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Simulating the impacts of future fire regimes and fire management strategies on vegetation and fuel dynamics in western Canada using a boreal fire effects model (BORFIRE)

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ABSTRACT: The long-term effects of different fire management strategies on boreal forest composition and fuels under future fire regimes were studied in four National Parks in western Canada using a boreal fire effects model. Longer fire cycles caused by increased fire suppression resulted in greater fuel accumulation and a general increase in fire behaviour. Long fire cycles favoured *Picea glauca*, *Picea mariana* and *Abies balsamea*, three highly flammable tree species. Shorter fire cycles established by prescribed burning decreased fuel load and fire behaviour. *Pinus banksiana* and *Picea mariana* stands survived under shorter fire cycles, but *Populus tremuloides* and *Betula papyrifera* were greatly favoured, mostly at the expense of declining *Picea glauca*. A shift in forest composition towards low flammability species such as *Populus tremuloides* and *Betula papyrifera* would cause a general decrease in landscape fire danger.

1 INTRODUCTION

As a result of climate change in the Canadian boreal forest region, future fire regimes are expected to support a general increase in fire intensity, fire severity (depth of burn) and fire season length (Flannigan & Van Wagner 1991, Wotton & Flannigan 1993, Stocks et al. 1998, Flannigan et al. 2001). Change in the fire regime is also expected to have an effect on the forest disturbance rate, or annual area burned. In Canada, stand-replacing crown fires burn over 2 M ha each year (Stocks 1991, Amiro et al. 2001) with typical fire cycles of 75-150 years depending on the local fire regime. Over millenia, tree species have adapted to this environment in different ways through fire survival and regeneration strategy. Because of differences in fire ecology traits, a change in the future fire regime will favour some species over others and cause a shift in forest composition (Weber & Flannigan 1997). In turn, this will affect forest biomass, or fuel conditions. Fuel dynamics also have a feedback effect on fire regime through flammability and fuel load which influence fire occurrence and fire intensity. The purpose of this study was to examine the impacts of future fire regimes and different fire management strategies on boreal forest composition and fuel dynamics.

2 STUDY AREA DESCRIPTION

Four National Parks were selected as study areas to represent a wide geographical range in the western boreal region (Figure 1). The mean July temperature (mid-fire season) ranges from 14.0°C in Wood Buffalo National Park to 16.5°C in Riding Mountain National Park (Atmospheric Environment Service 1993a, 1993b). Mean annual precipitation ranges from 353 mm in Wood Buffalo National Park to 508 mm in Riding Mountain National Park, of which most occurs in summer. The majority of the forest in all study areas is comprised of *Picea mariana* (Mill.) B.S.P., *Pinus banksiana* Lamb., *Populus tremuloides* Michx. and *Picea glauca* (Moench) Voss in mixed or pure stands. *Betula papyrifera* Marsh., *Larix laricina* (Du Roi) K.Koch and *Abies balsamea* (L.) Mill. are common associates in the western boreal region, but only in smaller amounts. Eastern deciduous species such as *Quercus macrocarpa* Michx., *Ulmus americana* L. and *Fraxinus pennsylvanica* Marsh. can also be found in Riding Mountain National Park. Topography in all four study areas is flat to gently rolling with many small waterbodies scattered across the landscape. The fire season ranges from April-September in southern areas to May-August in the north but burning conditions commonly reach very high levels in all study areas (Simard 1973, Harrington et al. 1983, McAlpine 1991). The Wood Buffalo National Park and Prince Albert National Park fire regimes are dominated by natural fire, although Prince Albert National Park is increasingly using prescribed burns to manage ecosystems. The Elk Island National Park fire regime is dominated by prescribed burns which are mainly conducted in the spring, although some burns may be done in the autumn. Riding Mountain National Park has relatively few natural wildfires and prescribed burns are conducted infrequently.

