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Remote sensing of burn severity: experience from western Canada boreal fires*

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Abstract. The severity of a burn for post-fire ecological effects has been assessed with the composite burn index (CBI) and the differenced Normalized Burn Ratio (dNBR). This study assessed the relationship between these two variables across recently burned areas located in the western Canadian boreal, a region not extensively evaluated in previous studies. Of particular interest was to evaluate the nature of the CBI–dNBR relationship from the perspectives of modelling, the influence of fire behaviour prediction (FBP) fuel type, and how field observations could be incorporated into the burn severity mapping process. A non-linear model form best represented the relationship between these variables for the fires evaluated, and a similar statistical performance was achieved when data from all fires were pooled into a single dataset. Results from this study suggest the potential to develop a single model for application over the western region of the boreal, but further evaluation is necessary. This evaluation could include stratification by FBP fuel type due to study results that document its apparent influence on dNBR values. A new approach for burn severity mapping was introduced by defining severity thresholds through field assessment of CBI, and from which development of new models could be incorporated directly into the mapping process.

Additional keywords: composite burn index, fire severity, fuel type, Landsat, Normalized Burn Ratio.

Introduction

The boreal forest is the largest forest region in Canada, representing ~77% of all wooded land (Weber and Stocks 1998; Natural Resources Canada 2006). Within the boreal, fire is considered among the most widespread of disturbance agents (Weber and Van Cleve 2005). The effects of fire will shape landscape structure, composition and function, and influence both the rates and processes of ecological succession and encroachment (Lentile *et al*. 2006). Fire often spreads in a non-uniform manner across a forest landscape, and vegetation differentially affected by fire will respond by following different pathways to post-burn recovery (Weber and Stocks 1998). These pathways are manifested through modification of species composition and age structure, regulation of forest insect and disease occurrences, and changes to nutrient cycling, habitat productivity and biodiversity, amongst others (Volney and Hirsch 2005). New pressures, however, are changing how these ecological processes and successional pathways may proceed as a result of fire. These pressures result from the unknown consequences of a changing climate, and their impacts on the nature and dynamics of fire relative to biophysical and ecological changes in the boreal. At best, current projections suggest that in conjunction with climate change, the area burned will increase, as will fire season length, fire intensity and fire severity (i.e. fuel consumption) (Wotton and Flannigan 1993; Flannigan *et al*. 1998, 2005). It is from these perspectives that the ability to map and quantify burn severity on the landscape has been of increasing interest in the recent literature (Key and Benson 1999; van Wagtendonk *et al*. 2004; Cocke *et al*. 2005; Epting *et al*. 2005; Clark and Bobbe 2006).

There is inconsistency in the use of terminology and definitions surrounding fire severity and burn severity (see Jain *et al*. 2004; Key and Benson 2006; Lentile *et al*. 2006). For the purposes of this study, we selected and defined burn severity as the degree of ecological and physical change caused by fire (Key and Benson 2002). It's considered a measure of the post-fire environment, and is defined by the environmental characteristics after the fire because it represents what was left (Jain *et al*. 2004; Chuvieco *et al*. 2006; Lentile *et al*. 2006). The assessment of burn severity in the field tends to be more of a judgmental process than one based on direct measures. An example is the composite burn index (CBI), that was designed to assess burn

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severity by rating the average burn condition on a plot (Key and Benson 2006). The CBI is an indicator that has been associated to spectral changes observed from pre- and post-burn remote imagery when assessment of ecological change as a result of fire is of interest (Key and Benson 2006; Lentile *et al*. 2006).

Knowledge of burn severity can potentially serve a multitude of resource management applications. Linking burn severity information to post-fire vegetation conditions improves modelling of long-term successional dynamics and estimates of future timber volume, within spatially defined areas (Schimmel and Granström 1996; Arseneault 2001). Rapidly produced post-fire burn severity maps can also aid local forest managers with timber salvaging efforts, help plan regeneration efforts, and address issues of erosion and site rehabilitation, similar to that described by the Burned Area Emergency Rehabilitation (BAER) program (McKinley *et al*. 2003). Burn severity information provides ancillary data useful for a multitude of fire-related studies that may include wildlife habitat alteration (Paragi *et al*. 1996; Joly *et al*. 2002), water quality assessment (Minshall *et al*. 2001), runoff predictions (Parsons *et al*. 2002; Easterbrook 2006), and seed source analysis (Charron and Greene 2002; Rajora and Pluhar 2003). An increasing national and international need for comprehensive carbon budget models could also benefit from burn severity information, given estimates that over 30% of the Earth's carbon is stored in boreal forests (Kasischke 2000), and fire is known as a major disturbance agent for releasing stored carbon (Conard *et al*. 2002; Zhang *et al*. 2003). More recent studies have even employed radiative transfer models to create burn severity simulations that can be applied under variable site conditions observed from different spectroscopic sensors (Chuvieco *et al*. 2006; De Santis and Chuvieco 2007). Fundamentally, however, the assessment of burn severity, particularly over large fires, is a time consuming and costly process from in-situ surveys alone, thus rationalising the interest by those who have explored the use of remote sensing data and methods (Lentile *et al*. 2006).

The assessment of post-fire effects from satellite remote sensing data is not a new concept, and while several sensors have been evaluated, the use of the Landsat Thematic Mapper (Landsat TM) has been most frequently reported (Lentile *et al*. 2006). The Landsat TM is characterised by its systematic repetitive coverage, large archival database, multispectral coverage in the visible, near infrared (NIR) and shortwave infrared (SWIR) portions of the spectrum, and images are acquired at spatial resolutions considered appropriate for mapping fires at this scale (Clark and Bobbe 2006). Several image bands and vegetation indices have been correlated with field measures of burn severity or used to assess wildfire effects (Kushla and Ripple 1998; Epting *et al*. 2005). While the normalised difference vegetation index has been a frequently used method to detect burn severity, results suggest it is not sufficiently responsive in areas of sparse vegetation (Brewer *et al*. 2005; Cocke *et al*. 2005). Landsat TM bands 4 and 7, which represent the NIR and SWIR portions of the spectrum, respectively, and their combination into a vegetation index, was first employed to assess burned areas in Spain by López-Garcia and Caselles (1991). Following fire, NIR reflectance decreases as a result of foliage consumption or damage, and SWIR reflectance increases because of a reduction in canopy shadow and moisture (van Wagtendonk *et al*. 2004). The difference over sum of these two image bands results in a band ratio referred to as the Normalized Burn Ratio (NBR), and its difference computed from pre- and post-burn images (dNBR) has subsequently been developed and used as a remote indicator of burn severity (Key and Benson 1999, 2006).

Several studies have assessed the relationship between field and remote sensing estimates of burn severity over a wide range of fires as defined by the CBI and dNBR (Key and Benson 1999; van Wagtendonk *et al*. 2004; Brewer *et al*. 2005; Cocke *et al*. 2005; Epting *et al*. 2005; Clark and Bobbe 2006; Roy *et al*. 2006). Within these studies, the relationship between these variables has mostly been described by linear or second degree polynomial functions, and the mapping of burn severity has been undertaken by an often subjective process of thresholding dNBR radiometric values into three or more discrete classes that range from low to high. While reflectance does vary across vegetation or fuel types non-uniformly with burn severity (White *et al*. 1996), it is not commonly assessed within individual fires. The objective of this study was to build from previous work by assessing the relationship between CBI and dNBR over four fires that occurred in three ecozones (boreal plains, taiga plains, boreal cordillera) across the western Canadian boreal (Ecological Stratification Working Group 1995), a region that has not been extensively evaluated in previous studies. Of particular interest was to ascertain the model relationship between CBI and dNBR, assess the influence of fuel type on burn severity values, and to develop an approach to produce burn severity maps that could be linked to field assessments. These issues resulted in the three questions addressed by this study:

1. What model describes the relationship between CBI and dNBR for these Canadian boreal fires?
2. Does fuel type influence remote sensing of burn severity represented by dNBR?
3. How can field information be used to create locally meaningful thresholds in thematic classification and mapping of burn severity?

