CLIMATE CHANGE SCIENCE INSTITUTE
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Disentangling natural and anthropogenic controls on terrestrial vegetation growth trends

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References:

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Jiafu Mao, et al. (2016) Human-induced greening of the northern extratropical land surface. Nature Climate Change, doi: 10.1038/nclimate3056.

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Article

Global Latitudinal-Asymmetric Vegetation Growth Trends and Their Driving Mechanisms: 1982–2009

Jiafu Mao [1,*], Xiaoying Shi [1], Peter E. Thornton [1], Forrest M. Hoffman [2], Zaichun Zhu [3] and Ranga B. Myneni [3]

Part One: Global Latitudinal-Asymmetric Vegetation Growth Trends and Their Driving Mechanisms

Background

- The **global enhancement of plant growth** was detected and simulated particularly over the northern mid-high latitudes (Myneni et al., 1997; Zhou et al., 2001; Buitenwerf et al., 2015);
- Natural environmental factors regulate vegetation growth and its variability, and **human activities directly or indirectly alter** their variations (Lucht et al., 2002; Piao et al. 2014; Zhu et al., 2016);
- Discriminating these anthropogenic perturbations from natural factors is expected to increase in importance **as anthropogenic transformation of the Earth system becomes more pervasive**;

Objective

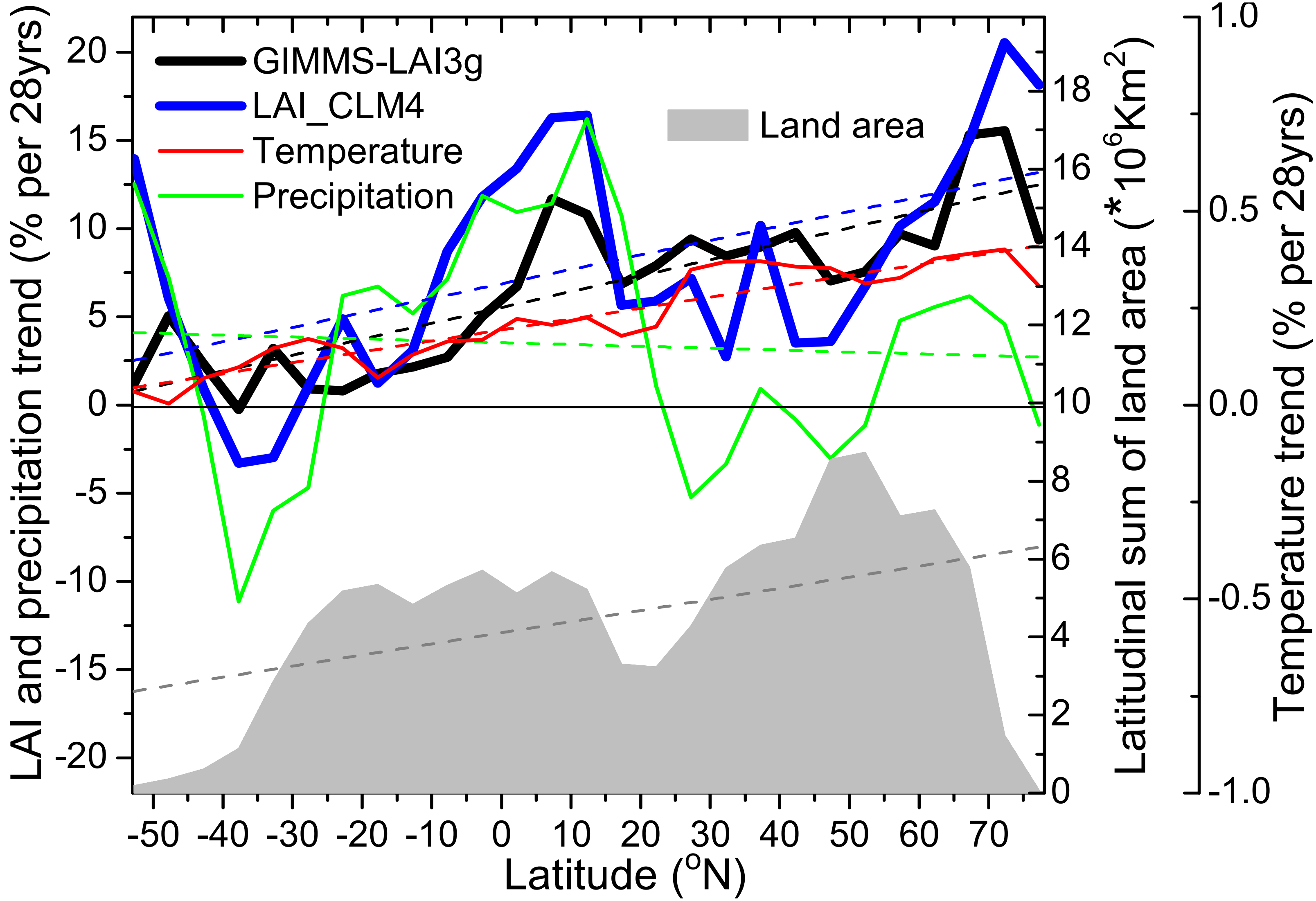
- ✦ Study the spatial and temporal changes of global vegetation growth for the past 3 decades;
- ✦ Characterize the response of vegetation activity to the inhomogeneous land warming;
- ✦ Evaluate the representation of the response relationship in land surface models;
- ✦ Examine the natural and anthropogenic controls on vegetation changes;

