Multi-temporal burned area mapping using logistic regression analysis and change metrics

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Abstract- **This paper describes a procedure developed for continental-scale mapping of burned boreal forest at 10-day intervals. The basis of the technique is a multiple logistic regression model applied to 1 km SPOT VEGETATION (VGT) clear-sky composites. Independent variables consist of multi-temporal change metrics representing 10-day and surrounding 30-day changes in reflectance and in two vegetation indices. The metrics account for seasonal phenological variation by normalizing them to the reflectance trajectory of background vegetation. Three spatial-contextual tests are applied to the per-pixel logistic model output to remove false burned pixels and increase the sensitivity of detection. The procedure was tested over Canada using conventional fire surveys and burned area statistics from the 1998-2000 fire seasons. The area of falsely mapped burns was small (2% commission error over two provinces), and most burns larger than 10 km^2 were accurately detected and mapped ($R^2 = 0.90$, $P<0.005$, $n = 91$). National-level VGT burned areas for 1998-2000 were within 3-17% of fire management agency burned area compiled by the Canadian Interagency Forest Fire Centre (CIFFC).**

I. INTRODUCTION

Biomass burning causes a wide range of global environmental impacts by modifying the land/atmosphere carbon balance, changing the Earth's albedo, and releasing aerosols that affect climate and radiation budget [1]. Fires also have direct effects on human populations due to episodic smoke pollution and the loss of valuable forest resources.

The Joint Research Centre of the European Commission is leading an international initiative aimed at producing spatially explicit, global burned area maps from satellite remote sensing. The Global Burned Area 2000 (GBA 2000) project involves a collaboration of eight research institutes that have developed regional algorithms to map monthly burned areas in 2000 using SPOT VEGETATION (VGT) imagery. The 1 km resolution burned area products are targeted mainly at the scientific community for global change modeling related to fire emissions, terrestrial carbon budget, and land cover. This paper describes the development and validation of a GBA 2000 algorithm designed for 10-day mapping of burned boreal forest in Canada.

II. MODEL DEVELOPMENT

The burned area mapping procedure was developed using 1998 VGT data and training pixels across Canada representing forest that burned during that year (n=2504) and forest types not subjected to burning (n=2821). A wide range of forested pixels not subject to burning in 1998 was selected, including coniferous, deciduous, mixed coniferous-deciduous, northern transitional, and previously burned forest. This selection would ensure that the algorithm would perform well when applied to all forested areas in Canada.

Logistic regression was used as the basis for the multi-temporal burned area algorithm, as it is suitable for classifying the state of a dichotomous variable based on multiple explanatory variables. In this application, a multiple logistic regression model was derived to classify the burned (value=1) and unburned (value=0) training pixels. Candidate predictor variables consisted of multi-temporal change metrics and single-date reflectance values derived from the VGT composites for the period April 21-October 10, 1998. The change metrics were defined by 10- and 30-day changes in reflectance (red, NIR, and SWIR channels) and in two vegetation indices (VI): NDVI and an analogous SWIR based VI (SWVI) that is sensitive to boreal burns [2]. The 10-day changes were computed by differencing a pixel's reflectance or VI value from two consecutive 10-day composites. 30-day metrics were based on the cumulative 30-day change surrounding each 10-day change. The addition of a 30-day change metric may aid in identifying false burn signals (e.g. cloud shadow) flagged by a 10-day change, as such pixels are unlikely to also have a large corresponding 30-day reflectance drop.

Two special features of the change metrics were considered for their calculation. First, each pixel's 10- and 30-day change was normalized to the reflectance trajectory of similar background vegetation. This normalization accounted for reflectance changes attributable to seasonal vegetation phenology. Such an adjustment is especially critical during the fall senescence period when decreasing NIR reflectance of boreal forest understory vegetation may cause multi-temporal algorithms to produce false burns.

A second feature applied to the change metrics is that any pixels in the nominally clear 10-day composites contaminated by snow or atmosphere are skipped. In our algorithm development and application using 1998-2000 VGT data, pixels were flagged as contaminated if red reflectance was greater than three standard deviations from the mean growing season (July-August) reflectance of their respective background vegetation groupings.

A multiple logistic regression model combining the 20 candidate variables was developed using backward stepwise elimination. Beginning with all 20 variables, the variable with highest standard error was manually removed at each step until only one variable remained. The criteria used to select the "best" overall model from the set of models containing between 1-20 variables were the explanatory power of the various models measured from McFadden's Rho-squared statistic (analogous to the R^2 coefficient), balanced by the computational demand required by a model with many parameters. Based on this trade-off, the stepwise model containing four variables was chosen, which included two 10-day and two 30-day change metrics (Rho-squared=0.77; $p < 0.005$).

$$p(\text{burned}) = 1 / [1 + \text{EXP} -(4.7 + 0.216\times\delta\text{SWVI}_{10} + 0.033\times\delta\text{SWIR}_{10} + 0.217\times\delta\text{NDVI}_{30} + 0.072\times\delta\text{Red}_{30})] \qquad (1)$$

