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Northern High-Latitude Ecosystems Respond to Climate Change

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The northern high latitudes are an area of particular importance to global climate change. As a system dependent on freezing conditions, the top of the planet contains vast amounts of carbon in biomass, soils, and permafrost that have the potential to interact with the atmosphere through the biosphere, hydrosphere, lithosphere, and cryosphere. If released en masse, this carbon would greatly exacerbate the levels of greenhouse gases in the atmosphere.

Over the past 2 years, a growing body of research has provided evidence of substantial but idiosyncratic environmental changes, with some surprising aspects, across the region. This article reviews some recent findings and presents a new analysis of northern vegetation photosynthetic and productivity trends tracked from Earth-observing satellites.

Monitoring the Arctic Ecosystem

Since the early 1980s, atmospheric carbon dioxide (CO_2) concentrations have increased by more than 40 parts per million globally, due largely to anthropogenic emissions from fossil fuel burning. Northern latitude heating over the approximately 125-year instrumental record, especially above 50°N, is well documented [*Hansen et al.*, 2006]. Surface changes coinciding with these perturbations include 5- to 13-day advances in the onset of northern growing seasons, increases in boreal insect disturbance, and increases in fire frequency and severity.

Ecosystem responses to heating also have been observed and catalogued in various ways [*Walker et al.*, 2006]. These include fairly straightforward responses of cold-limited systems where plant growth and establishment are increasing along with temperature, such as higher shrub density [*Tape et al.*, 2006] and latitudinal tree line advance [*Lloyd*, 2005]. These changes in the high latitudes are strongly tied to changes in albedo and energy budgets [*Chapin et al.*, 2005].

Nonintuitive responses also have been observed, including declines in tree ring widths in some locations [*D'Arrigo et al.*, 2007], flat to declining trends in boreal forest greenness [*Goetz et al.*, 2005], and associated model simulations of recent declines in terrestrial vegetation productivity (K. Zhang et al., Satellite remote sensing detection of a recent decline in northern high-latitude terrestrial vegetation productivity with regional warming and drying, submitted to *Journal of Geophysical Research-Biogeosciences*, 2007, hereinafter referred to as K. Zhang et al., submitted manuscript, 2007). Flux towers across Canada, which calculate net ecosystem exchange of carbon, indicate that some sites are carbon neutral even in the presence of higher temperatures [*Bergeron et al.*, 2007].

These observations typically show large spatial and temporal variability, requiring a more nuanced framework for understanding how changes in high-latitude ecosystems

