape that would influence the current year’s fire behavior. We think that this model may have application across the southern part of Canada where First Nation and modern human populations are highest, and where modern fire suppression efforts are most effective (Figure 5). This model is based upon data from Banff National Park, in the Montane Cordillera ecozone; Banff has one of Canada’s most extensive records of burn area, fire cause, and detailed FWI calculations (White 1985, Fuenekes and Van Wagner 1995, Rogeau *et al.* 2002, Van Wagner *et al.* 2006). This information can be evaluated for the periods of 1880 to 1940 when frequent human ignitions occurred, and from 1940 to 1980 when actions to prevent cultural ignitions and suppress fire intensified. For the period 1890 to 1980, the frequency of dry years with extended periods of extreme fire weather has fluctuated, but occurred about 2 times per decade. Several years per decade had at least some days of moderate to high fire weather (White 1985).

Since 1880, human ignitions have caused >60% of the burn area in Banff (White 1985, Wierzchowski *et al.* 2002). This prevalence of human-caused fire may seem high, but it is useful to consider that as late as the 1960s, a decadal average of 45% of Canada’s national burn area was classified as human ignited (Stocks *et al.* 2003). On the nearby eastern slopes of Alberta, 71% of the massive burn area of 1968 was lit by people (Pyne 2007: 311). As noted above, for central Saskatchewan, Weir and Johnson (1998) and Weir *et al.* 2000 documented more than a 50 yr fire history period (1890 to 1945) that was dominated by human-caused settlement burning, and this only maintained the long-term, 25 yr fire cycle that had occurred in the period 1795 to 1890 (Table 2). However, the area of unplanned, human-caused burns in both central Saskatchewan and Banff declined after 1940, similar to

the national area decadal averages of only 13% in the 1970s, 12% in the 1980s, and only 6% in the 1990s. Stocks *et al.* (2003) attribute this national proportional decrease to expanded detection and monitoring in northern ecozones where lightning fires are most common, and to reductions in human-caused burn area through fire prevention and aggressive initial attack. For further comparison, the area burned by humans in Alaska also declined from 26% of the total in the 1960s and 1970s to 5% in the 1990s and 2000s (Kasischke *et al.* 2010). Elsewhere, for northern regions globally, documented cases in which humans likely caused a significant proportion of the burn area include several time periods and locations in northern Sweden (Granström and Niklasson 2008), and the Kama district of Russia for the period 1700 to 1960 (Drobyshev *et al.* 2004). For all Russian boreal forests for the period 2003 to 2005, Achard *et al.* (2008) describe how climatic variation and people interacted to increase burn area by 2.5 times in zones with high human activity, and that only one third of the area burned can be explained by climatic anomalies alone. The Mongolian sub-boreal forest and steppes may have current fire regime conditions particularly analogous to historic periods in southwestern Canada and northwestern United States (Johnson *et al.* 2009). From 2001 to 2007, satellite monitoring showed over 30% of Mongolia’s forested lands burned. Although lightning ignitions do occur (Johnson *et al.* 2009), ignition by humans causes the majority of the burn area (Farukh *et al.* 2009). The potential importance of long-term cultural burning in Mongolia could be significant. Burning over 30% of the forest over seven years would not be unexpected based on analyses of long-term conditions in several forested regions in which fire scars from the period since *circa* 1800 indicate an ongoing mean fire interval of <25 years (Valendik *et al.* 1998, Byambasuren *et al.* 2010).

