ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Causes of spring vegetation growth trends in the northern mid–high latitudes from 1982 to 2004

To cite this article: Jiafu Mao *et al* 2012 *Environ. Res. Lett.* **7** 014010

Environ. Res. Lett. **7** (2012) 014010 (7pp) doi:10.1088/1748-9326/7/1/014010

Causes of spring vegetation growth trends in the northern mid–high latitudes from 1982 to 2004

Jiafu Mao[1,3], Xiaoying Shi[1], Peter E Thornton[1], Shilong Piao[2] and Xuhui Wang[2]

[1] Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[2] Department of Ecology, College of Urban and Environmental Science, Peking University, Beijing 100871, People's Republic of China

E-mail: maoj@ornl.gov

Received 14 December 2011
Accepted for publication 4 January 2012
Published 24 January 2012
Online at stacks.iop.org/ERL/7/014010

Abstract
The Community Land Model version 4 (CLM4) is applied to explore the spatial–temporal patterns of spring (April–May) vegetation growth trends over the northern mid–high latitudes (NMH) (>25°N) between 1982 and 2004. During the spring season through the 23 yr period, both the satellite-derived and simulated normalized difference vegetation index (NDVI) anomalies show a statistically significant correlation and an overall greening trend within the study area. Consistently with the observed NDVI–temperature relation, the CLM4 NDVI shows a significant positive association with the spring temperature anomaly for the NMH, North America and Eurasia. Large study areas experience temperature discontinuity associated with contrasting NDVI trends. Before and after the turning point (TP) of the temperature trends, climatic variability plays a dominant role, while the other environmental factors exert minor effects on the NDVI tendencies. Simulated vegetation growth is broadly stimulated by the increasing atmospheric CO_2. Trends show that nitrogen deposition increases NDVI mostly in southeastern China, and decreases NDVI mainly in western Russia after the temperature TP. Furthermore, land use-induced NDVI trends vary roughly with the respective changes in land management practices (crop areas and forest coverage). Our results highlight how non-climatic factors mitigate or exacerbate the impact of temperature on spring vegetation growth, particularly across regions with intensive human activity.

Keywords: vegetation growth trends, temperature turning point, NDVI, CLM4

S Online supplementary data available from stacks.iop.org/ERL/7/014010/mmedia

1. Introduction

Remarkable global warming has been documented in recent decades, especially during the spring in the Northern Hemisphere (NH) [1]. The relationship between vegetation and spring temperatures, with temperature as the primary driver of vegetation growth in large areas of the NH, has been extensively investigated [2–8]. Increased spring temperatures generally stimulate vegetation growth by lengthening the growing season and enhancing productivity, and thus have great implications for global biophysical and biogeochemical cycles [9].

Although widespread greening tendencies associated with warming have been observed, the decreases of vegetation growth occurred during the 1980s and 1990s [7, 8, 10]. By applying a piecewise regression approach, Piao *et al*

[3] Address for correspondence: Environmental Sciences Division, Building 2040, Room E277, MS6301, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831-6301, USA.

[7] and Wang *et al* [8] have quantitatively characterized the temporal–spatial discontinuity features of the spring (April–May) normalized difference vegetation index (NDVI) and its response to temperatures from 1982 to 2006 over Eurasia and North America (NA), respectively. They concluded that the vegetation growth trend in spring is not continuous throughout the 25 yr period (1982–2006). Spring vegetation greening or browning trends in different periods are strongly associated with rising or decreasing spring temperature changes at the continental scale.

In addition to large-scale temperature effects, other environmental factors such as CO_2, nitrogen deposition, land use land cover change (LULCC) and underlying physiological mechanisms that determine changes of spring vegetation activity are not yet well quantified [4, 11]. Gong and Ho [5] estimated that satellite-sensed spring NDVI trends in the NH could be chiefly explained by variability of atmospheric circulations and their association with temperature change, but 38% of these trends may be due to non-climatic change impacts in the period 1982–2000.

Understanding the causes of the response of spring vegetation growth to different environmental factors is an important step in distinguishing the roles of naturally and anthropogenically forced climate variability on terrestrial ecosystem properties. Hence, we used a process-based model, Community Land Model version 4 (CLM4) [12] driven with historical climate change, CO_2 concentration, atmospheric nitrogen deposition and land use change, to better understand the attribution of spatial and temporal variations in spring NDVI to multiple global change factors in the northern mid–high latitudes (NMH) (>25°N) between 1982 and 2004. In particular, we have improved on the analysis of Piao *et al* [7] and Wang *et al* [8] by focusing on the extent to which spatial and temporal non-climate environmental factors control spring vegetation growth before and after the turning point (TP) of spring temperature trends.