Study area

Analysis was conducted on four fires, totaling ~95 296 ha burned, located in three different ecozones and ecoregions of the western Canadian boreal forest (Table 1; Fig. 1; Ecological Stratification Working Group 1995). Two fires, located in north-central Saskatchewan, burned in the summer of 2003. One fire, which occurred along the Alberta–Northwest Territories (NWT) border, in Wood Buffalo National Park (WBNP), and one fire in the central Yukon, both burned in 2004. The more northerly fires located in the NWT and Yukon were characterised by colder winter temperatures, lower annual precipitation, and less diverse fuel types than the more southerly fires located in Saskatchewan (Table 1). These fires were used as an indicator of the burn severity characterisations and relationships from the perspective of CBI and dNBR, for this region of Canada.

Methods

Field data collection

Field crews established a total of 161 CBI plots throughout the four fires, including 23 in Green Lake, Saskatchewan, 18 in

Table 1. Study area characteristics for the four fires analysed

Property	Fire			
	Saskatchewan Green Lake	Saskatchewan Montreal Lake	NWT Wood Buffalo	Yukon Dawson
Burned area (ha)	4299	21 653	51 968	17 376
Start date	28 July 2003	28 May 2003	11 July 2004	21 June 2004
End date	10 August 2003	28 July 2003	5 August 2004	15 September 2004
Average temperature January (°C)	−18.1	−18.1	−24.1	−26.7
Average temperature July (°C)	16.6	16.6	16.5	15.6
Annual precipitation (mm)	415	415	362	324
Ecozone[A]	Boreal plains	Boreal plains	Taiga plains	Boreal cordillera
Ecoregion[A]	Mid-boreal uplands	Mid-boreal uplands	Hay River lowland	Yukon plateau-north
Dominant upland tree species[B]	Balsam poplar Balsam fir Trembling aspen Jack pine White spruce	Balsam poplar Balsam fir Trembling aspen Jack pine White spruce	Black spruce Jack pine Trembling aspen White spruce	White spruce
Dominant lowland tree species[B]	Black spruce Tamarack	Black spruce Tamarack	Black spruce	Black spruce
FBP system fuel types[C]	C2, C3, D2	C2, C3, D2	C2, C3	C2, D2, M2

[A]Ecological Stratification Working Group 1995; Environment Canada 2006.
[B]Balsam fir (*Abies balsamea* (L.) Mill.), balsam poplar (*Populus balsamifera* L.), black spruce (*Picea mariana* (Mill.) B.S.P.), jack pine (*Pinus banksiana* Lamb.), tamarack (*Larix laricina* (Du Roi) K. Koch), trembling aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss).
[C]Forestry Canada Fire Danger Group 1992.

Montreal Lake, Saskatchewan, 83 in Wood Buffalo National Park, NWT, and 37 in Dawson, Yukon. Plots were placed within homogeneous areas characterised by the degree of burn severity and tree species composition, and also located with due consideration for their intended association with the remote sensing image. The sampling process considered both the range of vegetation communities present and the range of burn severity levels (low, moderate, high) within these communities. All field data were collected during the growing season following the fire (Table 2), which corresponded with the extended assessment period recommended for CBI-based assessment of burn severity (Key and Benson 2006). A 100-m transect was established at each plot. At the centre point of the transect, plot photos were acquired and the global positioning system (GPS) coordinates recorded. Basal area per ha (BA ha^{-1}) by tree species was measured at the 10, 30, 50, 70 and 90 m mark using a metric Basal Area Factor 5 prism. Daily gridded weather maps were produced using noon local standard time weather data from nearby stations. Fire weather index (FWI) system components were then calculated for each grid cell (de Groot *et al*. 2007). Fire progression was mapped using the spatial fire management system (sFMS, Englefield *et al*. 2004) based on MODIS and AVHRR hot spot data and the nearest neighbour interpolation method. These data were used to compute the date that each grid cell within a fire burned, and from which the FWI values for that day and location were derived. Fire weather information compiled for each of these fires included the build-up index (BUI) and initial spread index (ISI) (Van Wagner 1987).

Fuel type, as defined by the Canadian forest fire behaviour prediction (FBP) system (Forestry Canada Fire Danger Group 1992), was determined from the species composition that was recorded at each plot. In the FBP system, 16 general fuel types are defined by the combination of fuel elements present on a site that influence fire behaviour and burning conditions, and include forest floor and organic (duff) layer characteristics, surface and ladder fuel characteristics, and stand structure and composition characteristics (Forestry Canada Fire Danger Group 1992). Sites were classified as C2 (boreal spruce) or C3 (mature jack or lodgepole pine (*Pinus contorta* Dougl. Ex. Loud.) if there was ≥75% of conifer basal area and D2 (aspen-green) if there was ≥75% deciduous basal area. Mixed deciduous and coniferous content between these two values were classified as M2 (boreal mixedwood-green). These four FBP fuel types occurred on the fires analysed (Table 1).

The CBI is an attempt to quantify burn severity by assessing the magnitude to which the biophysical parameters of the site have been altered from pre-fire conditions as a consequence of fire (Key and Benson 2006). A 30-m diameter CBI plot was established around the centre of each transect. The CBI method generates a score for burn severity between zero and three (which corresponds to increasing severity) based on ratings of up to 23 biophysical variables, which are divided into five sections based on forest strata level, including substrates, herbs and low shrubs, tall shrubs and saplings, intermediate trees and mature trees. If a given strata level or individual attribute (e.g. % canopy mortality) is not present, it is not incorporated into the total CBI score. Some plots were also collected from unburned sites, each closely resembling the pre-fire ecology of a burned plot, and were used both to ensure unburned areas were being properly identified, and to draw inferences regarding burn severity as a

