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 (CO₂) 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.

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-gcm.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://gcftp.umiacs.umd.edu/data/vcf/) and show that most of the positive trends in Pg occur in areas with little or no forest.
Activity
Satellite Data of Arctic Photosynthetic heating over the past few years is likely to be extensive and recent observations because cycles in a hotter climate. Many studies are sensitive to multiple biophysical variables. Spanning a continuous record exceeding 25 years, satellite sensor time series as a direct estimate of terrestrial photosynthetic activity—nearly all were in tundra or grassland 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 \( P_g \) 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 Inter-governmental 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: \[ P - ET = Q = \Delta S \]

The net effect of these changes appears to be a widespread decline in plant-available moisture, with associated impacts on forest ecosystems.
productivity after 2000. These recent changes have been shown to reduce the seasonal amplitude of atmospheric CO2 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 [see Plot level measurements that document such, the common boreal tree species and dry air masses are relatively rare, and desert,’ it is rarely thought to be moisture-

Although the boreal forest ecosystem has
understood how high-latitude ecosystems are responding to a changing climate.

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References

Chapin, F. S., III, et al. (2005), Role of land-surface changes in Arctic summer warming, Science, 310, 657–660.
D’Arrigo, R., R. Wilson, B. Liepert, and P. Cherubini (2007), On the “divergence problem” in northern

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

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Declining</th>
<th>Increasing</th>
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<tbody>
<tr>
<td>All</td>
<td>86.1 (3%)</td>
<td>266.2 (9%)</td>
</tr>
<tr>
<td>Needle-leaved Evergreen Forest</td>
<td>37.8 (6%)</td>
<td>25.9 (4%)</td>
</tr>
<tr>
<td>Sparse Deciduous Forest (mostly Larch)</td>
<td>18.1 (4%)</td>
<td>64.4 (15%)</td>
</tr>
<tr>
<td>Herbaceous or Shrub</td>
<td>4.8 (1%)</td>
<td>31.9 (6%)</td>
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