2. Data set and methodology

2.1. NDVI data

We characterized spring NDVI as the average monthly composite NDVI for April and May. For observed vegetation growth, we used the satellite-measured NDVI dataset compiled by the NASA Global Inventory Monitoring and Modeling Systems (GIMMS) group from 1982 to 2004 [13]. The original biweekly NDVI with a spatial resolution of 8 km was aggregated onto a 0.5° grid at monthly intervals. Details of the methodology and applications for this corrected data (e.g., aerosol, cloud, volcanic and sensor degradation) have been comprehensively presented in previous studies [13, 14].

2.2. Model and experimental design

The CLM4 with carbon–nitrogen biogeochemistry was implemented to assess the response of spring NDVI to different large-scale drivers. To elucidate the relative effects of climate variability, atmospheric CO_2, nitrogen deposition and land use change on the spring NDVI trends over the NMH, we designed five simulations (table 1). In the set of experiments presented here, we drove the CLM4 with an improved and comprehensively evaluated 57 yr (1948–2004) atmospheric forcing dataset (6-hourly temperature, precipitation, wind, relative humidity, surface pressure, solar radiation and long wave radiation) [15]. Based on the subset (1948–1972) of transient meteorology, CLM4 was spun up at the spatial resolution of 2.5° by using atmospheric CO_2, nitrogen deposition and land cover on year 1850. It was then run to 1972, forced by repeating 25 yr climate variables with the transient CO_2 concentration, nitrogen deposition and historical land use data during 1850–1972, as described by Bonan and Levis [16], and Shi *et al* [17]. Starting from the same model state in 1972, five artificial experiments were conducted to examine the contributions of various forcings. The first simulation (E1) contained all driving datasets and included time-evolving meteorology forcing, CO_2 concentration, nitrogen deposition and historical land use data from 1972 to 2004 (hereafter referred to as 'ALL'). The second experiment set (E2) used transient climate forcing but kept other forcings constant at year 1972 levels (hereafter referred to as 'CLIM'). In the remaining simulations, a single factor was held at 1972 levels and all others followed historical transients. CO_2, nitrogen deposition and land use were held constant for experiments E3, E4 and E5, respectively. Single forcing factor effects were then estimated by differencing simulations. The impact of CO_2 on NDVI variation is the difference between E1 and E3 (hereafter referred to as 'CO_2'); for the nitrogen deposition effect, it is the difference between E1 and E4 (hereafter referred to as 'NDEP'); and the land use change-induced NDVI trend is evaluated by the subtracting E5 from E1 (hereafter referred to as 'LUC').

Table 1. Experimental design. T denotes transient variation for the related forcing during 1973–2004. C denotes the forcing is kept on year 1972 value.

Experiments	Climate	CO2	N deposition	Land use
E1	T	T	T	T
E2	T	C	C	C
E3	T	C	T	T
E4	T	T	C	T
E5	T	T	T	C

2.3. Analysis

To discover turning points of temperature data over the time period 1982–2004, we used a piecewise linear regression algorithm, which tracks the potential TP at which the trend changes at each point in space [18]. This method can detect the turning time, magnitude and significance ($P < 0.05$) of the potential change in temperature time-series trend, and has been widely used in previous research [7, 8, 19]. To inspect the different attributions of spring vegetation activity dominated by spring temperature changes, spatial distributions of NDVI trends from both the remote-sensed

