

Effect of climate and CO₂ changes on the greening of the Northern Hemisphere over the past two decades

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[1] Study of the effect of current climate changes on vegetation growth, and their spatial patterns improves our understanding of the interactions between terrestrial ecosystems and climatic systems. This paper explores the spatial patterns of vegetation growth responding to climate variability over Northern Hemisphere (>25°N) from 1980 to 2000 using a mechanistic terrestrial carbon model. The results indicate that changes in climate and atmospheric CO₂ likely function as dominant controllers for the greening trend during the study period. At the continental scale, atmospheric CO₂, temperature, and precipitation account for 49%, 31%, and 13% of the increase in growing season LAI, respectively, but their relative role is not constant across the study area. The increase in vegetation activity in most of Siberia is associated with warming, while that in central North America is primarily explained by the precipitation change. The model simulation also suggests that the regression slope of LAI to temperature increases with soil moisture, but decreases with temperature. This implies that the contribution of rising temperature to the current enhanced greening trend will weaken or even disappear under continued global warming. We also find that the effects of both vegetation precipitation use efficiency and atmospheric CO₂ fertilization on the greening trend increase as soil moisture becomes limiting. **Citation:** Piao, S., P. Friedlingstein, P. Ciais, L. Zhou, and A. Chen (2006), Effect of climate and CO₂ changes on the greening of the Northern Hemisphere over the past two decades, *Geophys. Res. Lett.*, *33*, L23402, doi:10.1029/2006GL028205.

1. Introduction

[2] Understanding how vegetation growth responded to the interannual climatic variations in the recent decades is a critical requisition for projecting future ecosystem dynamics. Enhanced terrestrial vegetation growth in the middle and high latitudes of the Northern Hemisphere over the past two decades has been well documented [Zhou *et al.*, 2001; Nemani *et al.*, 2003]. However, the mechanisms for this phenomenon are still under debate. For example, Ahlbeck [2002] employed statistical analysis methods to demonstrate that the increase in atmospheric CO₂ concentration was the primary driving force for enhanced vegetation growth, while Kaufmann *et al.* [2002] suggested that the greening

of northern region was chiefly driven by rising temperature. More recently, Lucht *et al.* [2002] found that temperature change alone largely explained the vegetation greening trend in the boreal region. Concurrently increased precipitation is also suggested as a possible cause for the increase in vegetation productivity over China and USA [Piao *et al.*, 2005; Nemani *et al.*, 2002].

[3] There is little doubt that many environmental factors affect vegetation dynamics. The real question is how much each major factor contributes to the observed signals. On the other hand, since the drivers of this change, especially climate factors, exhibit distinct temporal and spatial variations, the recent responses of vegetation activity to global change were spatially heterogeneous [Myneni *et al.*, 1997a; Zhou *et al.*, 2001]. A few studies have been conducted to evaluate the relative roles of different factors that may be responsible for the enhanced vegetation growth [e.g., Lucht *et al.*, 2002], but little has been done to estimate the spatial patterns of these possible mechanisms.

[4] The primary purpose of this article is to investigate the spatial patterns of mechanisms controlling current enhanced vegetation growth in the Northern Hemisphere, using a mechanistic terrestrial carbon model ORCHIDEE (Organizing Carbon and Hydrology In Dynamic Ecosystems model) and relevant data sets. We focus on how recent changes in precipitation, temperature, atmospheric CO₂ concentration have influenced vegetation growth over different regions in the mid and high latitudes of the Northern Hemisphere (>25°N) during the period of 1980–2000. We infer vegetation growth stage from both the model simulated and satellite derived leaf area index (LAI) value during the growing season (May to September).