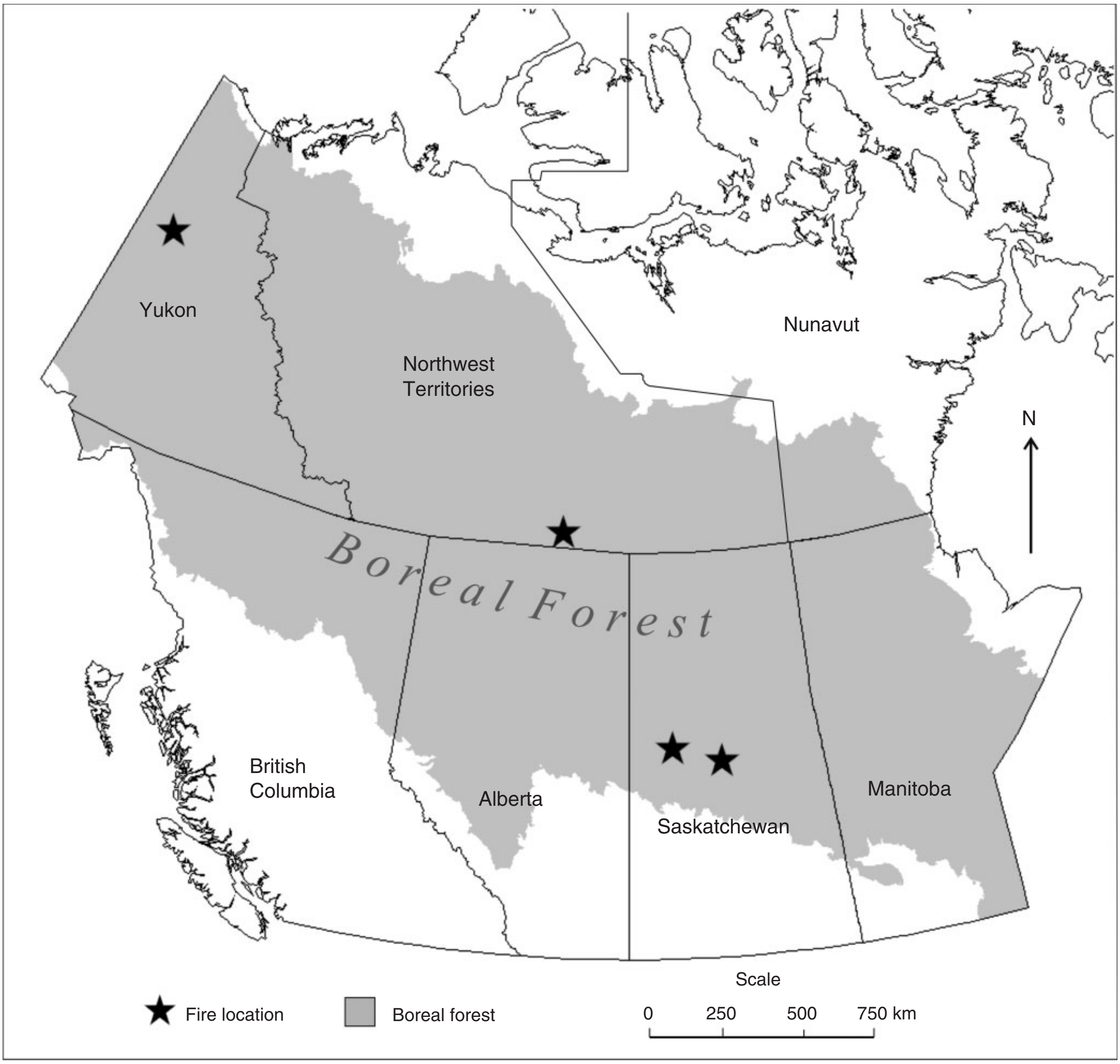

Fig. 1. Location of the four fires analysed within the western Canadian Boreal defined by the Ecological Stratification Working Group (1995).

function of site ecology. For this study, total CBI was used as the field measure of burn severity.

Image data collection and image processing

Pre-fire and post-fire Landsat-5 or Landsat-7 imagery was acquired for each fire (Table 2). Image selection attempted to minimise temporal and phenological differences between image pairs, with timing set after leaf flush and during the growing season (Burns and Honkala 1990*a*, 1990*b*; Peterson and Peterson 1992). Burn severity results during the growing season have reportedly been similar as long as moisture content and phenology between pre- and post-fire images are as similar as possible (Key and Benson 2006). All images were orthorectified with a 1st-order polynomial model, by an image-to-image registration, using Natural Resources Canada's Centre for Topographic Information archived Landsat imagery (Geobase 2005*a*) and Canadian Digital Elevation Data (Geobase 2005*b*). For all images, sufficient ground control points were collected to achieve a root mean square error (RMSE) of near or <0.5 pixels (Table 2).

All images underwent a radiometric correction, first to convert raw digital number (DN) values into radiance, and then to convert radiance values into top-of-atmosphere reflectance (Chander and Markham 2003; NASA Goddard Space Flight Center 2006). For bands 4 and 7 of each image pair, the need for

Table 2. Summary attributes of satellite image acquisition and orthorectification results
RMSE, root mean square error presented in pixel units (1 Landsat TM pixel is 30 m^2)

Property	Saskatchewan Green Lake	Saskatchewan Montreal Lake	NWT Wood Buffalo	Yukon Dawson
Fire year	2003	2003	2004	2004
Fire ID	102	104	21	30
Pre-fire image date[A]	2 August 2001 (L5)	12 August 2001 (L7)	10 July 2004 (L5)	9 August 2003 (L5)
Pre-fire image path/row	39/22	37/22	46/18	62/15
Pre-fire orthorectification RMSE (pixels)	0.46	0.41	0.36	0.46
Post-fire image date[A]	25 July 2004 (L5)	19 August 2004 (L5)	23 August 2005 (L5)	13 July 2005 (L5)
Post-fire image path/row	39/22	38/22	45/18	62/15
Post-fire orthorectification RMSE (pixels)	0.49	0.23	0.47	0.40
UTM zone	13	13	11	8

[A]L5: Landsat 5 Thematic Mapper; L7: Landsat 7 Enhanced Thematic Mapper+.

radiometric normalisation was statistically tested by comparing a set of pseudo-invariant dark and bright targets from the pre- and post-fire images, and where necessary pre-fire values were regressed against and then normalised to post-fire values (Epting *et al*. 2005; Key and Benson 2006).

The NBR was computed for each image date, and dNBR was calculated as the difference in NBR for each dataset (image pair) according to Eqns 1 and 2, respectively (Key and Benson 2006):

$$\text{NBR} = (\text{TM4} - \text{TM7})/(\text{TM4} + \text{TM7}) \quad (1)$$

$$\text{dNBR} = \text{NBR}_{\text{pre-fire}} - \text{NBR}_{\text{post-fire}} \quad (2)$$

NBR values can theoretically range from -1 to $+1$, and dNBR values can range from -2 to $+2$. The pixel values of dNBR within a 3×3 pixel window were averaged and correlated with CBI values sampled in the field.

Data analysis

There were four components to the assessment of burn severity that included (1) descriptive analysis of CBI and dNBR; (2) statistical analysis and modelling of CBI and dNBR; (3) an analysis of variance (ANOVA) test of dNBR by fuel type; and (4) employment of the empirical model for thematic mapping of burn severity.

Descriptive statistics of CBI and dNBR were computed for each fire as well as the result from pooling the data from all fires into a single dataset. These statistics were associated with field photographs from which accompanying information on FBP fuel type, CBI score, and dNBR value were added. This descriptive analysis facilitated a characterisation of burn severity from the field over the fires sampled.

Pearson correlations and scatterplots were initially conducted to assess the nature of the relationship between CBI and dNBR. The predictive relationship between these two variables has most frequently been described with linear and second degree polynomial model forms (van Wagtendonk *et al*. 2004; Cocke *et al*. 2005; Key and Benson 2006). Would these model forms perform similarly for western Canadian Boreal fires or would a model form customised to the data distributions encountered be preferable? Burn severity and vegetation recovery is an ecological concept that is dynamic over time (Key 2006). The very nature of burn severity is inherently non-linear, which has been exemplified in scatterplots between CBI and dNBR (van Wagtendonk *et al*. 2004; Key 2006), and the second degree polynomial model form was previously an attempt to describe this relationship.

To provide a comparison as to what has been reported in the literature, the linear and polynomial model forms were fit with the data from each fire and compared with a non-linear model form created through a graphical visual analysis of the relationship between CBI and dNBR, and application of Datafit software (Oakdale Engineering 2002). Datafit performs a single-independent or multiple-independent variable non-linear regression based on a library of 600 pre-defined regression models using the Levenberg–Marquardt non-linear least-squares curve fitting algorithm (Oakdale Engineering 2002). All three models were applied to each fire, compared with the coefficient of multiple determination (adjusted R^2) and RMSE, and subsequently validated with a cross-validation method that was replicated across 100 trials using a 20 percent random sample with replacement process (Efron and Tibshirani 1993).