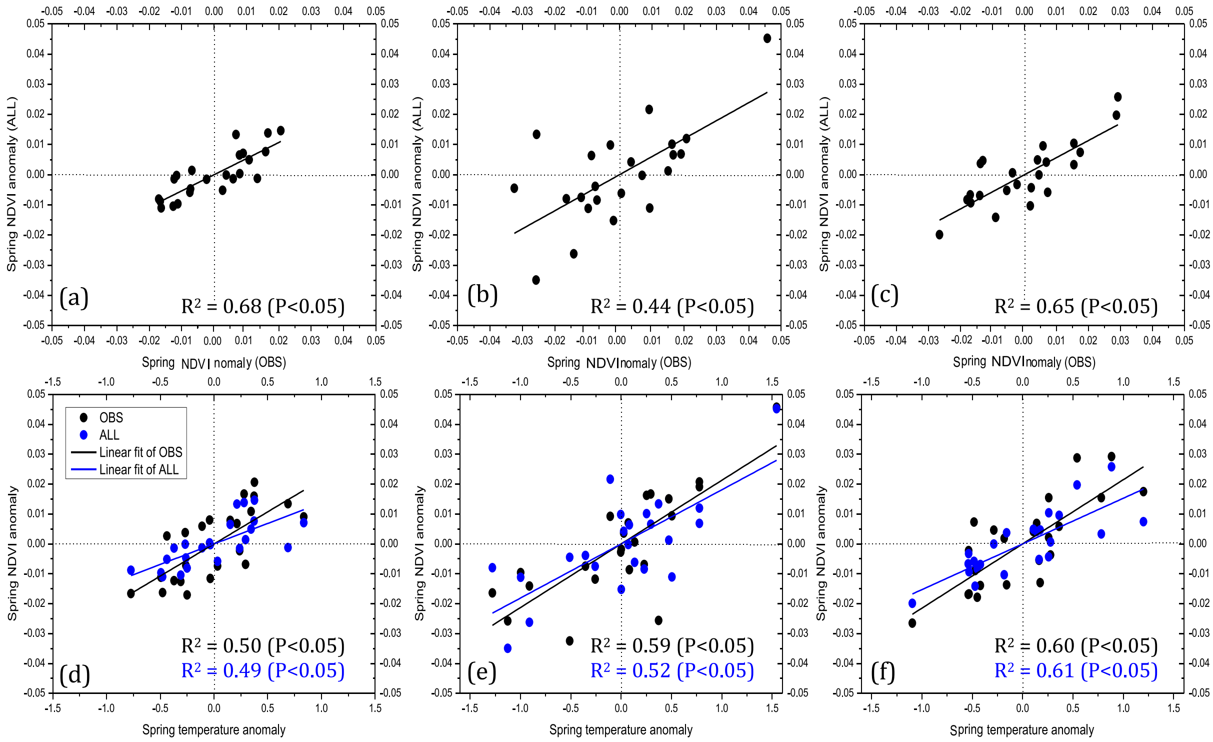

Figure 1. Spatially averaged correlations between the observed (OBS) and modeled (ALL, which has all the transient forcings as described in section 2.2) inter-annual anomalies of the NDVI in spring (April and May) over (a) the northern mid–high latitudes (NMH), (b) North America (NA) and (c) Eurasia from 1982 to 2004. Spatially averaged correlations between the spring NDVI and temperature anomalies (°C) for the OBS and ALL over (d) the NMH, (e) NA and (f) Eurasia from 1982 to 2004.

NDVI and CLM4 simulations were calculated separately before and after the turning years of temperature trends. For the direct comparison of model simulations with satellite derivations, we transformed model results to a half-degree latitude–longitude grid using bilinear interpolation, and analyzed common estimations between 1982 and 2004.

3. Results and discussion

Both the satellite observation and CLM4 show increased spring NDVI over the entire NMH (0.8×10^{-3} yr^{-1}, $P = 0.03$, 0.4×10^{-3} yr^{-1}, $P = 0.14$; respectively), suggesting an overall greening trend of spring vegetation for the time period of 1982–2004 (figure S1 available at stacks.iop.org/ERL/7/014010/mmedia). At the continental scale, squared correlation coefficients between the satellite-measured (OBS) and simulated spring NDVI are 0.68 for NMH ($p < 0.05$), 0.44 for NA ($p < 0.05$) and 0.65 for Eurasia ($p < 0.05$) (figures 1(a)–(c)), which signify the general similarities between the two products. Seasonal cycles of observed and simulated monthly NDVI magnitude and its change across the NMH exhibit that vegetation growth peaked in the northern summer season (June, July and August) but large NDVI increases occurred in the early or late growing season (figure S2 available at stacks.iop.org/ERL/7/014010/mmedia). Similar larger NDVI trend in spring than in the growing season qualitatively indicates the agreement between the process model and satellite data in earlier greening of high-latitude vegetation over the 23 yr study period. Analyses on spatial distribution of the correlation coefficient between the spring NDVI observation and model further reveal that 81% of the NMH have a positive correlation coefficient and more than 49% of the studied area shows a significant positive correlation (figure S3 available at stacks.iop.org/ERL/7/014010/mmedia). Strong positive correlations exist in the highlands of NA and Eurasia and week negative correlations occur in the mid-latitudes of America. In general, the remarkable similarities between these two data sets suggest that CLM4 spring NDVI is well aligned in phase with the remote sensing parameter and can reliably identify changes in vegetation growth over the NMH.