Approach

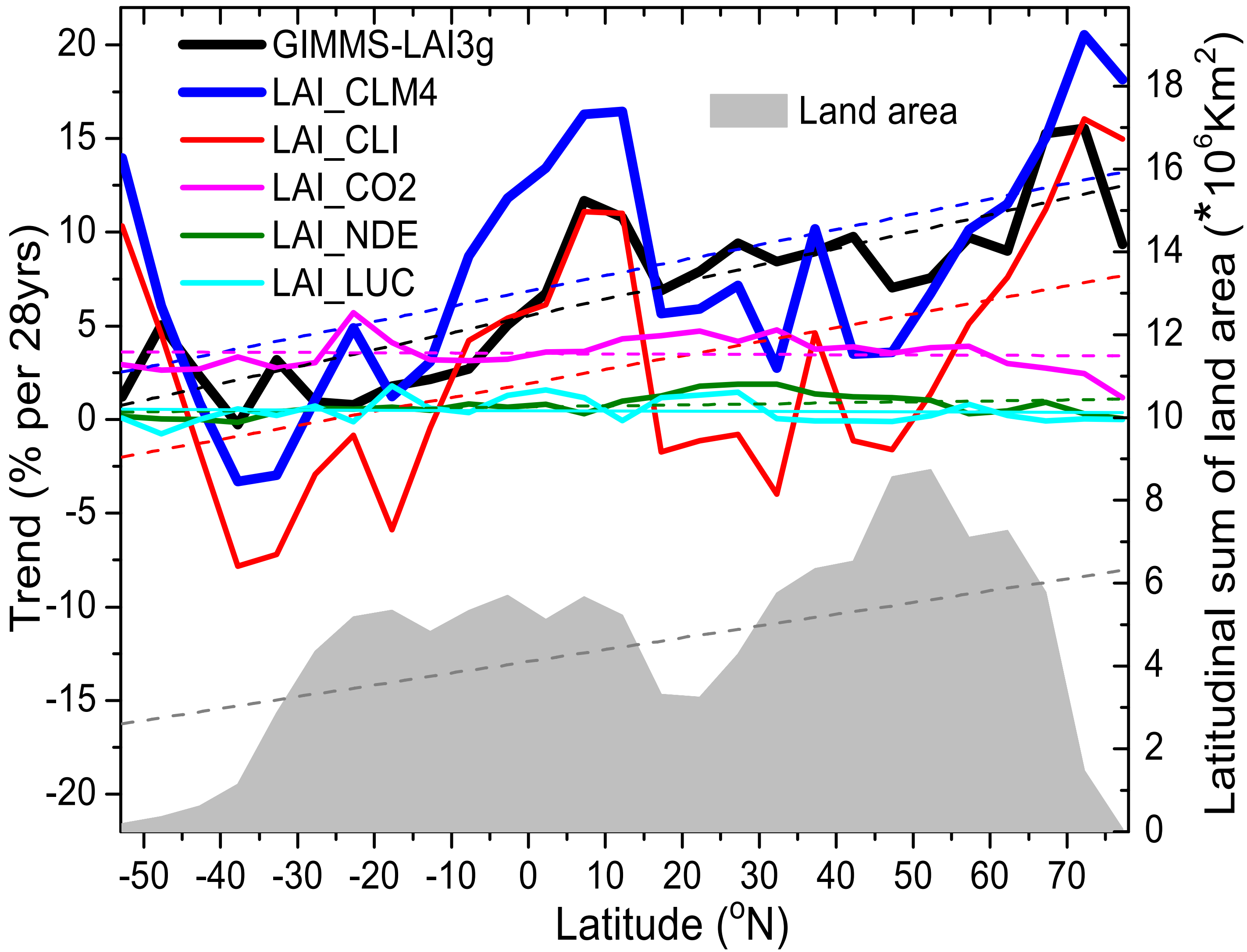
- ✦ We used the latest Leaf Area Index (LAI) dataset, the LAI3g;
- ✦ We used this satellite LAI to evaluate single-factor and multi-factor simulations from the CLM4;

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

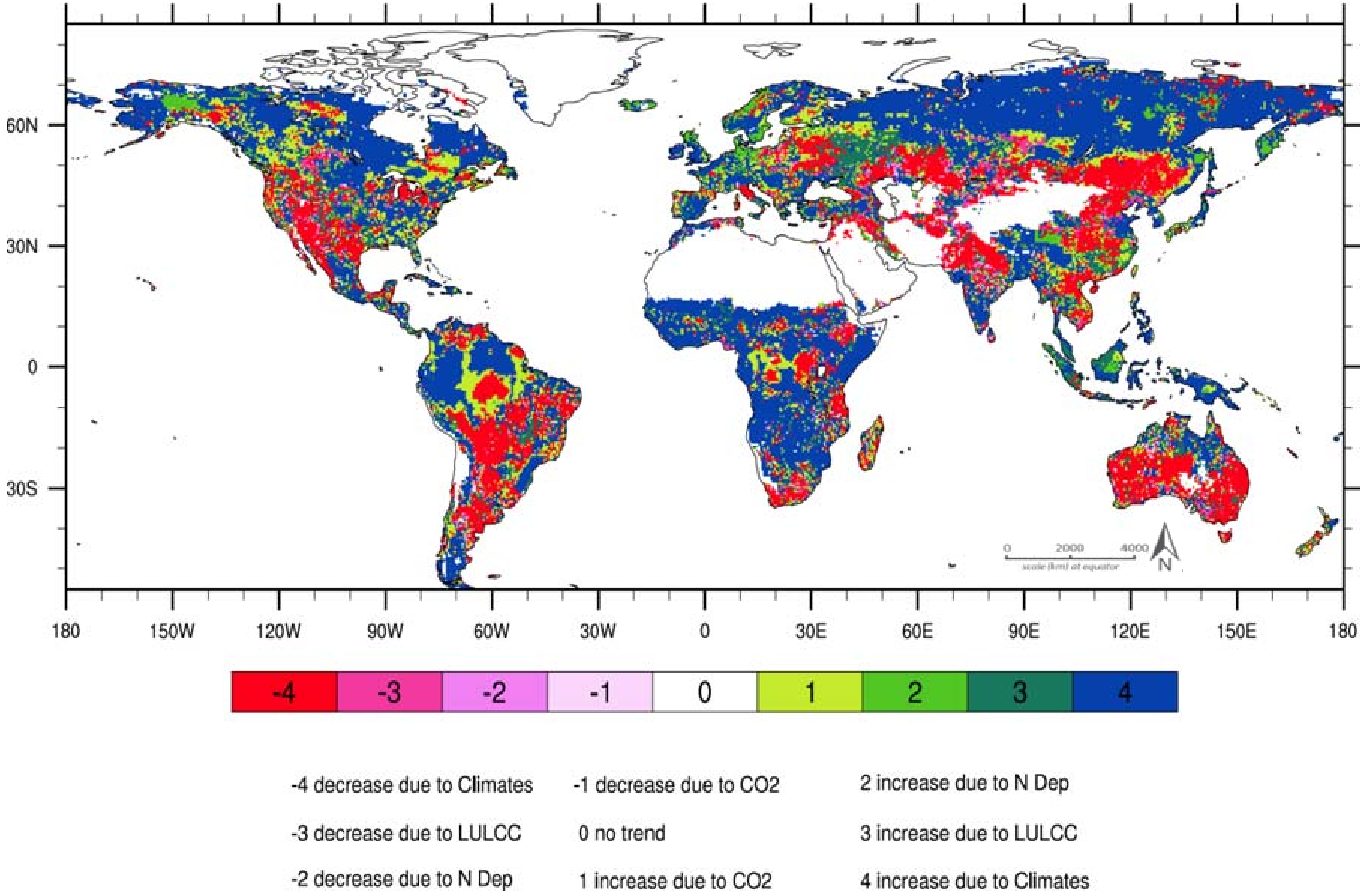
Experimental design. "T" denotes transient variation for the related forcing during the study period. "C" denotes the forcing is kept on the first year value.



