

Observed and predicted responses of plant growth to climate across Canada

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[1] Using satellite observations from 1981–2000, and data interpolated from surface weather stations, we examined the association between gross photosynthetic activity (Pg) and climate across the boreal forest and tundra of Canada. The response of annual and interannual Pg was tightly coupled to climate, and seasonal associations between Pg and climate varied with plant functional types. The most important variable for modeling summer growth of conifer forests was the previous spring minimum temperature, whereas tundra responded primarily to summer maximum temperature. Using general circulation model predictors to 2050, we project that tundra will continue to grow vigorously in the coming decades while conifer forests will not. Increased tundra productivity will likely be associated with changes in vegetation composition (e.g., woody proliferation). If these biotic responses are stationary and persist as predicted, terrestrial carbon budgets will need to be modified. **Citation:** Bunn, A. G., S. J. Goetz, and G. J. Fiske (2005), Observed and predicted responses of plant growth to climate across Canada, *Geophys. Res. Lett.*, 32, L16710, doi:10.1029/2005GL023646.

1. Introduction

[2] Considerable evidence indicates that late 20th century temperatures were anomalous in relation to the last 1,800 years [Moberg *et al.*, 2005] and are impacting species productivity and physiology, and altering the distributions of many species [Parmesan and Yohe, 2003; Root *et al.*, 2003]. This is readily apparent in the rapidly changing northern high latitudes [Arctic Climate Impact Assessment (ACIA), 2004]. Changes in productivity resulting from high latitude warming in recent decades have also been associated with changes in the interannual variability of the carbon cycle [Keeling *et al.*, 1996; Myneni *et al.*, 1997; Lucht *et al.*, 2002]. Interpreting the response of plant growth at high latitudes to climate is crucial for understanding the feedbacks between temperature, land cover and atmospheric CO₂ [Houghton, 2003].

[3] Space-based remote sensing allows vegetation to be consistently and continuously measured. Global vegetation has been monitored since 1981 using the normalized differenced vegetation index (NDVI) derived from the Advanced Very High Resolution Radiometers (AVHRR) [Brown *et al.*, 2004]. The NDVI data, at 8-km resolution and 15-day return interval, leverage the contrast in reflectance between the infrared and red portions of the electromagnetic spectrum and are well correlated to chloroplast

density and absorption of photosynthetically active radiation. Together these serve as a strong proxy for gross photosynthesis (Pg) at this spatial scale [Myneni *et al.*, 1995; Goetz and Prince, 1999]. When merged with climate data from ground-based stations, the satellite record allows us to infer the relationship between climate, growth, and functional type on an interannual basis [Goward and Prince, 1995; Xiao and Moody, 2004].

[4] Our objectives were to model Pg as a function of climate to understand recent trends in the satellite observational record as a function of plant functional type, and to explore the potential for future change. Specifically, we sought to 1) model annual Pg; 2) model summer plant growth for different cover types (e.g., conifer forest) as a function of seasonal climate variables (e.g., spring precipitation); and 3) use the seasonal Pg model to predict to the year 2050 using General Circulation Models (GCMs).

2. Study Area and Data

[5] We examined the entire Canadian boreal forest and associated tundra areas. The forested areas are dominated by needle-leaf evergreen species that have adapted to long, cold winters (e.g., *Picea mariana* and *Abies balsamea*) intermixed with broadleaf species (e.g., *Populus tremuloides*). Tundra areas are composed of grass species, lichens, sedges, mosses, and dwarf shrubs (e.g., *Betula nana* and *Ledum groenlandicum*).

[6] The AVHRR-NDVI data were produced as part of the NASA Global Inventory, Monitoring and Modeling project. They are the most current AVHRR data on rectified Earth surface reflectance and have been calibrated to account for orbital drift, cloud cover, sensor degradation, and the emission of volcanic aerosols [Brown *et al.*, 2004; Tucker *et al.*, 2005]. We linearly transformed the NDVI measurements to gross photosynthetic activity ranging from 0–1 [Goetz and Prince, 1999; Goetz *et al.*, 2005].

[7] We compared the Pg record to minimum and maximum monthly temperature and total monthly precipitation from Canada interpolated from ground-based stations on a 10-km grid through January 2000 by the Canadian government's Regional, National and International Climate Modelling project [McKenney, 2004]. The Pg data were resampled to a one-month time interval and 10-km spatial resolution to match the climate data, which are spatially and temporally coarser.