2. Methods and Data Sets

[5] The ORCHIDEE model is a process oriented dynamic global vegetation model (DGVM) which simulates global carbon and water cycles [Krinner *et al.*, 2005]. The ORCHIDEE model is composed of three coupled sub-models: a surface-vegetation-atmosphere transfer model SECHIBA, a biogeochemical process model STOMATE and a third model dealing with ecosystem dynamics (i.e., sapling establishment, light competition, tree mortality) inspired from LPJ [Sitch *et al.*, 2003]. SECHIBA simulates on a half-hourly time step the processes of photosynthesis, energy and water exchanges between atmosphere and land, as well as the soil moisture budget. The development of foliage and the flows of carbon within the ecosystem pools (i.e., carbon allocation, litter decomposition, and soil carbon decomposition) are calculated by the STOMATE sub-model, at a daily time step. ORCHIDEE consists of five vegetation carbon reservoirs, four litter reservoirs, and three soil reser-

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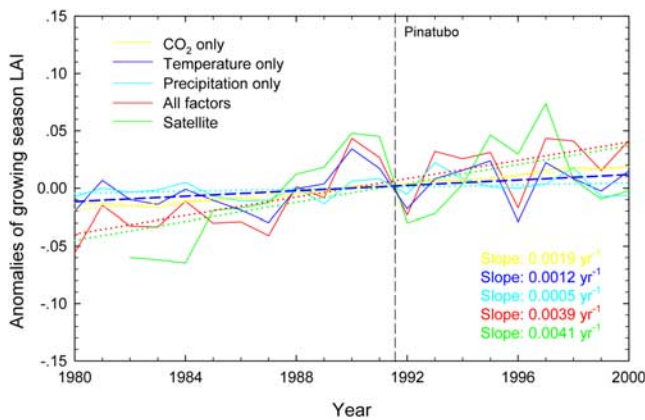


Figure 1. Interannual changes in anomalies of growing season (May–September) LAI in Northern Hemisphere ($>25^{\circ}\text{N}$) estimated by simulation S1 (only considered CO_2 increase effects), S2 (only considered temperature change), S3 (only considered precipitation change), S4 (considered the effect of atmospheric CO_2 and climate variability) and remote sensing.

voirs. The vegetation assimilation in ORCHIDEE is based on work by Farquhar *et al.* [1980] for C3 plants and Collatz *et al.* [1992] for C4 plants. Carbon allocation among leaves, stem and roots occurs according to the allocation scheme of Friedlingstein *et al.* [1998]. In the model, the LAI is calculated from foliage biomass, assuming a fixed specific leaf area (SLA) value. The model has been extensively validated against observed eddy covariance flux data at various sites around the world [Krinner *et al.*, 2005]. It also realistically simulates the distribution of global LAI and transient responses of carbon fluxes to climate variability [Krinner *et al.*, 2005; Ciais *et al.*, 2005].

[6] After running the ORCHIDEE model at the spatial resolution of 2 degree until the carbon pools reach equilibrium based on transient climate (1901–1910) [Mitchell and Jones, 2005] under constant pre-industrial atmospheric CO_2 concentration of 286.05ppm, we made simulations from 1860 to 1900 with the variable climate of the period of 1901–1910 and CO_2 concentration data during 1860–1900. It was then run to 1979 with transient climate forcing [Mitchell and Jones, 2005] and historical atmospheric CO_2 concentration data [Rayner *et al.*, 2005]. This state was used as the initial condition for the 1980–2000 simulation. In order to assess the relative contribution of rising atmospheric CO_2 concentration, temperature, precipitation, and other climate factors, we generated four simulations using different input variable during 1980–2000, as in a previous study [Lucht *et al.*, 2002]. In simulation S1, only atmospheric CO_2 is varied, and climate variables are held constant. In Simulation S2, only temperature is varied, and in Simulation S3, only precipitation is varied. In the last simulation, S4, atmospheric CO_2 and all climate variables are varied. The effects of other climate changes except temperature and precipitation are evaluated by subtracting the sum of S1, S2 and S3 from simulation S4. Finally, the individual contribution of each factor (atmosphere CO_2 , temperature, and precipitation) is defined as the ratio of

growing season LAI trend from each corresponding simulation (S1, S2, S3, respectively) to that of the simulation S4.