Latitudinal gradient of percentage change (%/28 yr) in LAI and climates for 1982–2009



Latitudinal gradient of percentage change (%/28 yr) in observed LAI and factorial CLM simulations



Simulated dominant driving factors for LAI trends between 1982 and 2009

Summary and significance

- Over the 28-year period, both the remote-sensing estimate and CLM4 simulation show ***a significant increasing trend*** in annual vegetation growth;
- ***Latitudinal asymmetry*** appeared in both products, with small increases in the Southern Hemisphere and larger increases at high latitudes in the Northern Hemisphere;
- The south-to-north asymmetric land surface warming was assessed to be ***the principal driver*** of this latitudinal asymmetry of LAI trend;
- Heterogeneous precipitation decreased this latitudinal LAI gradient, and ***considerably regulated*** the local LAI change;
- CO_2 fertilization during the last three decades was estimated to be ***the dominant cause for enhancement*** in global mean vegetation growth;
- Human induced land use/land cover change and nitrogen deposition produced slightly increasing global LAI ***and the regionally dependent impacts***.

Summary and significance

- Simulated CLM4 LAI ***compares well*** with an independent satellite-based estimate in terms of annual trends and correlations with climate;
- Model-data analysis provides ***process attribution information*** not available from the observations alone;
- These validation exercises provide ***new global-scale metrics*** for evaluation of model outputs and help prioritize improvements in model performance across different scales.

Greening of the Earth and its drivers

Objective

- Three long-term satellite leaf area index (LAI) records and ten global ecosystem models were used to understand how dynamics of terrestrial vegetation are responding to global environmental change for the period 1982-2009.

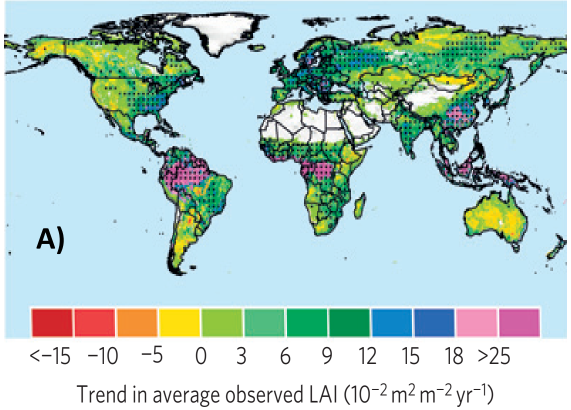
New Science

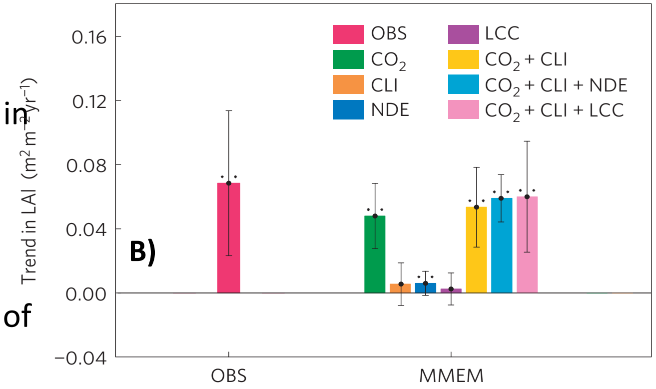
- We identified a persistent and widespread increase of growing season integrated LAI (GSILAI) or greening) over 25 to 50% of the global vegetated area, whereas less than 4% of the globe shows decreasing GSILAI (browning) [Fig. A].
- Model-based interpretations of these data demonstrated significant correlation to CO_2 fertilization (70%), nitrogen deposition (9%), climate change (8%) and land cover change (LCC; 4%) [Figs. B and C].
- CO_2 fertilization effects dominated in the tropics, whereas climate change was the dominant driver in the Tibetan Plateau. LCC contributed most to regional greening in southeast China and the eastern United States [Fig. C].

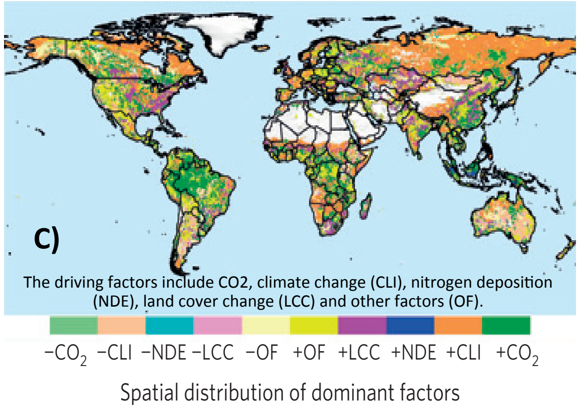
Significance

- We clarified mechanisms driving vegetation dynamics for the past 3 decades.
- We demonstrated significant anthropogenic influences on the productive capacity of terrestrial vegetation.
- We propose new areas for future terrestrial ecosystem model improvements.

Citation: Zaichun Zhu, Shilong Piao*, Ranga B. Myneni, Mengtian Huang, Zhenzhong Zeng, Josep G. Canadell, Philippe Ciais, Stephen Sitch, Pierre Friedlingstein, Almut Arneth, Chunxiang Cao, Lei Cheng, Etsushi Kato, Charles Koven, Yue Li, Xu Lian, Yongwen Liu, Ronggao Liu, **Jiafu Mao**, Yaozhong Pan, Shushi Peng, Josep Peñuelas, Benjamin Poulter, Thomas A. M. Pugh, Benjamin D. Stocker, Nicolas Viovy, Xuhui Wang, Yingping Wang, Zhiqiang Xiao, Hui Yang, Sönke Zaehle and Ning Zeng, 2016. Greening of the Earth and its drivers. **Nature Climate Change,** doi: 10.1038/NCLIMATE3004.