As the dependent variable in our conceptual model, we use the cumulative area burned

on the landscape over fire season (Figure 6). This is important because for almost all Canadian ecozones, vegetation burned early in the year is unlikely to re-burn later in the year, and forested vegetation types will sometimes not re-burn for several years (Lavoie and Alexander 2004). Cultural fires most commonly occur during two seasonal pulses—early and late in the fire season when vegetation is cured, ignition is easy, and fires have relatively low rates of spread and flame lengths (Lewis and Fergusson 1988, Boyd 1998, Kasischke and Turetsky 2006, Pyne 2007, Farukh *et al.* 2009; Figure 6a, b). During years of moderate fire danger (Figure 6a), the early season ignitions burn dormant vegetation on moist soils, smolder lightly, and usually go out over night as the relative humidity rises, or in a few days as vegetation greens up (Lewis 1980). In contrast, in dry years when soils have low moisture content or when spring rains do not occur, these early season burns can persist (Anderson 2010) and begin to spread (Figure 6b), possibly well in advance of the lightning season (Granström and Niklasson 2008, Farukh *et al.* 2009). Significantly, these fires would then be active during the spring foliar moisture dip when conifer needles are highly flammable (Van Wagner 1977) and may thus burn large areas of conifer forests. Further, in dry years, existing spring-season or new cultural ignitions could continue into the summer (Figure 6b), resulting in fires additional to those ignited by lightning, occurring during the main period of seasonal drought (Farukh *et al.* 2009). However, where cultural fire is uncommon, or is easily contained in moderate fire danger years, the area burned is less but occurs during a major pulse during summer when lightning occurs (Figure 6d).

We propose several fire regime outcomes that could occur from this interaction of weather with cultural and lightning ignition patterns.

- Due to early- or late-season ignition during cooler and moister conditions, cultural fires tended to burn a relatively

large fraction of the landscape being burned with low to moderate severity. As conditions were less favorable for fire spread, the area burned resulted from a relatively large number of smaller fires (Lewis and Fergusson 1988, White *et al.* 2005, Granström and Niklasson 2008). This is in contrast with the recent pattern of an increasingly exclusive regime of large, mid-summer, intense fires in Canada and some other areas of the boreal forest (Stocks *et al.* 2003, Drobyshev *et al.* 2004, Bridge *et al.* 2005, Kasischke *et al.* 2010).

- Early season cultural and lightning ignitions that are not suppressed can smolder for sustained periods during persistently dry conditions (Lawson *et al.* 1997, Otway 2007) and, combined with other ongoing human ignitions (Farukh *et al.* 2009), result in large areas burning in the mid-summer fire season even in the absence of further lightning ignition (Pyne 2007: 61-63, Anderson 2010).
- Cultural fires were typically lit near human occupation areas (Drobyshev *et al.* 2004, Achard *et al.* 2008), and thus are often burned away, not towards, high human use in mid-summer. This reduced the risk of high intensity fires (from both lightning and cultural causes) burning over areas important to people during mid-summer drought periods (Lewis and Fergusson 1988, Granström and Niklasson 2008). This pattern of historic burning may be relevant to contemporary landscape-level fire restoration programs.
- In most Canadian ecozones, frequent cultural burning can maintain areas of grasslands, shrublands, or open conifer forests, and inhibit the development of dense conifer cover (e.g., Johnson-Gottesfeld 1994, Weir and Johnson 1998). These open-fuel types are flammable under the low to moderate fire weather conditions that occur frequently in most ar-



eas of the country (Figures 3, 4; Table 1), particularly when herbaceous fuels are cured in the spring or fall (Lewis and Fergusson 1988, Stocks *et al.* 1989, Johnson-Gottesfeld 1994). In contrast, closed conifer forests are usually most flammable during mid-summer droughts (Johnson and Wowchuck 1993). This positive feedback loop in which cultural fires remove dense conifer forests and maintain fuel types that facilitate future fire use, even during moderate fire danger, is probably a key link between people, weather, and fire frequency (Lewis 1980, Pyne 2005: 132-134).

- The overall area burned can change dramatically through interactions between cultural ignitions and weather. When cultural fires are eliminated, particularly during moderate fire danger years, burn area can be very low (Figure 6c) because cultural fires are not purposely ignited in the limited areas that are flammable (White 1985, Pyne 1995: 133). Conversely, when drought and large numbers of cultural and lightning-ignited fires interact during dry years (Figure 6b), massive areas can burn (Achard *et al.* 2008, Farukh *et al.* 2009).