[7] Here we use a satellite-derived LAI dataset to validate our simulations. A global LAI data set was created from satellite observations of normalized difference vegetation index (NDVI) using a three-dimensional radiative transfer model and a global land cover map [Myneni *et al.*, 1997b] for the period 1981–2000. The NDVI data set was acquired from the Global Inventory Monitoring and Modeling Studies (GIMMS) group derived from the NOAA/AVHRR series satellites (NOAA 7, 9, 11 and 14) as documented in previous studies [e.g., Zhou *et al.*, 2001; Slayback *et al.*, 2003; Tucker *et al.*, 2005].

3. Results and Discussion

[8] Figure 1 illustrates interannual variations in model simulated and satellite derived mean growing season LAI in Northern Hemisphere ($>25^{\circ}\text{N}$) during 1980–2000. The ORCHIDEE simulated growing season LAI from simulation S4 shows a significant increasing trend with a rate of 0.0039 yr^{-1} which is close to the result from satellite data (0.0041 yr^{-1}). Contrary to the previous claim that the aerosols induced an increase in the diffuse fraction of shortwave downwelling radiation by the volcanic eruption of Mount Pinatubo in 1991 may enhance vegetation growth [Gu *et al.*, 2003], a significant LAI decline over the entire study area during 1992 was found in both the S4 simulation (-0.023) and the remote sensing observation (-0.029).

[9] The general agreement of LAI trend and its interannual variability generated from simulation S4 with satellite derivation ($R = 0.63$, $P = 0.004$) suggests that it is possible to use the ORCHIDEE model simulations to evaluate the mechanisms controlling the LAI changes. It is revealed from Figure 1 that the interannual changes of LAI in Simulation S4 and remote sensing data matches most closely with that in Simulation S2 which only considers temperature effects ($R = 0.87$, $P < 0.001$; $R = 0.57$, $P = 0.011$, respectively). However, due to increase in growing season LAI caused by precipitation change, modeled LAI show slight increasing trend from 1995 to 1998, while satellite derived LAI indicate decreasing trend during the same period. On the other hand, in simulation S1, the growing season LAI has a larger positive trend (0.0019 yr^{-1}) than in simulation S2 and S3. This result indicates that at the continental scale, the increase of LAI in the Northern Hemisphere seems to be primarily driven by increasing atmospheric CO_2 concentration (accounting for 49%), while the interannual variations in LAI are controlled by temperature change. In response solely to temperature changes (simulation S2), the growing season LAI has increased by 0.0012 yr^{-1} , contributing about 31% of the increase in S4 simulation. About 13% of LAI positive trend comes from the effects of precipitation changes.

[10] The spatial distribution of the ORCHIDEE simulated growing season LAI trends and their dominant driving factors are shown in Figure 2. While LAI increase/decrease may be attributed to more than one factor, at any given location, the one with highest contribution is defined as the factor with largest LAI increase/decrease for that location. The LAI trend in simulation S4 (Figure 2d) has quite similar