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Human-induced greening of the northern extratropical land surface

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Part Two:
Human-Induced Greening of The Northern Extratropical Land Surface

Background

- Significant **land greening** in the northern-extratropical latitudes (NEL) has been documented during the satellite era *(Myneni et al., 1997; Zhou et al., 2001; Lucht et al., 2002; Mao et al., 2013; Buitenwerf et al., 2015; Pan et al., 2011; Liu et al., 2015);*
- Discernable human impacts on the Earth's climate system have been revealed by using **statistical frameworks of detection-attribution** *(Hegerl et al., 2007; Bindoff et al., 2013);*
- These impacts, however, **were not previously identified** on the NEL greening signal *(Cramer et al., 2014);*

Objective

- Examine the spatial and temporal changes of vegetation growth in the NEL using latest satellite observations and coupled models;
- Attribute recent changes in NEL vegetation activity for the 1982-2011 period;

Approach

- Two 30-year-long remote-sensing-based Leaf Area Index (LAI) datasets;
    - *LAI3g (Zhu et al., 2013);*
    - *GEOLAND2 LAI (Baret et al., 2013);*
- Simulations from 19 coupled earth system models (ESMs) with interactive vegetation;
- Statistical frameworks of detection and attribution (D&A);

Multi-simulations from the CMIP5 archive

- **ALL: *historical anthropogenic and natural forcings***
  - *solar variability and volcanic aerosols as well as well-mixed greenhouse gases plus other anthropogenic factors such as aerosols, land use/land cover change (LULCC) and/or ozone;*
- **GHG: *greenhouse gases forcing only***
  - *anthropogenic well-mixed greenhouse gases;*
- **NAT: *natural forcing only***
  - *solar variability and volcanic aerosols;*
- **CTL: *internal variability only***
  - *unforced preindustrial control simulations;*
- **esmFixClim2: *CO_2 physiological effects***
  - *radiation code sees constant CO_2 concentration of year 1850, but carbon cycle sees historical followed by RCP4.5 rise in CO_2;*
- **esmFdbk2: *greenhouse gases radiative effects***
  - *carbon cycle sees constant CO_2 concentration of year 1850, but radiation sees historical followed by RCP4.5 rise in CO_2;*

IPCC D&A definition

- **Detection** *of change is defined as the process of demonstrating that climate has changed in some defined statistical sense without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small;*
- **Attribution** *of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence;*

Existing applications

- *Regional and global changes of temperatures;*
- *Precipitation, arctic moistening, atmospheric moisture content, tropical water cycle, river flow, and evapotranspiration;*
- *……...*

Hegerl et al., 2007; Bindoff et al., 2013; Cramer et al., 2014

Optimal Fingerprint methods

Observations Y are regressed onto the expected response to historical forcing changes X

- *If the scaling factor β for a particular forcing and its confidence interval are greater than 0, then the forcing is detected;*
- *Once a forcing is detected, it can be attributed if β and its confidence interval include 1;*

$$Y = \sum \beta_i x_i + \epsilon$$

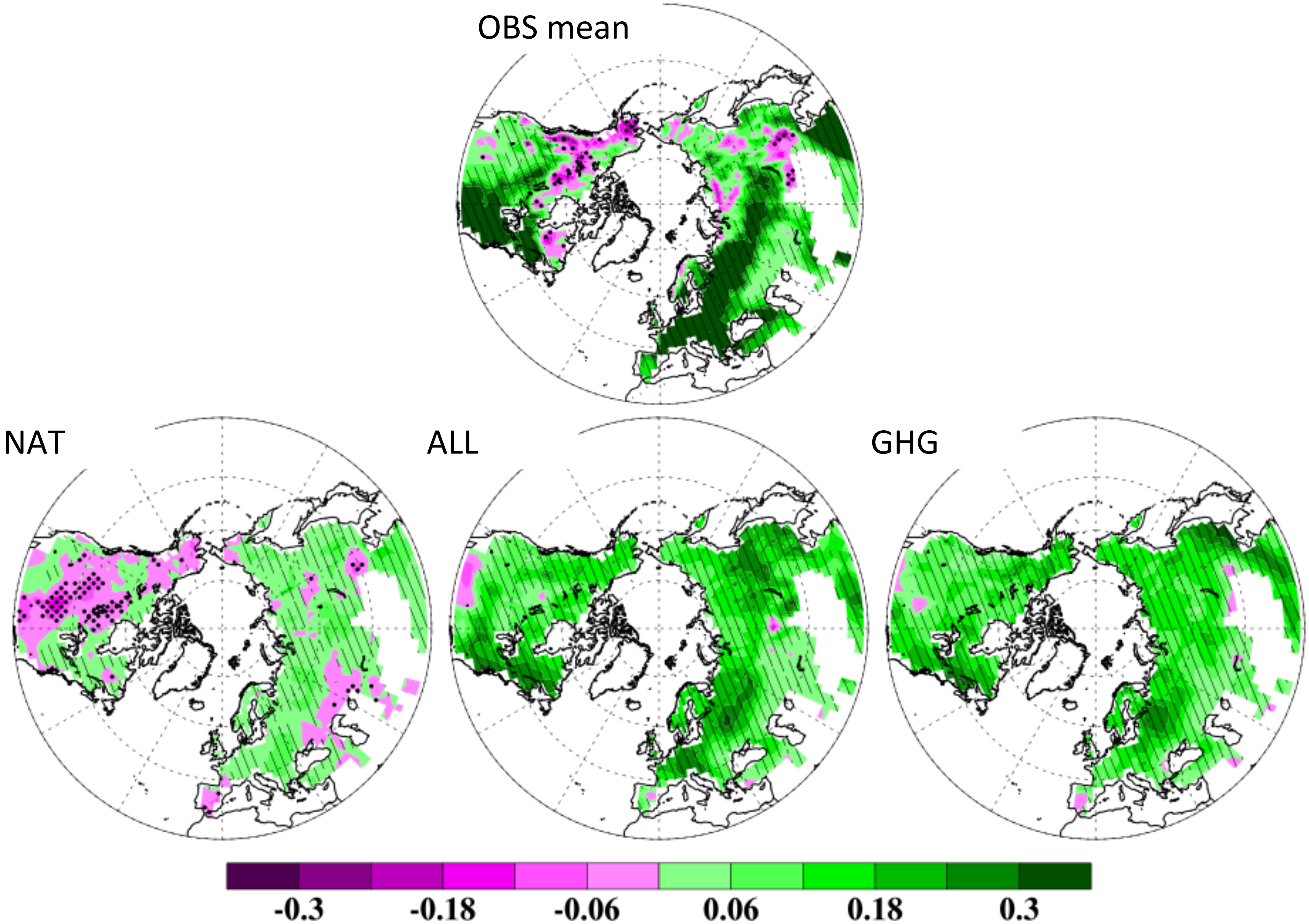
$Y =$ *Observations (LAI3g, GEOLAND and their average);*