Large fires typically burn a wide range of fuel types, which results in considerable spatial and temporal variation in fire effects such as fuel consumption (de Groot 2006; Jia *et al*. 2006). While fuel type variation within a fire has not typically been considered in the modelling of burn severity, there is potential for modulation of the CBI and dNBR relationship when fuel type information is considered. To assess this potential requires an assessment of the statistical distributions of CBI and dNBR as a function of fuel type. One-way analysis of variance (ANOVA) tests were conducted on each dataset to determine if statistical differences in dNBR existed among FBP fuel types identified within each of the burns. Tukey's multiple means comparison tests were subsequently employed to identify differences among FBP fuel types if it was identified as a significant factor within the one-way ANOVA. All statistical tests in this study were conducted at the 5% level of significance.

Thematic maps of burn severity have been produced by thresholding dNBR values to create broadly defined but discrete classes that range from low to high (Cocke *et al*. 2005; Epting

Table 3. Descriptive statistics of dNBR and CBI, for each dataset

Descriptive statistic	Saskatchewan		NWT		Yukon		All fires combined	
	CBI	dNBR	CBI	dNBR	CBI	dNBR	CBI	dNBR
n	41	41	83	83	37	37	161	161
Mean	1.65	0.37	1.75	0.31	1.69	0.40	1.71	0.34
s.d.	1.10	0.29	0.95	0.22	1.19	0.30	1.04	0.26
Minimum	0.00	−0.09	0.00	−0.09	0.00	−0.04	0.00	−0.09
Maximum	3.00	0.88	2.77	0.72	2.92	0.94	3.00	0.94
Range	3.00	0.96	2.77	0.81	2.92	0.98	3.00	1.00

et al. 2005; Key and Benson 2006). The difficulty with this process is in associating a meaningful threshold to a physical remote sensing value in dNBR units. Because burn severity is typically assessed in the field following the burn, an alternate approach would be to assign burn severity levels to CBI measurements. The model relationship between CBI and dNBR would then provide the basis to define dNBR severity threshold values. This approach of basing burn severity levels on field-derived CBI has similarly been recommended by Lentile *et al*. (2006). Based on photos and on-the-ground assessment, the burn severity of each plot was rated independently of CBI values by considering factors such as fire damage to trees and shrubs, the level of consumption of small branches, and the relative amount of mineral soil exposed as a result of the burn. This process resulted in field rankings of low, moderate and high burn severity for each site from which the upper and lower CBI values for these severity classes could be determined. These CBI values were input to the CBI–dNBR model to discretise the CBI into physical dNBR values to produce a classified image map of burn severity.

To provide a basis for comparison, the threshold values reported for boreal fires in Alaska by Epting *et al*. (2005) were employed to illustrate the differences in the resulting burn severity maps, and to present a frequency distribution of burn severity class. The extent to which these two burn severity maps corroborate each other has inferential implications regarding the use of published values relative to those derived from field observation. In this study, this exercise was undertaken for the Yukon Dawson fire.

Results

Descriptive statistics

Of the two Saskatchewan fires, there were 23 CBI plots in Green Lake and 18 CBI plots in Montreal Lake (Table 1). Given their close proximity and ecological similarity, the data were tested to determine if they could be pooled to generate a larger single database ($n = 41$). The data distributions for Green Lake and Montreal Lake were statistically similar, which resulted in the data being pooled into one fire dataset to represent Saskatchewan (CBI $P = 0.43$, dNBR $P = 0.22$). The three datasets that represented the fires in Saskatchewan, NWT and Yukon were also statistically similar, which permitted a fourth dataset that represented all fires to be created (CBI $P = 0.86$, dNBR $P = 0.13$). All post-fire image acquisitions for these datasets were undertaken at approximately the same stage of vegetative phenology

Table 4. Descriptive statistics of selected fire weather indices
BUI, build-up index; ISI, initial spread index

Descriptive statistic	Saskatchewan		NWT		Yukon	
	BUI	ISI	BUI	ISI	BUI	ISI
n	41	41	83	83	37	37
Mean	51	8.9	106	2.8	118	3.8
s.d.	19	6.7	8	1.6	4	0.9
Minimum	17	0.5	82	1.3	107	2.6
Maximum	71	17.7	122	8.9	126	6.4
Range	54	17.2	40	7.6	19	3.8

across all sites (see Table 2). Creating these four datasets provided the opportunity to compare the CBI–dNBR relationships from individual fires to a dataset comprised of all fires grouped together.

Burn severity values and their variability were relatively similar across the fires in Saskatchewan, NWT and Yukon (Table 3). From the image, dNBR was largest for the Yukon fire, and this was consistent with extreme burning conditions recorded by the range of consistently high BUI values at the time of burning (Table 4). The BUI is a numeric rating of the total amount of fuel in the organic layer available for combustion (Van Wagner 1987). The extremely high BUI values at the Yukon fire indicate the potential for very high fuel consumption in the forest floor. This explains, in part, the larger average dNBR value obtained compared with the other fires (Table 3). The BUI for the Wood Buffalo, NWT fire (Table 4) indicates that burning conditions were high to extreme as well, but the range was somewhat lower and more variable than the Yukon fire, and similar in trend to the lower average dNBR value for that fire (Table 3). The BUI values were lowest and most variable for the Saskatchewan fires, which indicates much higher forest floor moisture contents and lower fuel consumption. The average dNBR for the Saskatchewan fires was much higher than the Wood Buffalo NWT fire but less than the Yukon fire. This could be explained by the extremely high maximum ISI values (Table 4), an indicator of the fire rate of spread (Van Wagner 1987). Most fire growth and area burned occurs under high ISI values because of the high rate of spread, and faster spread rates will result in higher fire intensities. A higher fire intensity causes greater plant mortality and burn severity, which may explain the extremely high maximum ISI value that was associated with the relatively high dNBR value. In general, these results do suggest some association between

FWI system components and the severity of the burn observed from the remote sensing image.

The largest values in CBI didn't necessarily correspond with the largest value in dNBR, which suggests that there were some differences in their associations that varied by fire (Table 3). Across four FBP fuel types, more severe fires were associated with larger values of CBI and dNBR for those fires sampled in Saskatchewan, NWT and Yukon (Fig. 2). A greater amount of green foliage biomass and fine branching, and a smaller amount of bark scorching consistent with less severe burns, was evident across all fuel types (Fig. 2). From a visual perspective, these photographs illustrate some of the range of burn severity that was sampled within each FBP fuel type. As a result, the magnitudes of CBI and dNBR do correspond with the ecological inferences of burn severity, whereby larger values of these variables indicate higher levels of burn severity. Some caution is necessary when attempting to infer trends from field and image values alone when they are averaged over an entire burn, because their values will necessarily vary from the fuel types and burning conditions that occurred within a given fire.

