Burnt area mapping across Canada's boreal forest zone using SPOT VEGETATION calibrated with Landsat TM imagery

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1. Introduction

Wildfires are a major source of disturbance to the boreal forest ecosystem as they have been documented to burn as much as 1.5 percent (22 million ha) of its global area in a single year (Cofer et al., 1996). Fires in this ecosystem typically kill the standing trees and thus exert a dominant control on landscape level patterns of forest succession and stand age distribution (Johnson, 1992). Fire is an important factor modifying the carbon budget within the boreal zone, which covers less than 17% of the Earth's surface area, yet accounts for more than 30% of its carbon storage (Kasischke, 2000). Carbon storage is directly modified by fire owing to the combustion of forest and ground layer biomass into atmospheric carbon (CO2, CH4, CO). It is also indirectly modified due to shifts in stand age distribution and increased ground layer decomposition rates following fire (Kasischke, 2000). To assess these ecological and carbon budget impacts, a fundamental parameter that must be measured is the affected burnt area. This requires a method to map the spatial distribution of burnt forest over vast, remote areas in an accurate, consistent, and timely manner.

Coarse resolution (≈1 km) satellite sensors, notably the AVHRR aboard the NOAA polar orbiters, have proven to be effective for detecting active boreal fires (Flannigan and Vonder Harr, 1986; Li et al., 2000) and mapping the extent of burnt areas after fire (Cahoon et al., 1994; Kasischke and French, 1995, Fraser et al., 2000a). Such sensors are well suited to mapping boreal fires for several reasons: (1) they provide inexpensive, daily coverage of the global boreal zone; (2) more than 97% of the burnt area is caused by fire events >10 km2, a size that is larger than sensor resolution; and (3) most burning involves crown fires that destroy the forest canopy, producing a large and immediate change in reflectance that can be easily identified. However, for satellite-based burnt area mapping at continental scales to be more robust, accurate, and widely adopted, two important issues need to be addressed. First, the remote sensing burnt area products must be validated using the best available benchmark. Second, any systematic bias in burnt area estimation must be identified and accounted for through calibration or other means. When mapping burnt areas with coarse resolution sensors, an overestimation, or positive bias, may occur due to spatial aggregation effects where unburnt patches smaller than the sensor resolution are mapped as burnt (Eva and Lambin, 1998). The objective of this study was to address these validation and aggregation issues as they related to an application of SPOT VEGETATION (VGT) imagery for Canada-wide analysis of burnt forest area. There were three major components:

1. Annual mapping of 1998 and 1999 burnt forest across Canada using coarse resolution VGT imagery;
2. Mapping a representative sample of these burns using higher resolution Landsat TM imagery; and
3. Comparing the coarse and medium resolution burnt area estimates from this double sampling approach to conduct a validation and statistical calibration of the coarse resolution product.

2. Methods

Mapping of burnt boreal forest across Canada for 1998 and 1999 was performed using a hybrid technique developed for annual, coarse resolution mapping of burnt forest canopy (Fraser et al., 2000a). The method, dubbed Hotspot and NDVI Differencing Synergy (HANDS), combines active fire monitoring with multi-temporal change detection. Change detection and identification of new burnt areas were accomplished by differencing of a pair of post-fire season vegetation indices derived from anniversary date composite imagery. The locations of actively burning fires, detected with daily satellite imagery, were used to derive a spatially adaptive, statistical threshold for differencing and separating burnt areas. In this study, annual masks of 1998 and 1999 fire locations were created by compositing daily fire masks produced from NOAA/AVHRR imagery (Li et al., 2000) as part of the Fire M3 project http://fms.nofc.cfs.nrcan.gc.ca/FireM3/. The differencing component was accomplished using a vegetation index (VI) derived from SPOT VGT that provided optimal discrimination of burnt boreal forest based on the normalized difference between NIR and SWIR reflectance (Fraser et al., 2000b). The VI was computed from cloud free, 30-day VGT composites that were corrected for atmospheric, BRDF, and cloud contamination effects (Cihlar et al., 1997). The 1999 burnt area mapping involved differencing of September 1998 and 1999 post-fire season composites. For 1998 mapping, differencing was performed on composite VIs from May 1998 and September 1998 (VGT became operational in April 1998, precluding the use of an anniversary date composite from September, 1997).