$\beta =$ *Scaling factors (fitted using a total least square approach);*

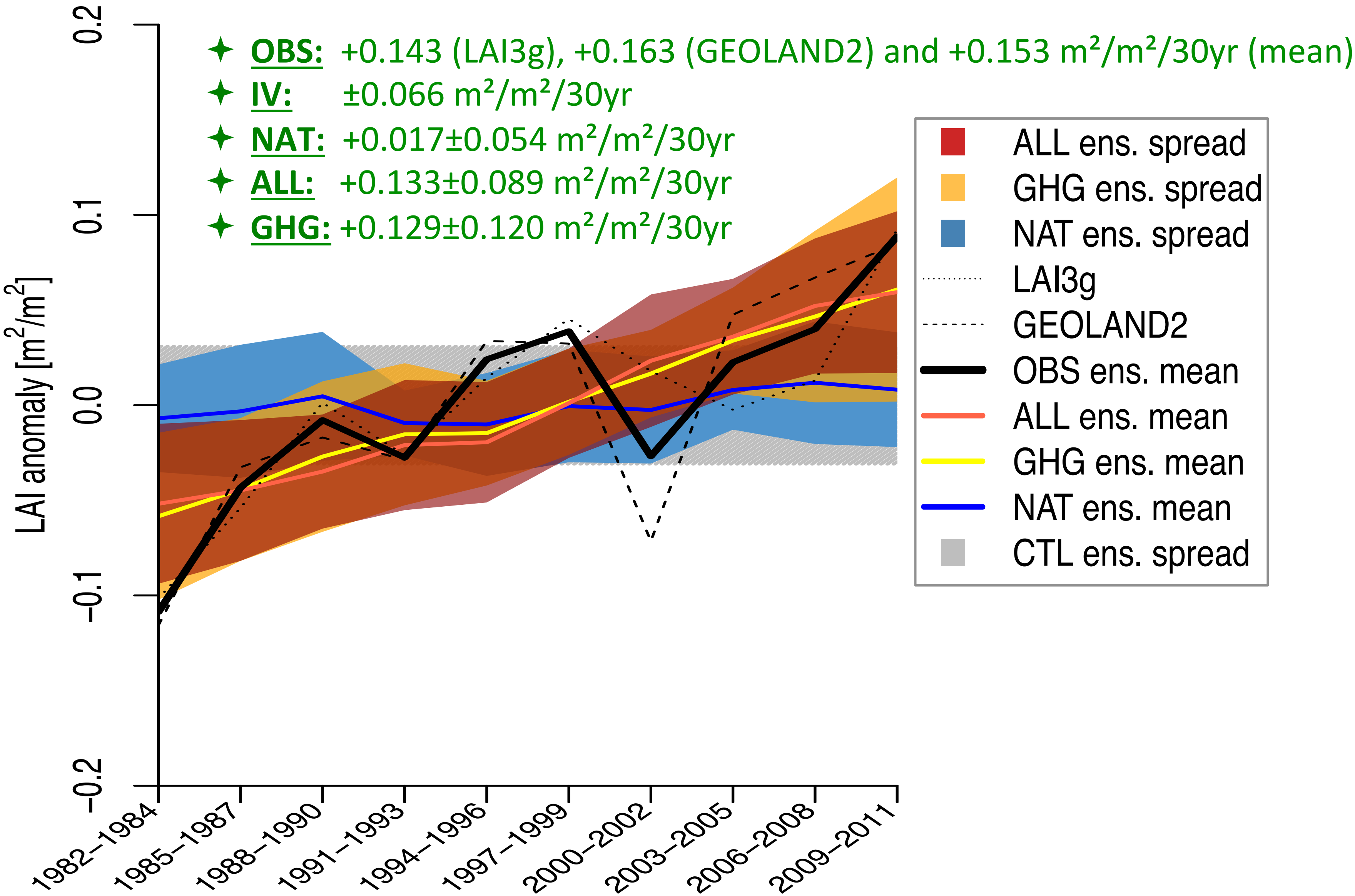
$X =$ *Forcings from CMIP5 simulations (ALL, GHG and NAT);*