In order to check the accuracy of the modeled response of spring vegetation growth to temperature, we performed linear regressions between the spatially averaged NDVI and temperature anomalies (figures 1(d)–(f)). Both the satellite and ALL NDVI anomaly displayed a significant positive correlation with the inter-annual temperature anomaly, with a correlation coefficient of 0.50 for OBS and 0.49 for ALL in NMH, 0.59 for OBS and 0.52 for ALL in NA, and 0.60 for OBS and 0.61 for ALL in Eurasia. Increasing temperature stimulated spring plant growth, but the opposite was true when temperature decreased. The broad consistency of the sensitivity of modeled vegetation growth to spring temperature variability with remote sensing observations demonstrates that CLM4 responds realistically to large-scale climate anomalies. These statistical analyses further suggest a potential utility of this model for evaluations of mechanisms controlling spring NDVI changes over the study period.

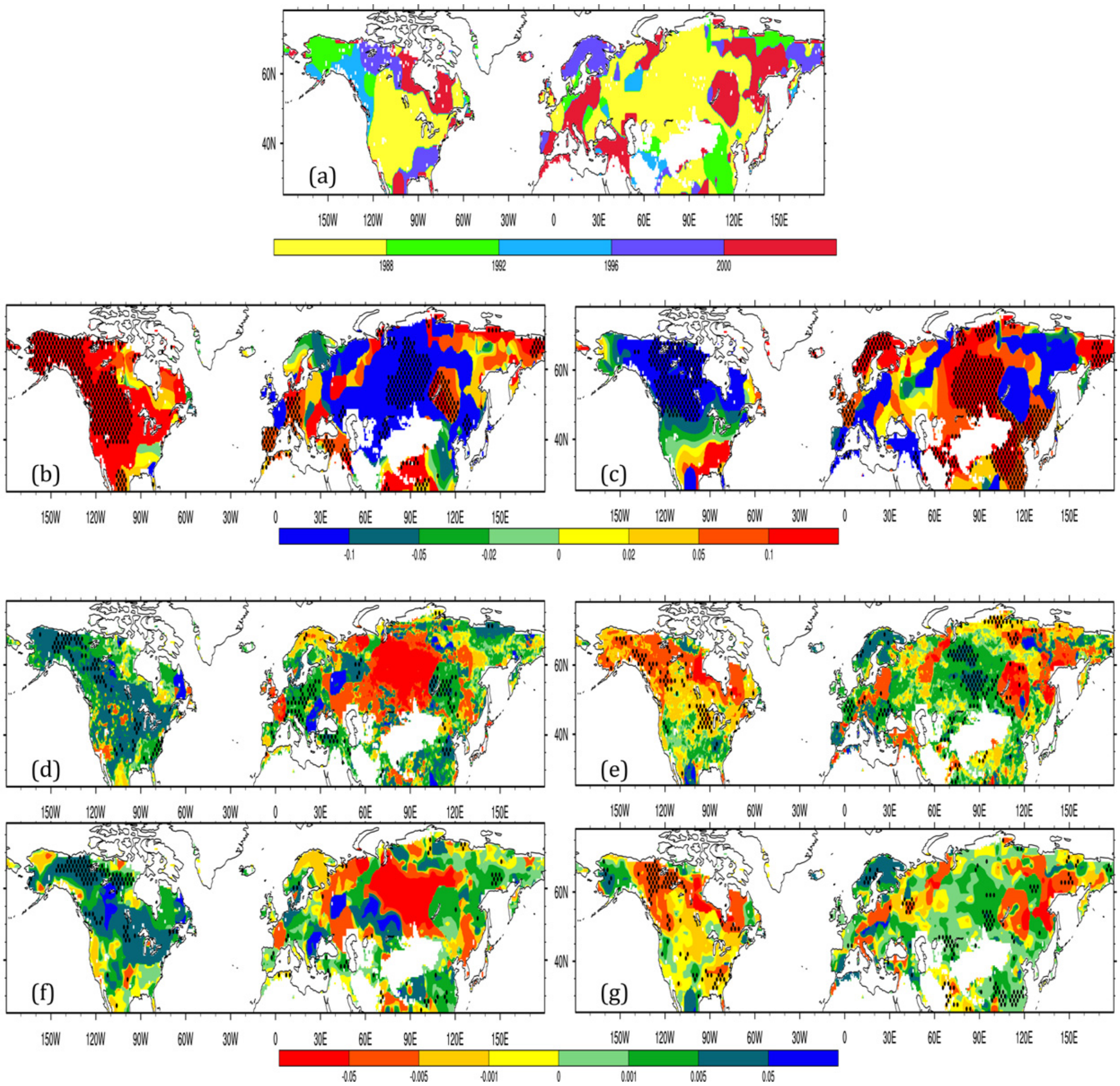

Figure 2. Spatial distribution of change in spring temperature (°C yr^{-1}) and NDVI (1 yr^{-1}). (a) Turning point (TP) of spring temperature analyzed with the piecewise regression approach. Trend in spring temperature (b) before its TP and (c) after its TP. Trend in remote-sensed spring NDVI (d) before TP of spring temperature and (e) after TP of spring temperature. Trend in spring NDVI from simulation ALL (f) before TP of spring temperature and (g) after the TP of spring temperature trend. The stippled areas represent the trends are statistically significant ($P < 0.05$).

The piecewise regression approach was applied to detect temporally inhomogeneous trends in temperature and the accompanying trends in vegetation growth for each pixel. Figure 2(a) shows the geographic features of the turning time for spring temperature trends. The turning point years are regionally variable, but occur for most areas around the year 1988 (figure 2(a)). Spring temperatures over most NA increased dramatically until the late 1980s (figures 2(a) and (b)) and then decreased afterward (figure 2(c)). Central Russia, however, exhibited decreasing spring temperatures before the TP of spring temperature and significant upward temperature trends afterward (figures 2(a)–(c)). Similar spatial patterns of temperature turning trends over NA were also observed in the Climatic Research Unit (CRU) temperature used by Wang *et al* [8], except in smaller areas like eastern Canada (Manitoba, Ontario and Quebec) (figures 1(c) and (d) in Wang *et al* [8]).

Between 1982 and 2004, the spatial distributions of observed changes in plant growth in the NMH match the spring temperature changes, and expose significant trends in the NDVI before and after the TP of spring temperature trends observed (figures 2(d) and (e)). Over most areas of NA, central Europe and eastern Russia, an increase of spring NDVI was observed with significant increasing temperature before the TP of spring temperature. Decreasing NDVI trends were observed over the same regions, associated with decreasing temperature after the TP