Forest Ecology and Management 556 (2024) 121756

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Assessing spatial patterns of burn severity for guiding post-fire salvage logging in boreal forests of Eastern Canada

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ARTICLE INFO

Keywords:
Ecosystem-based forest management
Disturbed forests
Black spruce
DNBR
RBR
RdNBR

ABSTRACT

Areas affected by forest fires are increasing worldwide, making salvage logging (i.e., harvesting fire-affected trees) an increasingly used practice to reduce the economic impacts of fire on forestry. However, salvage logging can have strong ecological impacts, notably on post-fire forest regeneration and biodiversity. Burn severity (i.e., the degree to which fires impact the vegetation and soil) is also a central element that interacts with pre-fire forest characteristics and salvages logging to control post-fire forest dynamics and biodiversity. In an ecosystem-based forest management context, spatial patterns of burn severity should thus be considered when planning salvage logging operations. This study presents a simple and innovative method to generate burn severity maps with Landsat and Sentinel-2 multispectral imageries to support salvage logging operations rapidly after a fire event. We assembled a unique dataset involving 330 plots from 10 burns (from 2010 to 2020) in which burn severity has been estimated on the field using the composite burn index (CBI) approach in eastern North America. CBI values were modelled as a univariate function of changes in spectral indices using the first cloud-free post-fire satellite images taken after the burns. Our results demonstrate that using free satellite images with straightforward methods can produce reliable and ecologically meaningful burn severity maps within the few weeks following a fire event. The method was then applied to a case study with salvage logging that illustrates how our burn severity maps could be a useful tool for guiding post-fire forestry operations in an ecosystem-based management context. We combined burn severity maps with pre-fire forest composition and age maps to assess immediate post-fire forest. We discuss how such an approach helps to guide salvage planning and maintain residual forests that are representative of the initial post-fire spatial variability in burn severity and pre-fire vegetation. We conclude that rapid mapping of burn severity after a forest fire event may offer many other applications for identifying and managing recently burned forests.

1. Introduction

Areas affected by forest fires are increasing worldwide due to global change (Kelley et al., 2019; Seidl et al., 2017), bringing new challenges for sustainable forest management. Salvage logging, harvesting standing trees affected by fire but still economically valuable (Leverkus et al., 2018, 2020), is becoming an increasingly common practice (Müller et al., 2019). On the one hand, salvaging burned forests allows for helping to maintain the total harvest volume targeted by forest industries or governments while reducing the areas harvested through conventional logging in green forests. The generalized use of salvage logging would thus reduce the total loss of timber affected by

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https://doi.org/10.1016/j.foreco.2024.121756
Received 17 October 2023; Received in revised form 2 February 2024; Accepted 3 February 2024

disturbances (i.e., the sum of logging and natural disturbances), which is of great interest in the context of climate-induced global increases in burned areas (Seidl et al., 2017, 2020). On the other hand, salvage logging constitutes an additional disturbance after the fire that may alter the overall forest resilience, a phenomenon known as compound disturbance effect (Paine et al., 1998; Buma, 2015; Kleinman et al., 2019).

There is undeniably a lack of knowledge on the long-term ecological impacts of salvage logging since most existing studies focus on the first five years following the initial disturbance (Thorn et al., 2018). However, many short-term studies have shown that salvage logging can strongly affect initial natural post-fire regeneration (Boucher et al., 2014; Greene et al., 2006; Splawinski et al., 2016) and burn-associated biodiversity (Lindenmayer et al., 2018; Thorn et al., 2018, 2020). For example, salvage logging in eastern Canadian boreal forests tends to favour encroaching broadleaved species (Greene et al., 2006; Boucher et al., 2014) and can also increase the risk of a disturbance-driven switch toward poorly regenerated forests or even non-forested vegetation (i.e., regeneration failure; Splawinski et al., 2016). Moreover, salvage logging removes essential habitats for a large community of saproxylic insects, birds and mammals taking advantage of dead and dying trees (Nappi et al., 2004; Azeria et al., 2011; Bognounou et al., 2021). Thus, while trying to improve the sustainability of forest management (through reduced impact on non-disturbed forested areas), salvage logging could affect the forest ecosystem resilience. Among existing sustainable forest management approaches, ecosystem-based management assumes, as a core principle, that forestry practices should conserve and emulate the landscape's variability and spatial patterns emerging from natural processes such as natural disturbances (Gauthier, 2009; Gauthier et al., 2023; Kuuluvainen et al., 2015). Conserving this variability represents a straightforward strategy to maintain plants and animal biodiversity adapted to those conditions.

Spatial patterns of burn severity, defined as the degree to which fire impacts the vegetation and soil through combustion and heating (Keeley, 2009), have a profound influence on many aspects of forest systems and dynamics, including tree mortality, post-fire recovery and succession, nutrient cycling, soil erosion, wildlife habitat, and overall landscape heterogeneity (e.g., Spigel and Robichaud, 2007; Turner, 2010; Boucher et al., 2016; San-Miguel et al., 2016). Therefore, drivers of managed forest post-fire dynamics (e.g., regeneration, biodiversity) should be seen as interactions between 1) pre-fire conditions, 2) burn severity, and 3) salvage logging (e.g., Boucher et al., 2014; Danneyrolles et al., 2020; Leverkus et al., 2018; Nappi and Drapeau, 2011). Within the theoretical framework of ecosystem management, the primary goal would be to minimize the potential compound disturbance effects by limiting the salvage logging rates (i.e., conserving a large amount of unsalvaged residual forests). Moreover, since burned forests can show high heterogeneity resulting from the interplay between pre-fire vegetation characteristics and burn severity patterns, the unsalvaged forests should also be representative of this inherent spatial variability (Nappi et al., 2011). To implement such an approach, it is thus crucial to assess the natural variability that emerges after a fire event to determine which areas of the burned forests are selected for salvage logging or to be left untouched. Furthermore, this initial assessment must be conducted promptly after the fire since salvage logging must be carried out swiftly to prevent the wood from being infested by wood-boring saproxylic insects (Boucher et al., 2020; Gervais et al., 2012), which would result in serious economic losses.