To provide a basis for validating and calibrating the coarse resolution burnt area maps, a sample of 173 fires from 1998-1999 was mapped at a 30-m resolution using 56 Landsat TM/ETM+ scenes (Fig. 1). Selection of the cloud-free TM scenes was optimized to reflect a wide distribution of Canadian terrestrial ecozones, fuel types, and fire sizes >200 ha, while maximizing the number of burns contained within a scene.

The algorithm used for TM-based burnt area mapping was originally designed and tested for use in post-fire timber salvage planning by the forest products industry. As such, it was optimized to map forested areas where >50% was burnt by crown fire, which represents the highest priority area for salvage logging. Unlike the HANDS technique, the algorithm requires only a single post-burn Landsat TM/ETM+ scene acquired in the same year of the fire. In an iterative process, potential new burnt areas are identified using a first approximation statistical threshold applied to a VI from TM that combines the NIR and SWIR channels. These pixels are buffered and clustered into discrete fire events, then each cluster is individually refined based on its unique signature. The final thresholds are thus self-adaptive to local variation in burn reflectance due to varying vegetation cover and fire severity within a TM scene. Validation of the technique was performed over a 65,000 ha burn using 1:20,000 colour-infrared aerial photographs. The burnt area derived using the Landsat TM technique agreed with the CIR maps to within 6 percent for complete burns.

A database was constructed for the 173 fires mapped from TM that included attributes for TM burnt area (ha), VGT burnt area (ha), fuel type, terrestrial ecozone, spatial fragmentation (VGT burn perimeter/√area), and spectral fragmentation (std. deviation of VGT VI). Fuel type and terrestrial ecozone were examined as potential stratifying variables, while the two fragmentation metrics were used to test the hypothesis that the relationship between coarse and fine resolution burnt area (i.e., aggregation bias) varies with degree of burn fragmentation (e.g. Mayaux and Lambin, 1997). Simple and multiple regression analysis based on the 173 fires were used to develop calibration models to predict TM burnt area ('true' crown fire burnt area) based on VGT burnt area and the fragmentation metrics. The accuracy of both the uncalibrated and calibrated VGT maps was assessed by comparing total burnt area and RMS error {Σ(observed TM area – pred. TM area)2 / (n-2)]0.5} for the 173 fires.

3. Results and Discussions

The total burnt area of the 173 sample fires was 1,614,410 ha (9,332 ha mean area) from VGT, compared to 942,183 ha (5,446 ha mean area) from TM, a size that represents approximately 15% of the forest area burnt in Canada between 1998-1999 (CIFFC 1998, 1999). The VGT burnt area product thus overestimates the 'true' crown fire burnt area as estimated from TM by 71% on average. Figure 2 shows a comparison of the VGT and TM burnt area for a typical sample fire in which the VGT burnt area estimate is 67% larger than that from TM. Examination of the VGT and TM mapped areas suggests that this bias was mainly attributable to spatial aggregation effects, where the effective resolution of the composited VGT imagery was too coarse to identify islands of unburnt tree crowns contained within the outer burn boundary.

The VGT and TM burnt areas were linearly associated and highly correlated (r=0.96, p=<0.0001; Fig. 3). Based on this result, a linear regression model was considered appropriate to calibrate VGT burn areas. The regression calibration model explained a large proportion of the variation in TM area (R2=0.94, p<0.0001) and produced a standard error of 2,846 ha. None of the other variables examined (spatial and spectral fragmentation, ecozone) was helpful in improving the calibration model for coarse resolution burnt area. Total burnt area for the 173 sample fires after applying the linear calibration equation to VGT is 921,785 ha, which is, as expected, very similar to that derived from TM (942,183 ha).

This analysis demonstrates that spatial aggregation is a significant source of bias in mapping burnt areas in the boreal forest using coarse resolution imagery, such as that provided by VGT. Fortunately, a simple linear calibration model based on a double sampling approach with Landsat TM has been shown effective in removing this bias. Future work will be aimed at investigating the source of the residual differences between VGT and TM burnt area, developing a calibration model for NOAA/AVHRR to enable accurate historical burnt area mapping, and expanding the fire database for use in testing and improving the calibration function.