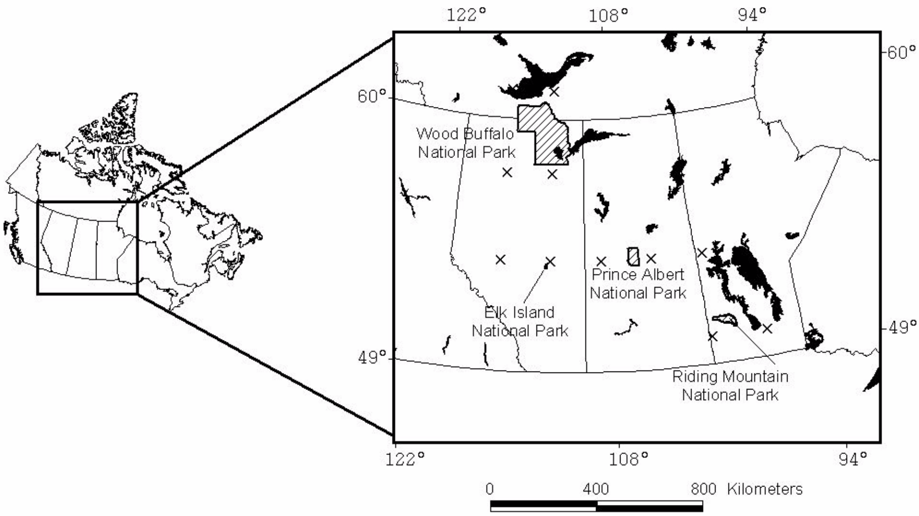

Figure 1. Location of study areas and gridpoint locations (X's) for the Canadian Global Coupled Model data used in the study.

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3 STUDY METHOD AND DATASETS

The study was conducted using a simulation approach to compare the long-term impacts of fire suppression and prescribed burning on current boreal forest stand types in western Canada under future fire regimes. Forest stand condition was simulated using BORFIRE, a boreal fire effects model. Future fire regime criteria were estimated from climate data provided by a general circulation model. Fire suppression and prescribed burning were incorporated through adjustment of fire cycle lengths. Several datasets were used to establish initial conditions and parameterize model processes. This includes datasets on vegetation, climate, fire weather, fire behaviour and fire cycles.

3.1 *Vegetation*

Forest inventories of the four National Park study areas were used to determine the species composition represented in the simulated boreal forest stands. The major forest stand types in each National Park were identified and summarized (Table 1). A total of 21 different pure and mixed stand types were simulated in the study.

3.2 *Climate, fire weather and fire behaviour*

Data output from the Canadian Global Coupled Model (CGCM1) (Flato et al. 2000) was used to represent future (2080-2100) climate conditions in the study areas. This time period has been used to approximate 2× CO_2 scenarios in previous climate change studies (Flannigan et al. 1998). Data provided by the Canadian Global Coupled Model was in the format of daily temperature, precipitation, relative humidity, wind speed and growing degree days (average of maximum and minimum temperatures above 5°C) for gridpoint locations around the study areas (Figure 1). The data covered the period from April 1 to Sept 30 for every year during 2080-2100. The growing degree days data was used in BORFIRE to estimate dates for leaf-flush and leaf-fall of *Populus tremuloides* and *Betula papyrifera*, seed ripening of *Picea glauca*, and spring green-up and autumn curing of herbaceous understory plants. Daily temperature, precipitation, relative humidity and wind speed were applied to the Canadian Forest Fire Weather Index System (Van Wagner 1987) to calculate daily fire danger parameters, or burning conditions. This included the Duff Moisture Code which represents the level of dryness of loosely compacted forest floor organic matter and depth of burn; the Buildup Index which is an indicator of the total amount of fuel available for combustion and can be used to estimate dead woody fuel consumption; and the Initial Spread Index which is an indicator of rate of fire spread. The daily Duff Moisture Code and Buildup Index were summarized to provide an average monthly distribution (mean, SD) by study area and time period. The Initial Spread Index data was similarly summarized using the highest monthly values (mean, SD) since those are the typical conditions under which most of the boreal forest burns. When a fire event occurred in BORFIRE simulations, this Fire Weather Index System dataset of burning conditions was used to calculate physical fire characteristics.

Fire behaviour, or the physical characteristics of individual fires, was calculated in BORFIRE by applying the Fire Weather Index System parameters to fuel types of the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992) and fire behaviour models. This resulted in depth of burn, fuel consumption and rate of spread values for each fire. Head fire intensity was calculated as the product of heat of combustion, fuel consumption and rate of fire spread (Byram 1959).

3.3 *Fire cycles*

Harrington and others (1983) studied the correlation of monthly area burned to monthly Fire Weather Index System parameters during 1953-80. Average monthly Duff Moisture Code showed the strongest relationship to monthly area burned in west-central Canada with r^2 = 0.29-0.65. While

Table 1. Summary of forest stand types in the four study areas (ha).