Several remote-sensed and field-based burn severity indices have been developed in recent decades (for a recent review, see Miller et al., 2023). One technique to quantify burn severity through remote sensing involves using spectral differences between pre-fire and post-fire satellite images. The most common spectral indices of burn severity are derived from the Normalized Burn Ratio (NBR; Key and Benson, 2006; Parks et al., 2019), computed as a ratio between near- and thermal-infrared bands in pre-fire and post-fire images (see methods for detailed equations). Field estimations of burn severity (Composite Burn Index; CBI; Key and Benson, 2006) generally validate NBR-derived remote-sensed indices. The CBI consists of estimating fire impacts on soil and vegetation in plots of 30 m in diameter and averaged to obtain a single unitless quantitative measure of burn severity (unburned to severely burned), ranging between 0 and 3. Strong statistical relationships between remote-sensed and filed-based estimations have shown the robustness of NBR-derived spectral indices to map burn severity at the landscape scale in many world ecosystems, including Canada's boreal forest (e.g., Key and Benson, 2006; Collins et al., 2018; Parks et al., 2019; Guindon et al., 2020).

In forest management, however, using burn severity maps based on spectral indices remains strongly limited due to their non-standardized units and nonlinear relationships with field-based measures (e.g., Morgan et al., 2014; Kolden et al., 2015; Parks et al., 2019). To overcome these limitations, some authors developed models that predict CBI maps with changes in spectral indices, which provide helpful information about field-observed fire effects (Boucher et al., 2017; Hudak et al., 2007; Morgan et al., 2014; Parks et al., 2019). Yet, since spectral indices may imply different fire effects depending on forest ecosystem types, ideally, such models must be region-specific (Reiner et al., 2022) and built on large sampling efforts (e.g., Picotte et al., 2019). Moreover, most models developed to date are not rapid enough to produce burn severity maps, with lags between the burn and the map production ranging from several months to $>$ 1 year (Guindon et al., 2020; Parks et al., 2019). Such long delays make the satellite-derived burn severity mappings useless for salvage logging operations that must be planned quickly after a fire to prevent wood degradation by wood borers or other degrading agents (e.g., Saint-Germain and Greene, 2009). The production of satellite-based CBI maps is now technically easy and quick. An excellent example is the USDA Forest Service RAVG program (*Rapid Assessment of Vegetation Condition after Wildfire*), which provides satellite-based CBI maps within 30–45 days following a fire event in US public lands (Miller and Thode, 2007; Miller et al., 2009; Miller and Quayle, 2015). These maps are used for several rapid post-fire management purposes.

This study aims to develop a satellite-based approach to produce medium-resolution burn severity maps right after a fire event for supporting and planning post-fire salvage logging operations in the eastern Canadian boreal forest. In comparison to Western North American forests, there has been considerably less research conducted on burn severity (Boucher et al., 2017; Parks et al., 2019). Our first objective was to model field-based burn severity estimates (CBI) for eastern Canadian boreal forests as a simple univariate function of changes in spectral indices (using Landsat or Sentinel-2 images), with post-fire images taken just a few weeks after the fire event (~15 to 65 days). Secondly, through a case study, we a posteriori illustrate how the produced burn severity mapping, in conjunction with maps of pre-fire forest age and species composition, can be a powerful tool for guiding post-fire salvage logging operations in an ecosystem-based management context.

2. Material and methods

2.1. Study area and burn selection

Our study area is the eastern North American boreal forest located in the province of Quebec, Canada (Fig. 1). More specifically, we focus on the area burned by ten burns that occurred between 2010 and 2020 (Table 1). In this studied region, the mean annual temperature ranges from − 2 to 4 °C. Precipitation exhibits a latitudinal gradient: rather continental in the west (800–1000 mm of annual precipitation) and coastal in the east (1000–1200 mm of annual precipitation). Topography is defined by mid-elevations (300–600 m) relatively rugged reliefs mainly composed of glacial till, rocky and organic deposits. Black spruce (*Picea mariana* [Mill.] Britton), jack pine (*Pinus banksiana* Lamb.) and balsam fir (*Abies balsamea* [L.] Mill.) dominate the landscape, along with associated species, such as paper birch (*Betula papyrifera* Marshall),