These potential interactions of cultural and biophysical factors allow us to reconsider further the hypothesis of ignition limitation. In many historic landscapes, human habitation areas and movement corridors were nearly saturated with human ignitions (Lewis 1980, Drobyshev *et al.* 2004, Granström and Niklasson 2008), with small, low intensity fires predominating in these areas during the marginal burning conditions (Pyne 1995, 2007) that occurred in most years, and particularly in the early and late fire season (Table 1). During drought years, these fires grew and amalgamated with lightning ignitions that predominated in areas lightly used by humans (Bridge *et al.* 2005). Ultimately, with ignition relatively

common, the amount of burn area was determined by the frequency of weather periods favorable for fire growth, and the temporal pattern of fuel recovery in areas burned in periods immediately past (e.g., a few months to a few years prior to re-ignition). These interacting spatial and temporal processes of ignition limitation require further research (Krawchuk *et al.* 2009).

Given the large area of Canada potentially affected by biophysical and cultural interactions on fire frequency, evidence of this burning should be apparent in global change studies. A recent analysis of sedimentary charcoal accumulation records, climate, and human use assembled from six continents (Marlon *et al.* 2008) shows that global burning gently declined from 1 AD to approximately 1750 AD, rose sharply from 1750 to 1870, then declined dramatically through about 1950 when reliable sample resolution ends. The exception to this pattern was in the northern circumpolar boreal forest (northern latitudes >55 degrees) where burning increased about 1750, but has remained relatively stable through the mid-1900s. From this global perspective, Marlon *et al.* (2008) conclude that a cooling climate may have driven reduced burning up until 1750, but since that time, rapid changes in global human land use practices such as expansion of agriculture, logging, urbanization, industrialization, and fire suppression are better correlated to the observed burn area. These effects are less apparent in the north due to low human populations. A similar global fire frequency pattern is inferred from methane levels observed in glacial ice cores. Ferrati *et al.* (2005) concluded that a dramatic reduction in burning since the 1500s, discernible from methane levels specifically from North America, might be the result of disease-driven human depopulation. These studies corroborate the spatial pattern of dendrochronology studies reported for Canada for the period since approximately 1650 (Table 2).

Further, the spatial and temporal variation of burning patterns observed in similar circum-boreal areas such as Mongolia and Canada described above (Johnson *et al.* 2009) offers interesting opportunities for further research of interactions between biophysical and cultural factors. Long-term quantification of variation of fire history in these areas (e.g., Table 2 for Canada, Byambasuren *et al.* 2010 for Mongolia) can be evaluated with potential causal covariates such as the instrumental weather record (e.g., Girardin *et al.* 2009); lightning ignition frequency (e.g., Weirzchowski *et al.* 2002); and First Nation, pastoralist, and settler population levels and activity patterns (e.g., Fernández-Giménez 1993, Weir and Johnson 1998, Boyd 1999, Binnema 2002). This interdisciplinary research could provide useful explanations for why some ecozones on the two continents historically appear to have had similar fire regimes that diverged widely in the past two centuries, as well as for the processes by which interacting biophysical and cultural factors influenced this change.

## **FIRE RESTORATION CASE HISTORIES IN PARKS AND PROTECTED AREAS**

The above review of spatio-temporal variation in Canadian fire regimes suggests that interacting cultural and biophysical factors are likely causing dramatic declines in fire frequency, particularly in southern areas of the country where human ignitions have been prevented for nearly a century, and fire suppression is most aggressive. Moreover, the long-term historical patterns of burning resulting from this interaction can help guide re-introduction of fire to protected areas where ecological restoration is contemplated. Here we describe four case histories in which an integrated biophysical and eco-cultural approach to fire restoration has either evolved or has been deliberately implemented.