Stand Type	Wood Buffalo National Park	Elk Island National Park	Prince Albert National Park	Riding Mountain National Park
Pinus banksiana	694,293		24,201	
Populus tremuloides	807,830	11,230	93,967	91,947
Picea mariana	1,187,333	320	32,213	
Picea glauca	201,570		5,378	38,710
Betula papyrifera		241		
Pinus banksiana / Populus tremuloides			17,675	
Pinus banksiana / Picea mariana			36,946	
Pinus banksiana / Picea glauca			3,531	
Picea glauca / Populus tremuloides	546,436	186	59,134	73,296
Populus tremuloides/ Betula papyrifera		207		
Other Forest	499,187	71	37,477	71,815
Non Forest	1,019,850	6,569	84,913	32,955
Unclassified	99,334			
Total	5,055,833	18,824	395,435	308,723

there is no way to accurately predict future area burned, Duff Moisture Code has shown the most reliability. Therefore, Duff Moisture Code values for 2080-2100 were used to estimate area burned under future fire regimes by correlation to actual current (1975-90) area burned statistics. It should be noted that the current area burned statistics are the result of current levels of fire suppression, so correlation results for future estimates of area burned must be interpreted as occurring under the same levels of fire suppression. Future (2080-2100) monthly area burned was calculated as the product of 1975-90 monthly area burned and the ratio of average 2080-2100 monthly Duff Moisture Code values to 1975-90 monthly Duff Moisture Code values. This provided a monthly area burned (mean, SD) dataset for each Park under future fire regimes and current levels of fire suppression. The monthly data was also summarized as annual area burned and fire cycles (Table 2). BORFIRE used the annual rate of area burned as the probability rate that a simulated stand would burn in any given year (e.g., a fire cycle of 50 years would have an annual probability of 0.02). If a fire event occurred during one of the simulation years, the model then used the distribution of average monthly rates of area burned to determine which month the simulated fire occurred. The Julian fire date was then randomly chosen from that month in the model.

To represent future fire regime scenarios with changes in fire management, fire cycle lengths were adjusted to meet managed objectives (Table 2). To manage for increased future wildfire activity in Wood Buffalo National Park, the future fire management goal was to reduce the increase in annual area burned by half through increased fire suppression. Specifically, the actual 1975-90 fire cycle in Wood Buffalo National Park was 74 years and the future estimated fire cycle (with no change in fire management) was 56 years, so the fire management scenario under the future fire regime was calculated as 65 years. As defined in Elk Island National Park management plans, future fire management scenarios include fire cycles of 100 years in all stand types, and 25 and 15 years in deciduous stands. This would be achieved primarily through prescribed burning. The future estimated fire cycle in Prince Albert National Park was extremely long because it was based on a very low annual burn rate that occurred during 1975-90. Although unrealistic over longer time scales, this scenario provided insight into the impacts of a fire exclusion policy. The future managed fire cycle of Prince Albert National Park was 75 years as recommended in park

Table 2. Summary of fire cycle lengths (years) used in the study.

	Unmanaged Scenarios	Managed Scenarios
Wood Buffalo National Park	56	65
Elk Island National Park	57	100, 25, 15
Prince Albert National Park	12,987	75
Riding Mountain National Park	137	100, 50, 25

management plans. Future fire management scenarios in Riding Mountain National Park were set at 100 and 50 years for all stand types, and 25 years in aspen stands to represent a range of future options.

4 MODEL PROCEDURES

BORFIRE quantitatively simulated tree community dynamics (species composition and stand density, average tree height and diameter) and biomass (above- and below-ground, live and dead organic material) (de Groot et al. 2002). Changes in those two state variables was based on processes of tree mortality, tree recruitment, tree growth, biomass decomposition, and biomass consumption by fire (Figure 2). Fire, climate and competition were the variables driving model processes. Tree community dynamics were driven by fire disturbance events which affected recruitment and mortality, and natural thinning due to intra- and interspecific competition within the stand. Biomass increased with tree growth, and decreased with decomposition of dead organic material and fuel consumption during fire. The model was process-driven using an annual time-step and simulated conditions at the stand level.