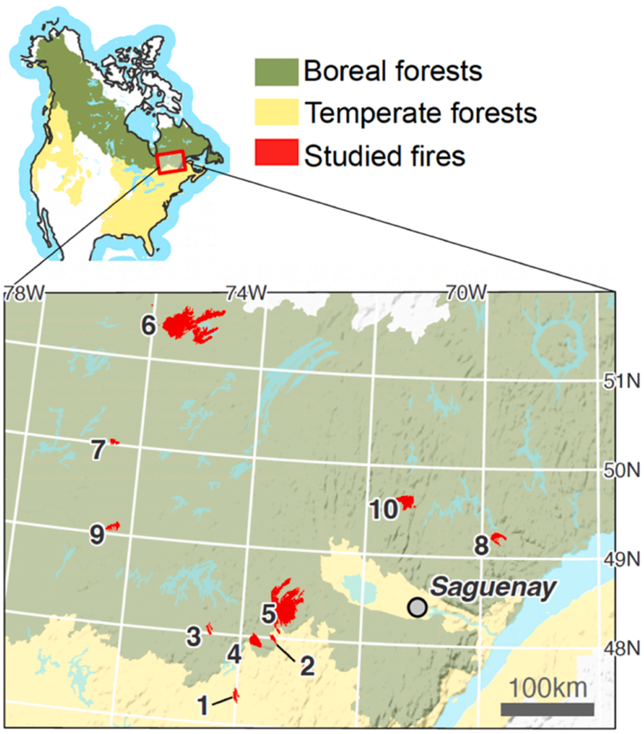

Fig. 1. Localization of studied area and fires used in our analyses.

Table 1
Information on the studied burns. The 1st column shows the burn reference number used in this study, displayed in Fig. 1. Fires are ordered by date (2nd column; peak in MODIS thermal anomalies data). Dates of field campaigns, the number of field-based severity assessment (CBI) plots, and references are shown in the 3rd, 4th and 5th columns, respectively.

Burn no.	Fire date	Field camp.	Area (10^3 ha)	N plots	Reference
1	2010-05-30	2011-08	6.1	22	Boucher J. et al. 2017
2	2010-05-30	2011-08	3.8	5	Boucher J. et al. 2017
3	2010-05-30	2011-08	4.4	2	Boucher J. et al. 2017
4	2010-05-30	2011-08	19.5	16	Boucher J. et al. 2017
5	2010-05-30	2011-08	125.9	15	Boucher J. et al. 2017
6	2013-06-22	2014-06	150.1	44	Bourdon J.-F. (in Parks et al., 2019)
7	2017-06-08	2017-08	4.1	90	Smetanka C. 2021
8	2018-06-30	2018-08	12.1	30	Smetanka C. 2021
9	2018-07-14	2019-09	8.5	50	Boucher Y. (unpublished)
10	2020-06-20	2020-06	25	45	Boucher Y. (unpublished)

trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* [Moench] Voss). Wildfire represents the principal natural disturbance in this region, with fire return intervals ranging from 120 to > 1000 years depending on local climate and vegetation fuel characteristics (Chaste et al., 2018; Couillard et al., 2022). The fire season begins in the spring after snow melts in May, and ends with the first snowfall in September-October, although most fires occur between June and August (Guindon et al., 2020).

2.2. Field-based burn severity estimation (CBI)

We assembled 330 CBI plots from ten burns, measured on the field between a few weeks and one year after the burns; these field-based burn severity assessment has been done in past studies (Table 1). CBI plots were built using the protocol defined by Key and Benson (2006), which defines the estimation of 23 variables specific to five vertical forest strata: (1) soil, (2) vegetation < 1 m in height, (3) shrubs and trees 1–5 m in height, (4) intermediates trees (sub-canopy regeneration), and (5) dominant and codominant trees. Four to five factors are measured in each stratum, including fire-exposed mineral substrate, forest floor consumption, percent of vegetation that survived the fire, and percent of black/brown foliage or canopy mortality. Finally, the 23 variables are averaged for the entire plot into an overall CBI. Each estimation is based on visual assessments through consensus by a team of 2 to 3 persons and is rated from 0 to 3, with 0 representing no burn effects and 3 representing the most severe burn impact.

2.3. Remote-sensed burn severity estimation

We mapped the changes in spectral indices for each studied fire using mid-resolution Landsat and Sentinel-2 multi-spectral images collected before and after fire occurrence. Landsat images were available for the whole studied period (2010–2020), while Sentinel-2 images were only available for the four most recent burns (2017–2020). Our objective was to produce maps of burn severity as fast as possible after the burns, so we restricted the choice of post-fire images to the same growing season (June-September) in which the fire occurred (initial assessment method; Key and Benson, 2006). We used Google Earth Engine to select relevant pairs of images and to mask cloud and shadow areas. We filled gaps (cloud and shadow areas) with pixels from other images to ensure the most complete coverage of the burned areas (i.e., cloud-free image mosaic). For the pre-fire images, the approach was to primarily retain the non-masked pixels temporally closest to the fire-starting date. For the pre-fire images, we retained all non-masked pixels that were available for the growing season preceding the burns (i.e., one year before). We then used the pre- and post-fire Landsat and Sentinel-2 mosaics pairs to compute changes in spectral indices that have been shown to be good proxies for burn severity (Guindon et al., 2020; Key and Benson, 2006; Parks et al., 2019, 2014). We first calculated the Normalized Burn Ratio (NBR) with the near-infrared (NIR) and thermal-infrared (SWIR) bands for both pre-fire and post-fire mosaics (Eq. (1)). The differenced Normalized Burn Ratio (dNBR) was calculated as a difference between pre- and post-fire NBR (Eq. (2)). Relativized forms of dNBR (RdNBR and RBR) have been proposed to better control for pre-fire vegetation characteristics when evaluating burn severity, and have been shown to better correspond with field-based measurements (Parks et al., 2014). As such, we also transformed dNBR indices into two relativized forms, RdNBR and RBR (Eqs. (3) and (4), respectively), to additionally evaluate their performance as predictors of field-based burn severity estimation.

