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Using Landsat data to assess fire and burn severity in the North American boreal forest region: an overview and summary of results

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Abstract. There has been considerable interest in the recent literature regarding the assessment of post-fire effects on forested areas within the North American boreal forest. Assessing the physical and ecological effects of fire in boreal forests has far-reaching implications for a variety of ecosystem processes – such as post-fire forest succession – and land management decisions. The present paper reviews past assessments and the studies presented in this special issue that have largely been based on the Composite Burn Index and differenced Normalized Burn Ratio (dNBR). Results from relating and mapping fire/burn severity within the boreal region have been variable, and are likely attributed, in part, to the wide variability in vegetation and terrain conditions that are characteristic of the region. Satellite remote sensing of post-fire effects alone without proper field calibration should be avoided. A sampling approach combining field and image values of burn condition is necessary for successful mapping of fire/burn severity. Satellite-based assessments of fire/burn severity, and in particular dNBR and related indices, need to be used judiciously and assessed for appropriateness based on the users' need. Issues unique to high latitudes also need to be considered when using satellite-derived information in the boreal forest region.

Introduction

The current special issue presents the results of six studies focussed on evaluating the use of satellite data for mapping fire and burn severity in ecosystems located across the boreal and subarctic regions of western Canada and Alaska. These ecosystems are dominated by wildfire in a region characterised by low solar elevation, short and variable growing seasons, cold soils with deep organic horizons, discontinuous permafrost that interacts with wildfire to control many biotic and abiotic processes, and highly flammable coniferous forest types that are subject to stand-replacing fires. Here, fire severity refers to the immediate impacts of fire on the environment, while burn severity references the degree of ecological change as a result of the fire. These terms are defined and described in detail later in the paper and follow the description given in Lentile *et al*. (2006).

The studies presented in the current special issue were primarily undertaken using the field data collection method and satellite remote-sensing data process reported by Key and Benson (2006). Research on using Landsat sensors to study within-burn variability in fire-disturbed sites has been undertaken by several researchers (see later section on previous research in the present paper and Lopez-Garcia and Caselles 1991). In particular, early work by Lopez-Garcia and Caselles (1991) using newly available Landsat Thematic Mapper (TM) imagery showed the utility of using Landsat TM, and specifically bands 4 and 7, to map variability of vegetation cover at burns in Spain in the mid-1980s. This is some of the first research to demonstrate the methods that led to the Normalized Burn Ratio (NBR).

For the papers reviewed in the current special issue, the field observation method used to assess damage from fire is the Composite Burn Index (CBI), and the satellite index used is the NBR and the differenced NBR (dNBR) derived from differencing pre-fire and post-fire NBR products prepared from Landsat TM or Enhanced Thematic Mapper plus (ETM+) data.

The theme for the present special issue originated during a series of workshops in 2005 and 2006 conducted by fire and remote-sensing scientists working in the North American boreal forest. In addition to the coauthors of the papers presented in this special issue, the participants in our working group included T. Nettleton, F. S. Chapin, S. Rupp and D. McGuire of the

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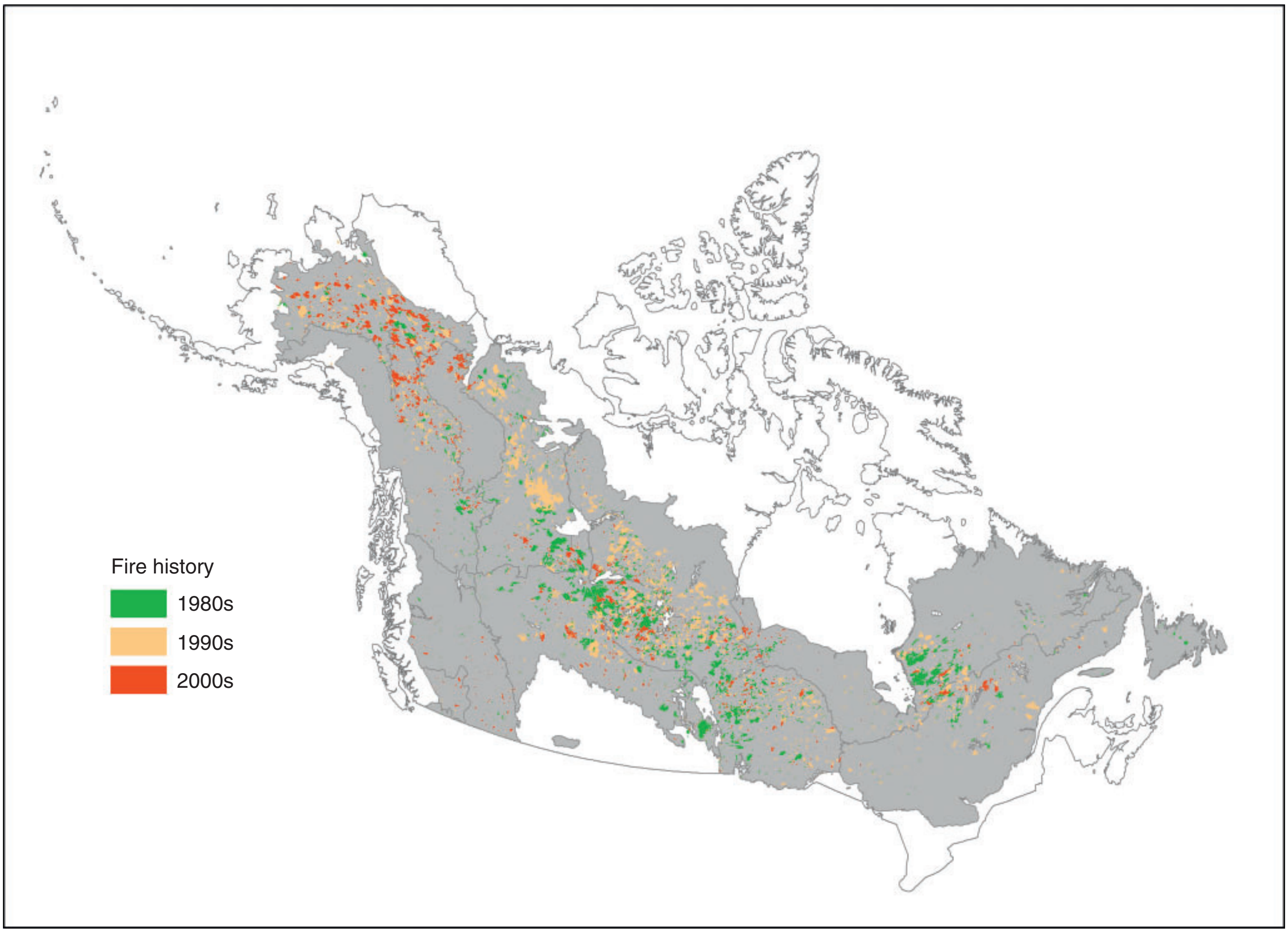

Fig. 1. Map of wildfires in the boreal regions of North America for 1980 to 2005.

University of Alaska, J. Johnstone of the University of Saskatchewan, and R. Jandt of the Alaska Fire Service, Bureau of Land Management. Two to three workshops per year were convened to discuss the approaches and results from the studies being conducted by the members of the working group.

Researchers from our group visited with C. Key and N. Benson in the spring of 2005 to develop a better understanding of the principles behind their methods (Key and Benson 2006). A workshop with the Alaskan participants was held in June of 2005 in Fairbanks, AK, to develop a consistent methodology for collection of the observations used to calculate CBI. As a result, the CBI field worksheet was modified to account for characteristics unique to the Alaskan boreal forest (Kasischke *et al.* 2008; Murphy *et al.* 2008).

The purpose of the present paper is to present an integrative overview of several studies published in this special issue and to provide a review of previous research results that have used field and remote-sensing data to assess fire and burn severity within the boreal region of North America. Four of the papers in the current special issue present comparisons between the NBR or dNBR and the CBI (Allen and Sorbel 2008; Hall *et al.* 2008; Hoy *et al.* 2008; Murphy *et al.* 2008). Several factors that contribute to variations in NBR in high northern latitude areas are identified (Verbyla *et al.* 2008). An evaluation of the utility of the CBI for assessing ecosystem characteristics that can be used to assess fire/burn severity in black spruce forests is also reported in the present collection of papers (Kasischke *et al.* 2008).

Fire in boreal ecosystems

Wildfires can be very large and often severe in the ecosystems of boreal North America (Kasischke *et al.* 2005*b*). Average annual area burned in Alaska and Canada, based on a record of over 50 years, is ~2 million hectares (ha), although fire in boreal North America is episodic with several extreme fire years occurring among many years where burned area was relatively small (Fig. 1; Stocks *et al.* 2002; Kasischke *et al.* 2005*b*). In 2004, more than 5.8 million ha burned in Canada and Alaska; this represents one of the largest fire years on record for the North American boreal region, and the largest fire year known for Alaska and the Yukon Territory based on reported fire statistics. Over the past four decades, there has been a doubling of the annual area burned across the North American boreal region (Gillett *et al.* 2004; Kasischke and Turetsky 2006). This trend has resulted in new challenges for fire management in the form of both increased landscape affected by fire, as well as intensified concerns about the effects that the increase in large wildfires may have on terrestrial ecosystems and carbon in the atmosphere.