Where:

p(burned) = probability of a pixel being burned during a 10-day interval

δSWVI_{10} = normalized 10-day change in a short-wave based vegetation index (SWVI) computed as [(NIR-SWIR)/(NIR+SWIR)]×100

δSWIR_{10} = normalized 10-day change in SWIR reflectance (scaled 0-2000)

δNDVI_{30} = normalized 30-day change in NDVI surrounding the current 10-day interval (i.e. $\delta\text{NDVI10}_{t-1} + \delta\text{NDVI10}_{t} + \delta\text{NDVI10}_{t+1}$)

δRed_{30} = normalized 30-day change in Red reflectance (scaled 0-2000)

The multiple logistic model was applied across Canada to the time series of VGT composites from the 1998 training year. The maximum probability produced by the model for all 10-day periods was selected to produce an annual probability of burning map shown in Fig. 1. A separate output channel was used to record the 10-day time period during which the highest probability occurred. This probabilistic or "soft" output provided by logistic regression is more flexible compared to a traditional "hard" change detection approach in that it provides a confidence level for the change product [3].

To derive a binary burned area mask from the logistic regression output, a cut-off probability threshold must be specified. In logistic modeling applications, a 0.5 threshold is To derive a binary burned area mask from the logistic regression output, a cut-off probability threshold must be specified. In logistic modeling applications, a 0.5 threshold is often adopted under the assumption that this will provide an ideal balance between omission (missed burns) and commission (false burns) error. For this application, the decision threshold was optimized using accuracy assessment curves that plot errors of commission and omission over a range of probabilities (Fig. 2). A 0.97 threshold was predicted to balance the area of missed burned pixels and false burned pixels at a national scale.

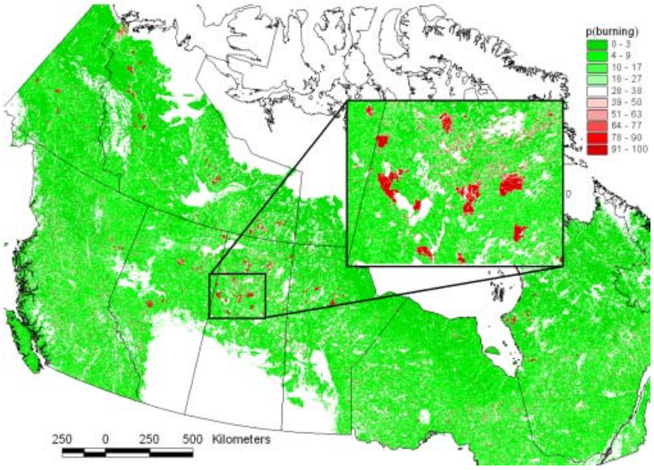

Fig. 1. Maximum probability (scaled from 0-100) of burning from the multiple logistic regression model applied to all 10-day periods in 1998.

Although the conservative 0.97 probability threshold was able to reliably identify most burn *events*, it did cause underestimation of their areas by about 34%. We also noted that the burn mask contained significant salt-and-pepper noise from burn clusters composed of just one or a few pixels. To remedy these limitations in the pixel-based regression model that exploits reflectance information only, a series of spatial-contextual tests was developed. The three tests were designed to decrease noise and increase the sensitivity of detection by means of a spatial contraction and expansion of the logistic burned area mask.

1. Eliminate contiguous burned area clusters that are composed of fewer than six pixels.
2. Use the remaining filtered high-probability pixels as "seeds" from which the burns are iteratively grown to lower probability pixels having a probability of 0.35 or higher.
3. Remove any grown burned area patch this is composed of fewer than 15% high probability pixels. This test is effective in removing false burns in a few cases where a small cluster of non-burned pixels with high probability grew over a large area of medium probability pixels.

III. APPLICATION OF MODEL

The above procedure was applied to Canada for the 1998-2000 forest fire seasons using a GIS macro that (1) calculates a logistic probability for each 10-day time

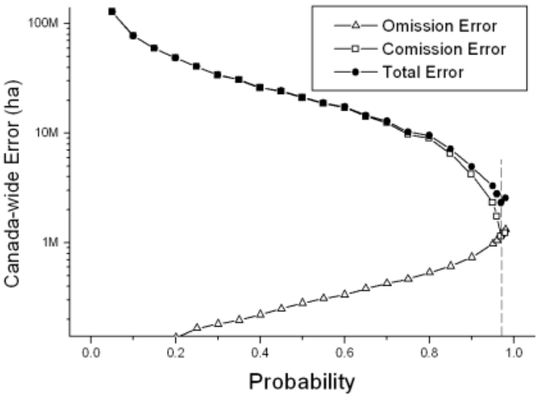

Fig. 2. Accuracy assessment curves showing the predicted national-level *area* of various errors over a range of probabilities from the logistic model.

period; (2) selects the highest annual probability for each pixel; and (3) applies the spatial/contextual tests. The resulting VGT product provided similar, but smaller national level burned areas by comparison to official statistics compiled by CIFFC. Burned area for 1998-2000 was 3,900,100 ha, 1,425,800 ha, and 631,100 ha, which was respectively 17.2%, 16.4%, and 2.5% smaller than conventional estimates.