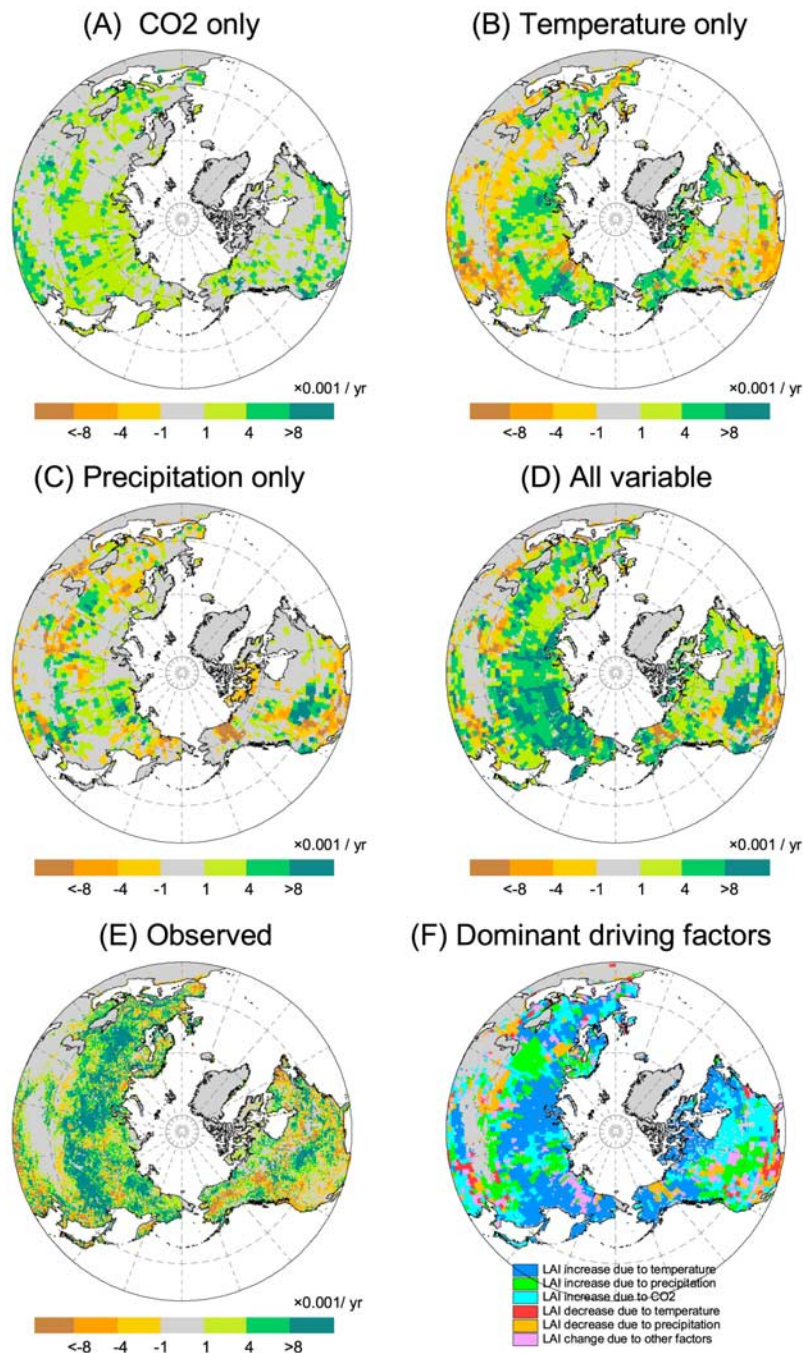


Figure 2. (a–e) Spatial distribution of growing season LAI trends and (f) their dominant driving factors from 1980 to 2000. (a) simulation S1, (b) simulation S2, (c) simulation S3, (d) simulation S4, and (e) remote sensing derived data. Color bar in Figures 2a–2e: trends in growing season LAI ($\times 0.001 \text{ yr}^{-1}$).

spatial patterns in comparison to analyses based on remote sensing (Figure 2e) as well, although there exists some difference in northern Europe and northeastern North America. It should be noted that changes in the remote sensing derived LAI can result not only from the effects of climate and CO_2 , but also from outbreaks of insect-caused tree death, and anthropogenic activities such as land management, afforestation, and deforestation. The most pronounced LAI increase appears in the boreal region ($>50^\circ\text{N}$), particularly over Eurasia. However, the driving force for this phenomenon is not the same across the continent. For

example, substantial LAI increase in Northwestern Siberia is explained by temperature warming (Figures 2b and 2f), while precipitation increase is the major force accounting for the LAI trends in North Sakha of Russia (Figures 2c and 2f). Additionally, remarkable increase in LAI is also simulated over the central and southeastern North America [Hicke *et al.*, 2002]. The increase in LAI in central North America is primarily attributed to precipitation changes (Figures 2c and 2f), while in southeastern North America, rising atmospheric CO_2 is the main cause. On the other hand, our simulations reveal that, unlike in boreal region,