$\epsilon =$ *Internal variability (CTL);*

Allen et al., 1999; Allen and Stott, 2003; Ribes et al., 2013

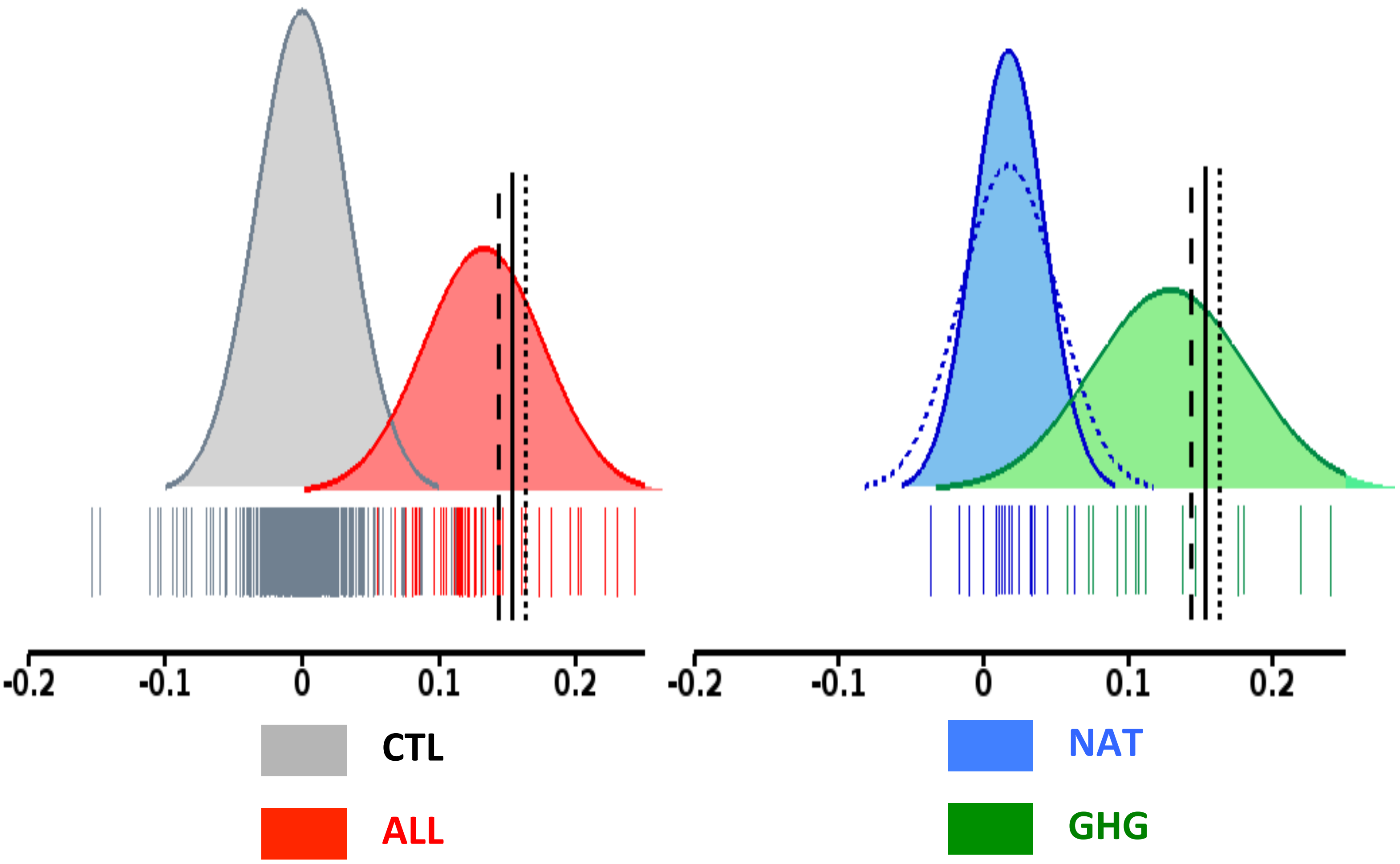


Spatial distribution of the growing season LAI trends

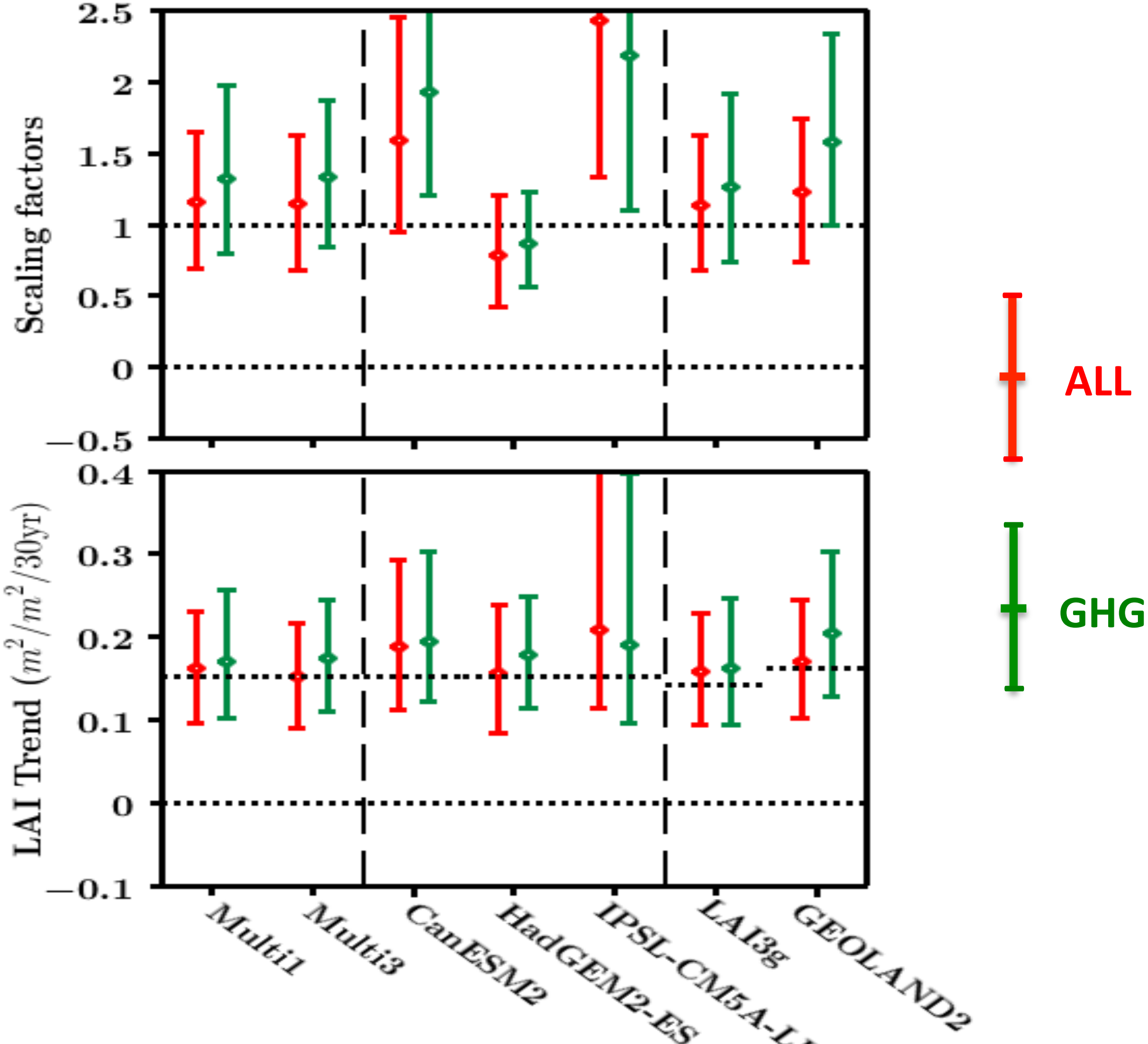


Observed and simulated LAI anomalies

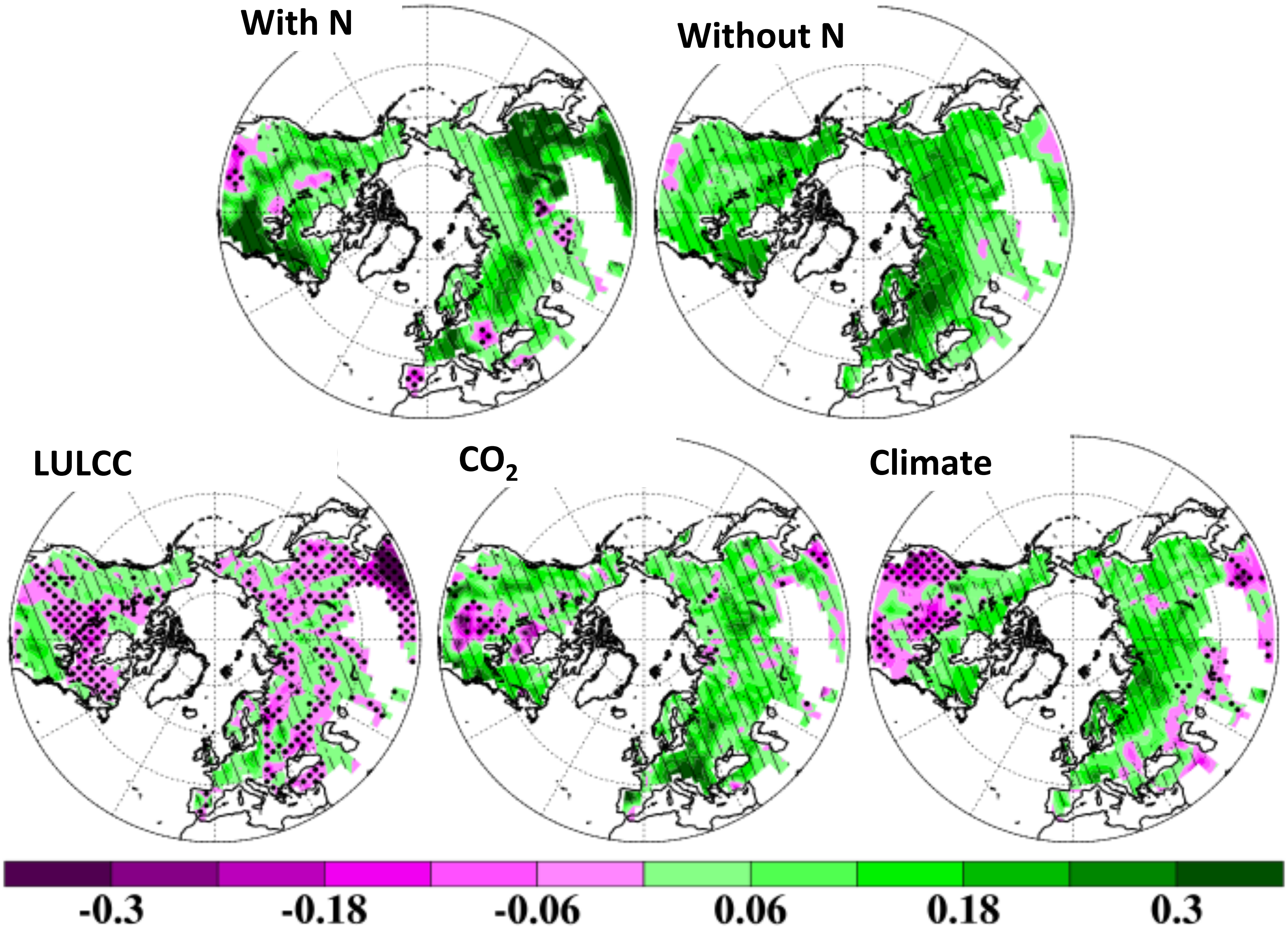