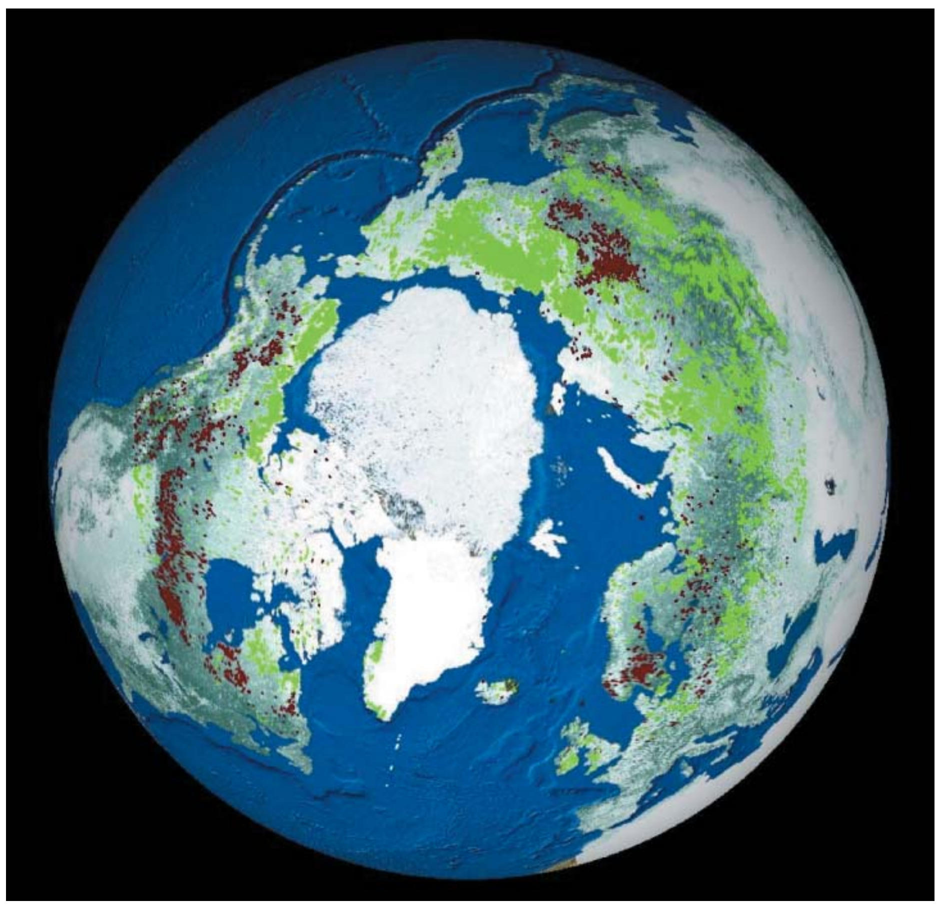

Fig. 1. Spatial distribution of trends in May to August photosynthetic activity (Pg) across the northern high latitudes from 1981 through 2005. Significant positive trends in Pg are shown in green, and negative trends are shown in rust. Areas of croplands, identified by the GLC2000 land cover data set (http://www-gvm.jrc.it/glc2000/), are not included in the analyses. The trends in Pg are overlaid on the percent of tree cover layer from the MODIS Vegetation Continuous Fields product (http://glcf.umiacs.umd.edu/data/vcf/) and show that most of the positive trends in Pg occur in areas with little or no forest.

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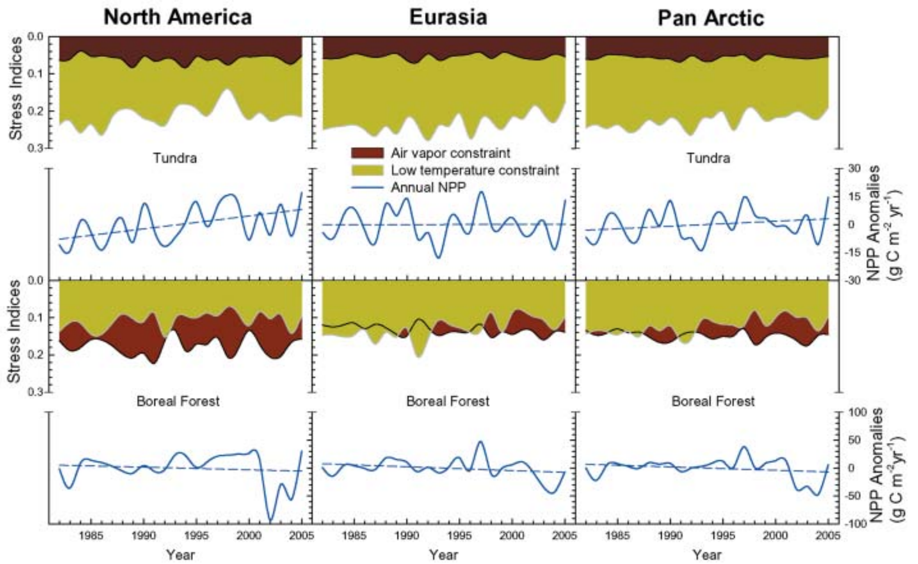

Fig. 2. Annual variations in estimates of vegetation net primary production (NPP) are shown with relative summertime stresses on vegetation for tundra and boreal forest. Rising temperatures and associated relaxation of low-temperature constraints to productivity drove a generally increasing trend in tundra NPP over the 24-year period, whereas increasing drought conditions after 2000 contradict the potential benefits of warmer temperatures and led to a large drop in NPP for boreal forest regions

will affect global carbon, water, and energy cycles in a hotter climate. Many studies are spatially limited or include data only through the first part of this century, and it is particularly important to include more extensive and recent observations because heating over the past few years is likely to be important in highlighting mechanisms controlling ecosystem responses.

Satellite Data of Arctic Photosynthetic Activity

Global satellite remote sensing data now span a continuous record exceeding 25 years, providing observations of the northern latitudes that are well calibrated, systematic, and sensitive to multiple biophysical variables.