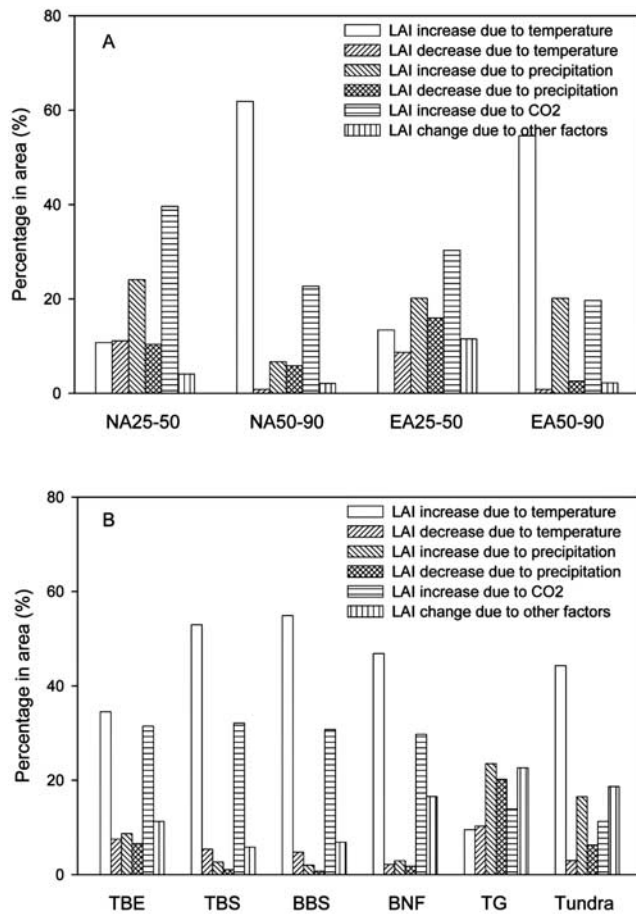


Figure 3. Ratios of areas occupying by each factor to the total for different (a) regions and (b) vegetation types. NA25-50, temperate region in North America (25–50°N); NA50-90, boreal region in North America (50–90°N); EA25-50, temperate region in Eurasia (25–50°N); EA50-90, boreal region in Eurasia (50–90°N); TBE, Temperate broadleaf evergreen forest; TBS, Temperate broadleaf summergreen forest; BBS, Boreal broadleaf summergreen forest; BNF, Boreal needleleaf forest; TG, Temperate grassland.

current rise in temperature alone does not benefit vegetation growth in most temperate areas (Figure 2c), although a significant positive relationships between NDVI and temperature is reported from previous study [Ichii *et al.*, 2002].

[11] To compare the driving forces for LAI changes between temperate and boreal regions, we divided the entire study area into 4 regions by continents and latitudes. For each region, we calculated the fraction of area controlled by each different driving force, which is shown in Figure 3a. This figure clearly depicts that the mechanisms of LAI changes are conspicuously different between boreal and temperate region. In the boreal region, the area where LAI increased mainly in response to temperature change is about 53% in Eurasia and 61% in North America, suggesting that temperature is the dominant controller responsible for enhanced vegetation growth over this region [Lucht *et al.*, 2002]. In contrast, the increase of LAI over temperate region stemmed primarily from atmospheric CO₂ fertilization effect (30% area of temperate Eurasia and 37% of

temperate North America), and precipitation (20% of temperate Eurasia and 21% of temperate North America).