Statistical analysis and modelling of CBI and dNBR

Across all burns including the dataset of all burns combined, CBI and dNBR were statistically and significantly correlated ($P < 0.001$) with correlation coefficients of 0.87 (Saskatchewan), 0.85 (NWT), 0.87 (Yukon) and 0.86 (all fires). A visual examination of scatterplots revealed that the relationship between these variables, however, was not strictly linear (Fig. 3). Inferences about their relationships based on the correlation coefficients alone would, therefore, be misleading. The general shape of the distributions were similar across all fires, which suggested that neither the simple linear nor second degree polynomial were the best suited to model the relationship between CBI and dNBR. A non-linear saturated growth model form was derived and appeared to provide a reasonable compromise relative to the fit parameters generated for the other model forms (Table 5). The highest R^2 and smallest RMSE was reported for the second degree polynomial, but these statistics are misleading because there is an asymptote beyond which larger values of dNBR would result in a prediction of smaller values of CBI (Fig. 3). Across all equations, the asymptote, computed as the first derivative equal to zero, ranges from a dNBR of 0.58 for the NWT fire to 0.77 for the Yukon fire. Beyond this range, CBI values would decrease to result in an unrealistic projection. A non-linear model form provided a more realistic characterisation of these variables compared with the linear and second degree polynomial model forms, at least for the fires sampled in this study.

The model fit parameters described by R^2 and RMSE were remarkably similar across all burns, and pooling the data from all of the fires did not result in a large difference in overall model performance when compared with any of the individual fires (Table 5). There were little differences in the magnitude of these fit parameters when compared with results generated from the cross-validation analysis (Fig. 4). Insofar as the data collected in this study indicates, using a single model to describe the relationship between CBI and dNBR will result in similar predictions to that generated from models based on the individual fires.

FBP fuel type and burn severity (dNBR)

The distribution of dNBR varied by FBP fuel type and the magnitudes of dNBR appeared to vary by fire, which may be attributed to the ecological region within which the fire occurred (Fig. 5). Furthermore, dNBR values by fuel type were statistically different for the fires in Saskatchewan ($P = 0.03$), NWT ($P < 0.001$) and all fires combined ($P < 0.001$), but they were similar in the Yukon ($P = 0.54$). The Yukon burn, however, occurred over a location that was predominately a C2 fuel type that may have resulted in an insufficient sample size from which to ascertain differences in dNBR values by fuel type (R. J. Hall, unpubl. data). Differences in dNBR response occurred with the C2 fuel type compared with others (Table 6). Generally, dNBR values tended to be larger or were among the largest for the boreal spruce (C2) fuel type compared with other fuel types (Fig. 5). These results were more indicative than definitive, which resulted in a need for further investigations to determine the extent that burn severity observed on remote sensing images may be influenced by vegetation fuel type and local ecological and physiographic characteristics of the areas burned.

Thematic mapping of burn severity

Thresholds for mapping burn severity classes are often defined by dNBR values (Lentile *et al*. 2006; Table 7). Burn severity thresholds through field sampling resulted in a CBI value of 1.6 to represent the difference between low and moderate burn severity, and a CBI value of 2.3 to represent the change from moderate to high burn severity. These values were converted into dNBR values (Table 7) based on the non-linear saturated growth model generated for each dataset (Table 5). Fig. 6 presents the thematic classification of the Yukon fire based on employment of burn severity thresholds from Epting *et al*. (2005) compared with those generated from field assessment of CBI. There were large differences in the frequency distributions of burn severity class as a result of the threshold values that were employed (Fig. 6). The use of threshold values from Epting *et al*. (2005) for boreal spruce in Alaska were considered the most similar to conditions of the Yukon fire relative to others reported (Cocke *et al*. 2005; Key and Benson 2006), and undertaken strictly for illustrative purposes. Assessing the accuracy of burn severity maps is difficult when the definitions of class limits are subjectively derived. Comparing these maps demonstrates the impact that establishing threshold values will have on the thematic presentation of burn severity. While the assignment of burn severity ratings in the field remains a subjective decision, its association to field attributes such as the CBI does provide a mechanism from which thematic maps of burn severity can be created through its relationship to dNBR.

Discussion

CBI–dNBR modelling

This study reports a new, non-linear model based on a saturated growth model form to describe the relationship between CBI and dNBR. Previous papers have not illustrated the relationships between these variables (Epting *et al*. 2005; Clark and Bobbe 2006), while those who have suggest it is either linear (Cocke

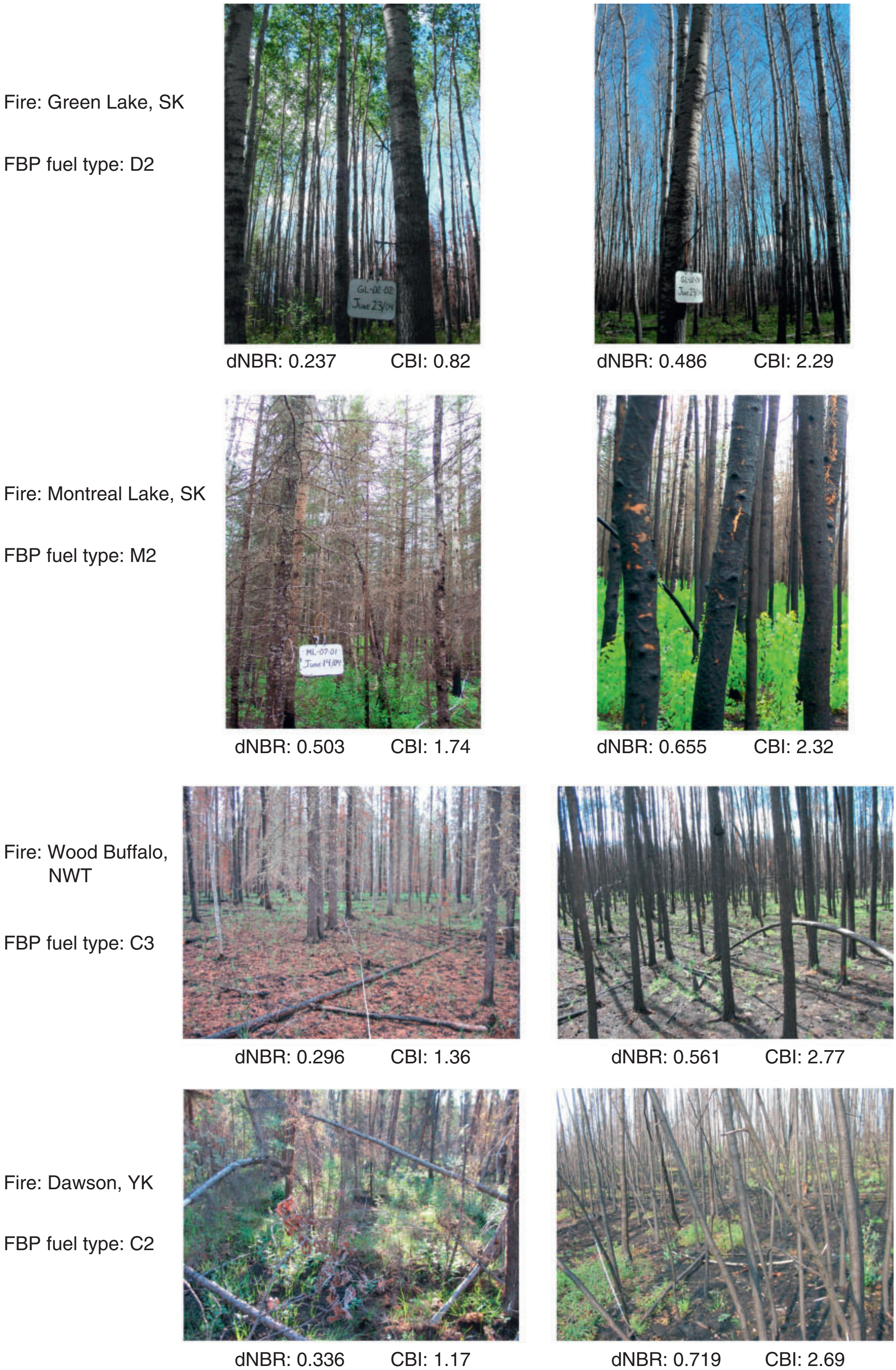

Fig. 2. Field photographs depicting burn severity by fuel type.