$$NBR = \frac{NIR - SWIR}{NIR + SWIR} \tag{1}$$

$$dNBR = NBR_{prefire} - NBR_{postfire} \tag{2}$$

$$RdNBR = \frac{dNBR}{\left|NBR_{prefire}\right|^{0.5}} \tag{3}$$

$$RBR = \left(\frac{dNBR}{\left(NBR_{prefire} + 1.001\right)}\right) \tag{4}$$

2.4. Model fitting

We tested the relationships between field-based CBI estimations and satellite-based spectral indices (i.e., dNBR, RdNBR and RBR) using three univariate models. First, a value of each spectral indices was assigned to each of the CBI plots. Our data had different spatial resolutions: CBI was estimated into circular plots (Key and Benson, 2006), while Landsat- and Sentinel-2-based spectral indices maps were rasters with 30 m and 20 m resolution, respectively. For each CBI plot and spectral indices, we calculated the indices' weighted mean of all raster pixels included in an 11.3 m buffer around the plot's center, with the area covered by individual pixels in the buffer zone as weight. For each of the sampled burns, we also randomly sampled ten virtual plots within the surrounding unburned area (i.e., between 0.1 and 10 km outside the burn delimitation areas) to allow the models to fit spectral indices values to unburned reference plots (i.e., CBI=0). We then modelled CBI as a univariate function of each spectral indices (dNBR, RdNBR and RBR) based on the two sensors and with three different models: linear, second-order polynomial, and saturated growth (see detailed equations in Table 2).

2.5. *Predicted CBI maps*

Once the models were fitted, we produced CBI prediction maps from satellite-based multispectral indices maps. Because the different spectral indices were highly correlated, we predicted CBI values as a function of dNBR with the best model for the four burns in which both Landsat and Sentinel-2 data were available. We limited CBI predictions to the range 0–3 (predictions <0 and >3 were converted to 0 and 3, respectively). For the four most recent burns for which we had both Landsat and Sentinel-2 data, we compared the predictions made with the two sensors to understand how different data sources could influence the final products. Because Landsat and Sentinel-2 have different spatial resolutions (30 and 20 m, respectively), Sentinel-2-based predictions were aggregated at the Landsat resolution for comparisons.

2.6. *Case study analysis: a tool to support planning of salvage logging*

Our second objective was to illustrate how burn severity maps may guide ecosystem-based post-fire salvage logging. The proposed goal is to use burn severity maps to maintain post-fire residual forests (i.e., unsalvaged) that are representative of the proportion of post-fire types (combining burn severity and pre-fire forest characteristics). We used data from a burn that occurred in 2020 (#10 in Table 1 and Fig. 1). Since categorical variables are often easier to use for management purposes than continuous variables, we first produced a burn severity class map with the CBI predictions described above (from the dNBR map computed with Sentinel-2 images). Following Boucher et al., 2017, burn severity classes were defined as either unburned (CBI ≥0 and <0.3), low (CBI ≥0.3 and <1.75), moderate (CBI ≥1.75 and <2.25) or high (CBI ≥2.25 and ≤3). We then coupled this information with pre-fire vegetation data from Quebec's government forest maps (MFFP, 2018). These maps estimate the relative abundance of the main tree species in the canopy and contain 1:20,000 scale photo-interpreted polygons that estimate stand age across the landscape, which we classified into mature (> 40 years) and young (< 40 years). We used *k*-mean cluster analysis to classify forest composition. Composition clusters were combined with the age classes into five pre-fire forest types (see Fig. S5 for methodological details). To "a posteriori" illustrate how burn severity maps may guide ecosystem-based post-fire salvage logging, spatial data on sectors harvested through salvage logging were also extracted from Quebec's government forest maps. We finally calculated the area represented by all possible combinations of pre-fire forest types and burn severity classes after and before the salvage-cutting operations.

Table 2
Equations and R^2 values for each univariate model in which Composition Burn Index (CBI) is an univariate function of dNBR values obtained for the 330 CBI plots with Landsat images for the total CBI datasets (330 CBI plots; 10 burns) and with Sentinel and Landsat images but only for CBI plots estimated in fire events posterior to 2017 (217 CBI plots; 4 burns). All parameter estimates and R^2 values obtained with dNBR and other spectral indices changes (RBR, RdNBR) are given in Table S1.

Model	Equation	R^2		
		Landsat	Land. > 2017	Sentinel-2
Linear	$CBI = a \times dNBR + b$	0.76	0.68	0.67
2nd order polynomial	$CBI = a \times dNBR^2 + b \times dNBR + c$	0.82	0.74	0.69
Saturated growth	$CBI = dNBR \times (a \times dNBR + b)^{-1}$	0.83	0.74	0.76

3. Results

Our field sampling (CBI) and remote sensing data (dNBR from Landsat and Sentinel-2) covered a wide range of burn severity conditions. Indeed, the CBI estimated in 330 plots used for model fitting ranged from 0.3 to 2.9, with a median of 1.95 (Fig. 2). Initial cloud-free Landsat post-fire mosaics occurred 33–113 days post-burn, mapping 44% of the total burned areas within two months (Fig. S1). Sentinel-2 mosaics, taken 45–72 days post-burn, mapped 99% of the areas within 65 days (Fig. S1). Landsat dNBR for burned plots ranged from 231 to 1179 (median 663), and Sentinel-2 dNBR ranged from 144 to 981 (median 619; Fig. 2). Median Landsat dNBR for virtual unburned plots