4.1 *Tree community dynamics*

The model simulates the community dynamics of six major boreal tree species: *Picea mariana*, *Pinus banksiana*, *Populus tremuloides*, *Picea glauca*, *Betula papyrifera* and *Abies balsamea*. Each simulated stand could include any number of species. Stand density (stems/ha, by species) at the end of each annual time-step was a result of recruitment and mortality to the initial stand density. Recruitment occurred after a fire event as new seedlings for *Pinus banksiana* and *Picea mariana*, and as new sprouts for *Populus tremuloides* and *Betula papyrifera*. *Picea glauca, Picea mariana* and *Abies balsamea* recruitment was possible at each time-step in the understory of deciduous trees (*Populus tremuloides* and *Betula papyrifera*) or *Pinus banksiana* if a seed source was available, but recruitment could not occur under other coniferous trees due to limited light. All other tree species are shade intolerant and could not regenerate under any tree canopy. Mortality was separated into fire and natural mortality (or thinning). Stand thinning followed the fully stocked stand density algorithms of the Alberta Phase III Inventory (Alberta Forest Service 1985) for *Populus tremuloides*, *Picea glauca*, *Picea mariana*, *Pinus banksiana* and mixedwood stands (any conifer/deciduous mix) which were based on provincial forest inventories. Western boreal databases were not available for *Abies balsamea* or *Betula papyrifera*, so similar data from eastern Canada was used (Plonski 1974, MacDonald 1991, Payandeh 1991). In the case of non-pure stands, thinning occurred proportionately to stand density by species.

4.2 *Biomass dynamics*

Biomass was separated into live and dead, and above- and below-ground components. Live aboveground tree growth rates followed the Alberta Phase III Inventory and eastern Canada algorithms. The live below-ground (root) component was calculated as a proportion of aboveground biomass using Kurz et al. (1996). As a result of natural thinning, trees were killed and

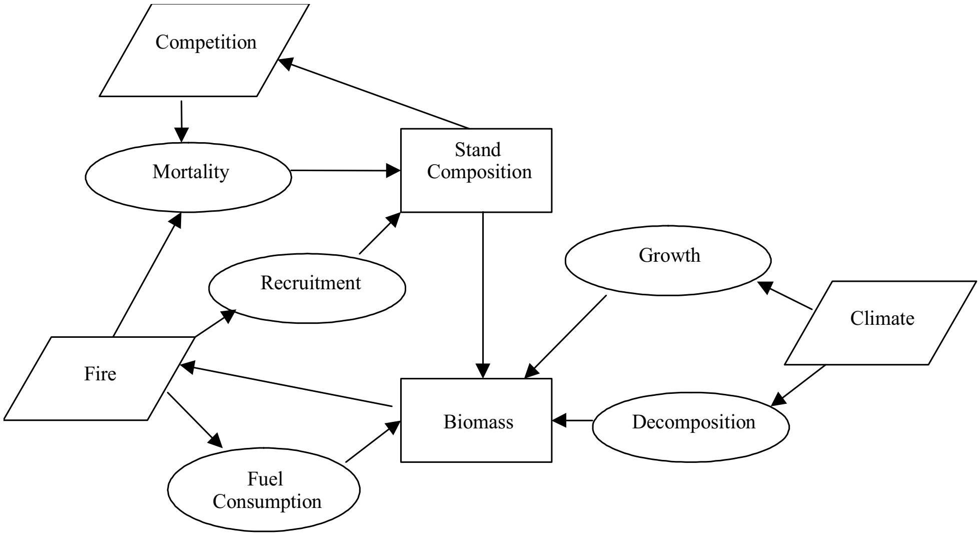

Figure 2. Simplified structure of the BORFIRE model showing state variables (square), processes (ellipse) and driving variables (parallelogram).

transferred to the appropriate aboveground and below-ground dead biomass pools. Standing dead stems fell at a rate of 10% annually and they were transferred to surface slash pools of branchwood (10% of tree) and coarse woody debris (90% of tree). Respiration of slash branchwood used the maximum decay rate of the fast soil carbon pool (representing a half life of 3-20 years) in the boreal west region of the Carbon Budget Model of the Canadian Forest Service (Kurz et al. 1992, Kurz and Apps 1999). The coarse woody debris respired at the maximum decay rate of the medium soil carbon pool (half life of 20-100 years) and standing dead stems respired at the medium soil carbon pool minimum decay rate.

Dead below-ground biomass was separated into three pools: a surface litter layer of dead foliage and fine (<1cm) woody material, a duff layer of loosely-compacted surface organic matter, and dead roots. Leaf and needle detritus was an annual input to the forest floor litter layer, and litter was similarly transferred to duff using rates of Keane et al. (1989). Through decomposition, branchwood and coarse woody debris was transferred from aboveground slash to the duff pool at a rate of 10% and 5% per year, respectively. In each time-step, 10% of dead root biomass and 73.5% of live fine roots (Kurz et al. 1996) were input to the duff layer. Respiration of litter and duff used the rates of fine and medium soil carbon pools for the west boreal region of the Carbon Budget Model of the Canadian Forest Service (Kurz et al. 1992) with the maximum rate occurring in the first year after fire and declining to the minimum rate by year 100. Dead root respiration similarly used the medium soil carbon pool rate.