4. References

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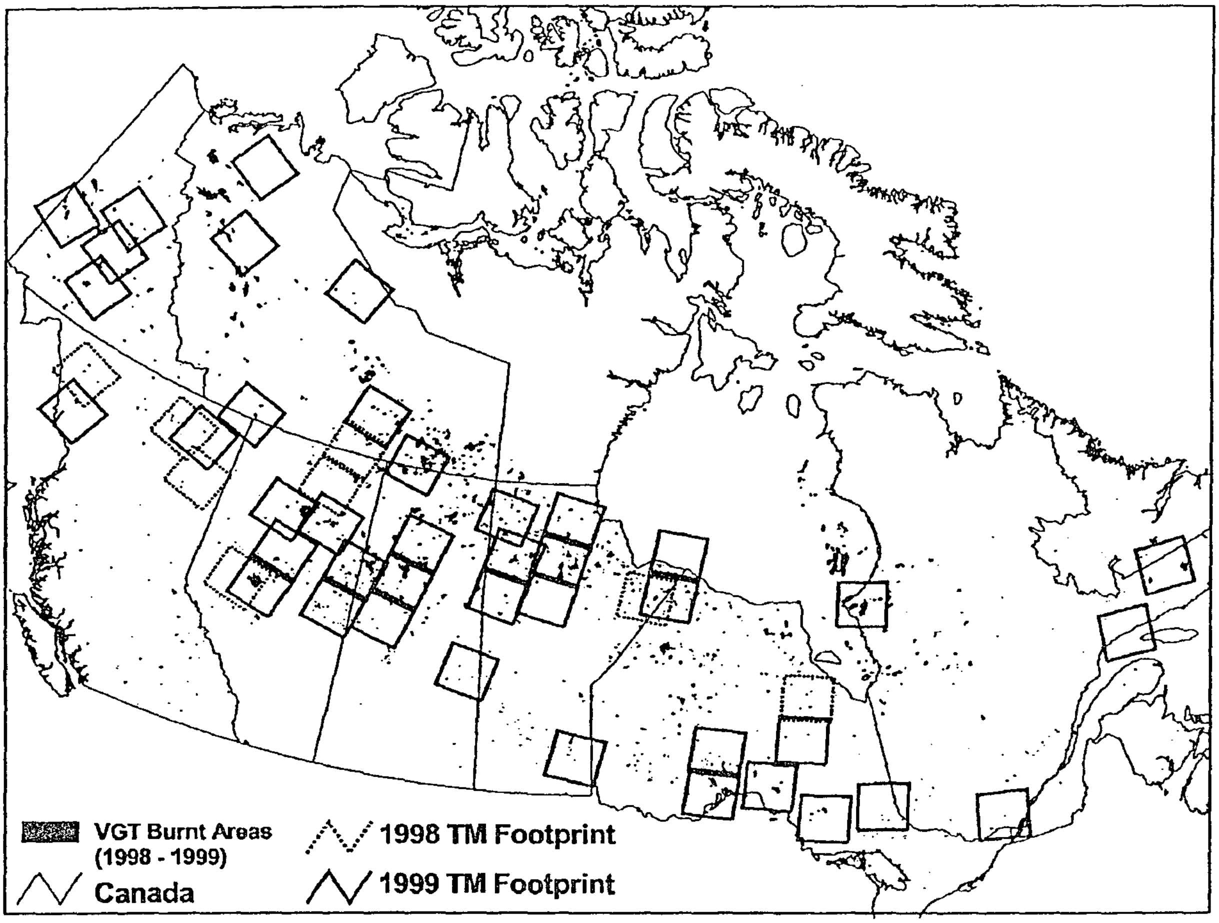

Figure 1. 1998-1999 forest burnt areas in Canada mapped using SPOT VGT (solid fill) and the footprints from the 56 Landsat TM/ETM+ scenes that were used to validate and calibrate the coarse resolution burnt area estimates.

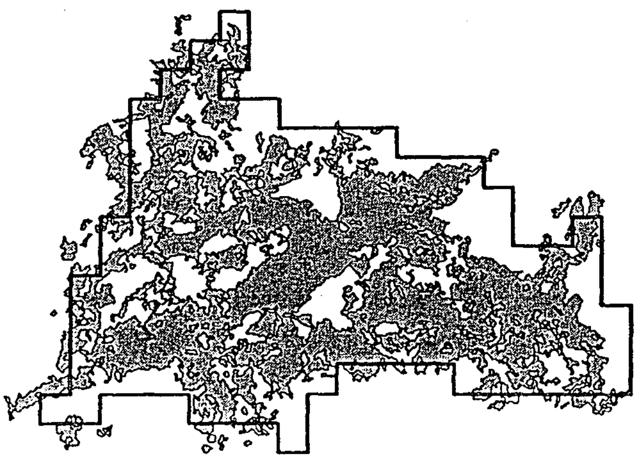

Figure 2. Burnt area derived from SPOT VGT (15,400 ha; thicker outer boundary) and Landsat TM (9,227 ha; shaded area) for a sample fire in Manitoba.

