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Debating the greening vs. browning of the North American boreal forest: differences between satellite datasets

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Abstract

A number of remote sensing studies have evaluated the temporal trends of the normalized difference vegetation index (NDVI or vegetation greenness) in the North American boreal forest during the last two decades, often getting quite different results. To examine the effect that the use of different datasets might be having on the estimated trends, we compared the temporal trends of recently burned and unburned sites of boreal forest in central Canada calculated from two datasets: the Global Inventory, Monitoring, and Modeling Studies (GIMMS), which is the most commonly used 8 km dataset, and a new 1 km dataset developed by the Canadian Centre for Remote Sensing (CCRS). We compared the NDVI trends of both datasets along a fire severity gradient in order to evaluate the variance in regeneration rates. Temporal trends were calculated using the seasonal Mann–Kendall trend test, a rank-based, nonparametric test, which is robust against seasonality, nonnormality, heteroscedasticity, missing values, and serial dependence. The results showed contrasting NDVI trends between the CCRS and the GIMMS datasets. The CCRS dataset showed NDVI increases in all recently burned sites and in 50% of the unburned sites. Surprisingly, the GIMMS dataset did not capture the NDVI recovery in most burned sites and even showed NDVI declines in some burned sites one decade after fire. Between 50% and 75% of GIMMS pixels showed NDVI decreases in the unburned forest compared with <1% of CCRS pixels. Being the most broadly used dataset for monitoring ecosystem and carbon balance changes, the bias towards negative trends in the GIMMS dataset in the North American boreal forest has broad implications for the evaluation of vegetation and carbon dynamics in this region and globally.

Keywords: AVHRR, boreal forest, burned areas, Canada, forest fires, GIMMS, NDVI trends, seasonal Mann-Kendall trend test

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Introduction

The boreal forest of the northern hemisphere stores approximately 40% of the total carbon in terrestrial ecosystems, containing essentially as much carbon as the tropical rainforests (Gorham, 1991; Kasischke, 2000; Vasander & Kettunen, 2006). Being such a large reservoir of terrestrial carbon, it is important to know if the boreal carbon balance is changing and, if so, in what ways. This is not only important as an input to the global carbon budget (Houghton, 2007), but also to provide individual countries with estimates of CO_2 uptake and emissions to assess their national budgets in meeting national and international targets (e.g. the

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1997 United Nations Framework Convention on Climate Change).

One important component of the carbon budget is the carbon sequestered in vegetation. Regional assessments of this value using field data alone are difficult, but significant improvements can be achieved through combining inventory data with remotely sensed observations (Kurz & Apps, 2006). Among the different spectral indices derived from satellite data, the normalized difference vegetation index (NDVI) has been the most widely used to assess spatial patterns and interannual trends of variables related to the carbon storage in aboveground vegetation, such as leaf area index, biomass, and productivity (e.g. Tucker & Sellers, 1986; Prince & Goward, 1996; Randerson *et al*., 1997; Goetz *et al*., 2005). Satellite datasets derived from the global area coverage (GAC) of the advanced very high resolution radiometer (AVHRR) began to be collected in the 1980s and have been widely used in global and regional assessments of temporal trends of NDVI (or vegetation greenness) and net primary production (e.g. Myneni *et al*., 1997; Nemani *et al*., 2003).

Recent warming trends in many regions has led to numerous assessments of the NDVI over time, particularly in the High Northern Latitudes. In many regions, consistent trends in the NDVI have been reported regardless of the dataset being analyzed; for example, NDVI increases ('greening') in the arctic tundra (Myneni *et al*., 1997; Jia *et al*., 2003; Goetz *et al*., 2005), or NDVI decreases ('browning') in the Chilean semiarid zones (Baldi *et al*., 2008). However, in other regions, the use of different datasets has led to conflicting findings, potentially due to differences in the processing and corrections applied to the satellite data (e.g. McCloy *et al*., 2005; Hall *et al*., 2006; Baldi *et al*., 2008).