A regional-level comparison of burned area by province/territory is presented for 1998 (Fig. 3). Note that, three provinces not shown in the graphs (NS, NB, and PEI) all had CIFFC burned areas smaller than 2000 ha and no VGT-mapped burns. Over the three years, most of the province-level VGT burned areas compare reasonably well to the official estimates from fire management agencies, with burned area being typically underestimated as in the national-level statistics.

Falsely mapped fires were identified at a national scale for the three years by comparing the 431 VGT-mapped burns against September VGT composite images before and after each fire season, and the location of active fires identified using daily NOAA-AVHRR imagery. There was no evidence of fire activity for 60 of the satellite-mapped burns, representing a commission error of 0.28% for 1998 (4 clusters covering 10,800 ha), 5.5% for 1999 (22 clusters and 78,100 ha), and 19.2% for 2000 (34 clusters and 121,300 ha).

A more detailed assessment of the satellite burned area product was performed using burned area surveys produced using GPS and photo-interpretation by fire management agencies in Alberta and Saskatchewan. The total 1999-2000 Alberta and 1998-1999 Saskatchewan burned area surveys cover 1.74 million ha, or 25% of the 1998-2000 national burned area. The VGT product by comparison mapped 1.65 million ha as burned over these provinces during the same periods, of which 31,300 ha was not associated with real fires, representing a commission error of 2%.

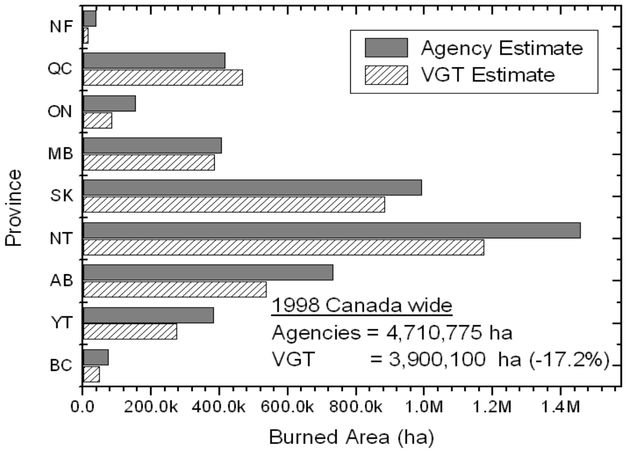

Fig. 3. Bar graphs comparing 1998 burned area by province based on official fire management agency statistics and the VGT-based mapping algorithm.

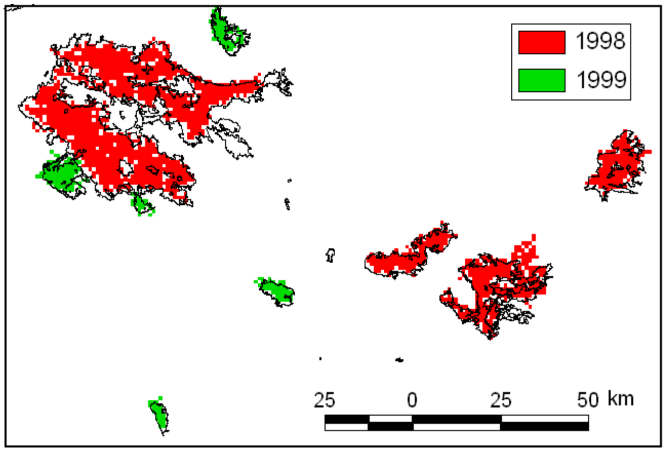

Fig. 4. VGT burned area masks (1998 = red, 1999 = green) for a region in Alberta subject to a range of fire sizes. Burn surveys produced by Alberta Environment are shown outlined in black.

The VGT algorithm did not map 496 of the 587 fires in the two provinces; however, these fires were mostly small and together comprise only 198,912, or 11.4%, of the 1.74 million ha of burned forest. The relationship between the individual burned areas from the fire agency surveys and satellite algorithm is strong ($R^2 = 0.84$, $p < 0.005$, n=587), with better mapping accuracy observed for fires larger than about 1,000 ha. Fig. 4 illustrates the above statistical results in a comparison of the VGT mask and fire surveys for a region in Alberta.

IV. CONCLUSIONS

Logistic regression is an effective tool for burned area mapping, since it can be used to identify an optimal combination of metrics for change detection. It also produces an output that represents probability of burning, to which an optimal cut-off probability level can be applied to achieve the desired balance between omission and commission error. The 10-day VGT burned area algorithm described in this paper produces relatively few false detections, but this occurs at the expense of missing most burns that are smaller than 10 km^2. However, in boreal environments, such burns contribute little to the total burned area.

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