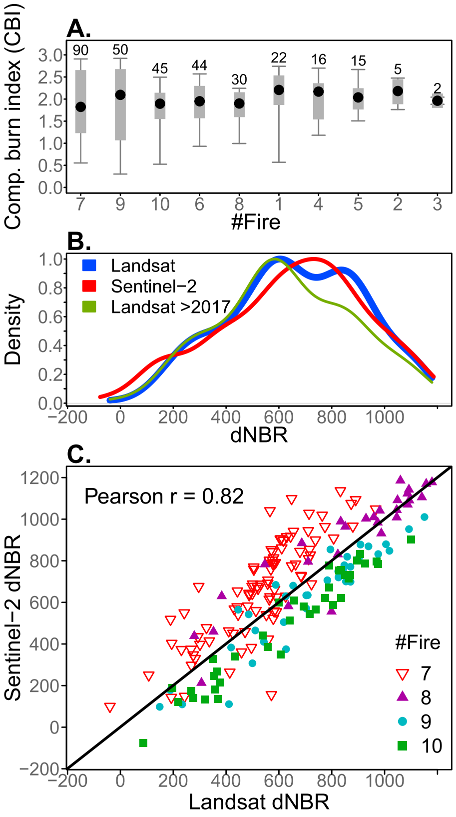

Fig. 2. Overview of data used for fitting the models. Graphic (A) shows the variation of the Composite Burn Index (CBI) values inside and between burns. Boxplots show the minimum and maximum values (segments), the 25th and 75th percentiles (grey rectangle) and the median values (black points) for each sampled fire. Fires are classified by the number of CBI plots sampled (shown above each boxplot). Graphic (B) shows the distribution of dNBR values obtained for the 330 CBI plots with Landsat images for the total CBI datasets (330 CBI plots; curve in blue) and with Sentinel and Landsat images but only for 217 CBI plots estimated in fire events posterior to 2017 (217 plots, curves in red and green, respectively). For those fire events posterior to 2017, graphic (C) compares dNBR values obtained with either Landsat or Sentinel images, with symbols indicating different fire events and the black line showing the theoretical 1:1 relationship.

(i.e., CBI = 0) was − 4 and − 7 for Landsat and Sentinel-2, respectively. Landsat and Sentinel-2 dNBR were highly correlated (Pearson r = 0.82) but showed systematic bias depending on burns (Fig. 2). Relativized forms RBR and RdNBR correlated with dNBR (Pearson r 0.84 to 0.99; Fig. S2), so we describe only the findings obtained with dNBR in the subsequent results, the index most widely used in the literature.Haut du formulaire.

The statistical relationships between CBI and dNBR showed good R^2 with all models (between 0.67 and 0.83; Table 2, Fig. S4). Landsat showed better results (R^2 between 0.76 to 0.83) than Sentinel-2 (R^2 between 0.67 to 0.76), although the results of the two sensors converged for the burns posterior to 2017 (i.e., data available with Sentinel-2; Table 2). The linear model showed the weakest R^2 (between 0.67 and 0.76) and a poor ability to predict low or high values of CBI (i.e., CBI <0.8 or >2.25, Fig. S3). Second-order polynomials showed higher R^2 (0.69 to 0.82) but failed to predict high values of burn severity (i.e., CBI > 2.25) because of a few outliers that tended to reverse the growth curve at CBI of 2.25 (Fig. S3). The saturated growth models showed the highest R^2 (0.76 to 0.83) and a good ability to predict both low and high CBI and were thus retained as the best model for the successive analyses. The results of other spectral indices (RBR and RdNBR) were highly similar (Fig. S3).

The CBI maps produced from remote-sensing spectral indices illustrate the capacity to predict burn severity on the ground (Figs. 3 and 4). Predictions obtained with different sensors (i.e., Landsat or Sentinel-2) differed moderately, with overall slightly higher predictions found with Sentinel-2 than Landsat (median of + 0.15). Large differences in predicted values with the two sensors were rare, with 90% of differences in predicted CBI between − 0.50% and 0.70% and 50% between − 0.06 and 0.35. Differences in the predictions between Landsat and Sentinel-2 tended to vary more between- than within- single burns. For example, burn no.7 showed a clear trend to higher predictions with Sentinel-2, while this trend was inverted in burn no.9 and 10. Despite such differences, the within-fire burn severity spatial patterns described by both sensors remained highly similar.

Our case study allowed a deeper post-fire ecological assessment by combining pre-fire vegetation (i.e. forest age and composition) and burn severity classes (Fig. 5). In this sector, the pre-fire forest landscape was composed of 52% of young forest stands (<40 years) induced by past logging activities, leaving the remaining 48% into mature conifers (black spruce and jack pine) or mixed forests (balsam fir and paper birch) (Fig. 5). According to our model, the landscape has mostly burned at low and medium severity, while high-severity burning was less frequent. Salvage logging operations occurred only in 14% of the burned area (Fig. 5), mainly focusing on mature stands dominated by black spruce and jack pine (64% and 19% of the salvaged area, respectively; Fig. 5). For each combination of pre-fire vegetation and burn severity classes taken separately, salvaging rates ranged from 10% to 39% in mature pre-fire forest types.

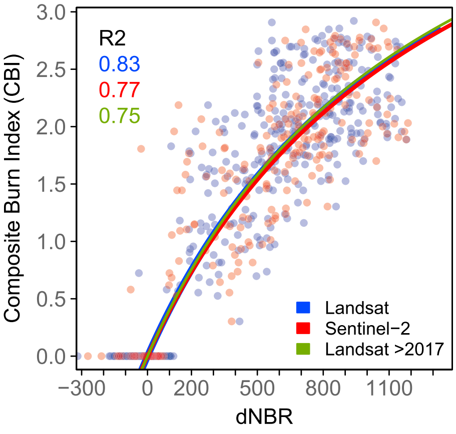

Fig. 3. Field-based burn severity estimation (Composite Burn Index; CBI) as a function of remotely sensed changes in dNBR with the saturated growth model. Blue point cloud and line show the relationships between CBI and Landsat-based dNBR for the whole dataset (330 CBI plots). The red point cloud and line show the relationships between CBI and Sentinel-2-based index (217 CBI plots; only 4 burn posterior 2017). The green line shows the relationships between CBI and Landsat-based index but only for fire events posterior to 2017. Randomly sampled virtual plots were also added to allow the models to fit spectral indices values to unburned reference plots (i.e., CBI=0; see *Methods*). The values at the top-left corner of the graph indicate the R^2 obtained (following the same colour legend as mentioned above).