year of spring temperature trends. Similarly, over central Russia, increased NDVI trend is associated with increased temperature, and decreased NDVI trend is associated with decreased temperature, but the warmer temperature and greener vegetation occurred after the spring temperature TP year. Our analyses of observed temperature and vegetation growth trends are consistent with previous findings that, over the NH, plant growth is positively correlated with spring temperature [3–5, 7, 8, 11].

Spatial distributions of the CLM4 simulated spring NDVI trends before and after the TP of spring temperature changes are shown in figures 2(f) and (g). Compared to remote sensing analysis, on average, the NDVI trends in simulation ALL have quite similar spatial patterns for most areas during the two periods, although there are some differences in southwestern Russia (figures 2(d) and (f)), Alaska and southeastern America (figures 2(e) and (g)). Strong similarity is also seen over central eastern China, where both observations and simulations show increasing NDVI somewhat inconsistent with the expected trend from temperature decreases before the TP of spring temperature (figures 2(b), (d) and (f)). This suggests that the response of vegetation structure to temperature may be geographically modified in association with varying trends of other driving factors like CO_2, nitrogen deposition and LULCC [11, 20–22]. We explore in the following section to what extent different drivers influence the spring vegetation activities during different periods of spring temperature TP between 1982 and 2004.

Spatial distribution of CLM4 predicted NDVI trends from different factorial experiments and their dominant control factors before and after the TP of spring temperature are displayed in figure 3. The spatial patterns of NDVI trends with simulation ALL (figures 2(f) and (g)) and CLIM (figures 3(a) and (b)) are quite close for different periods of spring temperature TP, further confirming that climate change is the dominant factor for long-term vegetation growth. Before the TP of spring temperature, the direct physiological effects of increasing CO_2 enhances the favorable effects of climate change for southeastern America, southwestern Europe and southeastern China (figure 3(c)). After the spring temperature TP, CO_2 fertilization effects canceled out the negative impacts of climate change over large areas of continental NA and continued to stimulate the plant growth significantly over the southern Russia and eastern China (figure 3(d)). Nitrogen deposition increased significantly over the majority of NA and eastern Eurasia for the two time periods, while there were evident decreases in central Europe particularly after the TP of spring temperature (figures S4(a) and (b) available at stacks.iop.org/ERL/7/014010/mmedia). As a result of nitrogen availability, increased nitrogen deposition enhanced the plant growth significantly in central NA, west Europe and southeastern China, while the decreasing nitrogen deposition stresses NDVI significantly in west parts of Russia (figures 3(e) and (f)).