Parameterized frequency distributions of LAI 1982-2011 30-year-long trends



Results from optimal D&A for 1982–2011 time series of LAI anomalies

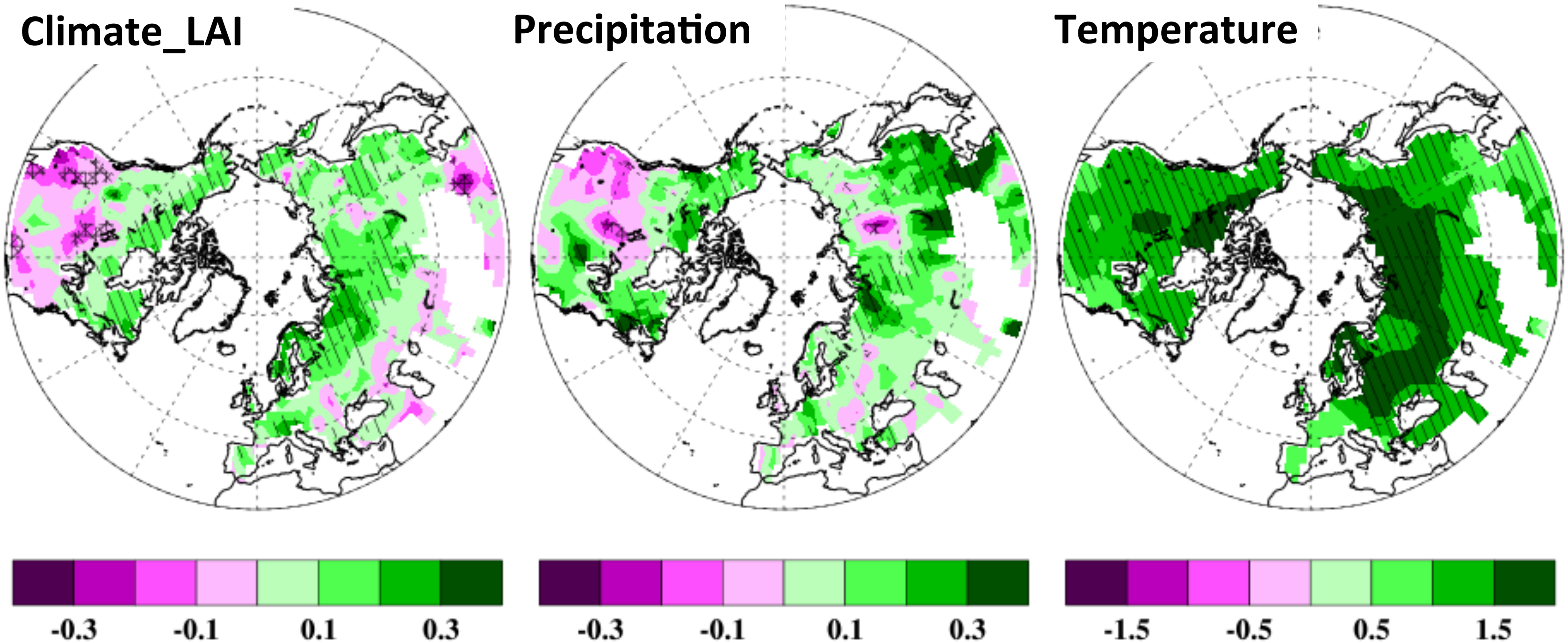


Multi1: *only one simulation from each model;* **Multi3:** *models with at least three members;* **Error bars:** *90% confidence intervals*