4. Discussion

Our objectives were 1) to develop a satellite-based approach to produce medium-resolution ecologically meaningful burn severity maps right after a fire event and 2) to illustrate how such maps could guide postfire salvage logging operations. We assembled the largest field-based burn severity estimation dataset in eastern North America. Field-based estimations were then modelled as a simple univariate function of changes in spectral indices (using Landsat or Sentinel-2 images).

4.1. Spectral indices for ecologically meaningful burn severity maps in eastern North American boreal forests

Our results show that satellite images can be used with simple statistical models to produce burn severity maps that are ecologically meaningful, reliable, and thus useful for forest management. Using the largest field-based burn severity estimation dataset in eastern North America, these findings corroborate the strong correlations found over the last two decades in western North American forests (e.g., Key and Benson, 2006; Allen and Sorbel, 2008; Parks et al., 2014; Morgan et al., 2014; Parks et al., 2019; Whitman et al., 2018; Harvey et al., 2019). However, changes in spectral indices imply different fire effects depending on forest ecosystem types, which thus makes the development of region-specific models essential (Reiner et al., 2022). Based on the behaviour of spectral indices, saturated growth models showed the best performances to predict CBI in our study area, regardless of the spectral index, as was also found in previous work (J. Boucher et al., 2017; Y. Boucher et al., 2017; Guindon et al., 2020). Moreover, our results demonstrate that such burn severity maps can be produced quickly after a burn (~15–65 days) based on a straightforward and inexpensive procedure, making it a very relevant and powerful tool for post-fire salvage logging operations. In comparison, the USDA Forest Service RAVG program provides CBI maps within 30–45 days following a fire event in US public lands (Miller and Quayle, 2015). This time difference is not surprising given that the relatively high latitudes of our study area are more frequently covered by cloud formations, making satellite images less consistently usable. Moreover, our results show that Landsat and Sentinel-2-derived burn severity metrics consistently correlate with CBI values. Differences in CBI predictions made with Landsat and Sentinel-2 data are likely mostly linked to different image timing than sensors (Howe et al., 2022). This suggests that both sensors could produce burn severity mosaic maps, depending on which satellite provides the first cloud-free – even partial – images of the area of interest.

4.2. Burn severity maps as a tool to preserve natural variability in residual un-salvaged forests

Our case study illustrates the relevance and facility of using satellite-derived burn severity maps in guiding salvage logging operations by improving the ability to identify and map post-fire forest stand diversity to minimize the additional impact of salvage logging on disturbed forests. Indeed, in North American boreal forests, spatial patterns of pre-fire