[8] We used a map of Canada's vegetation to aggregate Pg and climate models [Palko *et al.*, 1995]. This map allowed us to stratify by plant functional types characterized broadly as needleleaf evergreen and deciduous forests

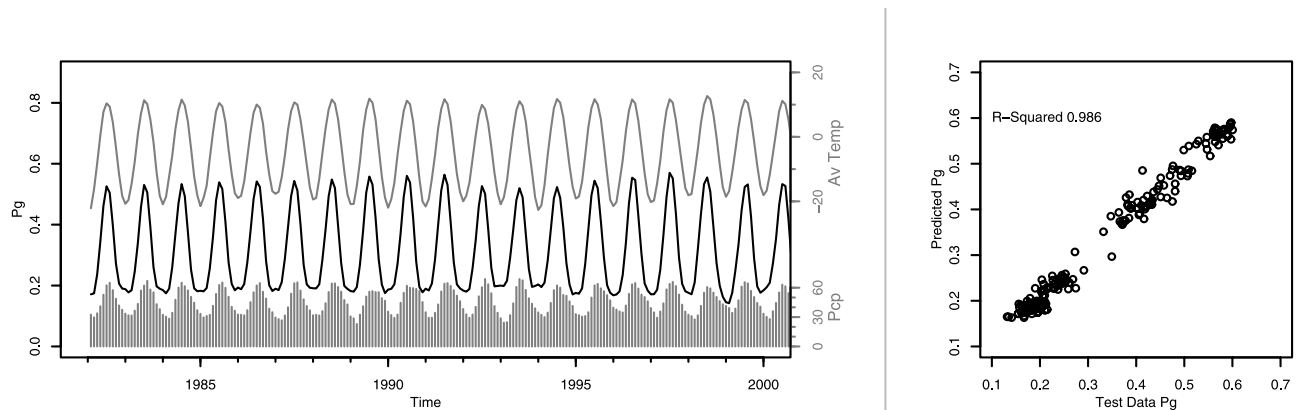


Figure 1. The seasonal cycle of plant growth, temperature, and precipitation from a random sample of 100 million ha in boreal Canada (left). A random forest that models Pg as a function of climate captures 98.6% of the variance in a separate 100 million ha sample (right). See color version of this figure in the HTML.

(continuous forest in which 76–100% of the canopy was coniferous or broadleaf trees respectively), transitional forest (the northern forest extent where trees are discernible but occupy less than 50% of the area), and tundra. Agricultural, rangeland, and developed areas were omitted to minimize land management influences on Pg.

[9] GCM simulations developed as part of the Arctic Climate Impact Assessment were used to predict future growth trends [ACIA, 2004; Kattsov and Källén, 2004]. The composite GCM included five recent-generation models that output monthly temperature and precipitation data arrayed on a 2.5° grid.

3. Statistical Modeling of Plant Growth and Climate

[10] Breiman and Cutler’s random forests (RF) ensemble prediction method was used to model Pg and climate [Breiman, 2001; Liaw and Wiener, 2002]. In the RF algorithm, prediction is obtained by aggregating regression trees constructed using different random samples of the data (i.e., bootstrap aggregation or “bagging” [Breiman, 1996]), and choosing splits of the trees from subsets of the available predictors, randomly chosen at each node [Breiman, 2001]. This ensemble regression method is a non-parametric approach for generating and combining decision trees. The RF models in this study were obtained by aggregating 1,000 regression trees. The RF model was tuned so that the number of variables tried at each split was optimized with respect to out-of-bag error estimates (the portion of the data not drawn into the sample) [Liaw and Wiener, 2002]. To perform the modeling, we randomly subset 200 million hectares. Half of the data were used to build the models and half to test the accuracy. All analysis was done with the randomForest package [Liaw and Wiener, 2002] in the R programming environment [R Core Development Team, 2005].

[11] The high latitudes of Canada experience severe temperature and precipitation seasonality. Using all the data (every month) we constructed a model whose predictions captured 98.6% of the variance in the withheld Pg data (Figure 1). This comparison indicated that seasonal climate and vegetation conditions are closely coupled, as predicted

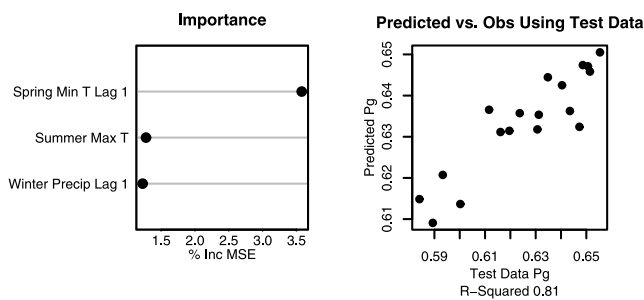
by bioclimatologic theory and dynamic global vegetation models [Lucht *et al.*, 2002].

