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Fire mapping in a northern boreal forest: assessing AVHRR/NDVI methods of change detection

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Abstract

Understanding natural fire regimes is crucial to developing harvesting scenarios and conducting sustainable resource management in the boreal forest. To gain this understanding, resource professionals need efficient and cost-effective data collection methods that can operate over vast and isolated landscapes. We compared three Advanced Very High Resolution Radiometer (AVHRR)/Normalized Difference Vegetation Index (NDVI) methods of fire detection and mapping for a case study in northern Ontario, Canada, of the 1992, 1993, and 1995 fire seasons. Fire mapping accuracy was assessed by the spatial coincidence between mapped fires and ground-truthed information using a decision-tree approach and by testing the hypothesis that various calculated accuracy components were equal within an ANOVA design. Ground-truthed fire sizes and shapes were correlated with the AVHRR/NDVI-mapped areas; however, light cloud contamination increased false detection of fires due to NDVI suppression. The multiple threshold technique of change detection provided better estimates of fire areas than did single threshold methods.

Keywords: Fire; Boreal forests; AVHRR; Accuracy assessment

1. Introduction

Sustainable forest management in the boreal forest requires that harvesting practices emulate natural fire disturbances (OMNR, 1994). Understanding natural fire regimes, including parameters of fire sizes, distributions, and counts, may simplify this requirement for managed terrestrial landscapes. Furthermore, fire regime data can be applied towards studies of carbon release/sequestering (Lund and Iremonger, 2000), modelling atmospheric emissions (Burke et al., 1997), monitoring climate change (Flannigan and Van Wagner, 1991), validating fire models (Li et al., 1997), and vegetation transition studies (Yemshanov and Perera, 1999).

In Ontario, the area north of 51° latitude (Fig. 1) is the least managed with respect to fire control (Martell and Boychuk, 1997). Thus, this 43-million hectare area provides a unique opportunity to study northern boreal forests under a natural fire regime, where more than three million hectares have burned during the past 50 years.

In the past, forest fire-mapping efforts involved field (Gillis and Leckie, 1996) or aerial surveys, and disturbance patches were manually sketched onto forest and highway maps (Williams, 1953). The current

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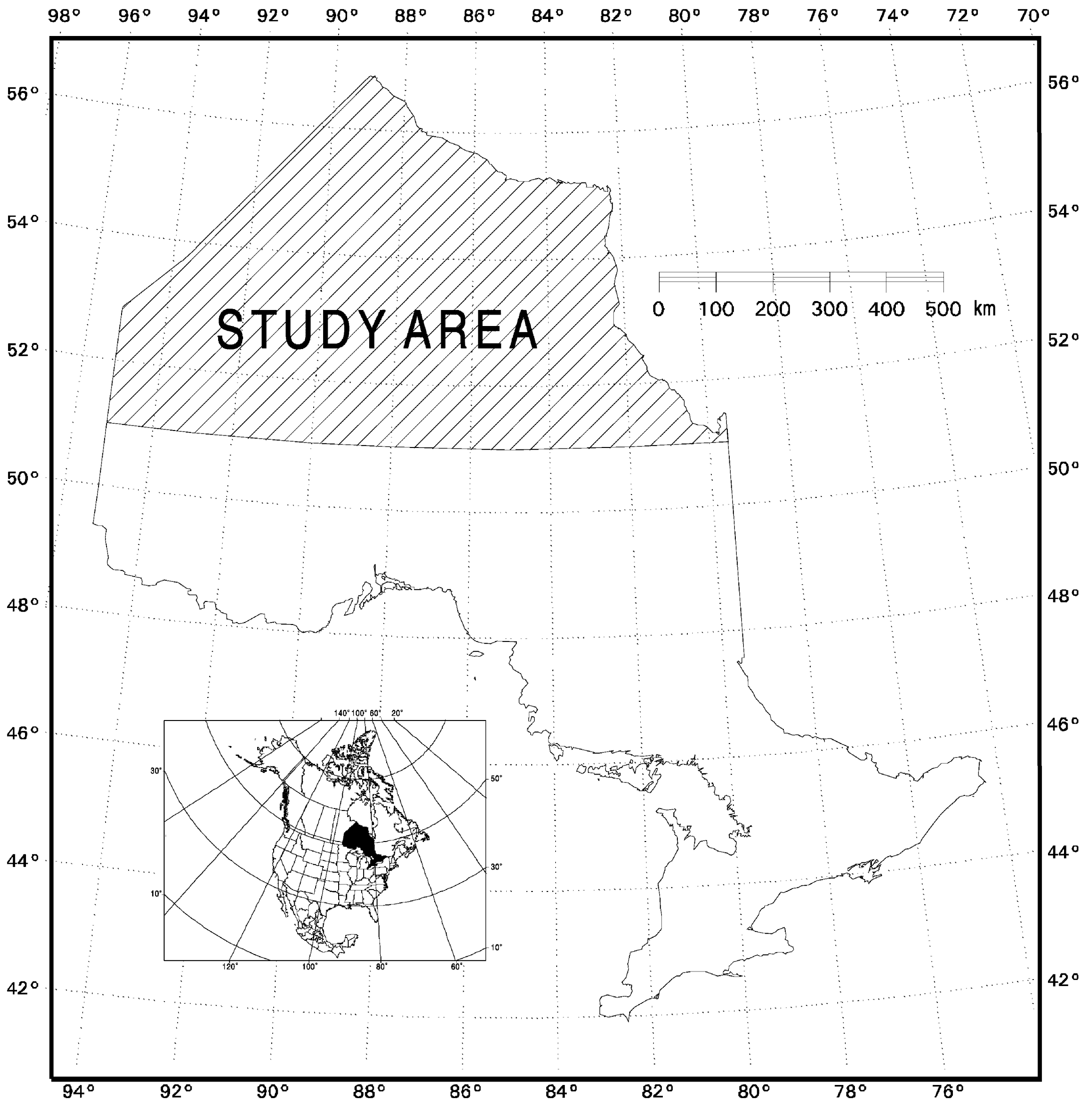