We updated and expanded a photosynthetic trend analysis of the northern high-latitude normalized difference vegetation index (NDVI) record from the NOAA advanced very high resolution radiometer (AVHRR) satellite sensor time series as a direct estimate of terrestrial photosynthetic activity (*Pg*, after *Goetz et al.* [2005]). These data were produced as part of the Global Inventory Mapping and Monitoring Studies (GIMMS) project at NASA Goddard Space Flight Center [*Tucker et al.*, 2005], the longest-running routinely acquired satellite observations available globally. The data have been processed to account for orbital drift, cloud cover, sensor degradation, and the emission of volcanic aerosols. The time series currently runs from late 1981 through 2005. In analyzing the 25-year GIMMS-NDVI time series for each 8-kilometer land surface pixel, we excluded agricultural areas and the glaciated areas of Greenland above 50°N and we took into consideration the late May through August growing season (see *Bunn and Goetz* [2006] for consideration of alternate growing season windows).

A primary difficulty in understanding trends in the northern high latitudes is incorporating the multiyear lags in ecosystem production that are inherent to the long-lived and slow growing vegetation species that dominate the boreal forest. After data filtration to separate random trends from bona fide increases in *Pg*, we found that most of the northern high latitudes (88%) showed no significant deterministic trend in satellite-derived *Pg* over the period (Figure 1 and Table 1). Of the areas that show 'greening' trends—increases in photosynthetic activity—nearly all were in tundra or grassland areas. By contrast, the majority of 'browning' trends—declines in photosynthetic activity—were in forested areas. Those forest areas that showed greening were sparsely wooded taiga where the greening signal is presumably influenced by nonforest vegetation. These results are consistent with our other recent trend analyses and show that the northern high latitudes are not responding in a simple linear way to increased temperatures and potential growing season length.

Areas without significant trends in *Pg* are explained by related production efficiency model (PEM) calculations of regional net primary production (NPP), which incorporate satellite estimates of photosynthetic leaf area and surface meteorological information on atmospheric moisture as well as estimates of temperature controls on plant photosynthesis and respiration.

To assess annual NPP over the same region and time period described above, we applied the PEM, augmented with Moderate Resolution Imaging Spectroradiometer (MODIS) imagery and with daily National Centers for Environmental Prediction 'reanalysis' surface meteorology inputs that were corrected for regional bias by using the pan-boreal surface weather station network (K. Zhang et al., submitted manuscript, 2007). Mean annual NPP for the entire domain showed a significant positive productivity trend of 0.14% per year during the 1980s and 1990s, which coincided with rising temperatures and associated relaxation of low-temperature constraints on vegetation growth (Figure 2). Positive regional growth trends of the past two decades, however, were replaced by NPP declines after 2000, especially in boreal forests of Eurasia and Canada.

These results also showed that increasing moisture stress, indicated by a positive trend in the mean daily atmospheric vapor pressure deficit (VPD), offsets the potential benefits of longer growing seasons and low-son of these data with regional forest stand inventory records also indicates that the NPP decline was widespread and unprecedented for at least the past 50 years across central and western Canada, and for the past 24 years for the larger circumpolar Arctic.

Other Satellite-Derived Trends

Satellite observations of northern productivity trends conform to a host of other evidence indicating widespread changes coincident with a hotter climate.

Historical station records and recent Intergovernmental Panel on Climate Change climate model projections indicate greater regional precipitation trends in the high northern latitudes, while our satellite-based productivity trends indicate a recent widespread decline in boreal forest productivity due to drought. The apparent discrepancy between water supply and productivity trends can be explained by examining other components of the terrestrial water balance: $P - ET - Q = \Delta S$, where P is precipitation, ET is water loss through evapotranspiration, Q is discharge, and ΔS is the net change in water storage in plants, soil, and snow cover. Positive vegetation growth trends during the 1980s and 1990s coincided with higher temperatures and with earlier and longer growing seasons. Warmer temperatures increase the capacity of the atmosphere to hold moisture, however, and they impose stress on relatively low productivity boreal ecosystems to meet the additional evaporative demand. Regional declines in permafrost and deepening of the seasonal soil active layer with heating are likely increasing soil drainage and the volume of potential soil water storage for the region. River discharge trends from regional observation networks show a variable response to heating, with positive trends across large areas of Eurasia and declining trends across major portions of boreal North America [*Peterson et al.*, 2006].