[12] Our goal was to look beyond the magnitude and trends of Pg in the northern high latitudes, which has been the subject of considerable research using the AVHRR-NDVI record [e.g., Myneni *et al.*, 1997; Zhou *et al.*, 2001; Slayback *et al.*, 2003; Goetz *et al.*, 2005] and investigate the seasonal climate correlates of Pg in four plant functional types: conifer, deciduous, and transitional forests and tundra. While satellite proxies of Pg have a dynamic annual range, interannual changes in the signal are more than an order of magnitude smaller and more difficult to detect [Jenkins *et al.*, 2002; Xiao and Moody, 2004]. Cold and marginal environments represent the best opportunity for detecting patterns in interannual variability [Goward and Prince, 1995; Jenkins *et al.*, 2002]. We aggregated the time series for Pg and climate into four seasons: winter (DJF), spring (MAM), summer (JJA), and fall (SON). Seasonal climate data ranging from the previous spring through current summer were used to predict summer Pg because many plants, especially long-lived conifers, maintain growth stores from previous years [Larcher, 1995].

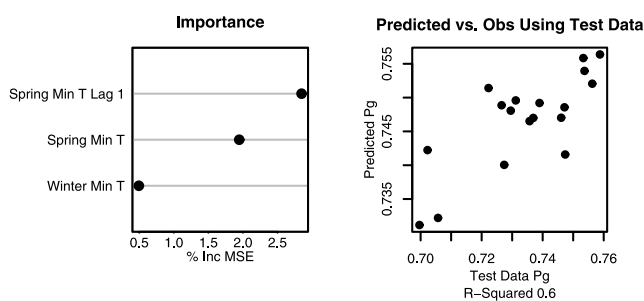
[13] The RF models predicted between 60–89% of the variance in the withheld summer Pg data, with predictive power increasing with the latitude of the cover types (Figure 2). The importance of the variables in the models was assessed by looking at each variable’s contribution to the ensemble prediction. That is, for each variable the mean square error was computed on the out-of-bag data for each tree, and then recomputed after permuting the variable 100 times. The differences were averaged and normalized by the standard error to produce a measure of importance [Breiman, 2001].

[14] All the forest groupings we examined ranked spring variables as the most important for summer Pg. The predictions for conifer forests were most strongly influenced by the previous spring minimum temperature. This association for Pg and minimum temperatures has been noted for woodlands [Xiao and Moody, 2004] and grasslands [Alward *et al.*, 1999] and has been important for modeling boreal forest net ecosystem productivity [Frolking, 1997]. Tree growth is often more strongly correlated to weather of the previous year due to needle longevity, deep rooting systems

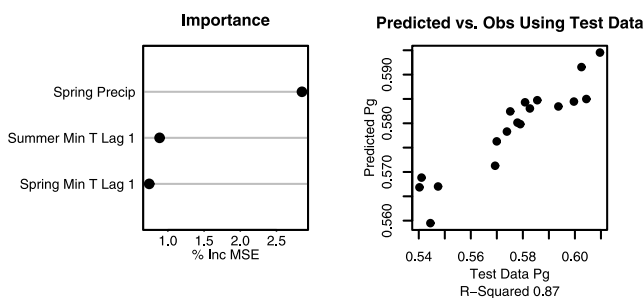
Conifer Forest



Deciduous Forest



Transitional Forest



Tundra

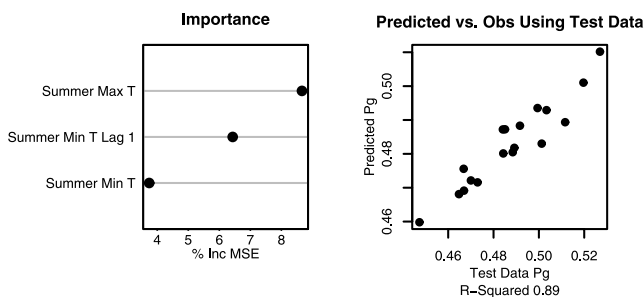


Figure 2. The importance of the top three variables for the RF model of summer Pg for four plant functional types (left). The fit between the predicted Pg and the test data is shown on the right.