Fig. 1. Location of study area in Ontario, Canada.

forest resources mapping standard in Canada is based on aerial-photograph interpretation (Madill and Aldred, 1977; Gillis and Leckie, 1993). The most modern mapping methods use helicopters and field crews outfitted with global positioning system (GPS) units to trace disturbance perimeters (Gillis and Leckie, 1996). However, in relatively isolated and inaccessible far northern Ontario, this method may not be the most economical approach to fire mapping.

The 1972 launch of the first Landsat satellite provided a means of detecting forest change (disturbances) from space (Iverson et al., 1989). Since then, thermal and middle infrared imagery have been used in several active-fire detection and mapping studies (Matson et al., 1987; Pereira and Setzer, 1993; Pozo et al., 1997), allowing the drastic thermal gradients between fires and unburned areas to be detected. However, post-fire disturbance patch detection provides another alternative to field and aerial methods, often relying on vegetation change mapping.

Vegetation change methods are based on the premise that when foliage containing chlorophyll is destroyed, the (red)/(near infrared) reflectance ratio for green vegetation changes. Thus, a vegetation index that is sensitive to the red (R) and near infrared (NIR) regions of the electromagnetic spectrum can be used to quantify vegetation change (Horler et al., 1983). Calculated vegetation indices, such as the normalized difference vegetation index (NDVI), have been used for post-fire disturbance mapping in boreal forests (Kasischke et al., 1993; Kasischke and French, 1995; French et al., 1995; Kasischke and French, 1997).

The NDVI (Rouse et al., 1973) is commonly calculated from R and NIR channels of the advanced very high resolution radiometer (AVHRR). Significant NDVI declines have been associated with vegetation disturbance patterns (Nemani and Running, 1997), including wildfires. In Alaska, NDVI decline thresholds have been established for determining whether vegetation greenness has decreased sufficiently to be considered a fire disturbance (Kasischke et al., 1993; Kasischke and French, 1995).