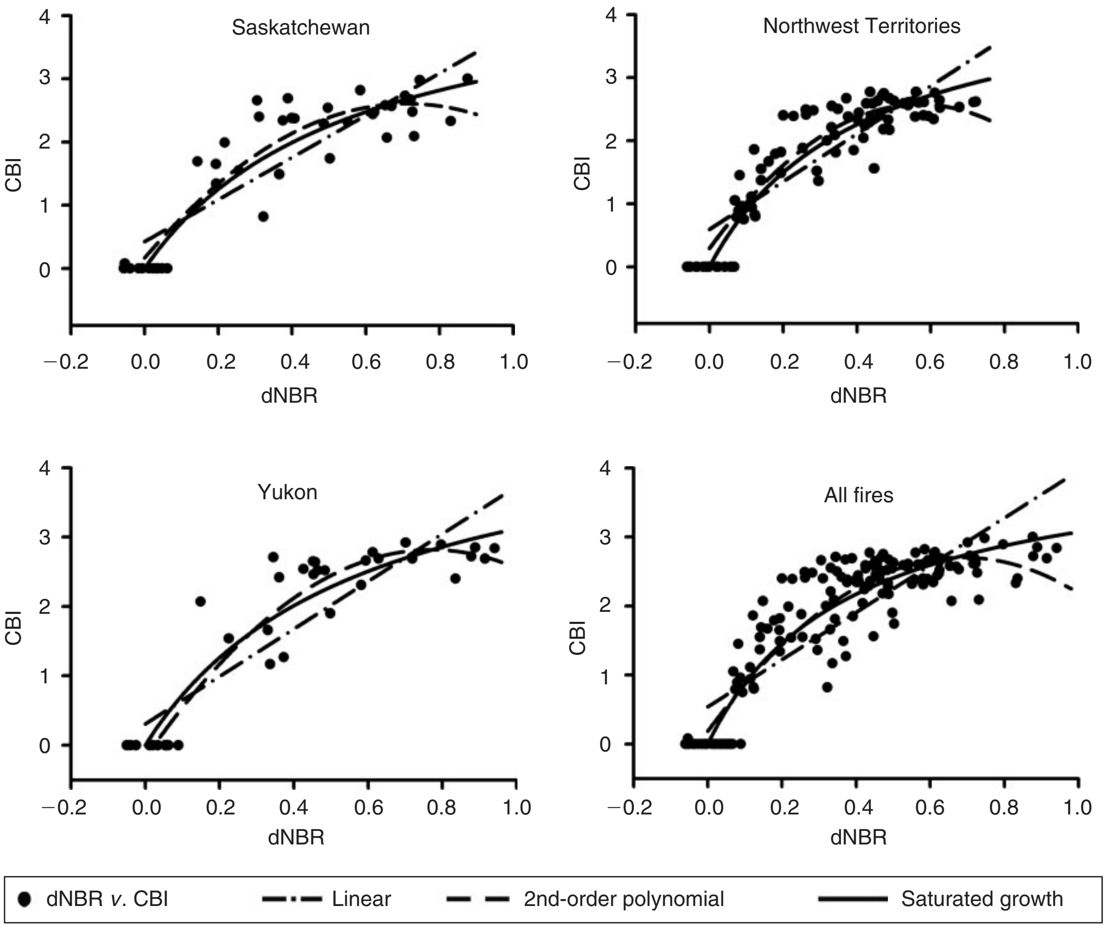

Fig. 3. Scatterplots and model relationships between composite burn index (CBI) and differenced Normalized Burn Ratio (dNBR).

Table 5. Linear, 2nd-order polynomial and non-linear modelling results for each of three individual datasets, as well as the pooled dataset
CBI, composite burn index; dNBR, differenced Normalized Burn Ratio; R^2, coefficient of multiple determination; RMSE, root mean square error

Model form	Saskatchewan					Northwest Territories				
	Model			R^2	RMSE	Model			R^2	RMSE
	a	*b*	*c*			*a*	*b*	*c*		
$CBI = a + b(dNBR)$	0.42	3.33		0.76	0.30	0.31	3.42		0.76	0.22
$CBI = a + b(dNBR) + c(dNBR)^2$	0.17	6.85	−4.81	0.85	0.19	0.19	7.79	−5.05	0.87	0.12
$CBI = dNBR \times (a[dNBR] + b)^{-1}$	0.21	0.12		0.82	0.22	0.20	0.12		0.82	0.17
	Yukon					All fires				
$CBI = a + b(dNBR)$	0.44	3.43		0.76	0.36	0.54	3.42		0.73	0.30
$CBI = a + b(dNBR) + c(dNBR)^2$	0.13	7.39	−5.05	0.88	0.18	0.18	7.33	−5.33	0.84	0.17
$CBI = dNBR \times (a[dNBR] + b)^{-1}$	0.20	0.12		0.85	0.22	0.22	0.09		0.82	0.20

et al. 2005) or curvilinear (van Wagtendonk *et al.* 2004). Recent studies are, however, starting to identify non-linear trends that are similar to results reported in this study (Key 2006; Wimberly and Reilly 2007). Burn severity simulations have shown that the increase in SWIR reflectance (in the 2080–2350-nm range; coincident with Landsat band 7) ceases with CBI values above ~2 to 2.5, whereas the decrease in NIR reflectance (in the 760–900-nm range; coincident with Landsat band four) is consistent with increasing burn severity (Chuvieco *et al.* 2006). This variable pattern exemplifies the non-linear association of dNBR with burn severity. The advantage of using a non-linear model form is in the interpretation or estimation of CBI values along the scale of varying dNBR that is reflective of burn severity observed on the image, and representative of the ecological dynamics of post-burn recovery whose pattern has been reportedly non-linear (Key 2006).

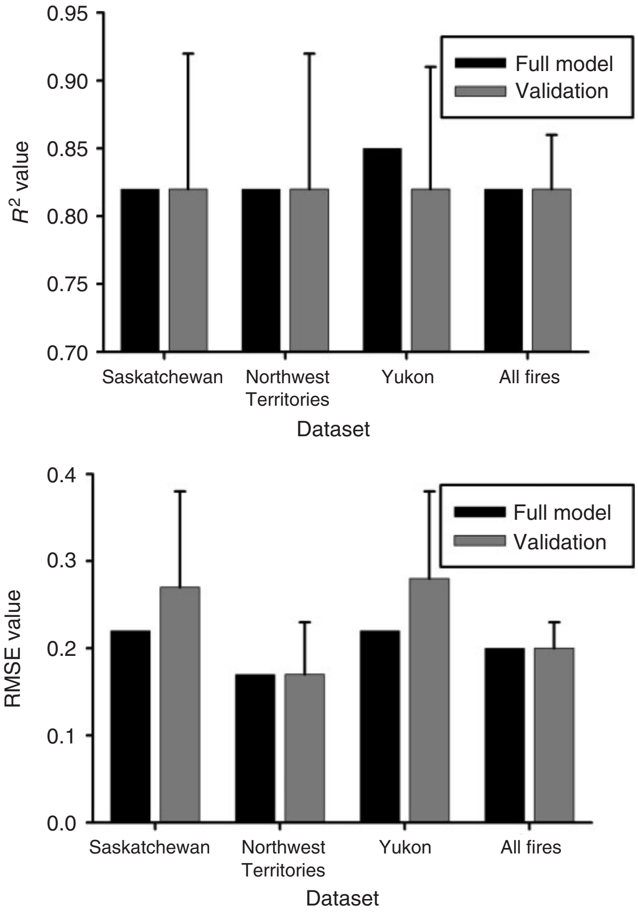

Fig. 4. Cross validation results for adjusted R^2 and root mean square error (RMSE).