One region where conflicting interannual trends in vegetation greenness may have important implications for assessments of the global carbon budget is the boreal forest of central Canada (Fig. 1). Three main issues seem to explain the observed trends derived from satellite data: climate changes, vegetation recovery in recently disturbed areas, and the use of different satellite data sources to retrieve the trends. Climate warming has been consistently associated with an increase in vegetation greenness ('greening') during the 1980s throughout central Canada (Myneni *et al*., 1997; Tucker *et al*., 2001; Slayback *et al*., 2003), despite the fact that forest extent remained basically stable (Masek, 2001). When the data record was extended to the 1990s and early 2000s, other studies showed how the persistent warming might have caused a negative trend in NDVI ('browning') across this region (Myneni *et al*., 2001; Dong *et al*., 2003), which may be caused by warmer but not wetter climate, thus increasing drought stress associated with greater evapotranspiration rates. This effect might have

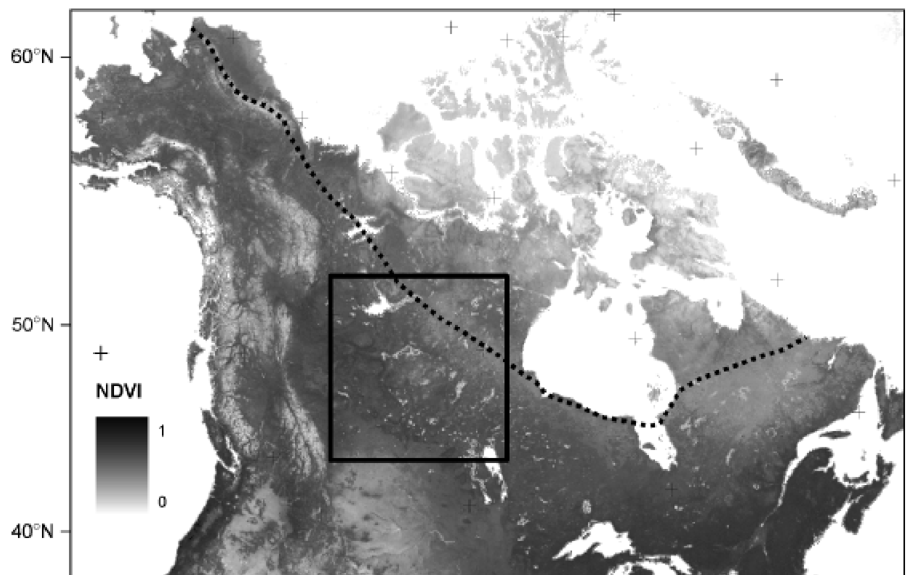

Fig. 1 The solid line embraces our study area in central Canada. The dotted line is an approximate reproduction of the line in Fig. 4 of the GIMMS user guide (Pinzón *et al*., 2007) that separates the boreal region (more affected by the satellite drift) from the northernmost tundra region (less affected). The growing season mean NDVI of the 1984–2006 period of the GIMMS dataset is shown in gray scale. GIMMS, Global Inventory, Monitoring, and Modeling Studies; NDVI, normalized difference vegetation index.

become a major constraint for vegetation growth since the early 1990s (Angert *et al*., 2005), which agreed with model projections (Zhang *et al*., 2007). In contrast, other remote sensing studies have shown a persistent greening throughout the 1980s and 1990s in central Canada (Zhou *et al*., 2001; Nemani *et al*., 2003; Reed, 2006; Kimball *et al*., 2007). Nevertheless, none of these prior studies accounted for a potentially significant source of browning and greening in boreal forests, the biomass reduction in areas disturbed by fire and its subsequent regeneration (Hicke *et al*., 2003; Neigh *et al*., 2008). Even if burned areas were excluded from the analysis, the finding of declining NDVI in areas with dense tree cover (Bunn *et al*., 2005; Bunn & Goetz, 2006) supported the hypothesis that drought stress reduced the photosynthetic activity of the Canadian boreal forest during the warmer 1990s (Goetz *et al*., 2005, 2007). In addition to the effects of climate change and postfire regeneration, a third issue may be involved in explaining the trends of vegetation greenness found in different remote sensing studies, i.e. the source and processing streams of the different AVHRR datasets used (Zhou *et al*., 2003; Simoniello *et al*., 2004; Stow *et al*., 2007). In some cases, opposite trends can even be found; for instance, a greening trend was observed in the boreal forest of Alaska when using the Pathfinder AVHRR Land (PAL) dataset (from 1982 to 2000) (Kimball *et al*., 2007), while the Global Inventory, Monitoring, and Modeling Studies (GIMMS) dataset showed a browning trend (from 1982 to 2003) (Verbyla, 2008). Presently, only the study by Olthof & Latifovic (2007) has evaluated the NDVI trends in this region based on data not derived from AVHRR-GAC data; these authors found that the SPOT VEGETATION 1 km^2 NDVI responded positively to warming from 1998 to 2004 in both dry and humid areas of Canada.

