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Estimating burn severity from Landsat dNBR and RdNBR indices across western Canada

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ABSTRACT

National parks in western Canada experience wildland fire events at differing frequencies, intensities, and burn severities. These episodic disturbances have varying implications for various biotic and abiotic processes and patterns. To predict burn severity, the differenced Normalized Burn Ratio (dNBR) algorithm, derived from Landsat imagery, has been used extensively throughout the wildland fire community. In Canada, few accuracy assessments have been undertaken to compare the accuracy of the dNBR algorithm to its relative form (RdNBR). To investigate the accuracies of these two algorithms in Canada's National Parks, we hypothesized that RdNBR would outperform dNBR in two specific applications based on former research by Miller and Thode (2007). The first was the capacity of the RdNBR to produce more accurate results than dNBR over a wide range of fires and secondly in pre-fire landscapes with low canopy closure and high heterogeneity. To investigate these questions, dNBR and RdNBR indices were extracted from Landsat imagery and compared to the measurements of the Composite Burn Index (Key & Benson, 2006). Following this, best fit models were developed and statistically tested at the individual, regional, overall, and vegetative levels. We then developed confusion matrices to assess the relative strength and weakness of each model. As an additional means of comparing model accuracy, we tested Hall et al.'s (2008) non-linear model in estimating burn severity for the study's western boreal region and individual fires. The results indicate that across all fires, the RdNBR-derived model did not estimate burn severity more accurately than dNBR (65.2% versus 70.2% classification accuracy, respectively) nor in the heterogeneous and low canopy cover landscapes. In addition, we conclude that RdNBR is no more effective than dNBR at the regional, individual, and fine-scale vegetation levels. The Hall et al. (2008) model was found to estimate burn severity in the western boreal region with a higher overall kappa than both the dNBR and RdNBR study models. The results herein support the continued research and pursuit of developing regional remote sensing derived models in western Canada.

1. Introduction

Since the last ice age wildland fire is considered to be the dominant disturbance agent across much of western Canada (Stocks et al., 2003). Consequently, a multitude of fire regimes can be found in western Canada, each possessing their own characteristics and spatial patterns. Wildland fire can drive biotic changes that are observed in landscape structure, composition, and species biodiversity, as well as change the function, rate, and pathways of ecological succession and encroachment (Lentile et al., 2006). In addition, fire can impact abiotic processes including soil and atmospheric nutrient cycling, as well as having direct implications for air quality from smoke emissions (Hardy et al., 2001). Under changing climate, Canadian wildland fire management agencies are becoming increasingly concerned with changes in fire season length, size and intensity, and financial cost (Tymstra et al., 2007). Fire projection models coupled with climate change forecasts predict increases in area burned, fire season length, fire intensity and burn severity (Wotton & Flannigan, 1993; Flannigan et al., 1998, 2005). In response, scientists and fire managers require the most accurate data available regarding landscape burn severity and estimates of total burned area so that they can calculate total carbon emissions and fluctuations in burned area over time. In addition, burn severity spatial data and the fire's perimeter can characterize fire-induced vegetation mortality along with associated unburned islands to create a mosaic landscape consisting of distinct forest type and age class patches (Miller & Urban, 1999; Fule et al., 2003).

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Canadian land managers, including provincial natural resource agencies and Parks Canada, are often limited in their ability to acquire wildland fire data in the field due to the lack of accessibility. Remote sensing products can be inexpensive, reduce safety hazards, and can provide more information when compared to traditional fire monitoring methods. This information can then be used by land managers and stakeholders for the purpose of monitoring vegetation, wildlife studies, soil and hydrologic changes, as well as various ecological processes.

Fire severity can be defined as the direct effects of the combustion process on vegetation such as tree mortality and the losses of biomass in the forms of vegetation and soil organic material (Jain et al., 2004; Lentile et al., 2006). Alternatively, burn severity can be defined as "the degree of ecological change to a landscape caused by fire" (Key & Benson, 2005). Inherently, field measured burn severity is not a direct measure but a subjective judgement that can change based on the context or resource being addressed (Lentile et al., 2006). Burn severity represents the majority of the research focus herein and is assessed in the field by classifying sites of similar visible burn characteristics.

The direct impacts of fire on vegetation include changes to the composition, density, and vigour of plant species as well as the overall moisture content of the vegetation, litter, and the soil of the burned area. For this reason, changes in the near and short-wave infrared regions of the electromagnetic spectrum following fire can be detected by multispectral remote sensing devices. Landsat's Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) sensors are appropriate for burn severity analysis because they record near infrared (NIR) and short-wave infrared (SWIR) reflectance in Bands 4 (B4) and 7 (B7), respectively. Band 4 is recorded in the wavelengths between 0.76 μm and 0.90 μm while Band 7 between 2.08 μm and 2.35 μm. Landsat TM/ETM+ Band 4 is primarily dependent on the refractive index of leaf morphology and discontinuities within the leaf (Puritch, 1981) while Landsat's TM/ETM+ Band 7 is sensitive to water content in both soils and vegetation, the lignin content of non-photosynthetic vegetation, and hydrous minerals such as clay, mica, and some oxides and sulphates (Elvidge, 1990; Avery & Berlin, 1992). In addition to the appropriate spectral bands, Landsat TM and ETM+ imagery provides moderate spatial resolution, is freely available in North America, and has an archive ranging from 1984 onwards, containing an extensive dataset covering most of Canada.