In contrast to other fire-dominated ecosystems, the major tree species in the North American boreal forest region are thin-barked and easily killed by fire, causing stand-replacing burns that are often severe enough to consume much of the surface organic material (Johnson 1992). Black spruce (*Picea mariana* (Mill.) BSP), white spruce (*P. glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), lodgepole pine (*P. contorta* Dougl. ex Loud. var. *latifolia* Engelm.), aspen (*Populus* spp.) and birch (*Betula* spp.) forests represent much of the forested landscape of the North American boreal region and are adapted to a fire-dominated system. Fire strongly controls forest succession and shapes the landscape-scale distribution of vegetation ecosystems in most regions of boreal North America (Chapin *et al*. 2006). Low evapotranspiration and cool, wet ground conditions of the boreal region promote a large buildup of organic carbon in the surface organic layer of forests (also known as duff) and peat deposits in forested and open peatlands. Because boreal forest ecosystems have low forest productivity (low aboveground biomass), these organic deposits hold the majority of organic-based carbon in many boreal ecosystems (Gorham 1991; Harden *et al*. 2000). In addition, the duff layers are variably impacted by fire, depending on variability in surface fuel moisture and duff thickness. Light fires will leave much of the duff in place, whereas severe fires can consume 10 to 30 cm or more of organic matter that may also result in exposure of the mineral soil surface (Miyanishi and Johnson 2002; Kasischke and Johnstone 2005; Harden *et al*. 2006; R. D. Ottmar and S. P. Baker, pers. comm., November 2007). In areas with permafrost, fire can variably impact the permafrost depth and active layer (the soil horizons above the permafrost that freeze and thaw annually), depending on how much duff or peat is removed (Swanson 1996; Burn 1998; Kasischke and Johnstone 2005). Permafrost is also a key driver of surface hydrology in many lowland ecosystems as well as in upland forests. As a result, the depth of the surface organic layer can be a major determinant of soil moisture (Hinzman *et al*. 2006) and how much surface organic material is consumed during a fire (Kasischke and Johnstone 2005). Boreal ecology, therefore, provides a very different set of circumstances in terms of fire impacts than is found in fire-affected temperate ecosystems.

The loss or damage to surface vegetation and other organic matter from fire has implications for a variety of ecosystem processes, land management decisions, and inputs to the modelling of fire effects on the carbon cycle. Post-fire forest succession is dependent on the level of consumption of stems, rhizomes, and roots in species capable of vegetative regeneration (Zasada *et al*. 1983); the level of exposure of mineral soil that is favourable for the germination and growth of trees from dispersal of seeds (Landhausser and Wein 1993; Johnstone and Kasischke 2005; Jayen *et al*. 2006; Johnstone and Chapin 2006; Kemball *et al*. 2006); and the dispersal distance to the nearest seed source (Johnstone and Chapin 2003). The depth of the remaining organic layer controls changes in post-fire soil moisture and temperature, thereby affecting the depth to permafrost (Swanson 1996; Burn 1998; Yoshikawa *et al*. 2002; Hinzman *et al*. 2006) as well as soil respiration (O'Neill *et al*. 2002, 2003, 2006; Bergner *et al*. 2004).

Consumption of large amounts of organic material, which occurs in severe fires, has implications for carbon cycling (Kasischke *et al*. 1995; Harden *et al*. 2000; Turetsky *et al*. 2002). Surface organic deposits in boreal forests and peatlands are significant, owing to very slow decomposition rates and the survival of deeper organic layers during multiple fire cycles (Zoltai *et al*. 1998; Harden *et al*. 2000). The older, deeper deposits have a higher carbon density compared with more recently deposited organic litter at the surface (O'Neill *et al*. 2003), resulting in more carbon consumed in fires that burn to greater depths (Kasischke *et al*. 2005*a*). Fire in these surface organic layers often burn in residual smouldering combustion that results in less efficient burning and higher emissions of carbon monoxide and other non-CO_2 trace gases than flaming fires (R. D. Ottmar and S. P. Baker, pers. comm., November 2007). With the onset of a changing climate, the total area burned in boreal North America is predicted to increase (Flannigan *et al*. 2005; Bond-Lamberty *et al*. 2007), and this may result in the deep organic layers found in boreal ecosystems becoming more vulnerable to burning because of warming of permafrost and the drying of peatlands (Kasischke and Johnstone 2005).

The prediction of increased fire occurrence with a changing climate presents challenges for land management. Understanding the relationship between fire severity and the ecological impacts of fire better enables land managers to plan for the future. Alaskan land managers require knowledge about vegetation response to fire in order to predict potential wildlife habitat and manage populations important for subsistence, recreation, and biodiversity. Sites where fire has consumed the forest floor and exposed the mineral soil (sites with high fire severity) achieve improved seedling establishment of future forests because many boreal tree species prefer a mineral soil substrate for successful germination (Landhausser and Wein 1993; Johnstone and Kasischke 2005; Jayen *et al*. 2006; Johnstone and Chapin 2006; Kemball *et al*. 2006). These sites are also the areas most vulnerable to the negative effects of erosion and invasive plant encroachment. By understanding vegetation response to fire severity, appropriate fuel maps can be developed to manage future fire on the landscape, to determine strategies for community protection, and to identify areas vulnerable to erosion, invasive plant colonisation, and accelerated permafrost thaw.

Improving our understanding of the level of fuel consumption in boreal ecosystems is of great importance for not only land management, but also for quantifying the contribution of forest fires to regional and global carbon emissions to the atmosphere. Impacts of boreal fires are geographically extensive and, in some years, can have continental or global-scale impacts. Large regional fire events over short time periods produce very high rates of emissions of several atmospherically important gases (gases that impact atmospheric chemistry, including radiatively active gases – those that cause the greenhouse effect). Atmospheric measurements of CO, O_3, and nitrogen oxides have pointed to boreal wildfires as a significant source of emissions to the atmosphere (Honrath *et al*. 2004; Lapina *et al*. 2006; Val Martin *et al*. 2006). For example, during summer 2004, there were times when CO from the Alaska and Canada fires exceeded anthropogenic CO in the New England region (Warneke *et al*. 2006) and exacerbated ozone levels as far south as Houston (Morris *et al*. 2006). By improving estimates of fuel consumption and fire emissions from boreal fires, we can improve interpretations of the sources for atmospheric measurements at locations far from the boreal region, thus improving our understanding of the impact of boreal fire on the atmosphere (Lapina *et al*. 2008).

Landsat remote sensing of boreal fires

The extensive impact of fire in boreal regions lends itself to study using satellite remote sensing. In contrast to lower latitudes, remote sensing-derived information in boreal North America is complicated by issues related to sun elevation angle, plant phenology, and limited, usable cloud-free Landsat data representing pre- and post-fire conditions. In particular, methods that require multiple images of the same location, especially images that match date of collection between 2 years (anniversary images) can be hampered by the limited data archives and large variability in interannual vegetative phenology (see Verbyla *et al.* 2008). Anniversary images can be very difficult to obtain for northern latitudes, especially Alaska, owing to data collection problems in much of the 1990s and in the year or two following the failure of the Landsat 7 ETM+ scan line correction mechanism (known as SLC off condition; Howard and Lacasse 2004). SLC off imagery from Landsat 7 was the only Landsat data available for many months until a ground station was established in interior Alaska for reception of Landsat 5 images.

The comparison of images for the same geographic area at two or more points in time, such as imagery representing pre- and post-fire conditions results in a change-detection exercise for which corrections for geometry, radiometry, and atmosphere are necessary (Lu *et al*. 2004). Geometric or orthorectification procedures to achieve subpixel registration accuracies are often recommended to ensure the detection of change is not a result of a given pixel between image dates representing different geographic locations on the ground (Coppin *et al*. 2004). Similarly, radiometric values recorded in satellite images contain uncertainties resulting from atmospheric effects and sensor variability that require corrections before analysis is undertaken. Employing some level of atmospheric correction becomes important to differentiate real change from noise (Schroeder *et al*. 2006). Corrections to surface or top-of-atmosphere reflectance or at minimum, a relative correction based on normalisation through pseudo-invariant features are often recommended between the images taken from pre- and post-disturbance time periods (Song *et al*. 2001; Lu *et al*. 2004). Employment of atmospheric correction procedures is considered particularly important when multiband ratioing such as vegetation indices or NBR are used in the detection of change (Gong and Xu 2003), as in the dNBR method.

Within the fire/burn severity literature, there has been considerable variation in the application of atmospheric correction procedures. Some studies chose not to employ atmospheric correction procedures (Miller and Thode 2007), whereas others report transformation of raw image data to reflectance (van Wagtendonk *et al*. 2004; Hall *et al*. 2008). Others have employed data converted to radiance followed by testing the necessity for normalisation based on pseudo-invariant features that may (Epting *et al*. 2005) or may not (Cocke *et al*. 2005) have been implemented. The variability in the degree of correction procedures employed may have contributed to the variation in results reported, and this may influence the comparability among the different studies. Generally, implementing some level of radiometric and atmospheric corrections and at least testing for the need for image normalisation procedures are recommended to ensure that differences in spectral response values between the pre- and post-fire images are attributable to vegetation and landscape responses caused by fire.

Approaches developed to use satellite remote sensing in boreal regions need to take these methodological issues into consideration as well as the ecological factors and management considerations related to site rehabilitation, site regeneration, wildlife habitat, and biodiversity. Despite these challenges, satellite remote sensing has long been and will continue to be an invaluable tool for assessing the impact of fire for both scientific and land management applications.

Terminology review and information requirements

As with any endeavour involving managers and scientists from different disciplines, an understanding of the nomenclature being used to study or describe a process or phenomenon is essential, and this is especially true in the fire science community. Jain (2004) provides a conceptual framework presented as the 'Fire Disturbance Continuum' for describing and discussing fire:

(i) the Pre-Fire Environment – the environmental characteristics of a site before the fire;
(ii) the Fire Environment – the environmental characteristics of a site during the fire (the processes involved with combustion of biomass, including fire intensity and fire behaviour);
(iii) the Post-Fire Environment – the environmental characteristics of a site immediately after the fire; and
(iv) Response – the longer-term biological, physical, and chemical responses of the environment (including ecosystems) at a site to variations in the effects of the fire.