Despite the fact that many field observational studies have independently evaluated the long-term response of the boreal forest to warming without the use of satellite data, it appears that no conclusive evidence has been found (known as the 'divergence problem') (D'Arrigo *et al*., 2008). Tree-ring widths and wood-density records show both negative (Barber *et al*., 2000) and positive relationships with temperature (D'Arrigo *et al*., 2008). Ecosystem flux studies based on eddy covariance methods also do not provide a consistent answer. For instance, a 1995–2004 CO_2 flux record from a black spruce forest tower in Manitoba did not show any clear correlation between warming and either carbon uptake or release (Rocha *et al*., 2006; Dunn *et al*., 2007). Bergeron *et al*. (2007), however, showed that, across several sites in Canada, annual gross ecosystem production was positively related to mean annual air temperatures and an earlier start of the growing season (with greater dependence on spring rather than summer temperatures).

Despite the important effects that climate may have on temporal variability of the carbon balance in the boreal forest that can be analyzed through variations in satellite-observed NDVI, fire may be a more significant driver of both carbon cycling (Kasischke *et al*., 1995; Harden *et al*., 2000; Bond-Lamberty *et al*., 2007) and trends in NDVI. In North America, recovery times to preburn levels for NDVI have been estimated to be around 6 (Goetz *et al*., 2007) to 9 (Hicke *et al*., 2003) years depending on fire severity, though, in general, the high NPP levels that occur in mature stands take much longer to recover. A complicating factor in analyzing postfire recovery using NDVI data is the fact that this may vary as a function of variations in fire severity. For example, in mature stands of black spruce boreal forest of North America, research shows that the depth of burning of the surface organic layer is a significant cause of regeneration differences (Johnstone & Kasischke, 2005; Johnstone & Chapin, 2006). In less severe fires, where typically 10–20 cm of organic matter remains unburned, postfire regrowth consists primarily of shrubs that reproduce vegetatively and spruce seedlings. In severe fires, where 3–8 cm of organic matter remains, there exists invasion of deciduous species, primarily quaking aspen (*Populus tremuloides* Michx.). In the severest fires, where <3 cm of organic matter remains, regeneration typically consists of a significant regrowth of quaking aspen. As a consequence of these regeneration differences, rates of postfire NPP increase from sites experiencing the least severe burns to sites with the severest burns (Johnstone & Kasischke, 2005; Johnstone & Chapin, 2006).

The goal of this study was to investigate whether different satellite-based NDVI datasets produced significant differences in observed trends in vegetation greenness over the past two decades. For this, we compared the temporal trends of burned and unburned areas of boreal forest in central Canada calculated from two datasets: the GIMMS dataset, which is the most commonly used 8 km dataset, and a new 1 km dataset developed by the Canadian Centre for Remote Sensing (CCRS) (Latifovic *et al*., 2005). We compared the NDVI trends between datasets along a fire severity gradient in order to account for the variance in regeneration rates.

Methods

Satellite datasets

To compare the NDVI trends of burned and unburned sites of the North American boreal forest, we used two

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NDVI datasets derived from the AVHRR, on board the satellite series of the National Oceanic and Atmospheric Administration (NOAA), that are available for central Canada over the growing season months (May–September) from 1984 to 2006.