In extensive, inaccessible, and unmanaged territories such as Ontario's far north, fire mapping has been conducted with coarse-resolution AVHRR imagery (Martín and Chuvieco, 1995; Cahoon et al., 1996). The AVHRR data format reduces data volume, analysis time, the number of required images, and the costs involved with obtaining, edge matching, and interpreting data, as compared with Landsat, Spot or comparable satellite platforms (Roller and Colwell, 1986; Teuber, 1990). Imagery from the AVHRR sensor (Rao, 1987; Kidwell, 1991) is easily accessible and costs only US\$ 0.0001 km^{-2} (Lunetta and Elvidge, 1998).

1.1. Goal and objectives

The goal of this study was to compare the spatial coincidence between fires mapped with the various NDVI change-detection methods established by Kasischke et al. (1993) and Kasischke and French (1995) with the ground-truthed data. The methods were used to map post-fire disturbance patches north of 51° latitude in Ontario for the 1992, 1993, and 1995 fire seasons. This goal led to three objectives:

1. To compare the general shapes and spatial relationships between ground-truthed and AVHRR/NDVI-mapped fire disturbances.
2. To detect any differences among the existing AVHRR/NDVI methods of fire disturbance mapping.
3. To determine whether existing AVHRR/NDVI methods of fire disturbance mapping have comparable accuracy in northern Ontario.

2. Methods

2.1. Data processing

Relatively cloud-free images were acquired early and late during each fire season studied, and these images were normalized to each other using an offset value (Kasischke and French, 1995). The AVHRR/NDVI values (−1.0 to +1.0) were represented by pixel values ranging from 10 to 210 on 1063 m × 1063 m spatial resolution, 10-day maximum value composite AVHRR imagery (Eidenshink and Faundeen, 1994). Three different threshold methods were applied to these images in separate treatments (Table 1).

In each treatment, the pixel values of the late image were subtracted from those of the early image, quantifying the NDVI change. Resulting values exceeding the threshold were coded as fires; the rest of the image was coded as background. Mapped fires smaller than 678 ha (six contiguous pixels) were considered noise and eliminated from analysis. To combine two threshold results for the lenient method, we retained only those pixels indicating fires from the 18 threshold that were within three pixels of fires identified by the 23 threshold.

Table 1
Thresholds used for fire mapping

Method	Description	Reference
Strict	24 scaled NDVI units	Kasischke et al. (1993)
Intermediate	23 scaled NDVI units	Kasischke et al. (1993)
Lenient	23 and 18 scaled NDVI units	Kasischke and French (1995)

The mapped fire images were re-sampled to 531.5 m resolution and geo-corrected to match the projection of the binary GIS ground-truthed data. The increased resolution ensured a smoother fire boundary following the second-order geo-correction with nearest neighbour re-sampling (ERDAS, 1997). Twenty-one ground control points were selected along distinctive hydrological features (e.g. shorelines, islands, rivers, and coastlines), yielding an acceptable root mean square (RMS) error of approximately 400 m (Martín and Chuvieco, 1995; Lunetta and Elvidge, 1998).

A comprehensive binary GIS database of fire patterns was used to ground-truth the AVHRR/NDVI-mapped fires as was done in Spain by Fernández et al. (1997). The database contained dates and locations of fires in Ontario for the study period and was compiled from hardcopy maps derived from field data, aerial photographs, and interpretation of Landsat images (Perera et al., 1998). The fire polygons in this database often abutted or were adjacent to other polygons, forming clusters; thus, all polygons within 1063 m (one AVHRR pixel dimension) of each other were coded to indicate membership to a common ground-truthed fire event (herein referred to as a single ground-truth fire). To remove effects of varying delineation scale among ground-truth fires, the truth database was rasterized to the same resolution as the mapped fires (531.5 m) and converted back to vector format, allowing direct area comparisons. Since the ground truth database was deterministic, no random error is associated with the mapped fires.

The geometric unions between detected fires and the ground-truthed database were computed for each treatment using ArcInfo (ESRI, 1997). Overlapping polygons were split and given attributes from both original polygons.