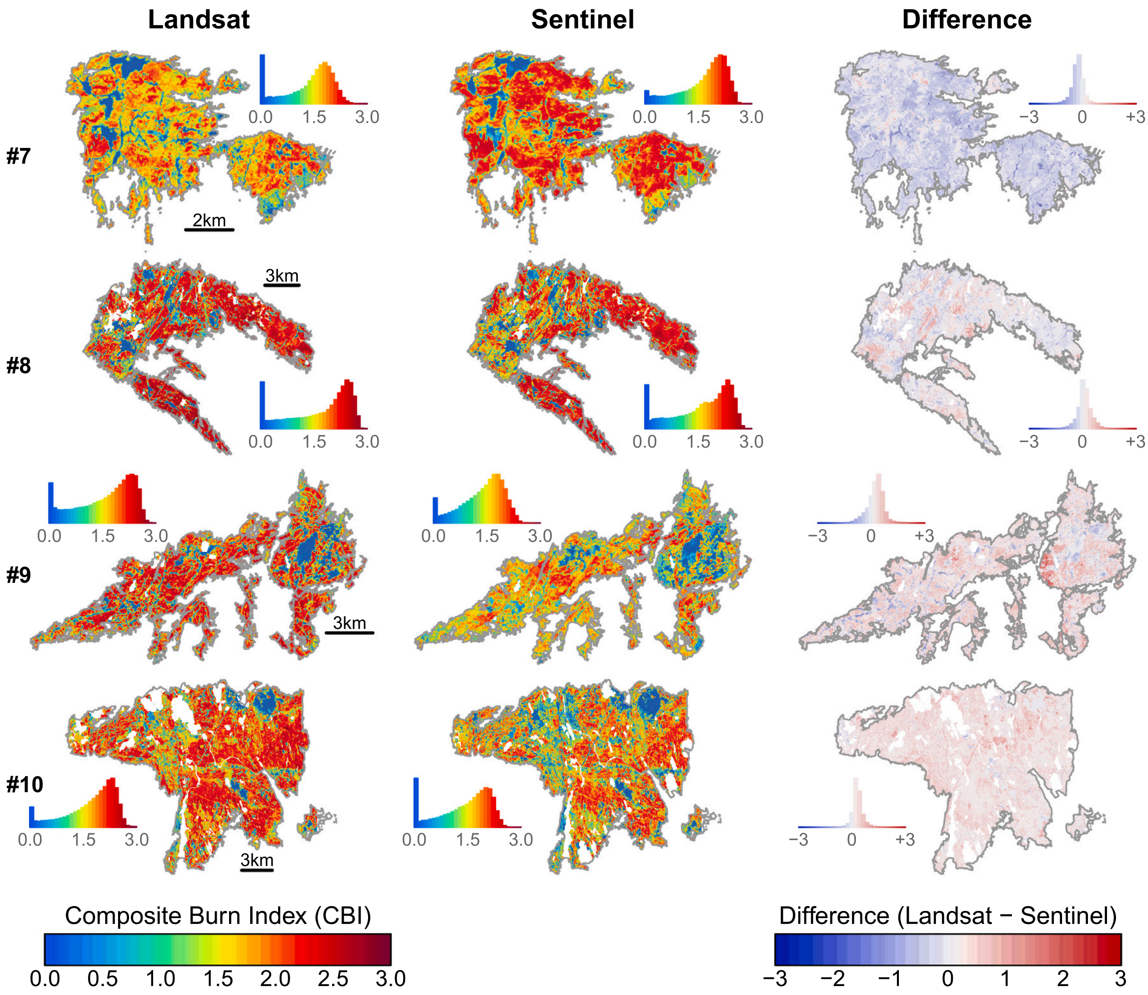

Fig. 4. Remote-sensed burn severity maps that can be used for ecosystem-based management. Predictions were made with the saturated growth model (see Fig. 2) for four burns for which both Landsat and Sentinel-2 data were available (burn reference numbers are shown at the left margin of the figure with a #). The maps show predicted CBI using Landsat or Sentinel-2-derived indices and differences in prediction between the two data sources. The histograms of each map show the distribution of values for pixels within the burn boundaries. Sectors in white within burn perimeters correspond to areas where it was impossible to obtain a cloud-free image within the first three months after the burn.

forest characteristics and burn severity are good indicators of post-fire tree mortality, regeneration and wildlife habitat quality and diversity (Baltzer et al., 2021; Boucher et al., 2016; Greene et al., 2004; Nappi and Drapeau, 2011; Perrault-Hébert et al., 2017). Spontaneous dynamic trajectories of regeneration, succession and biodiversity in salvaged areas can thus deviate from those in un-salvaged forests (Bognounou et al., 2021; Boucher et al., 2014; Greene et al., 2006; Splawinski et al., 2016). Nappi et al. (2011) thus proposed a simple ecosystem-based management approach that would aim to maintain a proportion of unsalvaged residual forests, which is representative of the spatial variability in burn severity and pre-fire vegetation. In our study, a substantial proportion of the burned landscape (~50%) was already altered by logging a few decades before the fire, which is highly representative of the fires occurring in the managed forests in eastern Canada (Boucher et al., 2017). Salvage logging then logically targeted mature stands that had not been logged previously. Although only 14% of the burned mature forests were salvaged, this introduced an additional dimension of potential compounded disturbance effects on those landscapes. However, only 14% of the mature forests were salvaged. This underlines the need to maintain a significant proportion of unrecovered residual forests representative of the spatial variability in burn severity and pre-fire vegetation. The procedure would ensure that a substantial proportion of the burned landscape is representative of the natural dynamics of the burned boreal forest that would occur without conventional (i.e. before fire) or salvage logging.

Beyond this simple general approach, the more precise retention parameters should be discussed. In the eastern Canadian boreal forest, the proportion of salvage logging in burned forests is generally less than 20% of total annual burned areas and never exceeds more than 50% for individual fires (see for ex.; Bouchard et al., 2023; Leduc et al., 2015; Nappi et al., 2011). This is mostly due to three additive constraints: the abundance of mature forests in the pre-fire landscape, the rapid loss of wood economic value due to wood-boring insects (Gervais et al., 2012) and the absence of a pre-existing road network in many boreal forest landscapes. Global meta-analyses of multi-taxa response to salvage logging have shown that high proportions (>50%) of naturally disturbed areas must be left unsalvaged to maintain the burn-associated biodiversity (i.e., taxa mostly found in disturbed forests; Thorn et al., 2020, 2018). We recommend that future research should aim to define retention thresholds that should be applied to each burn severity and pre-fire vegetation class separately. It would also be important to determine at which spatial scale these thresholds may apply, e.g., at the fire or the landscape scale (i.e., multiple fires over a territory). These thresholds may also be adjustable depending on ecological issues within different territories (for ex., minimizing impacts of salvage logging on tree regeneration and/or saproxylic insect biodiversity). The spatial configuration of residual unsalvaged forests should also be considered when planning salvage operations. It has been argued that residual

