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# Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance

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We analyzed trends in a time series of photosynthetic activity across boreal North America over 22 years (1981 through 2003). Nearly 15% of the region displayed significant trends, of which just over half involved temperature-related increases in growing season length and photosynthetic intensity, mostly in tundra. In contrast, forest areas unaffected by fire during the study period declined in photosynthetic activity and showed no systematic change in growing season length. Stochastic changes across the time series were predominantly associated with a frequent and increasing fire disturbance regime. These trends have implications for the direction of feedbacks to the climate system and emphasize the importance of longer term synoptic observations of arctic and boreal biomes.

climate change | environmental change | remote sensing | trend analysis

There has been substantial warming in the northern high latitudes in recent decades that has been associated with changes in the interannual variability of the global carbon cycle (1, 2). In the coming decades, anthropogenic climatic change will affect the productivity and physiology of plants in the northern high latitudes and further modify carbon cycling (3). Documenting and interpreting trends in plant growth at high latitudes is critical for understanding the associations and feedbacks between temperature, land cover, and atmospheric CO<sub>2</sub> (4).

The time series of normalized differenced vegetation index (NDVI) data derived from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) meteorological satellites, provides a way to continuously monitor vegetation around the globe (5). The NDVI data exploit the contrast in reflectance between the infrared and red portions of the electromagnetic spectrum and are well correlated to chlorophyll abundance and absorption of photosynthetically active radiation, which together serve as a strong proxy for gross photosynthesis (Pg) at broad spatial scales (6, 7). These data, at 8-km resolution and 15-day return interval, have been critical in developing our understanding of the trends in vegetation response to environmental conditions through the 1980s and 1990s. Earlier analyses of the satellite data indicated an increase in gross photosynthetic activity of high latitude vegetation from 1982 until 1991 (2). The eruption of Mount Pinatubo in 1991 initiated a short-term cooling of the globe (8), but photosynthetic activity continued to rise after the Pinatubo-induced cooling (9). Increased trends were primarily attributed to the earlier onset of greening and extension of growing season length (2, 8, 9). Here, we make use of an extended and refined satellite data set at high latitudes (5, 10) to show that these trends did not continue uniformly in time or space.

## Methods and Data

**Data.** We used four independent data sources across boreal North America (Canada and Alaska) to study Pg activity including: (i) a time series of satellite observations at 8-km (64

km<sup>2</sup>) spatial and 15-day temporal resolution, covering the period July 1981 to December 2003 (5, 10); (ii) a land cover typology map including agriculture, forest, and tundra categories; (iii) gridded temperature fields interpolated from ground-based meteorological stations over the period 1981 to 2000; and (iv) digital maps of wildfire extent between 1981 and 1997 (11).

The satellite NDVI data were produced as part of the National Aeronautics and Space Administration Global Inventory, Monitoring and Modeling Studies (GIMMS) project and are the most current AVHRR data on rectified Earth surface reflectance (5, 10). The GIMMS data have been calibrated to account for orbital drift, cloud cover, sensor degradation, and the emission of volcanic aerosols that attenuate the reflectance spectra. We transformed the NDVI measurements to photosynthetically active radiation absorbed by green vegetation cover, and treated this as a proxy for relative Pg ranging between 0 and 1 (6, 7). The data were stratified by vegetation type by using a map (1-km<sup>2</sup> resolution) of dominant vegetation classes produced by Natural Resources Canada (<http://geogratis.cgdi.gc.ca/clf/en>), which was resampled to match the spatial resolution of the AVHRR data. This map was used to select 10,000 random samples (64 × 10<sup>6</sup> ha) proportionally from natural vegetation cover including interior conifer forest (37.1%), deciduous forest (4.7%), mixed coniferous and deciduous forest (16.6%), and tundra (21.6%). We also used the vegetation type map to exclude a relatively small area of crop and rangeland in the Prairie Provinces of Canada. In the initial component of the analysis, any samples that had experienced fire disturbance were excluded by using the digital fire extent maps described below. Selected samples from the time series of Pg were compared with data on mean monthly temperature (°C) from Canada that had been interpolated by using thin plate spline smoothing from ground-based stations on a 10-km grid by the Canadian government's Regional, National and International Climate Modeling project ([www.glf.cfs.nrcan.gc.ca/landscape](http://www.glf.cfs.nrcan.gc.ca/landscape)). The climate data, available through January 2000, were resampled to the 8-km AVHRR data. We used data from the Canadian Fire Service Large Fire Database to identify the location of fires from 1981 to 1997, which were the most recent data available digitally (11). In a second component of the analysis, we compared the temporal trends in burned versus unburned areas during the three largest fire years (1981, 1989, and 1995). These episodic fire years also captured the early, mid, and late portions of the time series. Burned areas were screened and internally buffered to ensure adequate discrimination from unburned areas. All spatial data were coregistered to an Albers conic equal-area projection.

**Time Series Analysis.** A time series ( $y_t$ ) of seasonal Pg (the mean of June to August) was calculated for each 8-km grid cell from

Abbreviations: Pg, photosynthetic activity; NDVI, normalized differenced vegetation index; AVHRR, advanced very high resolution radiometers; ADF, augmented Dicky-Fuller.