### ***La Mauricie National Park***

La Mauricie National Park (LMNP) is a 536 km<sup>2</sup> area at the transition of hardwood and eastern white pine (*Pinus strobus* Douglas ex D. Don) stands of the Mixedwood Plains and the forests of the Eastern Boreal Shield ecozones, approximately 200 km NE of Montreal, Quebec (Figure 1). The park region has a complex fire history and is characterized by a mosaic of conifer, mixedwood, and deciduous forest vegetation. Eastern white pine is found in low numbers scattered throughout the park region with a few remaining stands along waterways. Red oak (*Quercus rubra* L.) is rare but occurs in association with maple (*Acer* L.) forests and mainly on hilltops in southern sections of the park. White pine and red oak are both recognized to be fire-adapted and to rely on potentially short fire cycles of <100 years (Cwyner 1977, Loope and Anderton 1998, Dey and Guyette 2000). Boreal forests at higher elevations have moderately long fire cycles of 100 yr to 200 yr (Bergeron *et al.* 2004b) within a mosaic of very long fire cycles in the eastern hardwood forest (Talon *et al.* 2005). The relatively short fire cycles near Quebec water bodies, as determined from tree-ring studies has, at times, been an enigma to ecologists. Bergeron (1991) suggested that this could be due to potentially unique lightning ignition patterns near lakes. Alternatively, historians and anthropologists propose that this may be due to human land use patterns along river and lake travel routes (Lewis and Ferguson 1988, Loope and Anderton 1998, Dods 2004).

The park began prescribed burning in 1991, focusing on restoring the eastern white pine stands that historically bordered lakes and rivers (Quenneville and Thériault 2001, Ortuno *et al.* 2009) but were removed by extensive logging in the 1800s (Domaine and Hebert 2008). The burning objective was to replicate a historic heterogeneous fire regime with an overall fire cycle of approximately <50 years.

Small, low-intensity thinning fires should maintain white pine stands that are resilient to the periodic large, high-intensity burns that occur at a cycle of over 150 years (Cwyner 1977, Guyette *et al.* 1995). Prescribed fire appears to be successful in removing competing hardwood and conifer species, notably balsam fir (*Abies balsamea* [L.] Mill.), while leaving seeds from large, fire resistant white pine trees to regenerate on burned substrates following good seed years (Domaine and Hebert 2008).

Currently, the LMNP management plan requires that the park maintain at least 50% of the long-term burn area as calculated for the areal extent of vegetation types stratified by estimated historic fire cycle. Few large fires are now occurring in the broader landscape (Lefort *et al.* 2004) due to potential climate change, reduced ignitions by humans, relatively few lightning ignitions (Morrisette and Gauthier 2008), and detection and rapid initial attack, resulting in a current fire cycle longer than 300 years (Table 2, Figure 5). Managers therefore predict that planned ignition prescribed fires will continue to be a dominant component of their programs. The park burning program is now expanding not only to include the maintenance of a few declining red oak stands, but also larger areas to restore the fire regime and age class distribution. The park cannot follow a strictly eco-cultural or biophysical perspective in restoring fire due to ecosystem changes that significantly affected species abundance and dynamics in the last two centuries, the size of the park, as well as a lack of information on historical fire use. Anthropogenic use of fire is at times a contentious topic in eastern forests (e.g., Clark 1995), but it appears likely that humans did periodically burn along travel routes or near campsites (Guyette *et al.* 1995). Constrained by relatively moist conditions and adjacent hardwood forests that were relatively fire-proof during the summer (Loope and Anderton 1998), these burns were usually not expansive. However, during dry periods, fires would spread into ad-

acent dry deciduous forests such as red oak, and possibly from here into upland areas of boreal forest. During serious droughts, large areas of the boreal forest also burned from lightning or human ignitions, and spread into pine stands. Significantly, the severity of these landscape-wide burns on white pine stands would be mediated by the smaller, more frequent human-caused fires that occurred previously. Thus, the development of the management program in LMNP is moving towards mimicking this large-area process with a long-term anthropogenic component that addresses the need for eco-cultural fires as a priority but ensures that larger biophysical fires also occur.