2.2. Generating accuracy metrics

For each treatment's geometric union layer, several spatial components were identified. From a broad perspective, fires were identified as being undetected (ground-truth fire exists but was not mapped), falsely detected (area was mapped but no ground-truth fire exists), or correctly detected (mapped and ground-truth areas coincide). Each correctly detected fire was further split into five components:

1. Total ground-truthed area
2. Unmapped ground-truthed area
3. Mapped ground-truthed area
4. Area mapped abutting ground-truthed area
5. Total mapped-event area

The five components were then combined to generate six accuracy response variables unlike when constructing an error matrix (Congalton and Green, 1999). Data normality was ensured by re-scaling the percent-type accuracy variables to proportions and transformed using the arcsine-square-root function. These variables measured:

1. (Mapped ground-truthed area)/(Total ground-truthed area)
2. (Area mapped abutting ground-truthed area)/(Total ground-truthed area)
3. (Total mapped-event area)/(Total ground-truthed area)
4. (Mapped ground-truthed area)/(Total mapped-event area)
5. (Area mapped abutting ground-truthed area)/(Total mapped-event area)
6. (Unmapped ground-truthed area)/(Total mapped-event area)

2.3. Comparing accuracy variables among methods

A 3×3 factorial ANOVA design was used to test the accuracy variables' null hypotheses of equality among the three threshold methods. Tests of significance ($\alpha = 0.05$) were conducted separately for each accuracy variable and fire season (1992, 1993, and 1995), totaling nine treatments. Significant differences were tested with Scheffé's post hoc tests ($\alpha = 0.05$) using harmonic means.

2.4. Decision-tree classification of areal and positional correspondence

A decision tree (Running et al., 1995; Friedl and Brodley, 1997) was implemented using successive decisions on various conditions of the accuracy variables to classify AVHRR/NDVI-mapped fires. Six generalized coincidence categories were developed to represent spatial and areal correspondence between ground-truthed and mapped fires.

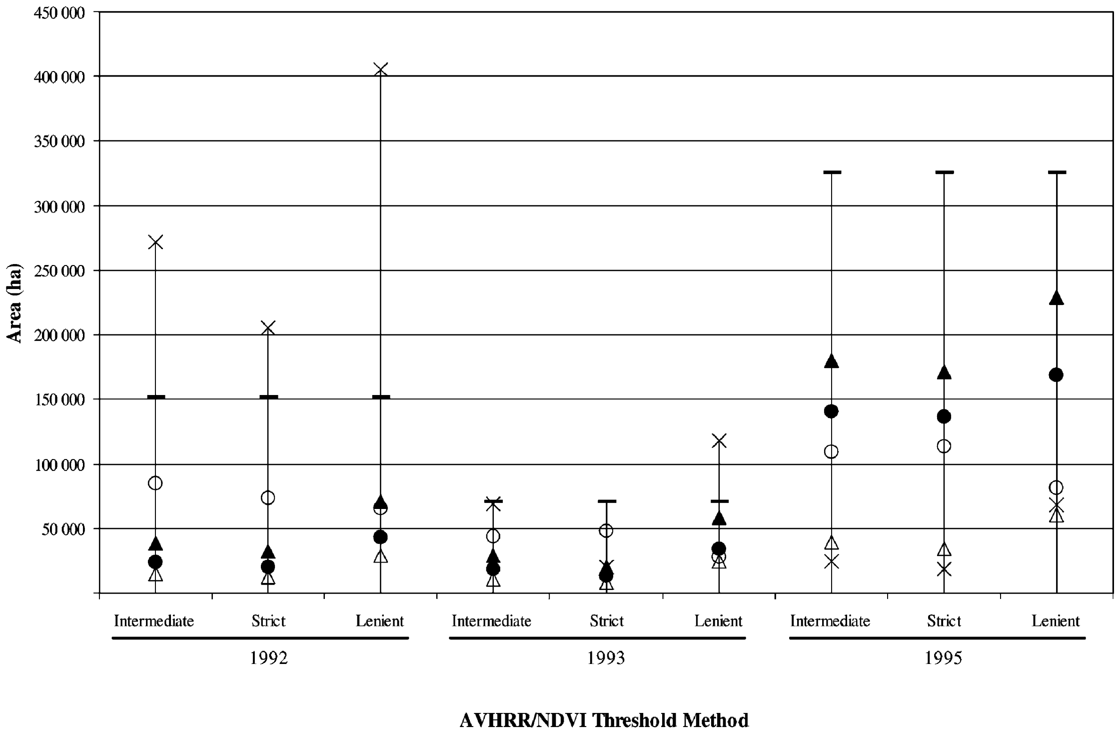

Fig. 2. Accuracy component areas, summarized for each treatment and year of study: mapped ground-truthed area (●); false detection (×); mapped event (▲); unmapped ground-truthed area (○); area mapped abutting ground-truthed area (△); and ground-truthed area (▬).