4.3 *Fire dynamics*

Fire was an important driving variable affecting post-fire vegetation response in BORFIRE. Tree community dynamics were driven by the physical characteristics of individual fires (intensity, severity, season of burn) to simulate plant response (tree death, recruitment) based on the fire ecology of each species. Fire recurrence was based on the fire cycles calculated in Table 2. In terms of bio-

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mass dynamics, fire affected the physical structure of the stand through loss of biomass during combustion and transfer between pools (e.g., live to dead, aboveground to below-ground).

4.4 *Fire ecology and effects*

The interaction of physical fire characteristics and plant fire ecology was a critical component of BORFIRE. The most important fire ecology traits for each species were summarized (Table 3) and each trait was quantified in the model as it affected tree mortality and recruitment under different fire conditions. Recruitment of *Populus tremuloides*, *Pinus banksiana* and *Picea mariana* followed the algorithms of Greene & Johnson (1999). To simulate postfire re-sprouting from the root collar in *Betula papyrifera*, recruitment was incorporated as a replacement of surviving individual trees. There are no good recruitment models for *Abies balsamea* or *Picea glauca*, so a basal area approach was used in a very similar fashion to Greene and Johnson (1999). *Abies balsamea* used the same algorithm as *Picea mariana*, and *Picea glauca* used a ratio factor of surviving tree basal area to basal area of a fully stocked pure stand. Long distance seeding of *Populus tremuloides* and *Betula papyrifera* was considered of minimal importance (Greene and Johnson 1997, Greene et al. 1999) and was not included in these model simulations. In order for regeneration to occur in the simulated stand, a protected propagule bank (*Populus tremuloides*, *Pinus banksiana*, *Picea mariana*, *Betula papyrifera*) or a surviving individual (*Picea glauca*, *Abies balsamea*) was required. Reproductive age and maximum lifespan were used to define the reproductive period for each species (Table 3). Tree mortality was based on the amount of crown scorch and cambium death during fire using algorithms from Ryan & Reinhardt (1988). Crown scorch height was calculated using Van Wagner's (1973) equation and fire intensity. Total crown scorch was estimated from crown scorch height (Peterson 1985). Bark thickness (Kozak & Yang 1981) and fire intensity were used to calculate cambium mortality. For the re-sprouting species (*Populus tremuloides* and *Betula papyrifera*), season of burn was important to tree mortality and re-sprouting ability as low intensity fires prior to leaf flush have been shown to girdle *Populus tremuloides* stems and prevent suckering (Weber 1990). Therefore, the model includes fire intensity and date of leaf-flush in the mortality and recruitment of *Populus tremuloides* and *Betula papyrifera*. Also, pure deciduous stands in the model do not burn after spring greenup of the understory, but they may burn after autumn leaf-fall when it is possible for the cured herbaceous understory to dry-out quickly with increased solar radiation reaching the forest floor.

4.5 *Biomass impacts*

Fuel (or biomass) consumption during a fire event was estimated in the model using fuel load and burning condition parameters. Slash consumption as correlated to Buildup Index by McRae (1980) was used to calculate biomass losses in branchwood and coarse woody debris pools. Total depth of burn was calculated using forest floor depth and duff moisture content (as estimated by Duff Moisture Code) using the same procedure as the FIRESUM model of Keane and others (1989). All biomass in the litter layer was assumed to be lost during combustion. The amount of duff biomass lost was determined using duff fuel load, duff bulk density (97 kg/m^3), litter depth (based on 36 kg/m^3) and total depth of burn.

A certain amount of the live biomass representing fine aerial fuels was also lost during fire. In the case of a crown fire, this amount was estimated as the foliage and stem bark components (Ter-Mikaelian & Korzukhin, 1997) for conifers and *Betula papyrifera*, and only the foliage for *Populus tremuloides* (which does not have flammable bark). In non-crowning fires, the model estimates no live biomass loss in *Populus tremuloides* and a 2% loss representing bark in all other tree species. All live trees that were killed by fire were transferred to the dead standing biomass pool, and all trees that were dead and standing at the time of the fire were transferred to the dead aboveground biomass pools of branchwood and coarse woody debris.

Table 3. Summary of important life history traits in relation to fire for tree species simulated in BORFIRE.