and a host of other physiological factors [Fritts, 2001]. At high latitude and high elevation, spring temperatures are often the most critical for establishing the year’s growth trajectory due to the timing of snow melt [Frolking, 1997;

Peterson and Peterson, 2001]. Deciduous forest predictions also used spring minimum temperature for predicting summer Pg, and included both the current and previous year spring minimum temperature. This indicates the importance of canopy establishment in deciduous trees, which regenerate each year and are tightly bound by early growing-season conditions [Barr et al., 2004]. Growth in deciduous forest was, however, more difficult to predict, possibly because vapor pressure deficit and soil moisture products were not included in (or available for) the current analysis. Whereas we attempted to develop models that were based on widely available weather data sets, additional bioclimatic variables may improve predictions [Larcher, 1995].

[15] The high latitude transitional forest predictions keyed on the current year’s spring precipitation. We interpret this as the growth response to late lying snow cover in these higher latitude sites that determines the rate and depth of thaw. The tundra areas were the only cover type to include a summer variable as the primary predictor of growth, keying most strongly on maximum temperature. Tundra plants generally have shallow rooting systems due to the prevalence of permafrost and saturated surface soils. As a result, the tundra areas were highly dependent on summer temperatures for growth, which has been increasing over the satellite observation period [ACIA, 2004].

4. Future Predictions of Summer Plant Growth

[16] Recent research indicates that trends from 1982 to 2003 in conifer forest Pg were negligible or slightly negative, while trends in tundra areas were generally positive [Goetz et al., 2005]. We sought to project future trends in Pg using the noted responses to climate as modeled above. The GCM data were registered to the Pg data and the vegetation map and monthly climate was extracted. When the GCM climate fields were used to project future Pg with the RF model, the observed trends in Pg were predicted to continue until 2050 (Figure 3). These projections assume, however, that plant growth response to climate will remain the same as during the two-decade observational period (1982–2000), and do not directly account for the ecological implications of, e.g., greater depths of seasonal thaw [Goulden et al., 1998] or increased woody encroachment in tundra areas [Sturm et al., 2001]. Woody encroachment, in particular, has the potential to change the Pg trends in tundra areas as shrubs are released and respond to different climate forcings than the

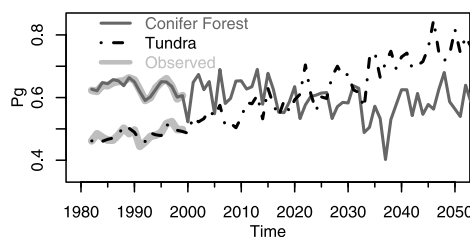


Figure 3. Projections for summer Pg for conifer forest and tundra using the composite GCM data through 2050. Fits between the models and the historical data are outlined in gray through 2000. See color version of this figure in the HTML.

herbs they replace. It is also possible that relationships observed will not hold if the climate system and ecosystems change in non-linear ways. Despite these caveats, this interplay between climate and cover types suggest that assumptions about the ubiquitous greening of high latitudes in response to global warming are overly simplistic. Our model results based on composite GCM predictions indicate that tundra Pg will approach that of conifer forests by 2020.

5. Conclusions

[17] Our results demonstrate climatic control over sub-continental-scale Pg, as observed with widely available weather station variables and satellite observational data sets. The importance of different variables in modeling summer Pg reflects the autecology of the plant functional types characterized by each broad vegetation cover type analyzed. Understanding the associations between plant growth and climate are critical given the ensemble predictions of anthropogenic-induced warming in high latitudes [ACIA, 2004]. Changes in high latitude plant growth could affect the carbon cycle in terms of terrestrial sequestration of carbon in standing stocks [Houghton, 2003] and woody encroachment of trees into tundra areas [Sturm et al., 2001]. Changes in plant growth can also cause feedbacks to the climate system by way of changing surface albedo and disturbance regimes [ACIA, 2004]. Our results indicate that different vegetation cover types respond uniquely to climate, and that changes in growth are likely to be specific to plant functional types. Predictions through 2050 indicate that tundra ecosystems will continue to increase in photosynthetic activity relative forest ecosystems. Models that predict the interplay between climate and vegetation need to account for these differential plant-type responses in order to adequately capture the direction and magnitude of growth trends taking place under a dynamic climate system.

[18] **Acknowledgment.** We gratefully acknowledge support from NOAA's Carbon Cycle Science Program.

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