### *Prince Albert National Park*

Prince Albert National Park (PANP) is an area of 3461 km<sup>2</sup> in the Boreal Plains ecozone (Figure 1), with a vegetation of conifer forest, transitional aspen (*Populus tremuloides* Michx.) parkland, and small prairies. The park has a rich fire history with surprisingly frequent fire occurrence: prior to 1890, the north and south halves of the park burned on 15 yr and 25 yr fire cycles, respectively (Weir *et al.* 2000). Area burned decreased substantially in the 1900s, and present-day fire cycles are in the range of hundreds to thousands of years (Table 2). Near the park's southwestern boundary, remnant patches of fescue prairie exist, although these have been shrinking due to encroaching aspen and shrubs. In contrast, the northern half of the park is boreal mixed-wood forest, with stands of jackpine (*Pinus banksiana* Lamb.), balsam fir, and black spruce (*Picea mariana* [Mill.] Britton, Sterns and Poggenb) interspersed by numerous large lakes, forming a classic northern Canadian landscape.

The park has a long history of prescribed fire use. As early as the 1930s, park wardens lit fires along the southern boundary in early spring to prevent high-intensity fires entering the park from nearby agricultural clearing (Trot-

tier 1985, Weir and Johnson 1998). Much of this burning was done while park wardens patrolled on horseback along park boundary trails, as evidenced by old park equestrian saddles inspected during the 1980s that still had sandpaper glued on the saddle-horn for the rapid lighting of matches (C. White, Parks Canada, personal observation). After a period of total fire suppression (about 1940s to 1970s), research during the 1960s showed that the extent of fescue prairie had declined severely in the preceding decades (Carbyn 1971). An ambitious prescribed fire research project, based upon a biophysical restoration approach, commenced in 1974 in the southwestern area of the park, apparently the first scientific application of fire ecology within the Parks Canada Agency. After a decade of treatments and data collection, the final report showed that burn treatments had indeed reduced shrub and aspen forest coverage and increased the frequency of native grasses (Trottier 1985).

In the 1990s, park staff returned to routine prescribed burning towards an objective of maintaining at least 20% of the park's long-term fire cycle (Parks Canada 1999). Initially, this use of prescribed fire was planned to facilitate a biophysical paradigm stressing subsequent management of lightning-ignited, high-intensity fires. Burn probability modeling suggested that a strategy of linking the large lakes with managed fuel breaks, including prescribed burns, could be a viable strategy for containing lightning fires within park boundaries (Parisien *et al.* 2007). Setting up this network of strategic burn units is currently underway, with burns conducted when funding and weather conditions permit. However, park staff recognized that in boreal mixedwood stands dominated with conifers, only a narrow range of weather conditions exists between a controllable prescribed fire and a rapidly moving wildfire. Thus, setting up this fuelbreak network has proceeded cautiously and gradually.

Most recently, park fire managers have returned their focus to the southwestern portion

of the park dominated by aspen with limited areas of fescue grassland (Frandsen 2008). In this latest initiative, park staff burn in the spring dormant-growth period within the habitat of a recently restored herd of plains bison (*Bison bison* L.). Although not explicitly recognized, this approach follows long-term patterns of First Nations' burning to enhance bison habitat (Hind 1971). Unlike burning in the dense forests in the northern area of the park, these spring season burns have lower intensities and are more easily managed. Further, in deliberately favoring bison, a species with long-term importance to humans, the park is tentatively recognizing fire's eco-cultural role. At PANP, then, restoring fire requires an integrated approach at the edge between the grasslands and aspen forests of the Prairie ecozone that have historical conditions strongly influenced by eco-cultural fires, and the Boreal Plains forests that have a biophysically driven regime of high-intensity, large-area fires, often started by lightning.