	Pinus banksiana	*Picea mariana*	*Picea glauca*	*Populus tremuloides*	*Betula papyrifera*	*Abies balsamea*
Regeneration Method	canopy-stored seed	canopy-stored seed	seed not stored	root suckers	root collar sprouts	seed not stored
Fire Resistance	moderate	low	low	very low	very low	very low
Seasonal Fire Effect	none	none	self-seeds only after autumn fire	does not re-sprout if burned prior to leaf flush	does not re-sprout if burned prior to leaf flush	none
Reproductive Age (yrs)	20-120	15-200	25-250	5-110	15-110	20-140
Shade Tolerance	intolerant	intolerant	tolerant	intolerant	intolerant	tolerant

4.6 *Physical fire parameters*

The occurrence of a fire event was simulated stochastically using a Monte Carlo process and the average fire cycle for the simulation period. If a fire event occurred during any annual time-step, the model determined the month of occurrence using the monthly distribution of area burned, and then the Julian fire date was randomly chosen from that month. The fire date was used to determine the state of hardwood flushing, understory condition, and the burning conditions as measured by the Fire Weather Index System. The model then randomly selected the Buildup Index, Initial Spread Index and Duff Moisture Code values for the fire event from the Fire Weather Index System dataset containing the historical temporal distribution of those values.

The Duff Moisture Code was used to calculate forest floor consumption, and Buildup Index was used to calculate aboveground dead biomass consumption. The average fire rate of spread (weighted by species) was calculated with the Initial Spread Index and tree species data using procedures of the Canadian Forest Fire Behaviour Prediction System. Fire intensity was calculated using the average fire rate of spread and fuel consumption during the fire. Fuel consumption was calculated in several steps following Canadian Forest Fire Behaviour Prediction System procedures. First, foliar moisture content at the time of the fire was calculated using the fire date, latitude, longitude and elevation data. This was combined with live crown base height to determine the critical surface fire intensity for crown fire to occur based on the species composition of the stand. The actual surface fire intensity was determined using the fire rate of spread (from stand composition, age and season of burn) and surface fuel consumption (litter, duff, dead and downed branchwood and coarse woody debris). If surface fire intensity was greater than the critical surface fire intensity, then a crown fire occurred and total fire intensity was calculated using rate of fire spread and total fuel consumption (surface fuels plus bark and foliage fuels).

5 MODEL SIMULATIONS

Each simulation was started with initial conditions of 1,000 seedlings per hectare for each species, and a standard duff biomass of 80 t/ha. This was to simulate the first year of a stand regenerating after fire. The forest stand types simulated in each study area were determined from the vegetation classifications for each National Park (Table 1). The model used data derived from the Canadian Global Coupled Model (fire weather and associated fire behaviour and fire cycles) to drive species composition and biomass dynamics in the study areas. Each simulation was run for 400 years to allow the stand dynamics to reach equilibrium under the driving variables. Each simulation scenario

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was repeated 25 times and averaged. Tree density by species and stand biomass during the final 100-yr period of the simulation were summarized.

6 STUDY RESULTS

A total of 42 simulations were run in the study. Average depth of burn, fuel consumption and fire intensity (Figure 3) increased with increasing fire cycle length in all simulation scenarios. The standard deviation of fire behaviour characteristics was high in all simulations and study areas. This was particularly noticeable in head fire intensity values, indicating that the simulated fire regime was often a mix of low intensity surface fires and high intensity crown fires.

The model simulations provided yearly data on stem density by species, and biomass by various aboveground and belowground pools. An example of the tree density data from the model simulations is presented in Figure 4. Stand density trends were dependent on species. Only *Betula papyrifera* and *Populus tremuloides* were able to survive short fire cycles of 25 and 15 years due to their re-sprouting ability. However, neither species was able to survive this fire cycle in Elk Island National Park due to the spring prescribed burn nature of the simulated fire regime. Because fires occurred early in the spring before leaf-flush, trees were girdled so re-sprouting was not stimulated. *Picea glauca* is a fire avoiding species, and it had low survival rates under fire cycles less than 100 years. For *Betula papyrifera*, *Populus tremuloides*, *Picea mariana* and *Pinus banksiana*, stand density generally increased with shorter fire cycles because of high initial recruitment levels and a shorter time period for natural stand thinning. Only *Picea glauca* and *Picea mariana* survived under the extremely long unmanaged fire cycles (12,987 years) of Prince Albert National Park because these species are able to produce and release regular seed crops in the absence of fire.