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**Table 1. Time series models for boreal North America (total) and the two dominant boreal vegetation cover types, tundra and forest**

	Boreal NA	Tundra	Forest
Model type	(1102 × 10 <sup>6</sup> ha)	(142 × 10 <sup>6</sup> ha)	(260 × 10 <sup>6</sup> ha)
Stationary with trend	162 (14.7%)	27.1 (19.1%)	30.9 (11.9%)
Stationary no trend	378 (34.3%)	45.1 (31.8%)	87.9 (33.9%)
Random walk with drift	349 (31.7%)	34.2 (24.1%)	100.7 (38.8%)
Random walk no drift	213 (19.3%)	35.3 (24.9%)	40.0 (15.4%)

of growth: by ≈10 days over the 22-year record. Interior forest areas, in contrast, did not reveal a consistent trend in maximum Pg or growing season length for the comparable observational periods. This finding was true whether the record was examined at regular 7-year intervals (Fig. 3), or divided into periods reflecting well defined vegetation response trends (1982–1991, 1992–1997, and 1998–2003) (see Fig. 1B).

**Spatial Distribution of Trends.** To examine the spatial distribution of the trends identified with the sampling approach, we ran the time series and trend analysis for each 64-km<sup>2</sup> grid cell location across all of Canada and Alaska and mapped the 22-year trends in growing season Pg (Fig. 4). Trends were analyzed by using the autoregressive models fitted with ordinary least-squares regression, and then classified as stationary or non-stationary. Statistical significance was determined by using both the ADF (18) and Vogelsang (13) tests. Across this 1,102 × 10<sup>6</sup> ha area, 51% of the grid cells were classified as stochastic (random) and 49% were classified as deterministic (stationary) by using the ADF tests (Table 1). Of the latter, 30% (14.7% of the total) displayed statistically significant trends, with just over half positive (52.4%) and the remainder negative (47.6%). Thus, 7.7% of the total area experienced significant increases in Pg (positive trends), and 7.0% displayed significant decreases (negative trends).

The slopes with positive trends were concentrated in tundra areas, whereas the negative slopes and stochastic drift cases were distributed throughout the interior forests (Table 2 and Fig. 4). The transition from positive to negative significant slopes occurred distinctly at the interface between forest and tundra. Further discrimination of strong positive and strong negative trends identified the location and spatial pattern of the largest changes in Pg over the time series (Fig. 4). The spatial coherence of the results with regard to land cover is striking, although we note that 62% of tundra areas and 74% of interior forest areas had slopes near zero (Table 2). Again, the results were essentially unchanged when the growing season was defined as May through September or May through October, except that a greater number of grid cells dropped

**Table 2. Magnitude of slopes for stationary models of tundra and forest vegetation cover types across boreal North America**

Slope magnitude*	Tundra, × 10 <sup>6</sup> ha	Forest, × 10 <sup>6</sup> ha
Strong negative	1.2 (1.6%)	14.4 (12.1%)
Negative	1.5 (2.1%)	11.4 (9.6%)
Near zero	45.1 (62.4%)	87.9 (74.0%)
Positive	15.9 (22.0%)	1.9 (1.6%)
Strong positive	8.6 (11.9%)	3.2 (2.7%)

\*Magnitude categories correspond to Fig. 4.

**Table 3. Area of different time series models for unburned forest and areas burned in three episodic fire years (1981, 1989, and 1995)**

Model type	Unburned, km <sup>2</sup> (%)	Burned, km <sup>2</sup> (%)
Stationary with trend	3,136 (22.4%)	576 (4.1%)
Stationary with no trend	5,440 (38.8%)	6,080 (43.4%)
Random walk with drift	3,584 (25.6%)	4,928 (35.2%)
Random walk with no drift	1,856 (13.2%)	2,432 (17.4%)

out, particularly at higher latitudes, due to an inability to fit the time series models to nonphotosynthetically active time periods.

**Burned Area Stratification.** The impact of fire disturbance on trends in Pg was assessed by using the database of large fires compiled for Canada (11), comparing burned and unburned areas of interior forest (12) for each of the four types of time series model fits (Table 1). Fire is an integral and increasingly frequent occurrence in boreal forest ecosystems (see Fig. 4 *Inset*) and varies in response to climatic warming and drying (11, 19). In the three largest fire years during the period of record (1981, 1989, and 1995), burned areas had far fewer stationary models with significant trends (4%), and a much higher percentage of stochastic behavior (Table 3). This lack of trend in burned areas is consistent with expectations, because any given area might burn at some point in the time series and then undergo a gradual recovery to pre-burn vegetation cover and density (20). A few of the negative deterministic trends in forest areas were associated with fire disturbance late in the record, mostly in interior Alaska, but burned forest areas across boreal North America were more likely to be classified as either stationary with no trend or stochastic. In contrast, areas not burned at any point in the period of record were more likely to be classified as stationary with >95% neutral or negative trends (Tables 2 and 3 and Fig. 4).

## Discussion

Growth in high latitude vegetation is widely expected to increase with rising CO<sub>2</sub> and temperature (19, 21). Our results indicate that tundra vegetation has conformed to this expectation over the past 22 years, with continued increases in photosynthetic activity as captured in the satellite data record (Fig. 4). This observation is supported by a wide and increasing range of local field measurements characterizing elevated net CO<sub>2</sub> uptake (22), greater depths of seasonal thaw (23), changes in the composition and density of herbaceous vegetation (21, 24), and increased woody encroachment in the tundra areas of North America (25).

In contrast, the response of interior forest areas to temperature change has been inconsistent with expectations of direct positive relationships between plant growth and either warming or CO<sub>2</sub> concentration. Neither the intensity nor the length of the growing season changed in a way that reflects a simple relationship with increasing temperature or CO<sub>2</sub>. In addition to the influence of fire disturbance, demonstrated here to be a key factor in detection of Pg trends, there are a number of other possible explanations for this apparent decoupling of growth and warming in forest areas, including drought stress (26, 27), nutrient limitation (28), insect and disease damage (29), and changes in resource allocation (30). Moreover, there is an emerging body of dendrochronology literature suggesting that temperature and woody growth relationships in high latitude trees are dependent on a complex interaction of landscape position and moisture availability (31, 32). We