2.5. General relationships and trends

Treatment summaries were prepared in graphical format (Fig. 2), allowing quick inspection of the accuracy components among threshold methods. The several possible relationships among accuracy variables were explored by calculating Pearson correlation coefficients ($n = 81$). Relationship strength and directionality were considered to be meaningful when $P < 0.01$ and $r > 0.80$. Finally, ground-truthed polygons and mapped-event areas were overlaid to allow comparison.

3. Results and discussion

3.1. General shapes, patterns, and spatial relationships

Approximately two-thirds of all fires were detected for the 1992 and 1993 fire seasons, but just over one third were detected for 1995 (Table 2). However, the average correctly detected area increases from 31 to 60% (85% in 1993 with the lenient method) between 1992 and 1995, thought to be a result of fire sizes and cloud contamination. The latest results compare with Martín and Chuvieco (1995) that can be explained by the existence of several large accurately mapped fires, and less accurately mapped smaller fires (Cahoon et al., 1996). These values are better than those reported by Flannigan and Vonder Haar (1986), who detected 37% of total fires. However, they concluded that in areas with no cloud contamination, their detection ability rose to 80%.

Pearson correlation coefficients among the various accuracy components were calculated only for those ground-truthed fires having some overlap with the AVHRR/NDVI-mapped area (i.e. detected fires). As expected, larger ground-truthed fires exhibited larger mapped areas ($r = 0.864, P = 0.000$) (French et al., 1996). Similarly, ground-truthed area, mapped ground-truthed area, and mapped-event area were

Table 2
Occurrence and area disturbed by forest fires in Ontario during the study period[a]

Year	Ground-truthed fires			Detected fires		
	Method	No.	Area[b]	Correct (no.)	False (no.)	Area correct (%)
1992	Strict	12	151900	8	101	25
	Intermediate	12	151900	7	88	21
	Lenient	12	151900	8	117	46
1993	Strict	10	70700	7	40	41
	Intermediate	10	70700	6	18	29
	Lenient	10	70700	7	45	85
1995	Strict	34	325900	13	13	55
	Intermediate	34	325900	13	10	52
	Lenient	34	325900	13	14	70

[a] Source: adapted from Perera et al. (1998).
[b] Areas are rounded to the nearest 100 ha.

correlated positively ($r > 0.800, P < 0.010$). Therefore, as fire size increased, so did the mapped-event area for each particular fire, with mapped-area increases noted within ground-truthed perimeters. These results are supported by Kasischke et al. (1993) and Kasischke and French (1995).

Overlaying ground-truthed perimeters on mapped-event areas allowed for quick examination of several fire pattern similarities/dissimilarities (Fig. 3). The ground-truthed and mapped shapes were generally similar (Kasischke et al., 1993; Li et al., 1999; Fernández et al., 1997), 1995 patterns being most similar. The fire edges may have introduce mixed pixels (fraction of area burned), potentially altering burned area calculations as demonstrated with fire boundary mapping using thermal data (Razafimpanilo et al., 1995).

The graph of treatment summaries (Fig. 2) indicates that the lenient threshold method allowed higher levels of falsely detected fires (Kasischke and French, 1995), mapped-event area, and mapped ground-truthed area. However, the lack of samples (only 3 years of data) limits the ability to test this hypothesis statistically. The areas depicted in Fig. 3 were also found to be representative of occurrence counts for the respective accuracy components presented in Table 2.

3.2. Differences among threshold methods

Of the six accuracy variables, five showed significant ($P < 0.05$) differences in the ANOVA statistical test for threshold methods in at least one fire season (Table 3). Scheffé's post hoc tests indicate that for accuracy variables with significant differences among threshold methods, other trends are evident. Most cases suggested homogeneous subsets that separate the lenient from the strict and intermediate threshold methods. These trends were relatively consistent for each year but were most pronounced for 1995. The accuracy variable measuring unmapped ground-truthed area in relation to mapped-event area is the most consistent across years; thus, the AVHRR/NDVI threshold method selected would impact the accuracy of the final fire mapping products. The areas obtained with the lenient method are generally higher for all accuracy variables except when measuring unmapped ground-truthed areas.