This framework provides a conceptual basis to help define the variety of terms used within the fire science community to describe the characteristics of fire and its effects. The current special issue addresses research associated with two of these terms: fire severity and burn severity. As noted by Lentile *et al.* (2006) and others, these terms are often used interchangeably in describing the post-fire environment, when in fact each refers to a specific location within the Fire Disturbance Continuum. Here, we follow Lentile *et al*. (2006), who defined fire severity as a measure of the immediate and direct impacts fire has on the environment (i.e. the Post-Fire Environment), whereas burn severity refers to the degree to which an ecosystem changes owing to the various influences of fire (i.e. Response). Understanding the difference in nomenclature used in describing the fire environment is important because it clarifies descriptions of information required for fire effects assessment and places the information within the framework of the Fire Disturbance Continuum.

A variety of surface characteristics can be used to quantify fire severity and many of these can be used, in part, to assess the ecosystem response to a fire (the burn severity; Table 1). As a broad set of users is interested in assessing and mapping fire and burn severity, a wide range of field measurements can be collected. In addition to measures given in Table 1, fire severity

Table 1. Examples of surface measurements that can be used to measure fire severity in boreal forest sites and the possible ecological or environmental effects (modified from Kasischke *et al*. 2008)

Surface measurement	Ecological or environmental effect
Canopy tree mortality	Stand age structure Seed availability
Canopy biomass consumption	Trace gas emissions Carbon and nutrient cycling Seed availability
Fraction of trees standing	Seed dispersal distance
Depth of burning of the surface organic layer	Trace gas emissions Carbon and nutrient cycling Availability of propagules in surface organic layer (affects level of vegetative reproduction)
Depth of the remaining surface organic layer	Substrate quality – bulk density, hydraulic conductance (affects substrate quality for seedling germination and soil water repellency) Soil temperature

can also be assessed based on many other factors specific to user needs, including flame conditions and post-fire soil colour to assess soil heating where surface organic material is thin and fire will have direct impacts on mineral soil chemistry.

In contrast to fire severity, burn severity, as Lentile *et al*. (2006) reviewed in detail, is not a direct measure, but a judgment that can change based on the time of observation and information available. Factors other than fire severity can influence ecological response to a fire, such as pre-burn forest type, degree of mineral soil exposure, and post-fire climatic conditions (Johnstone and Kasischke 2005; Johnstone and Chapin 2006). Because factors other than fire severity influence ecological response, generation of a map of burn severity requires information in addition to that provided through an analysis of satellite imagery, and requires data or information that describe burn severity in the context of the site and features of interest. The development of a 'burn severity' map from a remotely sensed image only provides a part of the information required to determine the trajectory of regeneration at a specific site. Integration of a satellite-derived 'burn severity' map with other data layers is essential in order to successfully interpret the influence of the fire on the ecosystem and its potential response to the fire (burn severity). Burn severity mapping, therefore, requires the user to properly define the need for the assessment. Likewise, it is incumbent on the producer of burn severity information to understand the requirements of specific users and to fully document the information used to create the product. It should be noted – as Lentile *et al*. (2006) do – that the term 'burn severity', although often used generically, is well rooted in the literature and nomenclature of the fire science community in describing post-fire effects. Therefore, despite its impreciseness, the term cannot be abandoned, but should be properly defined when used. In summary, burn severity is based on the integration of a broad set of attributes, and as a result needs to be precisely defined and used in accordance with its intended application.

In many of the papers reviewed for the present article, the authors describe approaches for using satellite data to map burn severity. Many (if not most) end users desire a map of burn severity, but such a product is difficult to derive from satellite imagery alone without some knowledge of field and vegetation conditions. Although there may be different measures and definitions of severity from the field perspective, there is not necessarily the complement from the remote-sensing image. There are a fixed set of spectral and spatial features derived from image analysis from which to correlate the field measure, and depending on the resolution of the sensor (e.g. Landsat), we are inherently dealing with a mixed pixel. As a result, measures of severity from the field may not fully correlate with the image. The satellite-derived measure is a spectral signature that, in the case of Landsat image data, represents the spectral characteristics of all objects within and around the 30-m pixel sample. This pixel-based measurement is temporally explicit (collected at a specific time), spatially dispersed, and represents a mixture of the various objects that absorb, transmit, or reflect the sun's energy at each pixel location. Although variations observed on satellite imagery provide information on the changes to the site that occurred as a result of a fire, how the ecosystem responds to the fire-induced changes is also a function of pre- and post-fire conditions, both biotic and abiotic, that cannot be obtained through image analysis alone.

For the current special issue, an attempt was made to clear confusion that might arise with terminology. In the present overview paper, we are comparing a variety of studies. Some of the earlier studies use the two terms loosely; therefore, for the present paper, the term fire/burn severity will be employed unless the context is clear (fire severity for measurement or assessment of immediate fire effects, and burn severity for assessment of the ecological or environmental response). The studies reviewed in both the overview of previous research and in the discussion of the special issue papers are all evaluations of within-burn variability found in fire-disturbed sites using remote sensing-derived information; the terms the authors use are not of significance as much as how the information derived from remote sensing is used to assess post-fire effects. Within each of the special issue papers, the terminology was defined in a way to properly frame its use for the particular study.

Overview of previous research on satellite mapping of fire/burn severity

Based on a review of the published literature, we identified 35 studies that used moderate-resolution (e.g. ~20- to 60-m pixels) and coarse-resolution (e.g. ~250- to 500-m pixels) satellite data to assess fire/burn severity (listed chronologically in Table 2), which date back to using Landsat Multi Spectral Scanner (MSS)

Table 2. Summary of studies that evaluated the use of remote sensing data for mapping of fire/burn severity

Studies shown in bold are presented in the present special issue. Acronyms used are as follows: BARC, burned area reflectance classification; CBI, composite burn index; dNBR, differenced Normalized Burn Ratio; ΔNDVI, differenced Normalized Differenced Vegetation Index; PC, principal-component transformation; RdNBR, relative differenced Normalized Burn Ratio; TC, tasselled-cap transformation; SMA, spectral mixture analysis

Study	Vegetation type	Remote sensing approach	Field observations	Results
Jakubauskas *et al*. (1990)	Pine forest, midwestern USA	Threshold of Landsat MSS band 4/ band 3 ratio	n/a	n/a
Lopez-Garcia and Caselles (1991)	Mediterranean forest and scrubland	Normalised differences between Landsat TM bands 4 and 7 (NBR) differenced at burn and unburned locations in image (in-scene dNBR)	% vegetated cover	Correlation coefficient = −0.97 (vegetation cover lower than 50–60%)
White *et al*. (1996)	Steppe, shrublands, grasslands, conifer forests, western USA	Supervised classification of Landsat TM data	Fire severity classes (three levels) from aerial photo interpretation	63% classification accuracy
Kushla and Ripple (1998)	Conifer forests, western USA	Regressions of TC wetness using Landsat TM data	Tree mortality	$R^2 = 0.78$ between TC transform and tree mortality
Patterson and Yool (1998)	Pine and oak forests, western USA	Supervised classification using TC and PC transformations of Landsat TM data	Fire severity class (four levels)	Kappa = 0.73 for TC transform, 0.62 for PC transform
Key and Benson (1999)	Conifer forests, western USA	dNBR derived from Landsat TM imagery for same year as fire (initial) and following spring (extended)	CBI	$R^2 = 0.64$ between CBI and dNBR for initial data, 0.84 for extended data (non-linear regression)
Michalek *et al*. (2000)[A]	Spruce forests, Alaska	Supervised classification of Landsat TM data	Fire severity classes (three levels) from surface observations and interpretation of aerial photos	n/a
Rogan and Franklin (2001)	Chaparral, hardwood, conifer grassland, desert succulents, western USA	Spectral mixture analysis and decision tree classification using Landsat ETM+ data	Fuel consumption categories from surface observation	Overall classification accuracies of 77% and 85%. Kappa = 0.71 and 0.85 for two burns
Rogan and Yool (2001)	Grassland, woodland, chaparral, western USA	Supervised classification using TC and various remote sensing indices derived from Landsat TM data	Fire severity class (three levels)	Kappa = 0.66 using TC greenness, brightness, and wetness transforms

Miller and Yool (2002)	Conifer forests and woodlands, western USA	dNBR severity maps (BARC products) and supervised classifications generated from Landsat TM data	Overstorey component of CBI	Kappa = 0.86 for supervised classification, = 0.38–0.63 for dNBR maps
Isaev *et al*. (2002)	Mixed conifer–deciduous forests in southern Siberia	dNDVI from SPOT and MSU data	Tree mortality from aerial and satellite photographs	$R^2 = 0.82$ between tree mortality and ΔNDVI
Bobbe *et al*. (2003)	Conifer forests, western USA	NBR and dNBR severity maps (BARC products) generated from Landsat TM data	Fire severity class (four levels), surface measures of fire severity	Fire severity class accuracy = 50% for NBR maps, 60% for dNBR maps
Diaz-Delgado *et al*. (2003)	Mixed vegetation types (unspecified) in Spain	dNDVI from Landsat TM data	Fire severity class (seven levels)	$R^2 = 0.55$ between fire severity and ΔNDVI
Ruiz-Gallardo *et al*. (2004)	Mixed vegetation types (unspecified) in Spain	dNDVI from satellite data	Field observations of erosion	Combined with other landscape features, ΔNDVI is a good indicator for erosion
Chafer *et al*. (2004)	Chaparral, savanna, woodlands in Australia	dNDVI from SPOT data	Fire severity class (six levels)	88% classification accuracy
Hudak *et al*. (2004)	Conifer forests, western USA	NBR and dNBR using Landsat TM and SPOT data	Field measures of aboveground and surface severity	NBR and dNBR more correlated with aboveground measures than belowground measures
van Wagtendonk *et al*. (2004)	Pine forests, western USA	dNBR derived from Landsat TM data	CBI	$R^2 = 0.89$ between dNBR and CBI, but saturates for CBI > 2.4
Alleaume *et al*. (2005)	Savanna, Namibia	dNBR derived from MODIS data	Combustion completeness from field observations	dNBR not correlated with combustion completeness
Brewer *et al*. (2005)	Grassland, shrubland, forests, western USA	dNBR derived from Landsat TM data	Fire severity classes (four levels) in multiple land cover types	Classification accuracy of 56% when land cover not considered, 96% when land cover accounted for
Bigler *et al*. (2005)	Subalpine conifer forests, western USA	dNBR derived from Landsat TM data	Fire severity classes (four levels)	No accuracy statistics presented
Cocke *et al*. (2005)	Pine forests, western USA	dNBR derived from Landsat ETM data	CBI and fire severity classes (four levels) based on pre- and post-fire measurements	Accurately identified severely burned areas
Epting *et al*. (2005)[A]	Conifer, deciduous, mixed forests and shrublands in Alaska	dNBR and other indices derived from Landsat TM imagery	CBI	$R^2 = 0.52$ (average for four events) between dNBR and CBI for different fire events