The models between the three datasets were remarkably similar to the model generated by combining CBI and dNBR data into a single dataset. The possibility of using a single model for all boreal forest burn severity mapping could hold particular relevance to management and monitoring agencies seeking a relatively inexpensive and repeatable method of collecting burn severity information to update resource inventories or management information systems, plan recovery efforts, or direct long-term planning. Roy *et al*. (2006) found the dNBR–burn severity relationship to be different in highly varying landscapes including the African savanna, South American tropical forest and Russian taiga. The results presented here, however, suggest consistency in that relationship across a range of ecoregions within the western Canadian boreal. Extrapolating model results generated in this study to other fires within this boreal region should be done with caution, however, until studies with additional burns are undertaken. Analysis of a larger sample of fires from the boreal and other forested ecological regions of Canada, with equivalent data products and equivalent sampling methodologies, would provide insights as to the possibility of using dNBR and a single model form.

Much of the literature in remote sensing of burn severity has been based on the arithmetic difference of the NBR at two dates (Lentile *et al*. 2006). While this study focussed on association of the total CBI to dNBR, additional insights into the nature of these relationships may be possible by partitioning CBI into different strata layers in order to determine if their relationships change with the remote sensing image. There is also growing evidence for computing the relative difference in dNBR that may improve the sensitivity to detect ecological impacts especially at the low and high ends of the scale (Miller and Thode 2007). Future work directed at CBI computed at different strata layers and the potential use of the relative difference in dNBR may result in new insights that pertain to the assessment of ecological effects of fire in the Canadian Boreal.

FBP fuel type and burn severity (dNBR)

Field sampling for burn severity typically strives to sample a full range of severity with equal sampling across all burn severity classes (Key and Benson 2006). Considerations for stratification by fuel type are not generally specified. The degree of post-fire change varies with vegetation type, annual growing season variability and time since fire (Lentile *et al*. 2006). For this reason, stratification among vegetation types, undertaking image comparisons at the same stage of vegetative phenology, and use of image differencing have been the recommended approaches from which to assess ecological change caused by fire (White *et al*. 1996; Cocke *et al*. 2005). Of these, the lack of stratifying for pre-burn vegetation type before burn severity analysis could constitute an area for future improvement in the modelling of burn severity. Boreal forest ecosystems support a broad range of fuel types that will burn with variable severities depending on the conditions at the time of the fire (Amiro *et al*. 2001). Thus, using FBP fuel type as a descriptor of vegetation type is one approach to ascertain its role in dNBR values.

dNBR values recorded on remote sensing images are influenced by pre-burn fuel types, and that influence is notably more obvious for some fuel types than others. Statistical differences in dNBR distributions between fuel types were more often observed with boreal spruce (e.g. C2) than with others (Table 6). C2 sites tend to contain more litter, duff, and more fine fuels throughout multiple forest strata levels compared with C3 (mature jack) sites or deciduous dominated sites (Forestry Canada Fire Danger Group 1992). Results from this preliminary fuel type analysis warrant further investigation into the effect of fuel type on burn severity modelling from remote sensing data. A sampling strategy designed specifically to test this effect could yield further insights into the importance of fuel type on predicting burn severity, and could also provide further justification for large-area fuel type maps derived from earth observation or other methodologies to better model burn severity at regional scales. There is a recognised need for high spatial resolution estimates of fuel types (Jia *et al*. 2006) that, if available, could be used to guide field sampling strategies and model development.

Thematic mapping of burn severity

While burn severity varies continuously over the landscape, it is often partitioned into broad discrete classes for convenience and practical application (Lentile *et al*. 2006). The challenge has been, and still is, to reduce the subjectivity often associated with defining burn severity thresholds. Severity is based

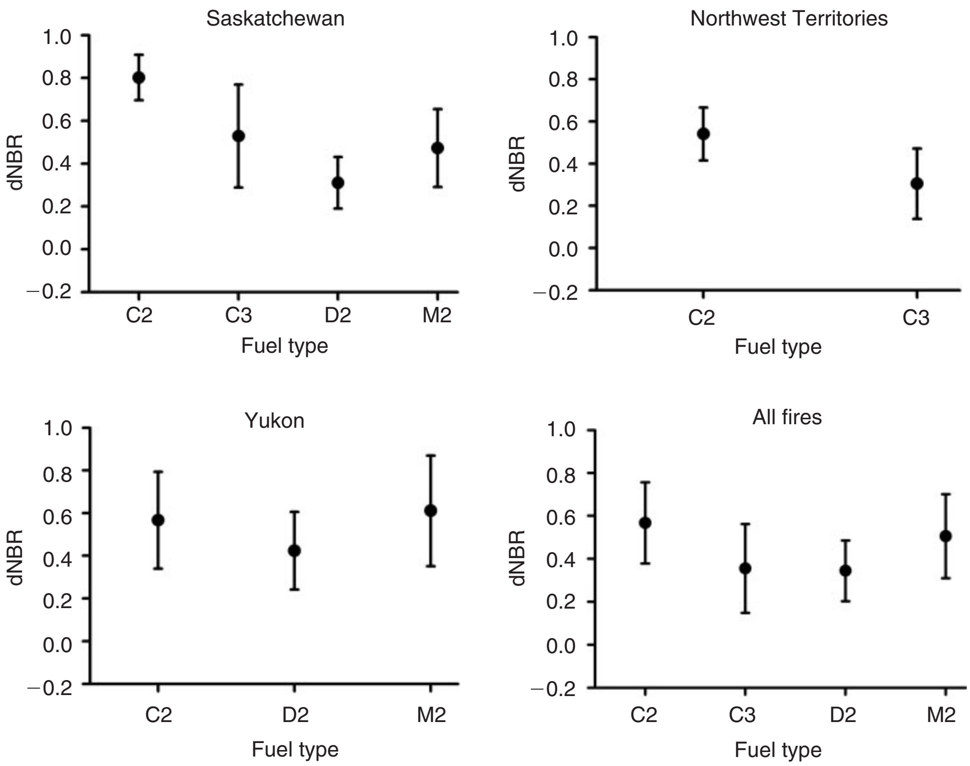

Fig. 5. Distribution of burn severity by fire behaviour prediction (FBP) fuel type (Forestry Canada Fire Danger Group 1992).

Table 6. Multiple means comparison of statistical differences in differenced Normalized Burn Ratio (dNBR) between fuel types

Dataset	Fuel type pair	Mean difference dNBR	Tukey's *P*-value
Saskatchewan	C2–C3	−0.309	0.05
Saskatchewan	C2–M2	−0.329	0.05
Saskatchewan	C2–D2	−0.491	0.03
NWT	C2–C3	−0.235	<0.001
All fires	C2–C3	−0.212	<0.001
All fires	C2–D2	−0.062	0.007

Table 7. Comparison of differenced Normalized Burn Ratio (dNBR) values used in thresholding burn severity

dNBR values in this study were scaled by 10^3 to facilitate comparison with published studies

Burn severity	Cocke *et al.* 2005	Epting *et al.* 2005	This study
Unburned	≤50	≤89	≤40
Low	51–240	90–274	41–283
Moderate	241–570	274–679	284–513
High	≥571	≥680	≥514

on observed changes that may be complicated by the seasonality of the images and whether the timing is for initial assessment or extended assessment time periods (Key and Benson 2006). As a result, it is particularly problematic when attempting to define class limits from a physical remote sensing value such as dNBR.