### *Banff National Park*

Banff National Park (BNP), Canada's first national park, lies at the eastern edge of the Montane Cordillera ecozone. For over a century, the park has been a proving ground for industrial-era fire management techniques, including removal of First Nations, fire education and prevention, fire suppression, and more recently, restoration of fire (White 1985; Binnema and Niemi 2001; Pyne 2004, 2007: 361-371 and 471-473). The park has a complex spatial and temporal fire regime over its 6640 km<sup>2</sup> area on the eastern slopes of the Rocky Mountains in Alberta. Since 1885, lightning and lightning-caused fires are uncommon compared to adjacent areas to the east and west (White 1985, Wierzchowski *et al.* 2002). Despite low lightning fire occurrence, the spatial pattern of long-term fire cycles ranged from <50 yr in the lower elevation montane region to >200 yr in upper subalpine

forests (Rogean et al. 2004, White et al. 2005). The overall area burned by fire in Alberta's eastern slope landscape (including Banff), averaged over all elevations and aspects, has dramatically changed over the past two centuries. Fire cycles increased from <80 yr prior to the 1760s, to about 175 yr for the next 150 yr, to over 6000 yr since the 1940s (Table 2; Van Wagner et al. 2006).

Park staff used an ecological land classification mapping system correlated to fire regime characteristics (White et al. 2005) as a basis to begin prescribed burning in 1983. A biophysical approach dominated early thinking. Burn units were assigned fire cycles and burn probabilities as a basis for a random selection process that would mimic lightning ignition (Lopoukhine and White 1985). However, managers soon recognized that the possibility of high-intensity fires escaping park boundaries required that social values and practical considerations, not a random number simulator, should prioritize burn locations. The program then followed two directions: 1) using mechanical thinning combined with prescribed fire, they built containment areas to reduce fire intensity adjacent to park infrastructure areas and to avoid the spread of fires beyond park boundaries; and 2) doing prescribed burns in areas that historically had short fire cycles, such as subalpine areas important for grizzly bears (*Ursus arctos* L.), and low-elevation, montane forests (Hamer and Herrero 1987, White et al. 2005, Pengelly and Hamer 2006). Again, the focus was on biophysical interactions of fire frequency with terrain and resulting vegetation patterns (Rogean et al. 2004).

In the 1990s, public concerns over fire risks and smoke, combined with the failure of trembling aspen to regenerate to heights >2 m after fire forced a re-evaluation of the program (Pyne 2004, 2007; White and Fisher 2007). A detailed review of the park's long-term ecosystem states and processes concluded that a wide range of anthropogenic changes in the ecosystem, including reduced hunting by humans,

predator control, and high human-use levels (that displaced wary predators) had allowed elk (*Cervus elaphus* L.) densities to increase beyond long-term norms (Kay and White 1995). Fire and ongoing high elk herbivory, in combination with prescribed fire, could actually eliminate some aspen stands (White et al. 1998). In addition, a major review of park land use practices recommended that ecological restoration would require a wide range of actions to manage human use to restore long-term ecosystem conditions (White and Fisher 2007). As a result, in the past decade, park ecological restoration has taken a much stronger eco-cultural focus (White and Fisher 2007). Researchers are working with Stoney-Nakoda elders to document pre-park establishment landscape use patterns (S. McGarvey, McMaster University, personal communication). First Nations representatives routinely attend park advisory committee meetings and are assisting park managers in culling human-habituated elk. Long-term patterns of human burning are of strong interest to fire managers. The current hypothesis is that high historic fire frequency on southwest-facing slopes and valley bottoms may be the result of First Nations' burning to maintain bison habitat (White et al. 2002). Interestingly, similar to Prince Albert National Park, public support for restoration of bison and its habitat may be the critical eco-cultural linkage that eventually drives a large part of the prescribed burning program (White et al. 2001).