(*Continued*)

Table 2. (Continued)

Study	Vegetation type	Remote sensing approach	Field observations	Results
Finney *et al*. (2005)	Conifer forests, western USA	dNBR derived from Landsat TM imagery, regression tree analysis	Fire severity classes (three levels) as a function of pre-fire fuels treatment	Fire severity varied as a function of pre-fire fuels treatment
Sorbel and Allen (2005)[A]	Conifer, deciduous, mixed forests and shrublands, Alaska	dNBR derived from Landsat TM imagery	CBI	$R^2 = 0.78$ (across 10 fire events) between CBI and dNBR across all fire events
Hammill and Bradstock (2006)	Shrublands, woodlands, Australia	ΔNDVI from SPOT and Landsat TM data	Fire severity class (five levels)	Classification accuracy dependent on pre-fire vegetation type
Roldan-Zamarron *et al*. (2006)	Shrublands, forests, Spain	dNBR and spectral unmixing using Landsat TM, MERIS, and MODIS data	Fire severity classes (four levels)	Classification accuracy of 74% achieved using spectral unmixing of Landsat TM data
Zhu *et al*. (2006)	Grasslands, woodlands, tundra, coniferous and deciduous forest sites located in seven different regions of USA	dNBR and RdNBR derived from Landsat TM imagery	CBI	$R^2 = 0.65$ to 0.84 between CBI and initial assessment (IA) dNBR, 0.71 to 0.91 between CBI and extended assessment dNBR, and 0.48 and 0.81 between CBI and IA RdNBR across all fire events in different regions. For specific vegetation types, $R^2 = 0.60$ to 0.74 between CBI and dNBR – used cubic and quadratic polynomials
Hudak *et al*. (2007)	Forested sites in Montana and Alaska, shrublands in California	Landsat TM-derived NBR, dNBR, RdNBR, NDVI, dNDVI, spectral mixture analysis	32 measures of fire effects	Variable correlation results found between field and remote sensing. NBR was found most often best correlated with field measures
Hyde *et al*. (2007)	Mountainous regions in western USA	Burn Severity Distribution Index derived from NBR data (Landsat TM data)	Gully regeneration	BSDI a good indicator for gully regeneration – NW slopes had poor results because of shadows
Gonzalez-Alonso *et al*. (2007)	Shrublands, forests, Spain	SMA of MERIS and SPOT data	Fire severity classes (four levels)	Classification accuracy of 51% for MERIS data and 70% for SPOT data
Kokaly *et al*. (2007)	Conifer, deciduous forests, western USA	dNBR (BARC product) derived from Landsat TM data	Ash cover, exposed soil, scorch height, additional surface measures of fire severity	dNBR map did not capture variations in surface fire severity measures in different severity categories

Lewis *et al*. (2007)	Shrublands and grasslands of California	SMA, NBR, dNBR, RdNBR from airborne hyperspectral (Probe-1) and Landsat TM	Fractional cover of seven components	$r = 0.32$ to 0.79; best correlations between field-measured uncharred-organic ground cover and SMA
Miller and Thode (2007)	Conifer forest, shrublands, Sierra Nevada Mountains of California and Nevada	dNBR and RdNBR derived from Landsat TM data	CBI	$R^2 = 0.49$ between CBI and extended assessment dNBR and 0.61 between CBI and RdNBR (exponential equations)
Robichaud *et al*. (2007)	Conifer forest, western USA	SMA with AVIRIS data and dNBR (BARC product) generated from Landsat TM data	Fractional components of ground cover remaining after the fire	$R^2 = 0.58$ between NBR/dNBR and % green vegetation and NBR and % litter
Smith *et al*. (2007)	Ponderosa pine and aspen, western USA	dNBR and SMA from Landsat ETM+	Percentage of live trees, forest floor biomass	$R^2 = 0.56$ for SMA char fraction *v.* live trees; $R^2 = 0.55$ for dNBR *v.* live trees; $R^2 = 0.55$ for SMA char fraction *v.* litter biomass; $R^2 = 0.52$ for dNBR *v.* litter biomass
Stow *et al*. (2007)	Shrublands and forests, California	TC transform and a supervised classification using Landsat imagery	CBI	Accuracy of 64% using TC transform, forests had higher accuracy than shrublands
Walz *et al*. (2007)	Deciduous forests in south-western Australia	dNBR generated from Landsat TM and MODIS data	Fire severity classes (four levels)	85% accuracy using Landsat dNBR, with lower accuracies achieved using MODIS dNBR
Allen and Sorbel (2008)[A]	**Conifer, deciduous, mixed forests, shrublands, tundra, Alaska**	**dNBR generated from Landsat TM data**	**CBI**	**$R^2 = 0.61$ for tundra to 0.71 for black spruce between CBI and dNBR, correlations improved for tundra using extended dNBR**
Hall *et al*. (2008)[A]	**Conifer, deciduous, mixed forests, western Canada**	**dNBR generated from Landsat TM data**	**CBI**	**$R^2 = 0.84$ (for all fire events) for CBI as a function of dNBR (quadratic equation)**
Hoy *et al*. (2008)[A]	**Black spruce forests, Alaska**	**dNBR generated from Landsat TM data, TC, PC, and other spectral indices**	**CBI (modified for Alaskan forests), additional field measures of burn severity**	**$R^2 = 0.34$ (average for two events) between dNBR. Low correlations found between field measures of fire severity and all satellite indices**
Murphy *et al*. (2008)[A]	**Conifer, deciduous, mixed forests, shrublands, Alaska**	**dNBR generated from Landsat TM data**	**CBI (modified for Alaskan forests)**	**$R^2 = 0.36$ (for six fire events) between dNBR and CBI**

[A] Studies conducted in the North America boreal region.

data to study severity and patterns of regrowth in Michigan pine forests (Jakubauskas *et al*. 1990). Although most of the studies in the present review were from the peer-reviewed scientific literature, we included three additional studies that describe two important programs in the USA – the Burned Area Reflectance Classification (BARC) approach used by the US Forest Service Burned Area Emergency Response (BAER) program (Bobbe *et al*. 2003; Hudak *et al*. 2004) and the Monitoring Trends in Burn Severity (MTBS) project (Zhu *et al*. 2006). Landsat TM or similar moderate-resolution data were used in most of studies, although three recent studies used coarser-resolution image data (MERIS and MODIS; Roldan-Zamarron *et al*. 2006; Gonzalez-Alonso *et al*. 2007; Walz *et al*. 2007). These studies were carried out in several different regions with different vegetation cover, including forests, shrublands, and grasslands in the western US (18 studies), forest, shrublands, and tundra in boreal and sub-boreal forests in North America and Russia (nine studies), shrublands, savanna, and forests in Australia (three studies), forests and shrublands in Spain and Portugal (four studies), and savannas in Africa (Namibia – one study).

Of the 41 studies listed in Table 2, 26 use Landsat-derived NBR or dNBR to map fire/burn severity or surrogate measures of severity, while four employ data from other sensors using equivalent spectral bands to the Landsat-based method. This approach uses the difference between the mid-infrared (IR, centred approx. 2.1 μm) and near-IR (centred approx. 0.8 μm), a comparison that highlights the impact on vegetation (near-IR) and bare, charred surfaces (mid-IR) that occur in a fire event (Key and Benson 2006). The methods used to evaluate fire/burn severity using remote-sensing data fall into four broad categories (some studies employed more than one method): (i) classification of satellite data into distinct severity classes (17 studies); (ii) correlation of the NBR and its derivatives (dNBR, Relative dNBR (RdNBR)) with the CBI (11 studies); (iii) correlation of the NBR and its derivatives (dNBR, RdNBR) with other surface measures of severity (nine studies); and (iv) correlation of other remote-sensing indices with surface measures of severity (14 studies).

The methods used to provide independent estimates of fire/burn severity for comparison with satellite remote sensing-derived fire/burn severity included the collection of field data or interpretation of aerial photography to provide: (i) user-specified classes of severity (17 studies); (ii) specific measures of severity, including overstorey tree mortality, combustion completeness, mineral soil exposure, ash cover, tree scorch height, fractional components of ground cover (including vegetation), depth of burning of the surface organic layer, tree crown consumption, erosion, and gully regeneration (10 studies); and (iii) the data needed to calculate the CBI (13 studies). One study tested more than one field technique. The CBI was developed as a method to 'calibrate' Landsat-derived dNBR with field-assessed severity (Key and Benson 2006). A CBI assessment is made from visual estimates of the impacts of fire in five different strata (substrate, herbs and low shrubs, tall shrubs and saplings, understorey trees, and canopy trees), and averaging the values for each stratum into a single measure.

The average classification accuracy for mapping of fire/burn severity using the dNBR method in the studies cited was 73%; however, the range of results was large because conditions for these studies varied widely, with classification accuracies ranging from 50 to 95%. From these studies (Table 2), classification accuracy varied as a function of spatial resolution of the satellite system with moderate-resolution data achieving higher accuracy than coarse-resolution data. Topographic influences (such as shadowing) also reduced classification accuracy. These studies also reported higher correlations between satellite and surface measures of fire/burn severity in forests than in shrublands and grasslands.