Figures 3(g) and (h) show the spatial distributions of the trend in spring NDVI for the simulation LUC, due to the LULCC, before and after temperature TP. Significant decreasing NDVI trends associated with land use change before the TP occurred in large parts of NA and eastern Russia (figure 3(g)), while significant increasing trends appeared over northwestern Europe and southeastern China. Declining trends in NDVI as forced by land use were even more prevalent after the TP year for NA and central eastern Russia. Some areas in western Russia and Eastern China experienced a significant vegetation greening after the temperature TP year. As indicated in figures 3(g) and (h), the effects of land cover change on NDVI trend are quite temporally and geographically dependent, signifying a redistribution of NDVI in response to the intensive historical changes of local land use. Significant changes of NDVI over temperate NA and China closely correspond to the expansion or contraction of crop areas (figures 3(g) and (h); figures S4(c) and (d) available at stacks.iop.org/ERL/7/014010/mmedia). Over the high latitudes located north of 50°N, the trends of vegetation NDVI seem to be primarily driven by changes in forest coverage (figures 3(g) and (h); figures S4(e) and (f) available at stacks.iop.org/ERL/7/014010/mmedia). Our results support previous conclusions [6, 21, 23, 24] that NDVI trends respond significantly to agricultural and agroforestry (afforestation and reforestation) practices, suggesting the importance of human activities for spatiotemporal dynamics of land surface.

Climate change is the primary driving factor in spring vegetation growth over most parts of the study areas both before and after the temperature TP (figures 3(i) and (j)). The LULCC makes a greater contribution to the increasing vegetation activity than climate variability and other forcings in parts of southeastern US and China. CO_2 and nitrogen effects are fragmented and contribute to the simulated present-day greening trend only in a marginal manner.

4. Summary

Our present study examines spring NDVI changes in response to climate, CO_2 fertilization, nitrogen deposition and land use/land cover change effects on the inter-annual timescale over the northern mid–high latitudes (>25°N) for the recent decades (1982–2004). A positive relationship between vegetation growth and temperatures in most northern ecosystems is evident both in the remote sensing and the CLM4 transient analysis. The distinct spatial response of NDVI to spring temperature based on the temperature turning point trends, in this study at least in part, are in agreement with widespread reports that recent enhanced vegetation trends over the Northern Hemisphere is primarily corresponding to the temperature changes. Employing the integrated process-based Community Land Model version 4 driven by multiple external forcings, the factorial contributions to temporal and spatial variations in NDVI trends for the different period of temperature turning points are also analyzed. Rising CO_2 is simulated to cause a general increase of vegetation growth. The predicted effects of nitrogen deposition on the vegetation growth are positive or negative dependent on the trend of the nitrogen change. The land use and land cover change influence relies on the type of land management and the latitudes where the conversion happens. On the whole, the complicated impacts of multiple non-climate factors on spring NDVI variations locally alter the climate-dominated inter-annual variations in the northern vegetation growth. Although several