The first dataset was obtained from the GIMMS team. The GIMMS dataset is the most commonly used dataset to model and evaluate vegetation patterns and trends around the world. It has a spatial resolution of $64\,km^2$, and contains two composite images per month. It has been corrected for sensor degradation, intersensor differences, cloud cover, solar zenith angle, and viewing angle effects due to satellite drift (using the empirical mode decomposition function; (Pinzón *et al*., 2004), volcanic aerosols, and other effects not related to vegetation change (it is not corrected for water vapor, ozone, and scattering due to tropospheric aerosols) (for details see Tucker *et al*., 2005). GIMMS is currently thought to be to be consistent with NDVI derived from SPOT VEGETATION and Terra MODIS satellite data (Tucker *et al*., 2005). Our second dataset was acquired from the CCRS. The CCRS dataset has a spatial resolution of $1\,km^2$ and contains one composite image based on a minimum cloud index algorithm every 10 days (Khlopenkov & Trishchenko, 2007). It has been corrected for sensor degradation using the NOAA-recommended post launch calibration, cloud cover and shadow contamination, as well as atmospheric corrections for water vapor, ozone, and aerosols (using constant aerosol optical depth) (for details see Latifovic *et al*., 2005). To correct for intersensor differences in spectral response function, we applied the absolute calibration coefficients at the top of the atmosphere available in Trishchenko *et al*. (2002) and Trishchenko (2009) to the raw NDVI data. Then, using the quality flags, we first discarded NDVI values with low quality (probability of presence of clouds, water, snow, or ice $>30\%$). We finally discarded all pixels where $>20\%$ of dates did not pass the former quality threshold (i.e. pixels with $>20\%$ of dates with probability of low NDVI quality $>30\%$).

Sampling of burned and unburned sites

We identified burned pixels for every year of the 1984–2006 period by applying the algorithm of Chuvieco *et al*. (2008) on the CCRS dataset. The algorithm relies on temporal comparisons of several spectral indices, as well as near infrared reflectance. It emphasizes the stability of the postfire signal to avoid false detections associated with clouds, cloud shadows, missed data, and radiometric calibration or geolocation errors between AVHRR sensors.

Most approaches that use satellite remote sensing data to estimate burn severity rely on shortwave infrared (SWIR) bands that are not available with the AVHRR sensor. Even with SWIR bands, there is no consistent approach for satellite mapping of fire severity in boreal forests (French *et al*., 2008). We used a logic-based approach to divide AVHRR burned pixels into three severity categories. Our approach was predicated on observations that the dominant forest cover in our study region was black spruce forest. In this forest type, a key fire severity characteristic is the depth of burning of the surface organic layer (Kasischke *et al*., 2008). Two of the factors that control depth of burning in black spruce forests include seasonal and interannual variations in climate (Amiro *et al*., 2001), and seasonal active layer thawing, where deeper fires occur later in the growing season due to greater thaw depths of soils (Kasischke & Johnstone, 2005).

Based on these factors, three categories of potential severity were used for fires during the 1984–1995 period depending on when the fire took place: low severity (before July 21st in years of few, small fires), medium severity (before July 21st in years of many, large fires), and high severity (after July 21st any year). Unburned pixels were selected within an area located from 10 to 30 km to the 1984–1995 burned pixels, as well as avoiding any burned pixels in the 1996–2006 period, water bodies, or nonforest land-covers (from Palko *et al*., 1995).

For each fire severity class we selected all GIMMS $64\,km^2$ pixels that were dominated by CCRS $1\,km^2$ burned pixels of that class ($>70\%$ of that class and $<10\%$ of any other single severity class or land-cover). Surrounding these GIMMS burned pixels, we selected the corresponding GIMMS unburned pixels (only those with 100% of CCRS pixels of the same unburned class).

Finally, to allow a direct comparison of the trends in the sampled pixels between the two datasets, we discarded all CCRS pixels (both burned and unburned) not contained within the GIMMS selected pixels. To reduce the sample size of CCRS pixels, we selected 16 CCRS random pixels completely included within each GIMMS selected pixel. The number of pixels for each class is summarized in Table 1.

Temporal trend analysis

Temporal NDVI trends in both datasets between 1996 and 2006 were calculated for sites burned between 1984 and 1995. In the unburned sites, trends were also calculated for the 1996–2006 period to allow for direct comparison with the burned sites and to avoid the influence of possible pre-1984 fires [we assumed that if any pixel was burned before 1984, a 12-year gap is

Table 1 Sample sizes for burned and unburned pixels of boreal forest across the fire severity gradient

	GIMMS	CCRS	GIMMS bootstrap	CCRS bootstrap
Low severity				
Burned	28	448	21	23
Unburned	162	2592	19	19
Medium severity				
Burned	137	2176	26	23
Unburned	550	9968	18	23
High severity				
Burned	118	1856	27	24
Unburned	465	10 288	17	23

The 'bootstrap' columns show the samples (of comparable sizes among classes and datasets) that were used to check for significant differences in a bootstrapped ANOVA (see 'Methods' section for details).
GIMMS, Global Inventory, Monitoring, and Modeling Studies; CCRS, Canadian Centre for Remote Sensing.

long enough for the NDVI to recover, compared with the 6-year NDVI recovery time observed by Goetz *et al.* (2006) and the 9-year recovery time from Hicke *et al.* (2003)].