The studies in Table 2 demonstrate that variations in surface reflectance detected by moderate-resolution satellite systems (Landsat, SPOT, MSU) were more influenced by variations in aboveground vegetation characteristics than surface (mineral soil, litter, and organic soil) characteristics, indicating that satellite techniques may be more suitable for mapping effects to aboveground vegetation than for mapping surface layer effects in many ecosystems. Several studies reported good relationships between remote sensing-derived indices and tree mortality or percentage green vegetation (Kushla and Ripple 1998; Isaev *et al*. 2002; Robichaud *et al*. 2007). In grassland savannas, Alleaume *et al*. (2005) found no correlation between dNBR and combustion completeness. In contrast to measures of fire/burn severity in the vegetation layer, Kokaly *et al*. (2007) found little correlation ($R^2 < 0.30$) between dNBR and other spectral indices and surface measures of ground-layer severity (e.g. ash cover, exposed mineral soil, depth of the surface organic layer, depth reduction in the surface organic layer). These results were not unexpected because spectral measurements from a 30-m sensor such as Landsat TM represent a mixture of surfaces within a pixel, and vegetation canopies will often obscure the ground surface, contributing more to the total spectral signature than ground-layer vegetation.

A review of the approaches used to measure fire/burn severity and results from these studies (Table 2) illustrates the diversity of fire regimes and surface effects of interest. Specifically, the researchers represented in the list of studies defined and assessed fire/burn severity based on the vegetation type and fire characteristics in the region under study. For example, the mixed coniferous–deciduous southern boreal forests of Siberia typically experience surface fires with some crowning. In this situation, tree mortality is a key measure of severity (Isaev *et al*. 2002). In contrast, highly flammable black spruce forests that are common to the boreal region of interior Alaska typically experience stand-replacing crown fires. In Alaska, depth of burning of the surface organic layer and crown canopy consumption are typical measures of fire/burn severity.

Several studies by US and Canadian scientists have used the CBI as a basis for evaluating the potential of using derivatives of the NBR for mapping of fire/burn severity through processing of Landsat TM/ETM+ data. Here we briefly review studies that used test sites in the conterminous US, while in the following section we review studies at sites in Alaska and Canada. Most studies focussed on using the dNBR, which is generated by subtracting the post-fire NBR from the pre-fire NBR (Key and Benson 2006). Two time periods have been used for the post-fire data (Zhu *et al*. 2006): (i) the Initial Assessment (IA) approach that uses data collected during the same year as the fire being studied; and (ii) the Extended Assessments (EA) approach that uses data collected during the year following the fire (Key and Benson 2006). In addition, several studies used an RdNBR that was calculated by dividing the dNBR by the square root of the pre-fire dNBR/1000 (Miller and Thode 2007). Taken as a whole, the results of these studies indicate that the specific methods of image analysis (RdNBR *v.* dNBR and IA *v.* EA) are not stable across analysis situations, and various situations can be assessed with some approaches better than others. These studies produced the following results (see Table 2):

(1) For study regions across the US, Zhu *et al*. (2006) found the EA approach produced higher correlations between dNBR and CBI compared with the IA approach.
(2) Miller and Thode (2007) found that RdNBR had higher correlations with CBI than dNBR using the EA approach for study sites located in California, whereas results of Zhu *et al*. (2006) in study regions across the US were mixed, with dNBR producing higher correlations in three regions, and RdNBR producing higher correlations for a single region as well as all regions combined. Using the IA approach, Zhu *et al*. (2006) found exactly the opposite result from the EA approach conducted by Miller and Thode (2007), with dNBR producing higher correlations with CBI than RdNBR.
(3) Zhu *et al*. (2006) found that correlations between dNBR or RdNBR (using the EA approach) and CBI were lower for study sites grouped by vegetation type, with higher correlations being found for forested sites compared with non-forested sites. The performance of the dNBR and RdNBR were evenly split, with dNBR producing the higher correlations for three vegetation types and RdNBR producing the higher correlations for the remaining three.
(4) Hudak *et al*. (2007) found (using an IA approach) that NBR and dNBR most often did better than RdNBR across eight fires in three vegetation biomes when compared with a suite of 32 field measures. This held true as well when all sites were combined.
(5) The highest correlations between the various dNBR and RdNBR approaches and CBI occurred when non-linear relationships (exponential, quadratic, cubic, other) were employed (van Wagtendonk *et al*. 2004; Zhu *et al*. 2006; Miller and Thode 2007).

Review and discussion of results from studies in the North American boreal region

Comparisons of CBI and dNBR

Five of the six papers included in the current special issue present analysis of Landsat TM/ETM+ for mapping fire/burn severity in a variety of sites in boreal North America. These along with a few others identified in Table 2 represent all of the published studies using remote sensing (Landsat) for mapping fire/burn severity in the North American boreal region that the authors were able to identify. Of these, six studies (four papers in the present issue and two others listed in Table 2) compared Landsat-derived dNBR with CBI (Table 3). These studies used data from 979 plots that were established to measure CBI within 25 fire events that occurred between 1999 and 2004. The field data collected for the studies reported in Sorbel and Allen (2005) and Allen and Sorbel (2008) were used by Epting *et al*. (2005) in their analysis. Epting *et al*. (2005) used image data that had been processed separately from the Sorbel and Allen (2005) study, making their results different. Five of the studies involved data collected across a variety of vegetation types, including conifer and deciduous forests (Epting *et al*. 2005; Sorbel and Allen 2005; Allen and Sorbel 2008; Hall *et al*. 2008; Murphy *et al*. 2008), and one involved collection of data within black spruce forests only (Hoy *et al*. 2008). The six studies all used the same field data collection method (CBI) and the same image processing methods to produce the dNBR products (a mixture of EA and IA products). This research produced the following results:

(1) In studies using all vegetation types (conifer and deciduous forest and tundra) (Table 3*a*), the correlation (R^2 or adjusted R^2) between CBI and dNBR assuming a linear relationship ranged widely and averaged 0.60 (range of 0.11 to 0.83) using the EA approach and 0.61 (range of 0.37 to 0.88) using the IA approach. Allen and Sorbel (2008) found high correlations between dNBR and CBI for specific vegetation types (R^2 ranged between 0.58 and 0.83; similar to the results of Zhu *et al.* 2006), and lower dNBR correlations for specific vegetation types were found by Epting *et al*. (2005) and Hoy *et al*. (2008) (R^2 ranged between 0.01 and 0.67) (Table 3*b*).
(2) Hall *et al*. (2008) reported a new, non-linear model based on a saturated growth model form that resulted in a higher relationship throughout the range of data than assuming a linear relationship using dNBR and CBI data produced using the EA approach. This result agrees with previous studies where non-linear results were reported (van Wagtendonk *et al*. 2004; Zhu *et al*. 2006; Miller and Thode 2007).
(3) In studies using the EA approach, the average correlation between CBI and dNBR sampled by Murphy *et al*. (2008) was much lower in fires that occurred during the extreme fire year of 2004 (average = 0.36, range of 0.11 to 0.64) compared with the fires sampled by Allen and Sorbel (2008) and Epting *et al*. (2005) that included sites that burned during less severe fire years (average = 0.73, range of 0.49 to 0.88).
(4) Both Epting *et al*. (2005) and Hoy *et al*. (2008) found better results with single-date NBR correlations with CBI (R^2 from 0.30 to 0.81) than with dNBR (R^2 ranged between 0.01 and 0.67).
(5) Both Hall *et al*. (2008) and Allen and Sorbel (2008) found that spruce forests had the highest average dNBR values whereas the deciduous forests had the lowest.
(6) For specific vegetation types, Allen and Sorbel (2008) found that the EA and IA approaches produced significantly different regression correlations for tundra vegetation, but these approaches had no effect on the correlations for black spruce forests (Table 3).
(7) Using data from all vegetation classes, Allen and Sorbel (2008) showed that the CBI from the intermediate tree stratum had the highest correlation with dNBR ($R^2 = 0.69$), whereas the CBI from the low and tall shrub strata had the lowest ($R^2 = 0.46$ and 0.43, respectively). Hoy *et al*. (2008) found that dNBR comparisons with overall CBI produced weak correlations ($R^2 = 0.34$ and 0.52) in black spruce sites. Hoy *et al*. found the best correlations for dNBR with the Canopy Fire Severity Index, a field measure of canopy severity that focusses on canopy consumption alone, while very poor correlations were found with field measures of surface severity (surface fuel consumption).