[12] Different vegetation types are also dominated by different driving factors (Figure 3b). The modeled increase in growing season LAI for all forest types is primarily because of global warming, and atmospheric CO₂ fertilization effect. For the temperate grassland, precipitation change has played the largest role for its LAI increase trend, while temperature and precipitation changes are the dominant driving factors of enhanced vegetation growth for tundra.

[13] Next, to further understand how the influence of climate or CO₂ on vegetation growth varies with other variables, we calculated the regression slopes of growing season LAI versus CO₂, temperature, and precipitation for each grid cell in each simulation S1, S2, and S3, respectively. The results show that the slope of LAI versus temperature significantly increases with increasing soil moisture ($R = 0.36$, $P < 0.001$) (Figure 4a), and decreases with rising temperature ($R = -0.44$, $P < 0.001$) (Figure 4b). The vegetation response to temperature for each grid cell (S_{LAI-T}) can be expressed as a function of soil moisture and temperature (equation 1).

$$S_{LAI-T} = 0.0005 \times Sm - 0.0016 \times T - 0.122 \quad (1)$$

· ($R = 0.51$, $P < 0.001$)

where T is temperature (°C), Sm is soil moisture content (mm), and S_{LAI-T} is the slope of LAI versus temperature (°C⁻¹) in each pixel representing the local vegetation response to temperature. This equation further describes that the effects of increasing temperature on vegetation growth depend partly on the balance between its positive effect through extending the growing season and negative effect through extending the soil moisture stress. Dry and warm conditions are associated with negative consequences for vegetation growth in response to increasing temperature, whereas wet and cool areas tend to have largest increase in vegetation growth with rising temperature.

[14] A significant and negative relationship is found between soil moisture content and the slope for LAI versus precipitation ($R = -0.49$, $P < 0.001$), suggesting that the vegetation precipitation use efficiency tend to increase as soil moisture becomes limited. Similar biosphere responses to precipitation are also found in previous studies based on long-term ground measurements [Huxman *et al.*, 2004] and remote sensing data [Prince *et al.*, 1998]. On the other hand, increase in soil moisture reduces the regression slope between LAI and atmospheric CO₂ ($R = -0.23$, $P < 0.001$), indicating possible greater atmospheric CO₂ fertilization effects over water stressed ecosystems.

4. Summary

[15] The model analyses of LAI trends over the last 20 years presented in this study are consistent with widespread reports of enhanced plant growth over northern ecosystems during the past two decades, and demonstrate that concurrent changes in climate and atmospheric CO₂ are the likely drivers of such greening trend. Moreover, our results also showed that the dominant controlling factor