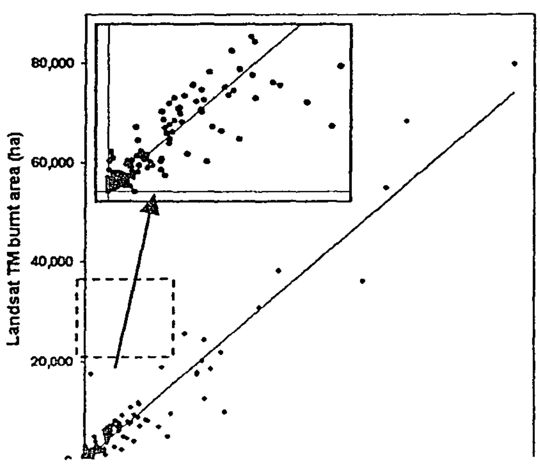

Figure 3. Relationship and regression line for VGT and TM burnt area for the 173 sample fires. The inset is used to clearly show the distribution of burnt area for smaller fires (i.e. <12,000 ha TM and <30,000 ha VGT).

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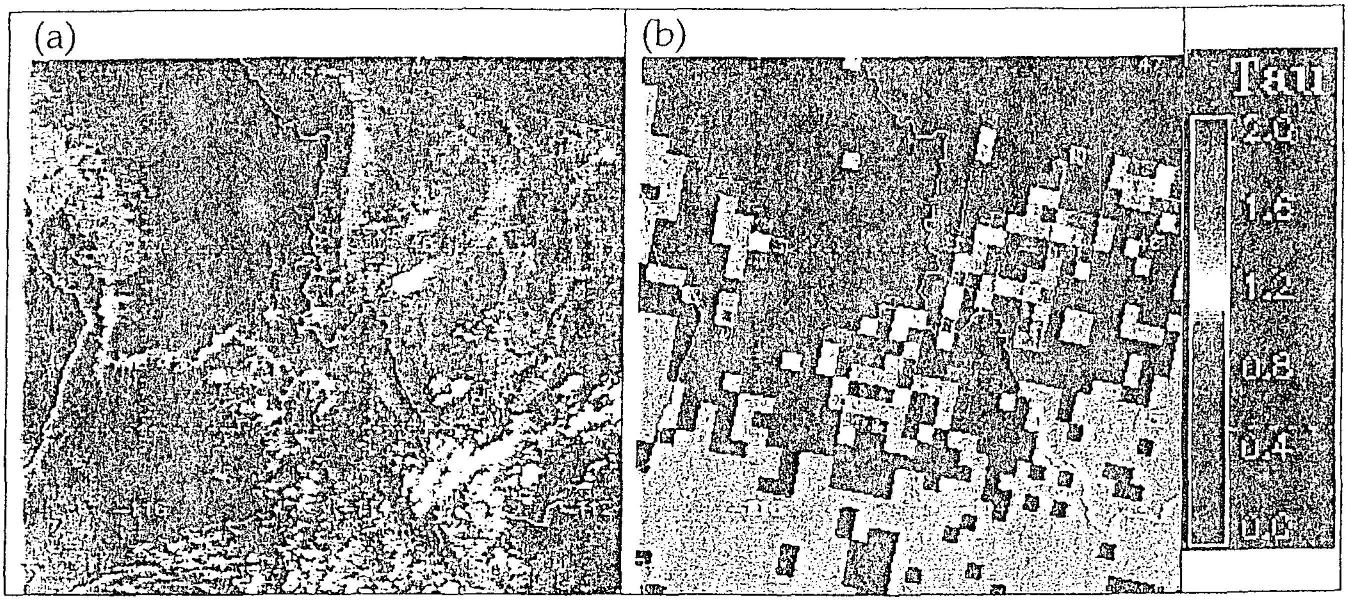

New methods and sensors

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Front cover: MODIS image of Wildfires in Montana and Idaho, Aug. 26, 2000: (a) color composite of the smoke and fires, red dots are fires detected by the MODIS 3.9 μm channel and the smoke is the observed as a composite of the MODIS blue, green and red channels. Burn scars are dark. (b) The smoke optical thickness derived from the MODIS data. The optical thickness is derived on resolution of 10 km, giving it the discontinued look. The color bar of the optical thickness is given on the right. (From Kaufman et al., this volume).