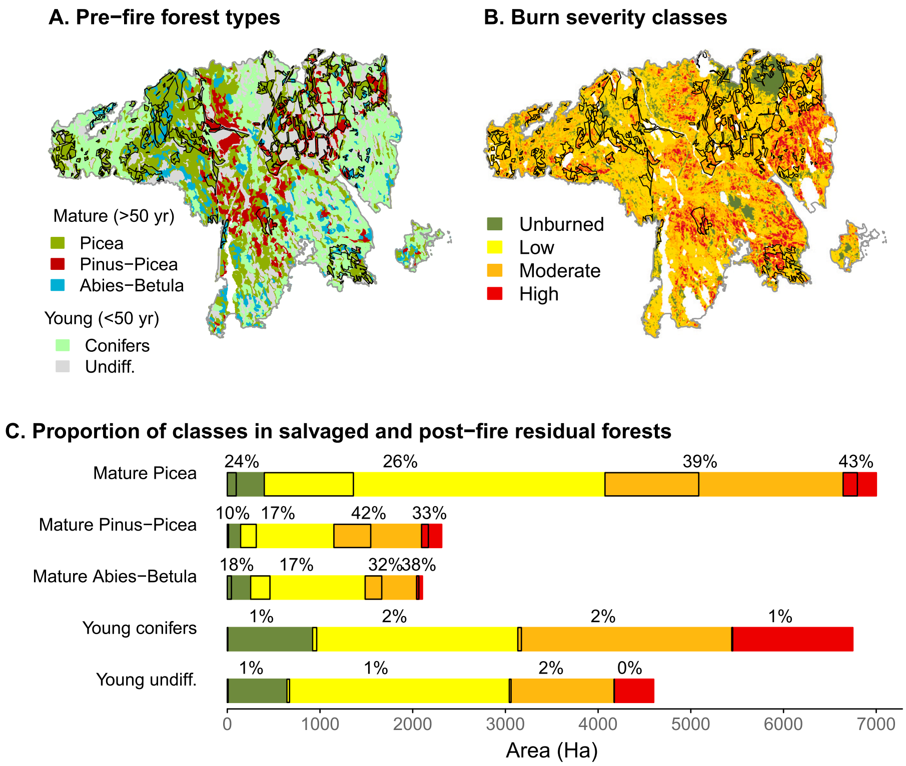

Fig. 5. Case study analysis with salvage logging: using burn severity maps to assess if the residual forest (i.e., unsalvaged forests) is representative of the initial spatial variability in burn severity and pre-fire vegetation. A) Pre-fire forest types obtained by classification of stand ages and composition (see Fig. S4 for details). B) Burn severity class map derived from CBI predictions with Landsat-based dNBR and saturated growth model. C) Area represented by all possible combinations of pre-fire vegetation and burn severity classes. Salvage-logged areas are shown with black contours on maps A and B, and their fractions in ha are also shown with black outlines in histograms C. Values shown in C indicate the percentage that has been salvaged (according to the total of each pre-fire vegetation and burn severity class separately).

forests should form large patches at the landscape level (Nappi et al., 2010; Nappi and Drapeau, 2011) and small patches and individual trees at the stand levels (Azeria et al., 2012; Boucher et al., 2016). The satellite-derived burn severity maps have a medium spatial resolution (30 to 10 m), allowing us to assess spatially specific metrics, thus ensuring that planned salvaged areas comply with such rules.

5. Conclusions

Our results demonstrate that it is possible to rapidly (~15 to 65 days) produce burn severity maps after fire using free moderate-resolution satellite imagery (J. Boucher et al., 2017; Miller and Quayle, 2015; Quintano et al., 2018; Reiner et al., 2022). Based on the largest field-based burn severity estimation (CBI) dataset in eastern Canada, our simple model equations can produce reliable and ecologically meaningful burn severity assessments for forests with similar characteristics to our study area. Such maps can be a decisive tool for many post-fire forest management operations, including the planning of salvage logging, as illustrated by our case study. The ability of governmental agencies and industries to produce such maps with free and easily accessible data will become critical in the context of climate change or under extreme conditions such as the record burned areas of the 2023 fire season (~1.5 Mha in Quebec's managed forests only), which could occur more and more frequently in the future (Barnes et al., 2023). We thus recommend that governmental agencies in charge of forest management systematically produce such rapid post-fire assessments to make them available to forest managers as quickly as possible. In this direction, government agencies worldwide involved in the management of public forested lands could draw inspiration from the USDA Forest Service RAVG program (*Rapid Assessment of Vegetation Condition after Wildfire*; Miller and Quayle, 2015; Reiner et al., 2022). In the case of salvage logging, forest managers should then combine burn severity maps with pre-fire forest characteristics (i.e., forest age and composition) and ensure that salvage logging leaves a significant proportion of residual unsalvaged forests that are representative of the spatial variability in burn severity and pre-fire vegetation. We advocate for implementing this approach across all eastern North American boreal forests to make salvage logging more ecologically sustainable. More generally, the rapid mapping of burn severity after a forest fire event will offer many other applications (e.g., regeneration failure assessment, wildlife habitat) for managing recently burned forests.

CRediT authorship contribution statement

Beaudoin Milène: Data curation, Methodology, Writing – review & editing. **Bonfils Djoan:** Data curation, Formal analysis, Methodology. **Bourdon Jean-François:** Data curation, Methodology, Writing – review & editing. **Boucher Jonathan:** Data curation, Methodology, Writing – review & editing. **Fournier Richard:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Waldron Kaysandra:** Writing – review & editing. **Guindon Luc:** Methodology, Writing – review & editing. **Rossi Sergio:** Conceptualization, Funding acquisition, Writing – review & editing. **Ibarzabal Jacques:** Conceptualization, Funding acquisition, Writing – review & editing. **Smetanka Charlotte:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology. **Boucher Yan:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing. **Danneyrolles Victor:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare no competing interests.

Acknowledgments

This project was founded by a NSERC RDC grant, la Direction de la recherche forestière du Gouvernement du Québec (project #142332132 to Y. Boucher) and a research grant from the Observatoire Regional de Recherche sur la Forêt Boréale (UQAC) to Y. Boucher. We especially thank Hugo Tremblay, Simon Marcouiller (MFFP) and their “fire team” for contributing to field data acquisition. We also thank Stelsa Fortin for providing feedback on a previous version of the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.121756.

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