3.3. Suitability of methods for use in northern Ontario

The decision-tree classification (Fig. 4) describes two dominant classifications of fire mapping accuracy: (1) coincidence category 5, representing high areal and positional concordance between ground-truthed and mapped fires (Fig. 5) and (2) coincidence category 3, representing high positional but low areal accuracy. Therefore, mapped fires generally have higher positional than areal accuracy. However, even when areal correspondence is low, most of the mapped area falls within ground-truthed fire perimeters.

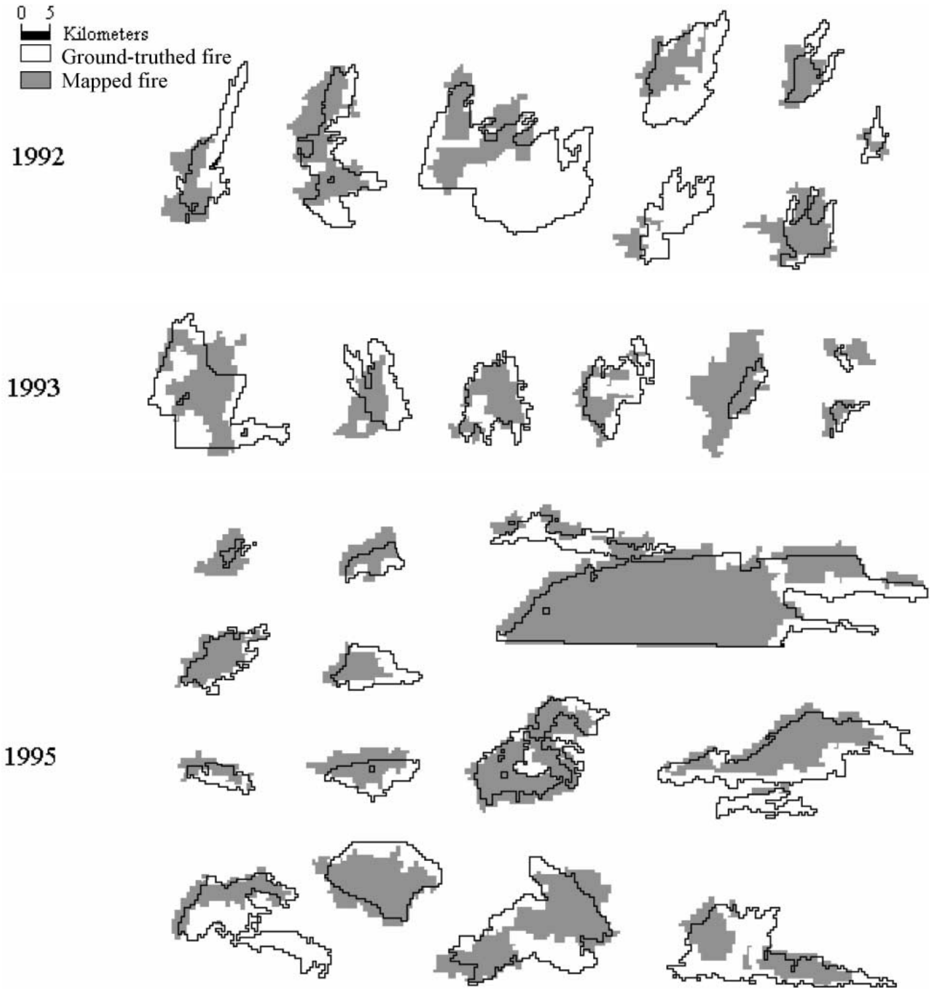

Fig. 3. Comparison of area mapped to ground-truthed perimeters for each detected fire. All cases were extracted from the lenient threshold treatment.