NDVI time-series often do not meet parametric assumptions such as normality and homoscedasticity. To account for this, temporal trends were calculated as suggested by de Beurs & Henebry (2005) using the seasonal Mann–Kendall trend test, a rank-based nonparametric test robust against seasonality, nonnormality, heterocedasticity, missing values, and both intra- and interannual autocorrelation (Hirsch *et al.*, 1982; Hirsch & Slack, 1984; Van Belle & Hughes, 1984). Checking for trends using the full temporal resolution of the NDVI seasonal dynamics, instead of using just the growing season average or maximum, not only avoids the loss of temporal information, but also makes more biological sense, since the relationship between NDVI and tree growth is more likely to be correlated at finer temporal scales (e.g. monthly) (Kaufmann *et al.*, 2004). The seasonal Mann–Kendall test calculates the existence of a monotonic trend within each intra-annual time-step (i.e. composite period) based on Kendall's tau statistic, by summing the number of times a particular time-step within a year has a higher or lower NDVI value than any previous year. Then it performs a heterogeneity test to see if this slope is consistent across all seasons (composite images). The test was run using the environmental statistics module (Millard, 2001) in S-PLUS (Insightful Corporation, 2007). For each pixel the resulting overall Sen's slope (Hirsch *et al.*, 1982) and *P*-value were stored. Significant results were assumed for *P*-values lower than 0.05.

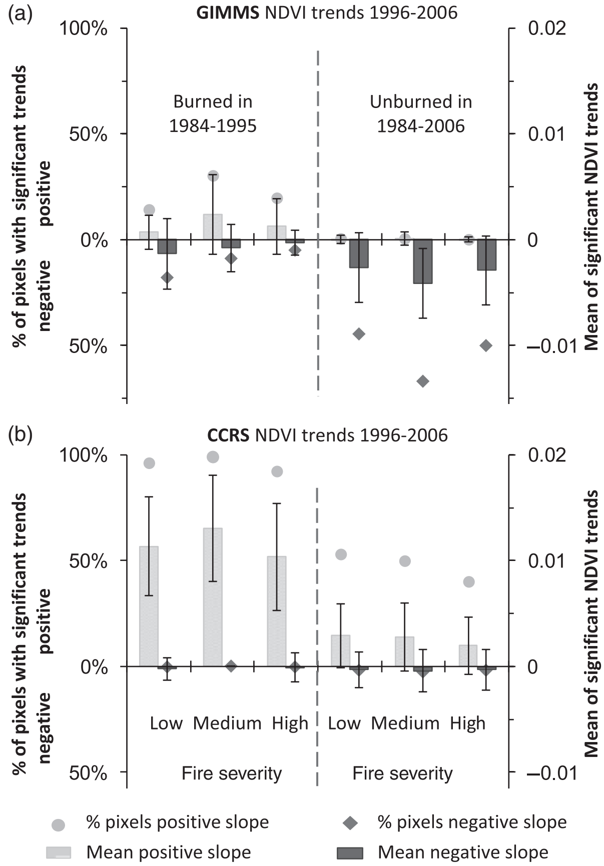

Fig. 2 Comparison of the NDVI trends (1996–2006) between the (a) GIMMS and (b) CCRS datasets for burned and unburned sites of the Canadian boreal forest along a fire severity gradient; low severity (before July 21st in years of few, small fires), medium severity (before July 21st in years of many, large fires), and high severity (after July 21st any year). Error bars represent one standard deviation. Significant trends (*P*-value <0.05) were obtained using the seasonal Mann–Kendall trend test, and slopes were computed using the Sen's method (Hirsch *et al.*, 1982). GIMMS, Global Inventory, Monitoring, and Modeling Studies; CCRS, Canadian Centre for Remote Sensing; NDVI, normalized difference vegetation index.

