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Changes in vegetation photosynthetic activity trends across the Asia–Pacific region over the last three decades

Baozhang Chen [a,b,*], Guang Xu [a], Nicholas C. Coops [b], Philippe Ciais [c], John L. Innes [b], Guangyu Wang [b], Ranga B. Myneni [d], Tongli Wang [e], Judi Krzyzanowski [b], Qinglin Li [f], Lin Cao [b], Ying Liu [g,**]

[a] State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, University of Chinese Academy of Sciences, 11A, Datun Road, Chaoyang District, Beijing, China

[b] Department of Forest Resource Management, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada

[c] Laboratoire des Sciences du Climat et de l'Environnement, Unité Mixte de Recherche Commissariat à l'Energie Atomique-Centre National de la Recherche Scientifique-Université de Versailles Saint-Quentin-en-Yvelines, Batiment 709, CE L'Orme des Merisiers, Gif-sur-Yvette F-91191, France

[d] Department of Earth and Environment, Boston University, 675 Commonwealth Avenue, Boston, MA 02215, USA

[e] Centre for Forest Conservation Genetics, Department of Forest Sciences, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada

[f] Forest Analysis and Inventory Branch, Ministry of Forests, Lands, and Natural Resource Operations, Victoria, BC V8W 9C2, Canada

[g] School of Soil and Water Conservation, Beijng Forestry University, Beijing 100083, China

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A B S T R A C T

The updated Global Inventory Modeling and Mapping Studies (GIMMS) third generation global satellite Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) dataset provides very detailed global information on the state of vegetation from 1982 to 2011. Using these data we investigated the changes in the vegetation photosynthetic activity in the Asia–Pacific (AP) (including Australia, South East Asia, China, and the Pacific Coast of North America) region, by discerning gradual changes into two key metrics: 1) the cumulative annual NDVI in each year and 2) the seasonality or variance in that index. We then assessed changes using break and turning points using three statistical models (least-square linear, expanded paired-consecutive linear and piecewise regression models). We found that the AP region overall experienced increasing NDVI from 1982 through 2011 with an average rate of 5.30×10^{-4} NDVI yr^{-1} (0.13% yr^{-1}). The annual NDVI increased from 1982 at a faster rate of 26.14×10^{-4} NDVI yr^{-1} (0.65% yr^{-1}) until a break in the trend after 1991 (after that the trend reduced to 5.78×10^{-4} NDVI yr^{-1}). In the Asia–Australia (AA) subarea of the AP, vegetation greening slowly increased at 8.71×10^{-4} NDVI yr^{-1} before 2003 and then increased to 28.30×10^{-4} NDVI yr^{-1} after 2003. In contrast, in the North America (NA) subarea NDVI rapidly increased initially at 18.72×10^{-4} NDVI yr^{-1} before 1992 and then marginally increased (3.96×10^{-4} NDVI yr^{-1}) after 1992. The turning points were found to be 2008 and 1987 for the AA and NA subareas respectively. Analysis of monthly NDVI data showed that the trends were positive for most of the months of the study period, particularly during the growing season. Geospatial analyses demonstrated that cumulative annual NDVI and the variance or seasonality across the large AP region varied across the different subareas. As well, we found evidence for different spatial patterns of the NDVI changes with strong spatial heterogeneity in the patterns of the break and turning points. This suggests complex and nonlinear responses of vegetation photosynthetic activity to regional climatic changes and other drivers.

1. Introduction

Vegetation, as the most important component of terrestrial ecosystems, fundamentally regulates the energy budget, water cycle and biogeochemical cycle in the land surface through photosynthesis, respiration, transpiration, surface albedo, and roughness (Jackson, Randerson, Canadell, et al., 2008). Photosynthetic activity affects the Earth climate system and maintains climate stability, through its coupling with transpiration (Anderson, Canadell, Randerson, et al., 2010). Understanding the dynamics of photosynthetic activity and its correlations with climate variability and climate change is one of the important issues of global change research (Nemani et al., 2003). Satellite remote sensing is unique and useful for monitoring vegetation dynamics and environmental changes over large coverage in a repeatable manner (Goward, Tucker, & Dye, 1985; Myneni, Hall, Sellers, & Marshak, 1995; Nemani et al., 2003; Tucker et al., 2001; Zhou et al., 2001).

* Correspondence to: B. Chen, State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A, Datun Road, Chaoyang District, Beijing, China. Tel./fax: +86 10 64889574.

** Corresponding author.

E-mail addresses: baozhang.chen@igsnrr.ac.cn (B. Chen), 1191184845@qq.com (Y. Liu).