Table 3
ANOVA table of probabilities[a]

Accuracy variable	*P*		
	1992	1993	1995
(Mapped ground-truthed area)/(mapped-event area)	ns	ns	ns
(Area mapped abutting ground-truth area)/(mapped-event area)	0.031	ns	ns
(Unmapped ground-truthed area)/(mapped-event area)	0.001	0.000	0.000
(Total mapped-event area)/(total ground-truthed area)	0.012	0.005	0.000
(Mapped ground-truthed area)/(total ground-truthed area)	0.026	0.000	0.000
(Area mapped abutting ground-truth area)/(total ground-truthed area)	0.007	ns	0.011

[a] $n = 81$; ns: not significant at $\alpha = 0.05$.

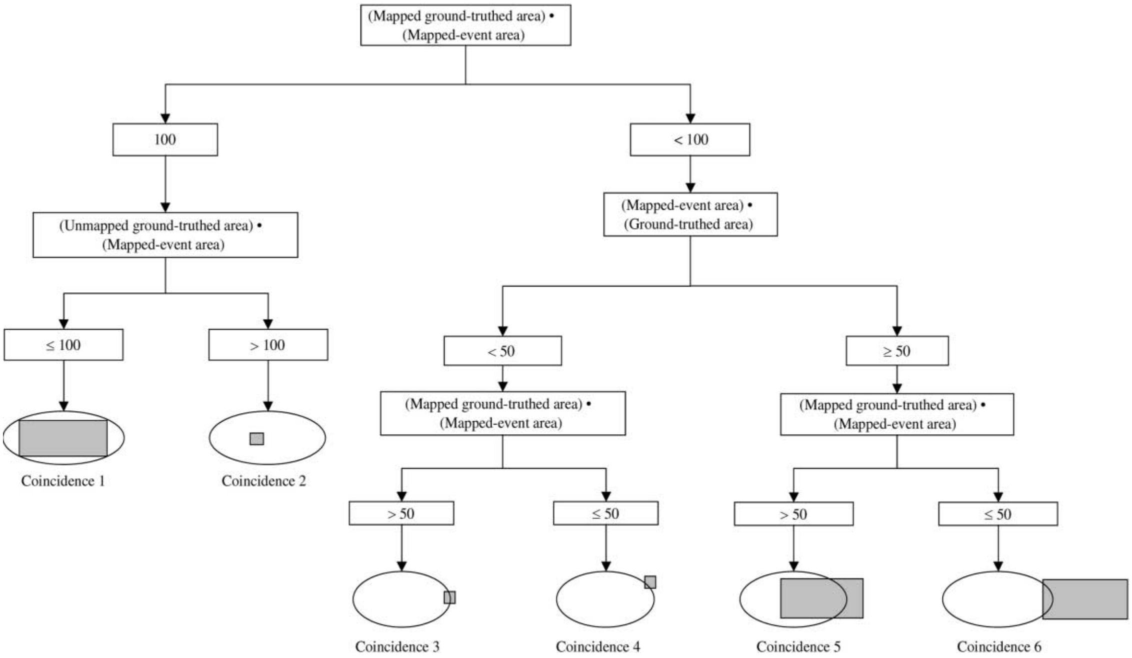

Fig. 4. Decision tree resulting in six generalized coincidence categories between mapped ground-truth areas (rectangular) and ground-truth areas (oval) ($n = 81$).

Given that there were no counts of coincidence category 1 and some occurrences of coincidence category 6, the overall accuracy required for mapping forest fires remains unclear. Without having reliable positional accuracy, it is difficult to combine fire distribution maps with the corresponding vegetation, hydrological, and climatic spatial databases for ecological studies. However, the high frequency of coincidence category 5 helps to maintain consistency between ground-truthed and mapped fire areas.