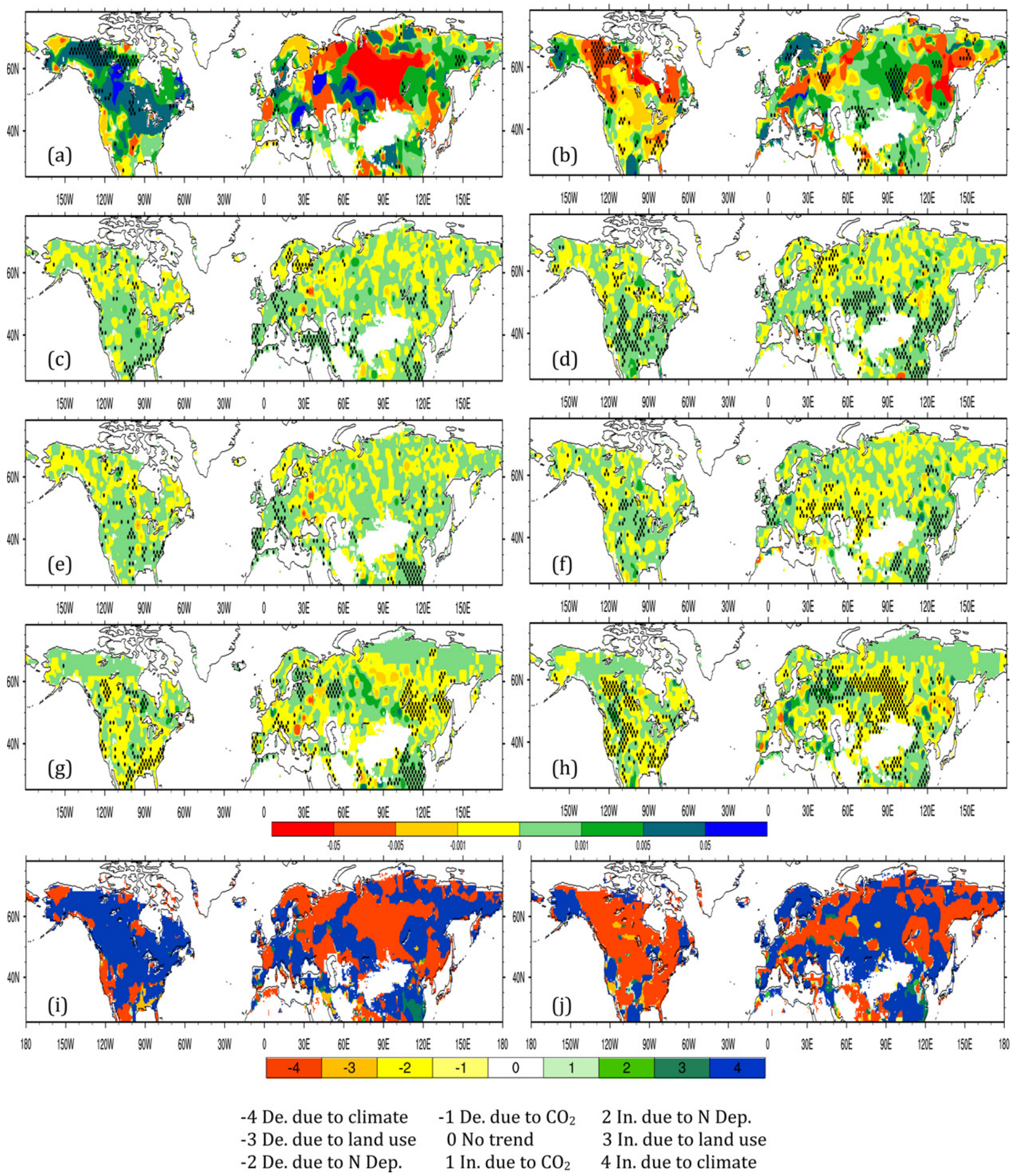

Figure 3. (a)–(h) Spatial distribution of trends in spring NDVI (1 yr^{-1}) and (i) and (j) their dominant drivers before and after the turning point of spring temperature change for the period 1982 and 2004. (a), (b) Simulation CLIM, (c), (d) simulation CO2, (e), (f) simulation NDEP, and (g), (h) simulation LUC.

uncertainties exist, the attribution of spatial and temporal variations in spring vegetation growth trends to different factors is helpful in advancing our knowledge about the nonlinear dynamics of vegetation growth in the mid and high latitudes. Future studies should examine the potential contribution to the temperature–vegetation trend associated with changes such as drought, ozone pollution and nitrogen fertilizer application [22, 25, 26].

Acknowledgments

This research is supported in part by the US Department of Energy (DOE), Office of Science, Biological and Environmental Research. Oak Ridge National Laboratory is managed by UT-BATTELLE for DOE under contract DE-AC05-00OR22725. Special thanks are given to Dr Sam

Levis at NCAR for his helps in CLM4 simulation, and to Terry Copeland Pfeiffer at ORNL for her text editing.

References

[1] IPCC 2007 *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press)

[2] Myneni R B, Keeling C D, Tucker C J, Asrar G and Nemani R 1997 Increased plant growth in the northern high latitudes from 1981–1991 *Nature* **386** 698–702

[3] Zhou L M, Tucker C J, Kaufmann R K, Slayback D, Shabanov N V and Myneni R B 2001 Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999 *J. Geophys. Res.* **106** 20069–83

[4] Lucht W *et al* 2002 Climatic control of the high-latitude vegetation greening trend and Pinatubo effect *Science* **296** 1687–9

[5] Gong D Y and Ho C H 2003 Detection of large-scale climate signals in spring vegetation index (normalized difference vegetation index) over the Northern Hemisphere *J. Geophys. Res.* **108** 4498

[6] Xiao J and Moody A 2005 Geographical distribution of global greening trends and their climatic correlates: 1982-1998 *Int. J. Remote Sens.* **26** 2371–90