There was greater forest fuel accumulation in all stand types at longer fire cycles. Under the extremely long unmanaged fire cycle in Prince Albert National Park, average stand biomass levels increased greatly for *Picea glauca* and *Picea mariana*, but decreased to almost zero in all other stands because of the inability of other species to survive under fire exclusion. Total biomass in each study area increased under longer fire cycles, but decreased in Prince Albert National Park when fire cycle was extremely long (Table 4).

7 DISCUSSION

The study results indicate that long-term fire management strategy can affect forest composition and fuel accumulation in forest stands. These changes can have an impact on fire activity through changes in fire behaviour including fuel consumption, depth of burn and fire intensity. There is also a cumulative effect of stand-level differences in fire behaviour at larger scales as a general shift in forest composition or change in fuel load or forest flammability can cause an increase or decrease in fire danger across the landscape.

In the case of Wood Buffalo National Park, increased fire suppression in the future would increase the amount of total Park biomass, but most of it would accumulate in live *Populus tremuloides* trees. This is because *Populus tremuloides* is faster growing than the other tree species. A longer fire cycle resulting from increased fire suppression would also shift the age-class distribution towards older stands which store more biomass. The increase in live tree biomass also caused an increase in forest floor biomass because of greater annual detrital input. In Elk Island National Park and Riding Mountain National Park, reducing the fire cycle length to 50 years or less through prescribed burning would dramatically reduce forest biomass and cause a rapid shift in species composition towards *Populus tremuloides*. This is because *Picea glauca* would quickly disappear from mixed *Populus tremuloides-Picea glauca* stands. The effects of increased fire suppression or prescribed fire found in the individual National Parks are not specific to each location and can be applied broadly to all of the study areas.

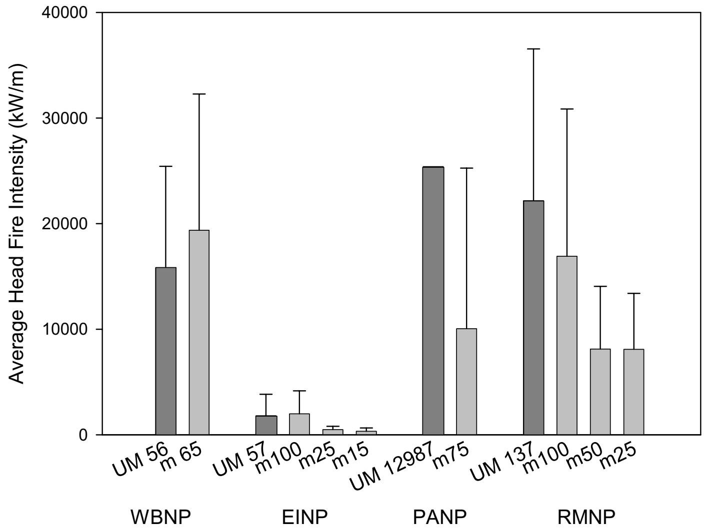

Figure 3. Summary of fire intensity (mean, SD) in Wood Buffalo National Park (WBNP), Elk Island National Park (EINP), Prince Albert National Park (PANP) and Riding Mountain National Park (RMNP) model simulations. Data is summarized by management and fire cycle scenarios (e.g., um56=unmanaged 56-yr fire cycle, m65=managed 65-yr fire cycle). Depth of burn and fuel consumption showed the same trends as fire intensity.

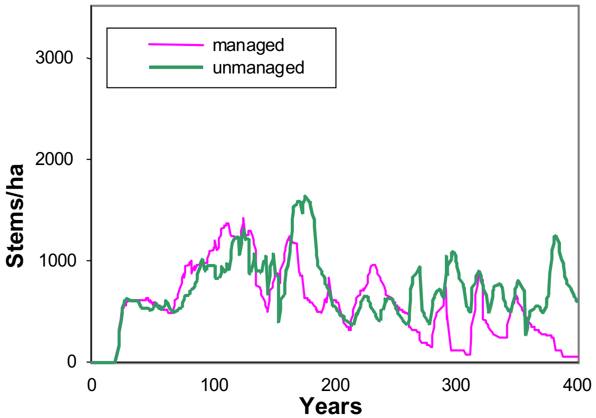

Figure 4. Example of simulation output showing Pinus banksiana stem density in Wood Buffalo National Park under different fire management (fire cycle) scenarios.