False detection was the largest problem within this study. The amount of extensive areas falsely mapped as fires was much higher than in the study by Kasischke et al. (1993), and occurrence counts were

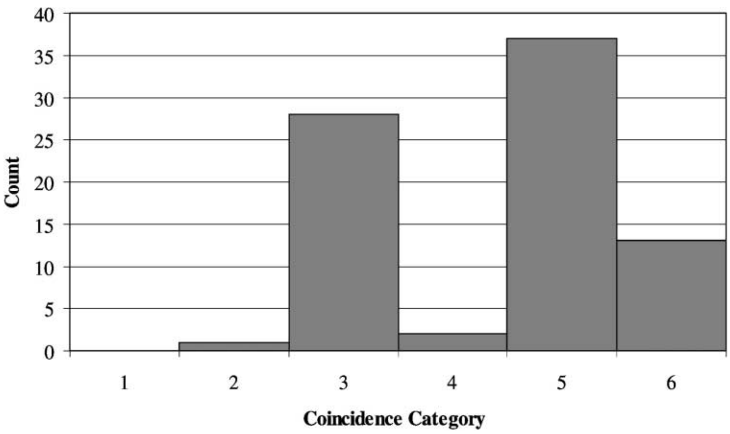

Fig. 5. Decision-tree classification ($n = 81$).

also high. Thus, the bulk of falsely detected area consisted of multiple small areas rather than a few contiguous areas. This fact, coupled with the coarse resolution of the AVHRR sensor, made it likely that falsely detected area would be significantly high (Hlavka et al., 1996).

The pattern of falsely detected fires for 1992 and 1993 seems to indicate cloud contamination, which reduced the NDVI (Martín and Chuvieco, 1995; Kasischke and French, 1995; Steyaert et al., 1997). Since clouds in this region are very common and extensive, the patchy pattern that thin clouds produce can easily, over a large area mimic many small "fire" signatures. It is not unreasonable to expect that clouds are responsible for the majority of falsely mapped fires. Other factors that could have reduced fire mapping accuracy include spatial resolution, areas of sparse vegetation (Hlavka et al., 1996), fire size (Kasischke et al., 1993), fire severity (White et al., 1996), and vegetation moisture content (Patterson and Yool, 1998). Thus, variations of these conditions across the vast study area, together with broad environmental gradients (Moritz, 1997), may account for inaccuracies of the mapped fires in the current study.

The model is very sensitive to the threshold value used, since the threshold value is the only basis upon which the NDVI imagery is assessed for fire occurrence. However, the thresholds used were developed, tested, and proven effective under similar northern boreal forest conditions. We considered three different threshold values from the literature to compensate for this sensitivity. Further studies should be directed at optimizing these thresholds, allowing accuracy comparisons with these baseline (null) values. Furthermore, analysis of land cover, soils, and vegetation for regions falsely mapped as fires could potentially provide insight to their misclassification.

4. Conclusions

The accuracy assessment and decision-tree procedures developed in this study provide an explicit and effective method for quantifying and visualizing individual fires and partitioning accuracy among them into components. The general shapes of AVHRR/NDVI-mapped fires were similar to the ground-truthed perimeters and ground-truthed fire areas were found to be correlated with the total AVHRR/NDVI area mapped and the area mapped within ground-truthed perimeters for each fire. These results are comparable to those revealed for interior Alaskan boreal forests (Kasischke et al., 1993).

Accuracy variables indicated two homogeneous subsets of fire mapping methods: (1) the method combining two different threshold methods of fire mapping and (2) the single threshold methods. We believe this split into two homogeneous subsets is a result of the additional area supplied by the second, much more relaxed threshold in the first homogeneous subset.

Due to very high false detection effects, accuracy was not consistent among fire seasons and was not continually within acceptable bounds for accurate fire mapping. Resulting in a patterned appearance, falsely detected fires were considered an artifact of light cloud contamination (NDVI suppression), a problem that should be considered rigorously in further attempts to post-fire disturbance. If falsely detected fires can be reduced, the double-threshold method used in this study would likely provide relatively accurate fire area estimations. Furthermore, by increasing replication (more than 3 years of study), trends better representing the study area may be extracted.

Therefore, existing AVHRR/NDVI methods do show promise for mapping fires in northern Ontario but will require further cloud screening to improve accuracy and increased replication to allow extrapolation of results to longer time-frames. With these mentioned improvements, the methods outlined in this paper should provide an efficient and cost-effective alternative to current airborne and field-level fire mapping practices for a vast expanse of unmanaged boreal forest (Stocks et al., 1996), thereby providing valuable insight into a natural fire regime which can be applied to various harvesting scenarios and ecological, climatic, and vegetation studies.

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