Resampling and analysis of variance (ANOVA)

Due to the fact that the numbers of pixels identified were very different across classes and datasets (Table 1), before conducting any statistical comparisons, we needed to find comparable sample sizes. We determined the minimum sample size necessary to capture the variance in the data for each class and dataset. For this, we calculated the increase in the cumulative variance when a new random pixel was included in the sample. We stopped when the increase in variance was $<5\%$. A bootstrap of 100 000 runs was necessary to get normal distribution sample sizes. The final (or bootstrapped) sample size of each class corresponded to the mean of these 100 000 runs (Table 1). Finally, to look for significant differences in the NDVI trends among burned and unburned classes, we also ran a bootstrapped ANOVA. In each of the 100 000 repetitions, we maintained for each class the sample sizes previously calculated, but randomly changed the actual pixels included for comparison. We recorded the number of times that significant differences (P-value <0.05) were found between classes and how many times class means were significantly different from zero. Comparisons between classes were based on the Sheffe's S procedure, which provides a confidence level for comparisons of means among all classes, and it is conservative for comparisons of simple differences of pairs.

Results

There were contrasting NDVI trends between the CCRS and the GIMMS datasets, with the CCRS dataset showing a general NDVI increase in both burned and unburned sites, while the GIMMS dataset exhibited a decrease in the unburned forest and minor trends (both positive and negative) in few burned sites (Fig. 2). In the CCRS dataset, almost all burned sites showed strong NDVI increases, always greater in percentage and magnitude than the increases experienced by the unburned forest sites (Fig. 2b). Contrary to this, in the GIMMS dataset (Fig. 2a), only 22% of sites burned between 1984 and 1995 showed NDVI increases during the 1996–2006 period, while 11% showed NDVI decreases (weak trends in both cases of absolute mean of Sen's slopes lower than 0.002). In the unburned forest, 54% of GIMMS pixels showed NDVI negative trends (with mean of Sen's slopes lower than -0.003), and $<1\%$ experienced slightly positive trends.

Fire severity had an effect on vegetation recovery as observed by the NDVI trends. Burned sites with medium fire severity (burned before July 21st in years of many, large fires) experienced the greatest NDVI increases in both datasets, though with much greater magnitude in the CCRS data (Fig. 2). The unburned forest surrounding sites of medium fire severity showed positive NDVI trends that did not differ from the other two severity classes in the CCRS dataset, but they showed greater NDVI decreases than the low and high severity classes in the GIMMS dataset.

The 100 000 bootstrapped ANOVAs (Table 2) showed that, with the exception of the medium fire severity class, the GIMMS NDVI trends did not significantly differ between the burned and unburned classes. Within the burned severity classes, the GIMMS NDVI trends did not differ and were not significantly different from zero 20% to 62% of times. Unburned classes did not differ significantly from each other, but their negative NDVI trends were significantly different from zero. In contrast, with the CCRS dataset (Table 2), the NDVI trends did differ between the burned and unburned classes, being positive and significantly different from zero in all unburned and burned classes (though significantly greater in the burned ones). Within the burned classes, the CCRS NDVI trends did not significantly differ among classes (only medium fire severity was significantly different from the other two classes 15% of times). There were no significant differences among the CCRS NDVI trends of the unburned classes. We also ran 100 000 Kruskal–Wallis tests to compare the same samples and the results were consistent with those from the ANOVAs.

Table 2 Percentage of times that the NDVI trends (1996–2006) significantly (P-value <0.05) differed between classes in the 100 000 ANOVAs that compared burned and unburned boreal forest sites along a fire severity gradient: low severity (before July 21st in years of few, small fires), medium severity (before July 21st in years of many, large fires), and high severity (after July 21st any year). (a) The lower left side of the matrix shows results for the GIMMS dataset and (b) the upper right side for the CCRS dataset. Gray cells highlight comparisons within the same dataset between burned and unburned sites. Last row (GIMMS) and last column (CCRS) show the percentage of times that the NDVI trends for each fire severity class were significantly (P-value <0.05) different from zero

% of 100 000 ANOVAs	Burned			Unburned			CCRS
	Low	Med	High	Low	Med	High	Zero
Burned							
Low		5	1	100			100
Med	5		15		100		100
High	0	0				100	100
Unburned							
Low	3				0	0	99
Med		97		2		0	98
High			58	0	1		91
GIMMS							
Zero	38	80	69	100	100	100	

GIMMS, Global Inventory, Monitoring, and Modeling Studies; CCRS, Canadian Centre for Remote Sensing; NDVI, normalized difference vegetation index.