In the meantime, using predominantly spring or fall prescribed fires, BNP is maintaining at least 50% of the long-term (1760 to 1940) fire frequency (Rogean et al. 2004, White and Fisher 2007). Where containment areas are suitable, spring-ignited prescribed fires or lightning ignitions are allowed to burn over long time periods with minimal management action. The burn areas of previous prescribed fires, combined with mechanical thinning, have helped block the subsequent higher intensity mid-summer fires from crossing park

boundaries. Walker and Taylor (2004) describe a similar example from Kootenay National Park (adjacent to Banff) where prescribed fire helped contain the area burned by lightning-ignited fires that burned later in the fire season.

### *Cowichan Garry Oak Preserve and Gulf Islands National Park Reserve*

Eco-cultural relationships dominate the approach taken by researchers and managers restoring fire to Garry oak (*Quercus garryana* Douglas ex Hook.) woodlands in protected areas within the Pacific Maritime ecozone such as the Cowichan Gary Oak Preserve and Gulf Islands National Park Reserve (Figure 2). The eco-cultural focus occurs because of strong recognition of First Nations' cultural practices in the area, the relatively infrequent occurrence of lightning fire, the small area of parks surrounded by urbanization or occurring on islands that will not likely be burned by large wildfires, and the numerous rare species that may have high fire dependence (Turner 1999, Pellet *et al.* 2007, Bjorkman and Vellend 2010).

In combination with biophysical studies on fuels, weather, lightning, and charcoal accumulation patterns (Pellatt *et al.* 2007), researchers have focused on First Nations' traditional knowledge of important resources such as camas (*Camassia* Lindl.) and how resource availability could be enhanced or sustained by cultural practices such as fire use (Turner 1999, Turner *et al.* 2003, Beckwith 2004). This work documents a legacy of knowledge accumulated through hundreds of generations of people living in and manipulating these ecosystems. However, fire restoration work in this ecozone remains limited. In cooperation with Hul'qumi'num First Nation, the Nature Conservancy of Canada's (NCC) managers of the Cowichan Gary Oak Preserve do small burns in plots linked to research programs at several Canadian universities. The NCC con-

ducted three management-scale burns in 2009. The Hul'qumi'num are routinely involved in the restoration, including the first post-European contact harvesting of camas that were stimulated by prescribed burning, several annual culturally focused school tours, and employment of band members by the NCC for burn planning and monitoring. The NCC staff provided in-kind work on First Nation lands in exchange for restoration assistance on the nature preserve.

## LESSONS LEARNED

Fire practitioners in Canadian parks and protected areas are stewards of combined eco-culturally and biophysically driven fire regimes. Similar to earlier generations of First Nations, today's land managers face the same issue in maintaining eco-culturally important patches of relatively frequent, low-intensity fire dependent ecosystems within a landscape matrix of less frequent, large area, high-intensity fire. From the above case histories, it appears that managers are recognizing significant spatial and temporal interactions on the edge between these two general fire regimes. Moreover, managers are rediscovering First Nations' traditional ecosystem knowledge of the human actions that were most practical for fire use in these northern regions where high-intensity fires are a dominant ecological force (Lewis and Ferguson 1988).

Management fires lit under an eco-cultural paradigm maintain an important component of the long-term regime while providing greater capacity for larger, higher intensity fires to occur with few negative ecological and socio-economic implications. Key lessons learned to date include:

- Fire is only one process in complex ecosystems that include human effects, predator and prey relationships, competition between species, herbivore browsing, and numerous other interactions. Thus,

restoring fire cannot be done in isolation. It must be done in the context of a holistic ecosystem restoration (Pyne 2007: 472-73, White and Fisher 2007).