Table 3. Summary of results of linear correlation between composite burn index (CBI) and differenced Normalized Burn Ratio (dNBR) for North American boreal region study sites

EA, extended assessment; IA, initial assessment. See text for discussion of these approaches

(*a*) All vegetation types

Study	Fire event	Plots	Analysis approach	CBI–dNBR relationship	Correlation (R^2/adj. R^2)
Epting *et al.* (2005)	Survey line	85	EA	Linear	0.49
	Witch	32	IA	Linear	0.67
	Jessica	47	IA	Linear	0.56
	Beverly	40	IA	Linear	0.37
Sorbel and Allen (2005); Allen and Sorbel (2008)	Witch, Jessica	79	IA	Linear	0.75
	Beverly	40	IA	Linear	0.45
	Otter Creek/Chitsia	35	EA	Linear	0.79
	Foraker	24	EA	Linear	0.75
			IA	Linear	0.88
	Herron River	25	EA	Linear	0.83
	Cottonwood Bar	19	EA	Linear	0.78
	Uyon Lakes	18	EA	Linear	0.78
	Milepost 85	85	EA	Linear	0.77
	All fires	289	IA	Linear	0.83
Murphy *et al.* (2008)	Lower Mouth	55	EA	Linear	0.44
	Winter Trail	52	EA	Linear	0.64
	Glacier Creek	39	EA	Linear	0.36
	Black Hills	66	EA	Linear	0.25
	Bonanza Creek	65	EA	Linear	0.36
	Clawanmenka	70	EA	Linear	0.11
Hall *et al.* (2008)	Green Lake, Montreal Lake	41	EA	Non-linear	0.82
	Wood Buffalo	83	EA	Non-linear	0.82
	Dawson	37	EA	Non-linear	0.85
	All fires	161	EA	Non-linear	0.82
	Green Lake, Montreal Lake	41	EA	Linear	0.76
	Wood Buffalo	83	EA	Linear	0.76
	Dawson	37	EA	Linear	0.76
	All fires	161	EA	Linear	0.73

(*b*) Specific vegetation cover types

Study	Vegetation type – fire event	Plots	Analysis approach	CBI–dNBR relationship	Correlation (R^2 or adj. R^2)
Epting *et al.* (2005)	Closed spruce	66	Combined	Linear	0.14
	Open spruce	55	Combined	Linear	0.25
	Spruce woodland	19	Combined	Linear	0.01
	Deciduous	35	Combined	Linear	0.29
Allen and Sorbel (2008)	Black spruce	134	IA	Linear	0.72
			EA	Linear	0.73
	White spruce	44	IA	Linear	0.58
	Deciduous	18	IA	Linear	0.68
	Tundra	93	IA	Linear	0.43 (0.78)[A]
			EA	Linear	0.81
Hoy *et al.* (2008)	Black spruce – Boundary	28	IA	Linear	0.52
	Black spruce – Porcupine	21	IA	Linear	0.34
	Black spruce – all plots	49	IA	Linear	0.34

[A]The adj. R^2 of 0.43 was the result when six tundra plots from the Witch and Jessica fires were included. When these plots were removed, the R^2 changed to 0.78.

These results along with results from studies presented in the previous section show a wide range of variability when comparing Landsat-derived severity with the field-based CBI severity assessment. As found in comparison of previous studies, one particular approach (dNBR, NBR, IA, or EA) does not consistently produce the best fit to the field-derived severity index (CBI).

Allen and Sorbel (2008) and Hall *et al.* (2008) found good correlations between field and remote-sensing data whereas the other studies produced poor correlations (Murphy *et al.* 2008 and

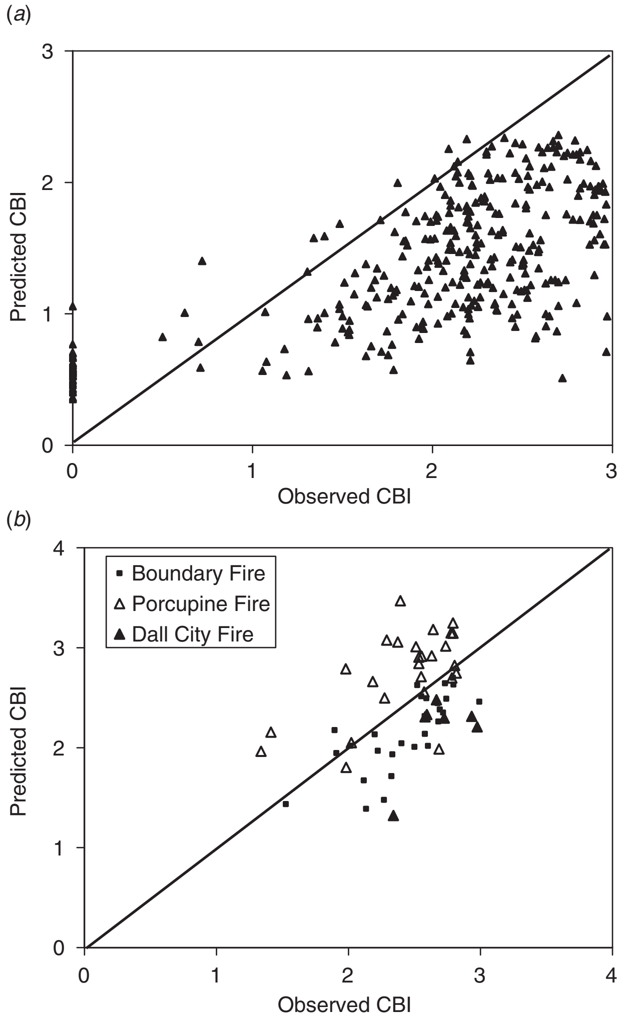

Fig. 2. Comparison between composite burn index (CBI) values predicted using differenced Normalized Burn Ratio (dNBR) with the equations of Sorbel and Allen (2005). (*a*) CBI data for all vegetation types from Murphy *et al.* (2008). (*b*) CBI data for black spruce data from Hoy *et al.* (2008).

Hoy *et al.* 2008). To evaluate the ability of dNBR to map variations in CBI across Alaskan sites, we used the equation developed by Sorbel and Allen (2005) to estimate CBI from Landsat dNBR data for the areas where Murphy *et al.* (2008) and Hoy *et al.* (2008) collected field data. The Sorbel and Allen (2005) equation (used to predict CBI from dNBR in this demonstration) was derived by combining the data points from all of their sites into one analysis (see Allen and Sorbel (2008) for a list of sites).

This relationship significantly underestimated CBI for the plots used in the Murphy *et al.* (2008) study that were established across all vegetation types in seven separate fire events (Fig. 2*a*). For all plots, the average observed CBI was 1.95 and the predicted CBI was 1.37, with a root mean square (RMS) error of 0.88. The CBI was underpredicted for most individual fire events not including unburned plots.

For data collected in black spruce stands to study the 2004 fires (Hoy *et al.* 2008), the predicted CBI values followed the expected trend, with the points being scattered around a line with a slope of 1 (Fig. 2*b*). For all points, the average predicted CBI value was 2.46 and the average observed CBI was 2.41, with an RMS error of predicted *v.* observed CBI of 0.46. For the individual fire events, however, there were significant biases: the predictor equation underpredicted CBI for the Boundary fire (observed = 2.43, predicted = 2.16, RMS error = 0.37) and the Dall City fire (observed = 2.69, predicted = 2.17, RMS error = 0.58) and overpredicted CBI for the Porcupine fire (observed = 2.42, predicted = 2.73, RMS error = 0.48).

This demonstration comparison of data collected from three studies using the same methods in Alaska demonstrates the difficulties the dNBR *v.* CBI approach has when applied to some situations. The predictor equation, developed by Sorbel and Allen (2005) at sites they have studied was not able to predict severity from dNBR at most sites sampled in the Murphy *et al.* (2008) study, while the black spruce sites sampled by Hoy *et al.* (2008) showed a more compatible set of samples to the predictor equation, yet it was not comparable for individual fire events. The reason for this is not fully understood. Murphy *et al.* (2008) have considered some explanations, and collected additional information at sites to work through the disparity in the two outcomes. Their sites were more often found in lowlands, whereas the Sorbel and Allen (2005) sites represent mostly upland types; the Hoy *et al.* (2008) sites were also primarily upland sites. Both Murphy *et al.* (2008) and Hoy *et al.* (2008) collected data at sites that burned in the extreme fire year of 2004, while the Sorbel and Allen sites are from earlier and more moderate fire seasons. The conclusion of Murphy *et al.* (2008) is that the dNBR metric does not adequately differentiate severity levels in the moderate to high severity range, and they suggest that dNBR can only be interpreted in conjunction with fire-specific field data. The results of Murphy *et al.* (2008) and Hoy *et al.* (2008) further endorse a need for additional studies to assess the dNBR index under a variety of ecological and fire conditions.

Additional comparisons between satellite indices and surface measures

Both Epting *et al.* (2005) and Hoy *et al.* (2008) evaluated the potential use of other spectral indices derived from Landsat TM/ETM+ data for mapping of fire/burn severity based on comparisons with CBI. Single-date, post-fire NBR produced higher correlations with CBI than dNBR, using data across vegetation types as well as for individual vegetation types. Epting *et al.* (2005) reported that although NBR was ranked among the highest of all indices when correlated with CBI data from all vegetation types, in three of the four burns, there was no significant difference between NBR and the ratio of Landsat TM/ETM band 7 to band 5. For CBI data from black spruce forests, Hoy *et al.* (2008) found the ratio of Landsat TM/ETM+ band 7 to band 5 had higher correlations with CBI than those from NBR and dNBR.

Hoy *et al.* (2008) performed correlations between several satellite indices, including dNBR, and field measures of fire severity other than CBI, including a canopy severity index and measures of surface severity, such as depth reduction in the surface organic layer. Their study found that the canopy severity index had higher correlations with satellite indices than did CBI, but that the measures of surface severity were poorly correlated with dNBR and other satellite indices. Previous studies reported similar results related to canopy *v.* ground surface severity (Kushla and Ripple 1998; Isaev *et al.* 2002; Kokaly *et al.* 2007). These results were not unexpected, as a remote-sensing measurement represents the average spectral response of all objects within a given image pixel, and the resulting spectral response patterns would depend heavily on pre-burn vegetation composition and structure. Reflectance from forested sites (even burned forest sites) is often dominated by the tree canopies because the ground surface is partially obscured by branches or shadowing from standing tree boles. Additionally, surface organic layer reduction, the main measure of surface severity, cannot be derived from spectral information alone.

Possible limitations on using dNBR to map fire/burn severity in high northern latitude regions

Both Verbyla *et al.* (2008) and Murphy *et al.* (2008) discussed possible reasons for the relatively poor performance of dNBR for mapping fire/burn severity in Alaskan boreal regions. Verbyla *et al.* (2008) demonstrated that changes in surface reflectance associated with topography can alter dNBR independently of forest cover type and fire/burn severity. They showed that seasonal variations in solar elevation angle also resulted in changes in the radiance values detected by satellite sensors, which would result in variations to dNBR values associated with solar elevation. Verbyla *et al.* (2008) reported considerable variability in the NBR values for unburned black spruce forests. In one case study of four stands that had similar pre-burn stand densities and CBI estimates that varied by 0.20 in the burned stands, the variation in NBR in the unburned stands resulted in a variation of 0.55 in predicted CBI (using the Sorbel and Allen (2005) equation). Finally, both Verbyla *et al.* (2008) and Sorbel and Allen (2005) noted that because in many cases the dNBR spectral response saturates at moderate to high severity levels, resulting in a non-linear relationship between CBI and dNBR at high values, the sensitivity of CBI to variations in dNBR at high severity levels is significantly reduced. Along with the other sources of variations discussed above, this lack of sensitivity may explain the poor performance of dNBR in predicting CBI as seen in Fig. 2.