Spatial distribution of the Growing Season LAI trends

Spatial distribution of LAI, precipitation and temperature trends



LAI *(m^2/m^2/30yr)*, **precipitation** *(mm/day/30yr), and* **temperature** *(°C/30yr) from the CMIP5 esmFdbk2 simulations.*

Discussion and summary

✦ Weaker interannual variability for the simulated LAI

- *Weak or no representation of vegetation mortality, disturbance and successional dynamics;*
- *Underestimation of interannual precipitation variability in CMIP models over Northern Hemisphere (NH) land;*

✦ Possible persistent biases in the multi-model ensemble means

- *Overprediction of growing season length due to advanced spring growth and delayed autumn senescence in NH temperate ecosystems;*
- *Early and late season model biases seem to be stationary in time for this study;*

✦ The lack of global offline LAI simulations

- *Better understanding and ranking the multiple reasons for deficiencies in CMIP5 simulations;*
- *Will be overcome in the CMIP6 by conducting the LS3MIP;*

✦ Limitations in long-term remote-sensing data

- *Contaminated by clouds and snow cover;*
- *Likely influenced in 1991 by the eruption of Mount Pinatubo and subsequent loss of orbit by NOAA 11, seen particularly in the world's forests;*
- *The merging of reflectance information;*
- *The observed interannual variability might be artificially increased, but our key findings are robust to these issues based on sensitivity tests;*

Discussion and summary

- NEL has experienced an ***enhancement of vegetation activity*** diagnosed in satellite vegetation indexes and CMIP5 simulations;
- Previous work has focused on phenological variation, interannual variability, and multiyear trends; spatiotemporal changes in LAI were ***attributed to variation in climate drivers*** (mainly Temperature and Precipitation);
- This work goes beyond previous studies by using D&A methods to establish that the trend of strengthened northern vegetation greening is ***clearly distinguishable from both IV and the response to natural forcings alone***;
- It can be ***rigorously attributed***, with high statistical confidence, to ***anthropogenic forcings***, particularly to ***rising atmospheric concentrations of greenhouse gases***;

Discussion and summary

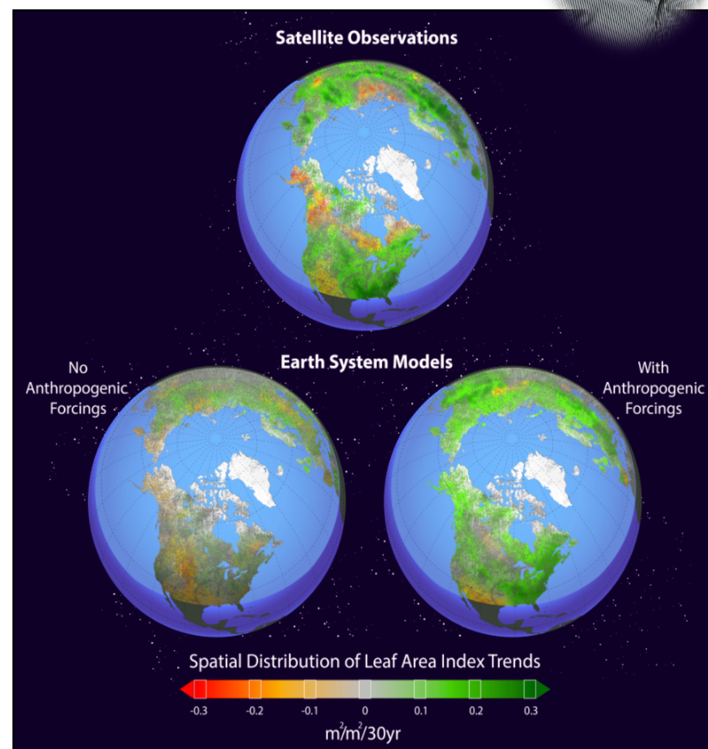
- ✦ D&A of vegetation growth is essential for ***strategic decision-making*** in ecosystem management, agricultural applications and sustainable development and conservation;
- ✦ Future vegetation growth and drivers ***remain to be determined*** because of ***nonlinear human-ecosystem-climate interactions*** under global warming (e.g., droughts, fire, vegetation acclimation to temperature and elevated CO_2, and nutrient limitation);
- ✦ Society should consider both ***intended and unintended consequences*** of its interactions with terrestrial ecosystems and the climate system;

High-Impact Publications – ACME, BGC SFA, TES SFA (CCSI)

The First Study to Demonstrate that Greening of Vegetation in the Northern Hemisphere is Caused by Anthropogenic Greenhouse Gas Emissions

Objective	• Use a formal detection and attribution algorithm to determine if the observed greening of extratropical Northern Hemisphere vegetation is caused by anthropogenic GHG emissions
New science	• Satellites observed an increase in Northern Hemisphere plant productivity from 1982-2011.This trend was present in simulations from 19 ESMs with combined anthropogenic and natural forcings. • Neither internal climate variability nor natural forcings alone could account for the trend, but with high statistical confidence, the observed greening can be attributed to the anthropogenic increase in atmospheric GHG concentrations.
Significance	• Climate drivers of increased Northern Hemisphere leafiness for the past 3 decades were clarified • This is the first definitive evidence of a discernible human fingerprint on physiological vegetation changes other than phenology and range shifts

Jiafu Mao et al. (ORNL authors: Mao, Shi, Thornton, Ricciuto, Hoffman). 2016. “Human-induced greening of the northern extratropical land surface.” *Nature Climate Change*, 10.1038/nclimate3056



Spatial distribution of leaf-area index trends observed by satellite and simulated by CMIP5 models over the period 1982–2011

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Thanks for questions and comments!

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