The simulations indicate that fire management strategy can impact fuel conditions and fire danger in three basic ways. The first is an impact on fuel type. An increase of *Populus tremuloides* and decrease of *Picea glauca* in forest composition is an expected outcome of shorter fire cycles. This change in forest fuel types would have a strong impact on fire behaviour at the landscape level because deciduous stands (*Populus tremuloides* and *Betula papyrifera*) have very low flammability. Fires only occur in these stand types when the understory is cured in the early spring and late autumn, and fire intensity is always low. On the other hand, coniferous trees such as *Picea glauca* are very flammable and promote high intensity fires. Overall, an increase in *Populus tremuloides* and a decrease in *Picea glauca* forest composition would cause a general decrease in fire danger on the landscape, and there would tend to be more spring and autumn fires and less summer fires. Obviously, an increase in fire cycle length would shift these changes in the reverse direction.

Table 6. Summary of total biomass (1000's tonnes) in each study area under managed and unmanaged future fire regimes.

Study Area	Fire Cycle	Dead Wood	Forest Floor	Live Trees *Pop. trem.*	*Pin. bank.*	*Bet. pap.*	*Pic. mar.*	*Pic. gla.*	Total
Wood Buffalo National Park	Unmanaged 56 yrs	32,412	164,077	61,209	11,048		20,411	1,314	290,470
	Managed 65 yrs	31,890	192,257	107,970	6,256		25,445	595	364,411
Elk Island National Park	Unmanaged 57 yrs	18	145	108		5.8	11	0	287
	Managed 100 yrs	14	199	112		2.5	18	3	342
	Managed 25 yrs	5	56	27		0.2	4	2	96
	Managed 15 yrs	5	56	27		0.4	4	2	95
Prince Albert National Park	Unmanaged 12,897 yrs	4,859	27,028	0	0		9,779	5,430	47,096
	Managed 75 yrs	3,803	27,532	22,079	1,278		1,752	193	56,636
Riding Mountain National Park	Unmanaged 137 yrs	1,636	12,258	12,970				724	27,588
	Managed 100 yrs	940	8,920	10,241				110	20,211
	Managed 50 yrs	844	5,663	4,610				120	11,237
	Managed 25 yrs	570	3,967	3,140				70	7,747

Another potential impact of future fire management strategy is a change in forest fuel load. Increased fire suppression will tend to promote greater fuel loads. This increases the potential for high intensity fires because of greater depth of burn and total fuel consumption, as shown by the simulation data. However, a greater fuel load does not necessarily result in a parallel increase in fuel consumption. For instance, an increase in live tree biomass has less potential for greater fuel consumption than an increase in dead woody material. An increase in forest floor material does not necessarily promote greater depth of burn either because this is largely controlled by weather and drying conditions prior to the fire. Even though higher fuel loads are associated with an increase in fuel consumption, the latter does not increase in proportion to the former because only a portion of the total fuel load is consumed during fire. In contrast to fire suppression and increasing fuel loads, short fire cycles from prescribed burning decrease fuel load and fire intensity by regularly removing much of the flammable surface debris.

A third possible impact of future fire management strategy is a change in flammability of some fuel types through a shift in age-class structure of the forest. In general, coniferous species are most flammable around the 10-40 year age-class period when stand density is very high and lower branches are close to the forest floor. As well, fine and medium dead fuel loads are very high during this period due to natural stand thinning. All of these conditions promote high intensity fires. Coniferous stands also become more flammable near the end of their lifespan as senescence occurs. Stand condition deteriorates and dead fuel loads increase during this time period as trees succumb to insects, disease and windthrow. High fuel consumption and fire intensity often occurs under these conditions. Therefore, it is possible that increased fire suppression or prescribed fire could cause a shift in the age-class structure that changes forest flammability.

8 CONCLUSIONS

Long-term fire management strategy can have an impact on future forest stand conditions that influence fire behaviour. Through increased fire suppression or the use of prescribed fire, fire cycle length and age-class structure of the forest can be manipulated. Shorter fire cycles will shift the forest composition towards a greater component of less flammable, deciduous tree species. With an increase in deciduous forest composition, there would also be a greater occurrence of low intensity spring and autumn fires and fewer summer fires. Short fire cycles will result in a younger forest age structure, so a greater proportion of the forest conifer component will be in a more flammable age-class. Greater fuel accumulation will occur under longer fire cycles, causing a general increase in depth of burn, fuel consumption and fire intensity. Very long fire cycles will create an old age-class distribution and result in a greater proportion of senescing conifer stands of higher flammability on the landscape.

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