Evaluating the ability of CBI to estimate fire severity in black spruce forests

Kasischke *et al.* (2008) collected field measurements designed to measure fire severity in black spruce forests in addition to the visual observations and assessments required to estimate CBI. Their study assessed several measures of fire severity (measures of the direct impacts of fire, such as depth of burning of the surface organic material) that related to how the ecosystem might respond (see Table 1). They found a low correlation between the field measures of severity and CBI summed from the four strata (R^2 ranged from 0.00 to 0.37), as well as CBI for the canopy stratum (R^2 of 0.00 to 0.36) and the CBI for the substrate stratum (R^2 of 0.06 to 0.49). These results indicate that even if it appears that dNBR can be used to map CBI for individual fires, it will be difficult to use this information to assess specific fire severity characteristics or to predict how black spruce forests are likely to respond to variations in fire severity.

Synthesis and conclusions

Methodological considerations

As presented in the current special issue and reviewed in this overview paper, several studies have evaluated the Normalized Burn Ratio (NBR) and the differenced NBR (dNBR – where pre and post-burn NBR are differenced) for mapping variations in fire or burn severity in the boreal regions across North America (van Wagtendonk *et al.* 2004; Brewer *et al.* 2005; Epting *et al.* 2005; Sorbel and Allen 2005; Chuvieco *et al.* 2006; Roy *et al.* 2006; Hudak *et al.* 2007; Lewis *et al.* 2007; Miller and Thode 2007; Smith *et al.* 2007; Walz *et al.* 2007; Allen and Sorbel 2008; Hall *et al.* 2008; Hoy *et al.* 2008; Murphy *et al.* 2008; Verbyla *et al.* 2008). The dNBR index has been employed by wildfire managers because it is a fairly simple way to assess the spatial variability in burns that, in several cases, has been shown to relate to fire/burn severity. However, researchers have identified more complete remote sensing-derived products that, in some cases, perform as well as or better than dNBR. The possible reasons for better performance are either: (1) the method uses information from other parts of the spectrum than just Landsat bands 4 and 7 (e.g. various multispectral image classification techniques as in Michalek *et al.* 2000; Rogan and Franklin 2001; Rogan and Yool 2001); or (2) it limits the spectral bands used to specific bands that relate to particular *in situ* phenomena of interest (e.g. spectral unmixing methods as in Smith *et al.* 2007). Smith *et al.* (2007) show a slightly better performance of a spectral mixture analysis (SMA)-derived measure of percentage char than dNBR when used to predict the percentage of live trees. This may be due to the fact that SMA is limiting the metric to the char signature, which on its own correlates to the percentage of live trees. Several studies that used multispectral classification methods produced very accurate maps of fire severity when compared with field data (Michalek *et al.* 2000; Rogan and Franklin 2001), supporting the idea that including more than two spectral bands may be better than limiting to two bands combined within an index.

In using the fairly simplified dNBR method, remote sensing trade-offs are made in order to provide fire products that are timely (as for BAER mapping) and consistent (as for the MTBS project; Eidenshink *et al.* 2007). The issue arises in how accurate the dNBR methods represent severity or the ecological factor(s) of importance to the user. In a study comparing NBR with ideal requirements of a spectral index designed to measure severity, Roy *et al.* (2006) found that NBR is insensitive to changes from burning, and is therefore not optimal for describing fire severity. Similarly, the CBI field data method has been developed to provide fairly straightforward, consistent methods of collecting field measures of severity, introducing trade-offs that may or may not be of consequence for the intended application.

A common approach for demonstrating the potential utility of the NBR or dNBR is through correlation with a surface measure of fire/burn severity – often CBI. Although the overall high level of correlation between dNBR or RdNBR and CBI found in many of the papers reviewed here demonstrates that Landsat TM/ETM+ and other similar satellite data have the potential for mapping fire/burn severity, experience from analyses within the Alaskan boreal region reported by Hoy *et al.* (2008) and Murphy *et al.* (2008) suggests there are limitations to the dNBR approach (Fig. 2). Although Hall *et al.* (2008), Sorbel and Allen (2005) and Allen and Sorbel (2008) found strong relationships between CBI and dNBR that were fairly consistent between sites located in different fire events, these results were not replicated in the other studies reviewed. The reason for this is not clear, but it may be related to differences in pre-burn vegetation fuel type (Hall *et al*. 2008) or variations in fire or abiotic site conditions (Murphy *et al*. 2008). Analysis by Murphy *et al*. (2008) was inconclusive, indicating that further investigation is needed to understand the mixed results. In the case of these boreal applications, problems may be attributable to remote sensing-based complications found at northern latitudes: image acquisition, solar illumination angle, and shadowing due to variable surficial topography (Verbyla *et al*. 2008). From these results, we conclude that although the dNBR can be used to map relative variations in fire/burn severity in boreal forests within individual fire events, it cannot be used consistently to map levels of fire/burn severity across regions or between years.

Results of Hall *et al*. (2008), Zhu *et al*. (2006), van Wagtendonk *et al*. (2004) and the data of Epting *et al*. (2005) demonstrate that, for many ecosystems, the relationship of CBI and dNBR is not linear for CBI values greater than $\sim$2.5. This presents a challenge in modelling the dNBR–CBI relationship and in using CBI when assessing areas of high severity. High-severity sites have the highest potential for the most significant changes to the environment, so are considered the most important to identify for remediation and assessment of fire effects. Additionally, the non-linear nature of the dNBR–CBI relationship found in some studies indicates that other studies where linear models were employed may not be fully capturing the possible range of severity. Additional sampling at severely burned sites and studies that capture the full range of severities are needed to adequately assess the suitability of linear or non-linear model forms that describe the relationship between dNBR and CBI.

As found by Hoy *et al*. (2008), dNBR and other satellite-based methods found a closer relationship with canopy severity than with surface fuel reduction. Similarly, Allen and Sorbel (2008) found the intermediate tree strata of the CBI best correlated with dNBR. If the fire impacts on the canopy are correlated with surface strata or total severity, then satellite-based measures might properly represent the true severity. However, as is the case in many boreal ecosystems, fire can differentially affect surface and canopy strata (Michalek *et al*. 2000; French *et al*. 2004). Satellite images operating at a 30-m resolution (such as Landsat) represent a mixture of information from all strata over more than 30 m of surface area where the canopy is often obscuring the ground surface. High-severity fires where surface fuels are deeply or completely consumed, which were common in the extreme fire year of 2004, may not be properly mapped from the dNBR–CBI approach if field samples do not represent the full range in surface severity that is present in the most severe fires. This is of particular importance in boreal ecosystems where fires of high severity are common, and variability in the highest severity fires can be large and have dramatic consequences to the post-fire soil temperature and moisture, plant succession, and emission of carbon-based gases to the atmosphere (French *et al*. 2002; Johnstone and Chapin 2006). The present special issue highlights the need for additional research to refine methods for using satellite data with field data to estimate the severity of fires in boreal ecosystems, particularly for black spruce forests.

Based on the results presented in these special issue papers and other research reviewed in the current overview paper, the conclusion of Zhu *et al*. (2006) that, 'In most cases, extended assessment dNBR provided high-quality, useful information on burn severity' may be premature. Specifically, following the approach employed to generate Fig. 2, the usefulness of the dNBR approach needs to be independently validated for specific regions and vegetation types to determine if the technique is capable of producing information relevant to burn severity assessment. Until such independent validation occurs, caution should be used in interpreting the results from studies that use the dNBR approach to analyse the spatial and temporal patterns of fire/burn severity (see for example Duffy *et al*. 2007; Holden *et al*. 2007). Because of the problems and uncertainties with the dNBR approach across many ecosystems outlined in the present special issue, the use of historic dNBR imagery for assessing temporal trends in fire/burn severity will require extensive field measures of severity over multiple years for both calibration and validation.

The diversity of study objectives and approaches for assessing fire/burn severity represented in studies listed in Table 2 indicates that developing one approach for mapping severity across regions may be neither feasible nor desired. Although a generic approach to defining a field measurement protocol that characterises fire or burn severity (such as the CBI of Key and Benson 2006) may be attractive in that it provides a simple, consistent approach to quantify the effects of fire and in some cases provides a mechanism to select severity thresholds using satellite remote-sensing data, such indices are only useful if they can predict the characteristics of fire/burn severity that are of interest to the end user. In most cases, end users of fire/burn severity information focus on specific characteristics of an ecosystem or an environment, such as tree mortality (Keyser *et al*. 2006), changes in soil repellency and surface runoff (Doerr *et al*. 2006; Lewis *et al*. 2006), changes to the permafrost regime and soil moisture and temperature characteristics (Yoshikawa *et al*. 2002; Kasischke and Johnstone 2005), variations in tree mortality, levels of biomass consumption during a fire (Kasischke *et al*. 2005*a*), post-fire soil respiration (O'Neill *et al*. 2002; Bergner *et al*. 2004) and patterns of post-fire seedling recruitment and succession (Landhausser and Wein 1993; Johnstone and Kasischke 2005; Jayen *et al*. 2006; Kemball *et al*. 2006), among many others. For example, in black spruce forests, low-severity fires usually only occur at the edges of fire events; for most of the area burned, canopy tree mortality is 100%. Because of this, common measures of fire severity in other ecosystems related to tree mortality, such as scorch height, are not useful for black spruce forests. In addition, consumption of understorey vegetation is extremely high in boreal black spruce ecosystems, so measures involving this canopy layer provide very little information regarding fire/burn severity (Kasischke *et al*. 2008).