[7] Piao S, Wang X, Ciais P, Zhu B, Wang T and Liu J 2011 Changes in satellite-derived vegetation growth trend in temperate and boreal Eurasia from 1982 to 2006 *Glob. Change Biol.* **17** 3228–39

[8] Wang X, Piao S, Ciais P, Li J, Friedlingstein P, Koven C and Chen A 2011 Spring temperature change and its implication in the change of vegetation growth in North America from 1982 to 2006 *Proc. Natl Acad. Sci. USA* **108** 1240–5

[9] Piao S, Friedlingstein P, Ciais P, Viovy N and Demarty J 2007 Growing season extension and its impact on terrestrial carbon cycle in the Northern Hemisphere over the past 2 decades *Glob. Biogeochem. Cycles* **21** GB3018

[10] Park H S and Sohn B J 2010 Recent trends in changes of vegetation over East Asia coupled with temperature and rainfall variations *J. Geophys. Res.* **115** D14101

[11] Piao S, Friedlingstein P, Ciais P, Zhou L and Chen A 2006 Effect of climate and CO_2 changes on the greening of the Northern Hemisphere over the past two decades *Geophys. Res. Lett.* **33** L23402

[12] Oleson K W *et al* 2010 Technical description of version 4.0 of the Community Land Model (CLM) *NCAR Tech. Note NCAR/TN-478+STR* (Boulder, CO: National Center for Atmospheric Research)

[13] Tucker C J, Pinzon J E, Brown M E, Slayback D, Pak E W, Mahoney R, Vermote E and Saleous N E 2005 An extended AVHRR 8 km NDVI data set compatible with MODIS and SPOT vegetation NDVI data *Int. J. Remote Sens.* **26** 4485–98

[14] Jeong S J, Ho C H, Brown M E, Kug J S and Piao S 2011 Browning in desert boundaries in Asia in recent decades *J. Geophys. Res.* **116** D02103

[15] Qian T, Dai A, Trenberth K E and Oleson K W 2006 Simulation of global land surface conditions from 1948 to 2004. Part I: forcing data and evaluations *J. Hydrometeorol.* **7** 953–75

[16] Bonan G and and Levis S 2010 Quantifying carbon-nitrogen feedbacks in the community land model (CLM4) *Geophys. Res. Lett.* **37** L07401

[17] Shi X, Mao J, Thornton P E, Forrest M H and Wilfred M P 2011 The impact of climate, CO_2, nitrogen deposition and land use change on simulated contemporary global river flow *Geophys. Res. Lett.* **38** L08704

[18] Toms J D and Lesperance M L 2003 Piecewise regression: a tool for identifying ecological thresholds *Ecology* **84** 2034–41

[19] Swift T L and Hannon S J 2010 Critical thresholds associated with habitat loss: a review of the concepts, evidence, and applications *Biol. Rev.* **85** 35–53

[20] Thornton P, Law B, Gholz H, Clark K, Falge E, Ellsworth D, Goldstein A, Monson R, Hollinger D and Falk M 2002 Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests *Agric. For. Meteorol.* **113** 185–222

[21] Piao S, Fang J, Zhou L, Guo Q, Henderson M, Ji W, Li Y and Tao S 2003 Interannual variations of monthly and seasonal NDVI in China from 1982 to 1999 *J. Geophys. Res.* **108** 4401

[22] Tian H *et al* 2011 China's terrestrial carbon balance: contributions from multiple global change factors *Glob. Biogeochem. Cycles* **25** GB1007

[23] Hurtt G, Frolking S, Fearon M, Moore B, Shevliakova E, Malyshev S, Pacala S and Houghton R 2006 The underpinnings of land use history: three centuries of global gridded land use transitions, wood harvest activity, and resulting secondary lands *Glob. Change Biol.* **12** 1208–29

[24] Potter C, Klooster S, Hiatt S, Fladeland M, Genovese V and Gross P 2007 Satellite-derived estimates of potential carbon sequestration through afforestation of agricultural lands in the United States *Clim. Change* **80** 323–36

[25] Angert A, Biraud S, Bonfils C, Henning C C, Buermann W, Pinzon J, Tucker C J and Fung I 2005 Drier summers cancel out the CO_2 uptake enhancement induced by warmer springs *Proc. Natl Acad. Sci. USA* **102** 10823–7

[26] Sitch S, Cox P M, Collins W J and Huntingford C 2007 Indirect radiative forcing of climate change through ozone effects on the land-carbon sink *Nature* **448** 791–4