- Recognizing long-term human roles as not only fire managers, but also hunters, gatherers, and cultivators is critical in restoration programs. However, ongoing studies and participation of First Nations in park management suggest that use of traditional knowledge should be treated as an ongoing process (Pierotti and Wildcat 2000). In some locations in Canada, it has been several generations since native peoples lived on the land. It will likely take active experimentation and learning for First Nations and interdisciplinary researchers to rediscover lost cultural practices and integrate them into modern park management programs (Turner *et al.* 2003, Lepofsky and Lertzman 2008).
- As fire programs scale up to a landscape level, managers are beginning to observe the interactions predicted between eco-cultural and biophysically driven fire regimes. For example, Parks Canada now allows some spring-season, human-ignited fires to burn into drought periods later in the year, with careful monitoring and periodic containment actions. Since 1990, these multi-season burns are now the largest single source of area burned in national parks on the eastern slopes of the Montane Cordillera ecozone (Brian Low, Parks Canada, unpublished data). Moreover, anthropogenic burns are becoming important influences on the burning patterns of subsequent mid-summer high-intensity fires caused by lightning (Walker and Taylor 2004).
- The diverse eco-cultural fire and biophysical interactions with ecosystem components (e.g., eastern white pine, bison, trembling aspen, elk, grizzly bears, and camas) that have importance to past

and current peoples link fire managers to a broad constituency of stakeholders. Bringing this variety of people and interests into the political decision-making processes (Pierotti and Wildcat 2000) is a necessary pre-requisite to successful fire management “at the edge” between smaller eco-cultural fires, and large, landscape level biophysically driven fires.

The evolving fire management direction of linking cultural and biophysical processes in Canadian protected areas is similar to parks elsewhere in the world. Kakadu National Park and the surrounding region in northern Australia has long been the international leader in this approach. Managers there use aboriginal traditional knowledge to ignite fires in select areas during the early and late fire season, and periodically use mid-summer high-intensity fires within this mosaic at a landscape level (Russell-Smith *et al.* 1997, Bowman *et al.* 2004). For several decades, Kruger National Park in South Africa prescribed broadcast burning to enhance wildlife populations. After a period of emphasizing lightning fires only, the park has now begun a new era of linking ecological and traditional knowledge to restore biodiversity. Researchers and managers are evaluating the heterogeneous ecological effects of point ignitions lit in various periods of the burning season combined with lightning (Govender 2004). In the western United States, Yosemite National Park uses prescribed burns in low elevation areas heavily used by humans (past and present), and at higher elevation, stresses maintenance of lightning-ignited fires (van Wagtendonk and Lutz 2007). Recently, research has focused on the long-term anthropogenic pattern of burning in Yosemite’s low elevation areas (Gassaway 2009). Williams (2000) discusses the implications of restoring aboriginal fires to American landscapes.

## CONCLUSION

Managers attempting to restore fire to Canada's landscapes are constrained by patterns of ignition, fuel, topography, weather, and potential for high-intensity fires that confronted First Nations prior to the modern fire suppression period. Increasingly, today's researchers and managers are consulting First Nations' elders whose ancestors have 10 millennia of fire experience in Canadian ecosystems (Parks Canada 2000). Because interests of today's park managers and long-term cultures may be similar (e.g., maintain biodiversity without destroying important human values), their approaches may become increasingly similar as fire management programs evolve.

Modern Canadian land use and political values limit human fire use within protected areas, likely to levels below historical conditions. Large fires caused mainly by lightning and unplanned human-ignitions will continue to burn most of the area, albeit also at reduced levels from historic conditions. However, ecosystem management of protected areas in Canada and other areas of the world is gradually evolving

to recognize human's important long-term influence on biophysical, ecological, and fire regime processes. This recognition enhances opportunities to re-engage humans in their important role in ecosystem restoration and stewardship. This process of re-engagement is essential for successfully managing processes such as fire that require strong stakeholder understanding and political support.

*... for humans, ecological and cultural edges are inextricably linked. In both cases they provide increased social and ecological resilience as they broaden the diversity of biological species and cultural knowledge that can be drawn upon for a livelihood. They allow humans to respond to expected natural cycles and inter-relationships, as well as the ability to manipulate these relationships for their own benefit. Equally important, they provide the means for people to better adjust to those times of unexpected and unpredictable change. (Turner et al. 2003)*

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