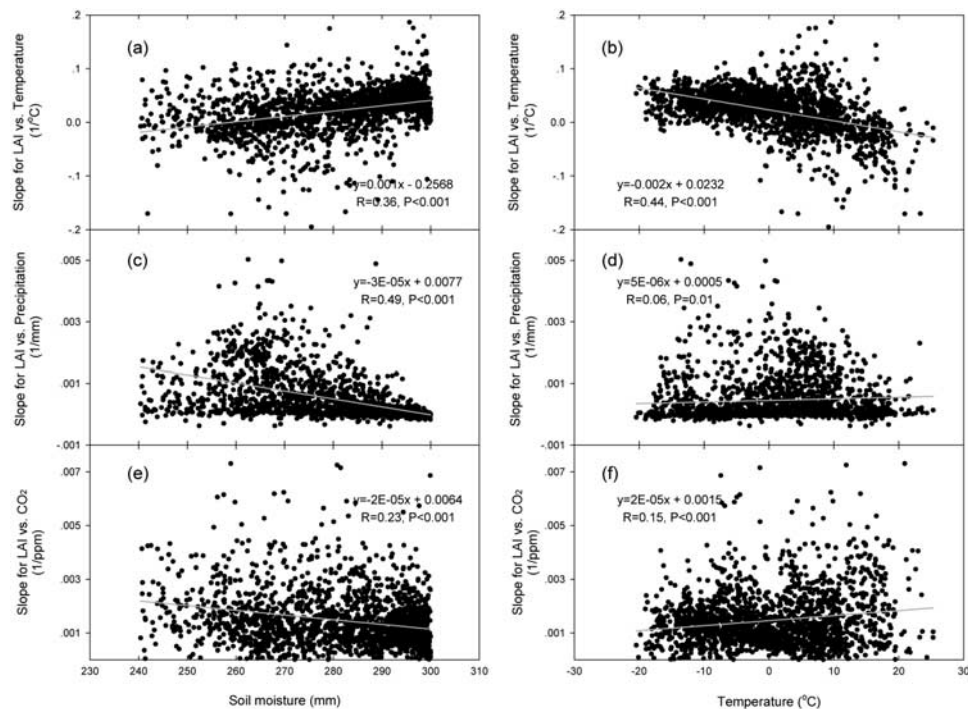


Figure 4. The relationships between (a) regression slope for LAI versus temperature and annual mean soil moisture, (b) regression slope for LAI versus temperature and annual mean temperature, (c) regression slope for LAI versus precipitation and annual mean soil moisture, (d) regression slope for LAI versus precipitation and annual mean temperature, (e) regression slope for LAI versus atmospheric CO₂ and annual mean soil moisture, and (f) regression slope for LAI versus atmospheric CO₂ and annual mean temperature. The regression slope for LAI versus temperature is calculated based on S2 simulation, and regression slope for LAI versus precipitation is calculated based on S3 simulation, and regression slope for LAI versus atmospheric CO₂ is calculated based on S1 simulation.

governing vegetation change is not constant across the Northern Hemisphere. Approximately 56% of the boreal regions have experienced an increase in LAI primarily due to temperature change. In contrast, vegetation growth in most temperate areas showed a negative trend LAI with current temperature change alone. Overall, the high degree of spatial heterogeneity of the mechanism investigated here point out a need for detailed studies using high spatial resolution climate data sets at different scales.

[16] It is always a challenge to predict potential vegetation growth in response to changing future climate regimes. Despite evidence that there are significant positive correlations between temperature and vegetation growth observed in this study and previous satellite based analysis [Zhou *et al.*, 2001], it would be too simplistic a conclusion that such greening trend of the Northern Hemisphere will be persistent as climate continues warming. The relationship of the response of LAI to temperature with soil moisture (positive correlation) and with temperature (negative relationships) presented here suggest that the effects of rising temperature on vegetation growth is likely dependent on both future changes in temperature and precipitation regimes. If there are no increases in precipitation associated with rising temperature, the current positive effect of warming on vegetation growth in the boreal region may weaken, or vegetation growth may even decline as observed recently [Angert *et al.*, 2005]. This is because the moisture deficit due to increasing evapotranspiration demand in a warmer world may negate the positive effect of temperature on

vegetation growth through extending the growing season length.

[17] In addition, the negative correlations between the LAI-precipitation slope and ambient soil moisture, and between LAI - CO₂ slope and soil moisture, suggest that vegetation resource use efficiency at large scale, such as the rain use efficiency and atmospheric CO₂ fertilization effect is modified by soil moisture contents, implying potential acclimation of vegetation under environmental change.

[18] In summary, while our estimates of the vegetation response to climate change provide new insight in combining remote sensing data with ecosystem models, there are a few points that deserve further study. Although the simple empirical statistical approach for evaluating temperature impacts on vegetation growth developed in this work should benefit our understanding and projection of terrestrial ecosystem responses to climate change, further validation and correction based on long-term ecosystems experimental studies are necessary. On the other hand, while general agreement exists between model estimated and satellite derived LAI, these simulations do not consider land use change, nitrogen deposition, and ozone pollution which inevitably introduce some uncertainty in model simulations. Further studies are needed to quantify the effects of all these factors on vegetation growth.

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