Recent reviews have verified the considerable variation in low, moderate, and high class values across regions and vegetation types (Lentile *et al.* 2006). In forested regions, remote sensing of burn severity is highly correlated with fire effects on overstorey vegetation (Patterson and Yool 1998). It is well recognised, however, that the satellite image spectral response is a function of all objects, including vegetative and non-vegetative features that occur within a ground resolution cell (Guyot *et al.* 1989). This study employed the CBI, a ground-based composite index, from which its empirical relation to dNBR was used to map burn severity. This approach is consistent with recommendations by Lentile *et al.* (2006) from which field measurements of CBI could be used as a basis to define locally meaningful dNBR thresholds. The major advantage of this approach is the use of field observations to determine severity rather than from dNBR values alone because there is no simple physical basis from which to define burn severity class limits.

If the mapping of burn severity into discrete classes remains an important objective, then a primary question pertains to the number of burn severity classes to map. Fewer severity classes increase consistency at the expense of map utility (Cocke *et al.* 2005). The approach employed in this study will work with any number of burn severity categories provided there is a logical basis from which to assign a severity rating to field measurements of CBI. A similar challenge arises, however, in that the

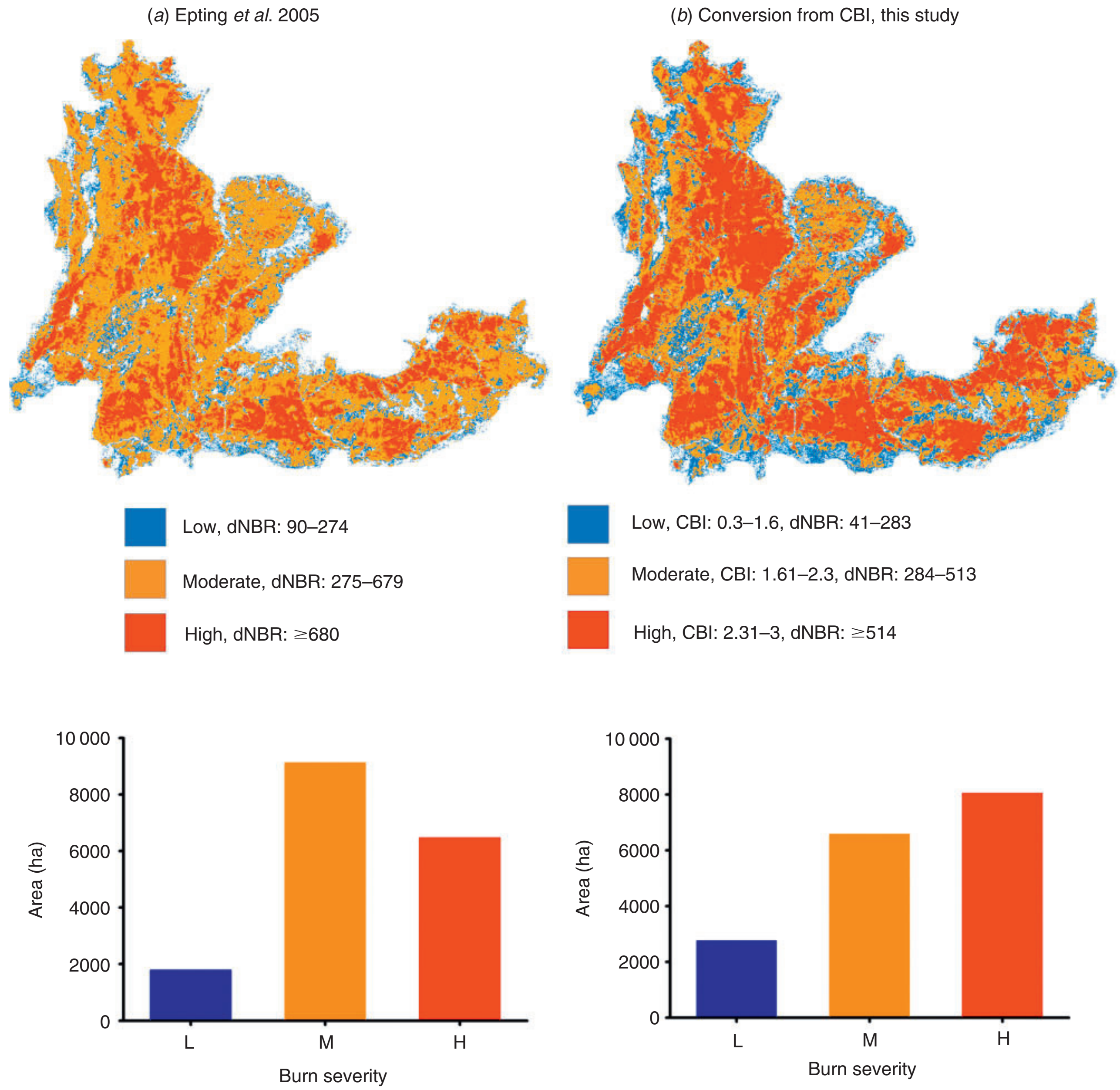

Fig. 6. Classified burn severity maps for the Dawson fire in Yukon based on threshold values from (*a*) Epting *et al*. (2005) and (*b*) conversion of field-based composite burn index (CBI) values to differenced Normalized Burn Ratio (dNBR). dNBR values from this study were scaled by 10^3 to match those of Epting *et al*. (2005).

confidence in CBI assignment to a burn severity class will likely reduce as the number of these classes increase.

Burn severity maps should be created for a given application, with threshold values chosen according to the relevant ecology of the application in question. For example, the level of burn severity at which caribou will no longer use a site for winter forage (Joly *et al*. 2002) may not be the same as the level of burn severity at which the area is not habitable for marten, migratory birds or predatory birds (Paragi *et al*. 1996; Yefremov and Shvidenko 2004). Further integration of remote sensing and field assessments are needed to improve knowledge of what remote sensing indices observe relative to fire effects in order to better understand the kinds of questions and applications for which remote sensing of burn severity may be employed.

Conclusions

This study answered three questions relevant to burn severity characterisation from field and remote sensing data using CBI and dNBR, from the perspectives of modelling, influence of fuel type, and mapping. A non-linear model form best characterised the relationship among these variables for the fires sampled in this study, and it offers distinct advantages over the linear and second degree polynomial model forms previously reported with respect to application over the full range of values encountered in the geographic region of study. The magnitude and distribution of dNBR values were influenced by fuel type and as a result, future improvements to model development may be possible if its influence could be incorporated into model development. The burn severity model parameter values over the fires mapped in Saskatchewan, Yukon and Northwest Territories were remarkably similar to the model generated from pooling to create a single dataset. Models developed were also considered fairly robust given the similarity in model fit statistics from the cross-validation. Further investigation to confirm the nature of this relationship over a larger sample of fires is recommended as preliminary indications suggest it may be possible to merge multiple fires within the boreal, at least within the region studied. This study presented an alternative approach for mapping burn severity that utilises the empirical relationship between CBI and dNBR. This approach provides the advantage of associating ground observations to independent measures of burn severity represented by the CBI. The results from this study are encouraging from the perspective of using field and remote sensing data for characterising burn severity. Addressing the areas of future work will further define how remote sensing-based methods of burn severity may be applied within boreal regions. In turn, these advancements will contribute towards improved knowledge in understanding the ecological effects of fires.

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