The variability in ecological conditions that can occur means that end users need to examine the method used to estimate fire/burn severity to be sure it fits with their need. Few studies have evaluated the utility of the CBI for assessing specific characteristics of the post-fire environment and ecosystem response that are often used to assess the impacts of fire (such as those presented in Table 1 and in table 1 of Kasischke *et al*. 2008). Much of the research conducted in black spruce forests in Alaska reported little correlation between CBI and other surface measures of fire/burn severity, primarily because most of the variation in black spruce CBI is due to variations in a single stratum, the substrate (Kasischke *et al*. 2008). Similarly, Odion and Hanson (2008) discuss issues of using total CBI scores as a measure of severity because CBI integrates all strata, when overstorey mortality may be the main indicator of severity in many situations. These results do not mean the CBI cannot provide useful information on fire/burn severity; however, they do indicate that researchers need to evaluate the utility of the CBI for estimating specific surface characteristics used to quantify fire/burn severity in the ecosystems they are studying and modify its use accordingly.

The application of satellite remote-sensing methods for assessing fire/burn severity in boreal regions involves issues that may not be factors in temperate regions. The dNBR technique, as well as other differencing techniques, relies on having images from before and after a fire that have had little to no change except from the fire event itself. Typically this is achieved using images collected on or near the same day of the year (anniversary images) to ensure solar illumination and vegetative phenology are as similar as possible. In boreal ecosystems, however, vegetation phenology is strongly controlled by factors other than day of year, such as seasonal weather and climate (Verbyla *et al*. 2008). The use of an image differencing method is a common means of controlling for topography between two images. However, as Verbyla *et al*. (2008) identified, fire can also be controlled by topographic conditions. Verbyla *et al*. (2008) presented a review of the effects of topography on NBR and dNBR at the typical low sun elevation angles found at the end of the fire season when fire severity analyses are often undertaken. The conclusions of their study suggest fire/burn severity could be underestimated in valley bottoms or on steep north-facing slopes using remote sensing owing to topographic shadowing. These topographic issues paired with issues of interannual variations in plant phenology in boreal regions, rapid phenologic and sun elevation changes, and limited image archives present many instances where remote sensing-derived results, and the dNBR technique in particular, can have problems. When assessing the information derived from remote sensing in northern latitudes, users need to be fully aware of issues that are unique to the region as they may compromise the results to be generated.

Information value and impact for land and wildlife management

Only in the last 5–10 years have land managers been able to include more data than the basic burn perimeter of a fire in their understanding of fire history and fire effects owing to new methods of mapping fire characteristics within the burn perimeter. Results by Hall *et al*. (2008) outlined the inherent value in using local field expertise in defining severity thresholds that can subsequently be applied to classify and map the spatial distribution of burn severity within a fire. Determining these thresholds is a function of fire mapping that land managers should ideally play a role in defining as they have the most interest in deriving maps suited to their information needs.

Although fires in the North American boreal forests are often very large in total burn area, they typically form mosaics with unburned islands and areas that have been burned to varying degrees. Although land and fire managers understand that the external perimeter of a fire does not mean that the entire internal area is burned, or burned to the same degree, it is a more difficult concept to convey to the local residents who only see a blackened landscape near their homes. After the severe Alaskan fire seasons of 2004 and 2005, several communities in north-eastern Alaska requested that the US Bureau of Land Management and US Fish and Wildlife Service increase fire suppression on the lands adjacent to private and Native Corporation lands (BLM 2005). Similar requests were raised at public meetings with other communities throughout interior Alaska. The residents were concerned about the ability of the surrounding land to support the traditional subsistence activities necessary for survival in many rural communities. Although the discussion is on-going, from this example it is apparent that the use of satellite maps that can depict unburned areas, low-severity sites (more likely to quickly return to pre-burn conditions) and high-severity sites (more likely to transition to deciduous forests important for moose populations) are of great value for understanding the overall effects of a nearby fire on subsistence activity and other land uses. Land managers require reliable burn severity maps in order to model vegetation and habitat response to the fire to address these and other concerns of the land users.

Fire and land managers look for high-severity sites to guide their site selection to evaluate erosion and permafrost changes following fires. Many boreal forest fires are far removed from roads, making field visits costly. Preselection of probable concern areas (i.e. high-severity sites) allows a more efficient use of aircraft time. Where infrastructure is present, high-severity sites may destabilise the nearby soil, causing landslides onto roadways or increasing the depth of the active layer, which can impact the foundation of nearby buildings.

As predictive modelling of vegetation responses to damage from fire improves, fire managers will have a greater ability to use burn severity maps to model fuel buildup following fire in areas that are left to natural succession. This would better enable managers to know if an active wildland fire is likely to be stopped by an older burn site, or if hazardous fuel treatment sites require further rehabilitation. In areas managed for wood products, as is true in much of the boreal region of Canada, a multitude of post-fire treatments are performed that include salvage logging, site preparation, and silvicultural practices such as tree planting in order to minimise the time involved in transitioning a fire-damaged forest back into a productive forest. Severity mapping is likewise of importance in these situations relative to immediate post-fire rehabilitation.

Research perspectives

The information provided from mapping, monitoring, and quantifying the severity of fire in boreal regions is of great use to researchers interested in the impact of fire on community and landscape ecology, the influence of climate change on boreal ecosystems, and the role of fire in the carbon cycle. Studies have used severity assessments in boreal ecosystems to study post-fire vegetation recovery (Dyrness and Norum 1983; Viereck 1983; Van Cleve *et al*. 1986; Duffy *et al*. 2007), fuel consumption from fire, and estimation of carbon gas emissions (Michalek *et al*.

2000; R. D. Ottmar and S. P. Baker, pers. comm., November 2007). Each of these applications requires a good understanding of the impacts of fire on both the aboveground (plant) and surface layers (surface organic matter and soil), because fire influences the entire ecosystem – both structure and function – in profound ways that include more than just tree mortality.

Remote sensing provides a unique tool for assessing fire effects for these and many other research objectives. However, as several studies presented in the current special issue demonstrated, dNBR and other remote-sensing methods to assess within-burn variability are not able to reliably predict the influence of fire on surface layer consumption, which is key in secondary succession and for knowing the magnitude of emissions from a fire event. For assessing fire emissions, research has shown consumption of the surface fuels (duff) is the most uncertain variable (Peterson 1987; French *et al*. 2004). In addition, smouldering combustion, most prevalent in surface fuels, can contribute more non-CO_2 greenhouse gases – gases that are more radiatively active – leading to increased influence of fires on greenhouse warming (Lapina *et al*. 2008). For prediction of post-fire vegetation recovery and succession, duff consumption is also a very important variable. Vegetation recovery in many boreal ecosystems is strongly dependent on regrowth through vegetative reproduction from propagules or from available seed in nearby unburned stands. Many of the vegetative propagules such as rhizomes and root suckers are relatively shallow owing to cold soils and deep organic horizons in boreal forests. Thus a severe fire, where surface organic material is consumed completely, will result in little to no vegetative reproduction, whereas less severe fires, where surface material remains and contains undisturbed root stock, can result in vigorous post-fire vegetation regrowth. From a fire emissions and post-fire vegetation recovery standpoint, understanding the effects of fire on the surface layer fuels is imperative and cannot be satisfactorily assessed with the existing metrics derived from remote sensing alone.

Concerns about the utility of dNBR and related remote-sensing approaches for mapping and assessing severity include two issues: (1) the problem of detecting the variability (such as depth to mineral soil) truly present in fires of high severity; and (2) problems of topography in northern locations. In high-severity fires (where the site is blackened and the canopy is substantially consumed), NBR or dNBR values can be similar for a wide range of post-fire duff depth. These high-severity fires can be the most important fires, from the standpoint of carbon emissions and vegetation reproduction, and are quite common in boreal regions where spruce are prevalent, such as Alaska. In the high latitude of the boreal region, topography introduces additional concerns related to remote-sensing assessment of burned areas. As reviewed by Verbyla *et al*. (2008), valley bottoms and north-facing slopes may not be properly assessed for severity owing to problems of sun elevation and acquisition of pre- and post-fire images that match with respect to sun angle and phenology. Topographic normalisation procedures may help to reduce the effect of topography on dNBR values, so these procedures should be tested by correlating field-based CBI values with dNBR from non- and topographically normalised images.

The results reviewed here indicate that dNBR-based severity maps need to be assessed with field observation, including a 'calibration' – as is often performed with a CBI assessment – as well as validation assessment to account for areas where dNBR may not produce an appropriate result. Field campaigns are still of great value in assessing the actual severity and effects of fire on a given site that are critical to several research questions. What remote sensing products of fire/burn severity can provide is a first approximation of fire's effects to help guide field data collections and to stratify the burned area based on aboveground severity.

In summary, satellite-based assessments of fire/burn severity, and in particular dNBR and related indices, need to be used judiciously and assessed for appropriateness based on the users' need. Often, remotely sensed information can add a unique perspective to the task and provide information unavailable through other means. In some cases, such as mapping of fire perimeters, satellite data can provide more complete and superior information than through any other means, especially in areas such as the remote boreal forests. However, more often, a combination of satellite images and field-based assessment is required for a full evaluation of fire effects. This is due to factors that are temporally sensitive as well as phenomena that are difficult to measure with spectral information alone. Issues unique to high latitudes also need to be considered when using satellite-derived information in the boreal forest region. Users need to be aware of the issues related to the remotely sensed products and be willing to modify their interpretations based on these limitations. Despite the inconsistent and sometimes poor results of CBI *v*. dNBR studies reported here and discussed in the papers presented in the current special issue, Landsat-based severity mapping provides an important tool for assessing fire effects, as long as circumstances and assumptions are properly understood.

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