French et al. (2008), in a detailed review, documented 41 studies worldwide which utilized moderate and coarse resolution satellite data to extract the Normalized Burn Ratio (NBR) and differenced Normalized Burn Ratio (dNBR) data to detect burn severity. Of these studies, 26 of them utilized Landsat imagery to derive the normalization of near infrared and shortwave infrared wavelengths to measure burn severity. NBR and dNBR are calculated as follows:

$$NBR = (\mathrm{B4}-\mathrm{B7}) / (\mathrm{B4}+\mathrm{B7}) \tag{1}$$

$$dNBR = \left(NBR_{\mathrm{prefire}} - NBR_{\mathrm{postfire}}\right) \tag{2}$$

To derive either the initial assessment (IA) or extended assessment (EA) dNBR images, suitable pre- and post-fire NBR grids are acquired and the images subtracted to yield the differenced Normalized Burn Ratio (dNBR). The extended assessment (EA) is the difference between the pre-fire NBR image and an image acquired one year post-fire, and this image is most commonly used in burn severity ecological assessments. In contrast, fire perimeter delineation and immediate burn severity mapping normally utilizes the initial assessment (IA) which is the difference between the pre-fire image and an image acquired in the same year as the fire event and as immediately following the fire event as possible. A recent variation of the dNBR approach is the relative differenced Normalized Burn Ratio (RdNBR). While the dNBR algorithm measures absolute change between the pre- and post-fire images, the RdNBR algorithm determines burn severity based on pre-fire reflectance and calculates the relative change caused by fire (Miller & Thode, 2007) as defined in Eq. (3):

$$RdNBR = \frac{NBR_{\mathrm{prefire}} - NBR_{\mathrm{postfire}}}{\sqrt{\left|NBR_{\mathrm{prefire}} / 1000\right|}} \tag{3}$$

The evaluation of the sensitivity of the dNBR algorithm to measure burn severity has been tested on a large number of fires in the USA (Zhu et al., 2006). From the studies discussed in French et al. (2008), an overall dNBR classification accuracy of 73% (range 50–90%) was determined across a range of fires. Miller and Thode (2007) compiled burn severity data from 14 fires in the Sierra Nevada region, USA, and found a coefficient of determination (R^2) of 0.49 for dNBR while the RdNBR reported an R^2 of 0.61. Zhu et al. (2006) also found overall that the RdNBR was a better estimator than dNBR within the more sparsely vegetated Southwest region and over a pooled dataset of all fires. They also concluded that RdNBR was a better estimate in landscapes that had either sparse or non-productive pre-fire vegetation, and therefore may provide a more consistent broad scale relationship to burn severity. Miller and Thode (2007) proposed two advantages of the RdNBR algorithm over the dNBR: 1) it provided a consistent definition for comparison across space and time and 2) classification accuracies should be higher in high severity categories, especially in heterogeneous pre-fire vegetation.

Only a limited amount of published literature regarding remote sensing of burn severity exists for Canadian landscapes. A pilot study conducted by Perrakis and Zell (2008) found promising results using Landsat to estimate burn severity across three fires in national parks of western Canada. Hall et al. (2008) investigated the relationship between dNBR and ground based burn severity measurements for four fires in Canada's boreal region reporting R^2 values as high as 0.84. They also discussed the need for future research in the Canadian boreal using RdNBR to better understand the effects of pre-fire vegetation on burn severity modelling from remote sensing data.

Based on this existing research we hypothesized that the RdNBR algorithm would perform better in heterogeneous or sparsely vegetated landscapes, as well as provide a more accurate index across our total study area. The goal of this research, therefore, is to assess and compare the capacity of both the dNBR and RdNBR algorithms to estimate burn severity. To fulfill this objective, dNBR and RdNBR data were derived from a number of Landsat scenes and compared with field estimates of burn severity across a range of fires. The difference in the capacity of the two datasets to estimate burn severity was first assessed on an individual fire basis. Fires were then stratified by both broad vegetation type (coniferous, broadleaf, and 'other vegetation') and region (Rocky Mountain, western boreal), and lastly all fires were pooled to assess the capacity of a generalised model to estimate burn severity across all fires. Finally, we assessed the capacity of a previously-developed model from Hall et al. (2008) to estimate burn severity over the western boreal region and the fires within that region. With this comprehensive examination of Canadian burn severity monitoring we anticipate a clearer picture of the strengths and weaknesses of these two algorithms will be realized which in turn should provide additional insight for model applications in routine burn severity research.

2. Data and methods

2.1. Study area and characteristics

Six fires were analyzed in this study all of which occurred in four Canadian national parks (Figs. 1 and 2). Three of the fires occurred in the Canadian Rockies and the remaining three in the western boreal