Discussion

Contrary to expectations, GIMMS-NDVI did not significantly increase from 1996 to 2006 in areas that had been burned between 1984 and 1995. Despite the potential presence of a maximum of 30% of nonburned forest within the GIMMS sample for burned sites, a minimum of 70% of burned area would likely have caused a positive NDVI trend following burns. In fact, the CCRS data, that also contained a maximum 30% of nonburned forest, showed strong NDVI increases in all sampled burned pixels. Previous work by Goetz *et al*. (2006) using the GIMMS dataset detected NDVI increases after boreal forest fires, but only by analyzing burn scars of three very severe fire years. However, regardless of the severity of the fire, given the steep rate of greening during postfire regeneration in the boreal forest (Kasischke & French, 1997), the NDVI would be expected to capture these changes. The presence of such positive responses in the CCRS data but not in the GIMMS data may indicate that the GIMMS data processing introduces a bias that tends to underestimate positive NDVI trends in the boreal forest of central Canada. A similar bias has been observed in South America, where GIMMS was unable to detect many known long-term ecosystem changes, while they were evident using PAL and Fourier-Adjustment, Solar zenith angle corrected, Interpolated Reconstructed (FASIR) datasets (Baldi *et al*., 2008). De Beurs & Henebry (2008) also showed how in some ecoregions of Northern Eurasia the choice of the PAL or GIMMS datasets can lead to different and even opposite effects of the northern annular mode on the land surface phenologies.

Positive trends in vegetation greenness have been observed in the Canadian boreal forest attributed to warming through an increase in the number of growing degree days and the growing season length (Nemani *et al*., 2003; de Beurs & Henebry, 2005; Reed, 2006; Kimball *et al*., 2007). However, recent studies using GIMMS reported a negative NDVI trend in the North American boreal forest suggestedly due to an increase in summer drought stress (Goetz *et al*., 2005, 2007). From our comparison of postfire NDVI trends between the CCRS and GIMMS datasets, the lack of postfire NDVI increases in burned sites and the presence of GIMMS-NDVI decreases in unburned areas may be due to processing algorithms of this dataset, and not necessarily to an actual decline in vegetation activity. Contrary to GIMMS, our CCRS results support the occurrence of a slight increase in vegetation greenness from 1996 to 2006 in the boreal forest of central Canada. Work by Stow *et al*. (2007) in northern Alaska also showed that GIMMS data did not capture the majority of the areas of more rapidly increasing greenness, which were detected by a 1 km^2 AVHRR dataset from the United States Geological Survey.

Several reasons that will require further investigation might be involved to explain different NDVI trends between the GIMMS and CCRS datasets in central Canada. The first hypothesis could be a possible 'over-correction' of the satellite drift contribution to the NDVI signal that may have caused a bias in the GIMMS dataset towards negative NDVI trends in the boreal forest region of central Canada. This boreal region is more affected by the satellite drift than the northernmost tundra regions [notice the dotted line that separates both regions in fig. 1, crossing from northern Alaska to the southern coast of the Hudson Bay, that is reproduced from fig. 4 of the GIMMS user guide (Pinzón *et al*., 2007)]. A dissimilar satellite drift correction between the two regions may explain the negative NDVI trends in the boreal region of central Canada, in contrast to the positive NDVI trends in the tundra region [notice that the same dotted line of Fig. 1 separates the negative NDVI trends of the boreal forest from the positive NDVI trends of the tundra region in fig. 4 of Goetz *et al*. (2005)]. A dissimilar satellite drift correction may also explain why the GIMMS dataset shows systematically lower mean NDVI values than the FASIR dataset to the south of the dotted line of Fig. 1, but systematically higher values to the north of it [see fig. 2 of Hall *et al*. (2006)]. A second hypothesis could be the larger pixel size and geolocation errors in the GIMMS dataset compared with the CCRS dataset. The lack of significant postfire increases in GIMMS-NDVI might be explained by the maximum value compositing of the GAC archive (several 1.1 km $\times$ 4 km GAC pixels are taken to produce one 64 km^2 GIMMS pixel). If this technique produces a systematic bias towards high NDVI values from nonburned GAC pixels surrounding the GIMMS burned pixels, the postfire NDVI trends of burned pixels would be contaminated by the signal of nonburned surrounding areas. In contrast to GIMMS, the better registration and full AVHRR 1 km^2 spatial resolution of the CCRS dataset minimizes the occurrence of mixed NDVI signals. For both datasets, we tried to minimize this problem by avoiding a 10 km buffer around water bodies, burned areas, and nonforest land-covers. A third effect to consider is the different temporal resolution of both datasets, which affects their sensitivity to capture changes in land surface phonologies. This was suggested by de Beurs & Henebry (2008) when comparing GIMMS and PAL datasets. The 10-day composites of CCRS (or PAL in their study) have 50% higher temporal resolution than the GIMMS 15-day composites. As a result, the 10-day composite datasets can capture higher interannual variability than GIMMS and can more accurately monitor changes at the beginning and end of the growing season, which can occur very rapidly in high latitudes.