The net effect of these changes appears to be a widespread decline in plant-available moisture, with associated impacts on forest

Table 1. Areas of significant deterministic trends in *Pg* by major land classes in 10^6 hectares.

Vegetation Type	*Declining*	*Increasing*
All	86.1 (3%)	266.2 (9%)
Needle-leaved Evergreen Forest	37.8 (6%)	25.9 (4%)
Sparse Deciduous Forest (mostly Larch)	18.1 (4%)	64.4 (15%)
Herbaceous or Shrub	4.8 (1%)	31.9 (6%)

productivity after 2000. These recent changes have been shown to reduce the seasonal amplitude of atmospheric CO_2 concentrations [*Buermann et al.*, 2007]. Although the boreal forest ecosystem has sometimes been referred to as a 'green desert,' it is rarely thought to be moisture-limited. Nonetheless, boreal forests have adapted to climate conditions in which hot and dry air masses are relatively rare, and as such, the common boreal tree species are less productive under these conditions. Plot level measurements that document moisture-limitation [see *Hall*, 1999] are now apparent in the ever-lengthening satellite record.

More detailed and coordinated work is required for the research community to reconcile the various changes being documented across the northern high latitudes. The International Polar Year, which runs through March 2009, provides an opportunity to combine in situ and space-based measures with models for the comprehensive assessment of the pan-Arctic to further understand how high-latitude ecosystems are responding to a changing climate.

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Turkey Makes Major Investment in Earthquake Research

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Following the devastating M_w 7.4 İzmit earthquake on 17 August 1999, major state-of-the-art earthquake studies were conducted in the Marmara region of northwestern Turkey. However, other faults with the potential to generate big and potentially devastating earthquakes occur in a variety of different tectonic regimes in Turkey, and these faults and regions have not received similar attention.

For example, the East Anatolian Fault (EAF) is influenced by the convergence of the Arabian and Anatolian plates along the Zagros-Bitlis suture zone. Faults in the Aegean Extensional Province (AEP) are purely normal faults. The main faults in the Marmara region occur within both transtensional and transpressional domains (locations are shown in Figure 1). All of these regions pose seismic hazards and also require focused study.

Therefore, different methods for earthquake prediction and hazard estimation are needed in each tectonic regime where the faults are subject to different forces and the earthquakes generated may provide different signals in the preseismic earthquake preparation period.

The Scientific and Technological Research Council of the Turkish Republic (TÜBİTAK) recently granted US$12 million to a consortium for a multidisciplinary and multilateral earthquake research project that started in November 2005 and will be completed by November 2009. A consortium member, the Earth and Marine Sciences Institute of the Marmara Research Center (MRC) of TÜBİTAK, is leading and coordinating the multilateral project, "Multi-Disciplinary Earthquake Researches in High Risk Regions of Turkey Representing Different Tectonic Regimes." Other consortium members are the Ministry of Construction and Settlement's General Directorate of Disaster Affairs (GDDA) and 14 universities. Several studies supported by the project include international collaboration with the U.S. Geological Survey; Massachusetts Institute of Technology's Earth Resources Laboratory; University of California, Berkeley; and the University of Darmstadt, Germany. Additional collaborations will be established as needed.

This new project focuses multidisciplinary studies in the Marmara Sea/Istanbul region, which is believed to be a seismic gap (a region seismically inactive at present but accumulating stress and thus posing great danger) and also in other regions where large earthquakes are expected, including the region encompassing the East Anatolian Fault System (EAFS) and the Aegean Extensional System (EAS). Realistic countrywide estimates of earthquake risk require mapping active faults, determining the strain accumulation and stress buildup as a function of space and time on these faults, determining the temporal and spatial distribution of historic and prehistoric earthquakes, monitoring a variety of phenomena (i.e., the time variation of the emanation of gas and water from faults as well as small earthquakes and the deformation of the crust) that may provide indications of future earthquakes, and better understanding the interaction between adjacent active fault segments.

These efforts require the continuation of ongoing geophysical and geological studies as well as the application of new methods of observations toward understanding earthquake processes. Multidisciplinary approaches being used include seismology, borehole tilt/strain measurements, Global Positioning System (GPS)/interferometric synthetic aperture radar (InSAR), and geochemistry of gas and water emanating from major fracture zones. These observations