Fire severity did not greatly determine the recovery rates of NDVI during postfire regeneration. Recovery rates of NDVI did not significantly differ between low and high severity classes and were only slightly faster in sites burned by medium severity. The lack of significant differences in the recovery rates of NDVI in burned pixels classified by the severity criteria may be due to several factors. First, the method used for defining severity only applies to a portion of the vegetation types present in the study region (e.g. black spruce forests, about 50% of the forest cover). Second, during the first 10 years following a fire, factors other than changes in the amount of green vegetation may result in changes in NDVI. For example, fires create large areas of charred organic material, as well as exposed mineral soil in severe burns, that become covered by regrowth of mosses (especially the very thin fire moss, *Ceratodon purpureus* Hedw.) and new dead plant litter. The progressive recovery of the postfire ground layer changes dramatically the background reflectance, which may result in NDVI changes not related to the level of recovery of the aboveground herbaceous and woody vegetation, particularly during the first few years of low NDVI values.

Conclusions

In this study, we detected positive NDVI trends in the Canadian boreal forest using the CCRS dataset that contradict the decline of vegetation activity observed in this and in previous studies based on the GIMMS dataset. The GIMMS dataset largely missed the postfire greening recovery, while the CCRS dataset, which has improved corrections and a much higher spatial resolution than GIMMS, did capture it under all conditions of fire severity. From these conflicting NDVI trends between the two datasets, regional trends derived from current coarse resolution satellite datasets should be taken with caution. The presence of a bias in satellite datasets has broad implications for the evaluation of global and national carbon budgets. Currently, the GIMMS dataset is the most broadly used coarse-spatial resolution dataset for monitoring ecosystem changes (Pettorelli *et al*., 2005), detecting long-term trends in vegetation growth and phenology (Kathuroju *et al*., 2007), providing inputs for primary production models (Cao *et al*., 2004), and acting as reference to model the carbon balance worldwide (Potter *et al*., 2005; Luyssaert *et al*., 2007). Hence, the presence of a long-term bias in the GIMMS dataset may affect the aforementioned studies. As the GIMMS user guide strongly encourages, results should be validated with independent data. In addition to the CCRS dataset, other remote sensing datasets with higher spatial resolution than GIMMS may help in this evaluation, such as the reprocessing of the GAC archive under the Land Long Term Data Record initiative, and the SPOT VEGETATION and Terra MODIS collections. Our study also suggests the existence of slight differences associated with fire severity that can be further investigated (e.g. by stratifying the analysis across different ecoregions and land-covers) using the CCRS dataset with its higher spatial resolution. Finally, we think that the evaluation of satellite datasets should not only be based on the physical and mathematical principles of image processing (e.g. assessing the effect of atmospheric corrections when comparing with surface parameter values; McCloy *et al*., 2005; Nagol *et al*., 2009), but also on comparisons with independent observations at the results stage (e.g. comparing satellite-detected trends of new datasets with previously known independent observations of change, like in this study and in Baldi *et al*., 2008).

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