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A common way to derive indicators on vegetation and environmental changes is to use spectral vegetation indices (VI). One of the most widely used VI is the Normalized Difference Vegetation Index (NDVI, Rouse, Haas, Schell, & Deering, 1973; Tucker, 1979). The NDVI exploits the contrast in reflectance between the infrared and red portions of the electromagnetic spectrum and has been found to be correlated well with leaf area index (LAI), chlorophyll abundance, absorption of photosynthetically active radiation (fPAR), and gross primary production quantity (GPP) (Goetz & Prince, 1999; Myneni et al., 1995). A number of researchers have used remote sensing imagery to investigate vegetation growth and ecosystem productivity or functioning (e.g. Beck et al., 2011; Box, Holben, & Kalb, 1989; De Jong, Verbesselt, Schaepman, & de Bruin, 2012; Defries & Townshend, 1994; Goetz, Bunn, Fiske, & Houghton, 2005; Miao, Yang, Chen, & Gao, 2012; Park & Sohn, 2010; Peng et al., 2011; Piao, Fang, Zhou, et al., 2003, Piao et al., 2011; Wang et al., 2011; Zhao & Running, 2010) at a wide variety of spatial and temporal scales.

Time series of NDVI data derived from the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) meteorological satellites are widely used (Myneni et al., 1995; Nemani et al., 2003; Tucker et al., 2001; Zhou et al., 2001). A number of studies analyzing changes in NDVI found that regional climate trends differentially impacted vegetation dynamics across different ecosystems at various spatial scales (De Jong et al., 2012; Myneni et al., 1995; Nemani et al., 2003; Zhao & Running, 2010).

Trends of increasing vegetation growth, also known as 'greening', have been documented in the Northern Hemisphere (NH) between 35° and 75° latitude (Beck et al., 2011; Slayback, Pinzon, Los, & Tucker, 2003; Zhou et al., 2001) and in few other regions, including the Sahel (Fensholt, Rasmussen, Nielsen, & Mbow, 2009; Olsson, Eklundh, & Ardo, 2005) and parts of Australia (Donohue, Mcvicar, & Roderick, 2009). Nemani et al. (2003) inferred a significant increase of Net Primary Productivity (NPP) from NDVI trends in northern high-latitude ecosystems during the period 1982–1999. By contrast, a decrease of photosynthetic activity over a large part of the boreal forests was found during 1982–2005 (Goetz et al., 2005) and during 1982–2008 (Beck et al., 2011). In addition, it was also found from NDVI observations that the general northern greening in the 1980s and the 1990s (Nemani et al., 2003; Zhou et al., 2001) was weaker in North America (Zhou et al., 2001) than over Eurasia (Piao et al., 2011). Further, De Jong et al. (2012) found that greening trends were weaker in the Southern Hemisphere (SH) than the NH. These findings consistently point out substantially different greening regimes among continents and regions.

The El Niño/Southern Oscillation, Pacific Decadal Oscillation and Arctic Oscillation/North Atlantic Oscillation are known as "natural patterns" of the Earth's climate, which exert important influences on regional climates around the world, especially on the Asia–Pacific (AP) region (including Australia, South East Asia, China, and the Pacific Coast of North America, see Fig. 1) (Catrin & John, 2013; Latif & Barnett, 1994; Newman, Gilbert, & Michael, 2003; Patterson, Chang, Prokoph, Roe, & Swindles, 2013), characterizing signatures in seasonally changing patterns of wind, air temperature, and precipitation. The AP region experienced faster environmental changes than the global average during the last few decades and will likely experience more climate extreme events and phenomena (Cruz, Harasawa, Lal, et al., 2007; Hansen, Ruedy, Sato, & Lo, 2010; USAID, 2010; Yao, Yang, Qian, Lin, & Wen, 2008). This region and its ecosystems are particularly vulnerable to climate changes (Preston, Suppiah, Macadam, & Bathols, 2006). The AP region also encompasses both developed and developing nations. This justifies a comparative investigation of changes in NDVI between the western (Asia–Australia (AA)) and the eastern part (North America (NA)) of the AP region. Considering the climatic uniqueness and importance of the AP region, we choose the AP region as the object of this study.

Most of the previous studies only used seasonal or annual mean NDVI, an indicator of cumulative annual vegetation productivity. The standard deviation of NDVI over a year which provides an indication of the seasonality or variance of the photosynthetic activity is another remote sensing indicator to capture vegetation dynamics. This study expands the NDVI time series analysis by including the annual s.d. indicator to assess changes in vegetation dynamics and to answer the question: how does NDVI seasonality change and is it consistent with the change of cumulative annual mean NDVI in the AP region?

Changes in vegetation dynamics can be characterized by seasonal changes, gradual trend changes and abrupt changes (De Jong et al., 2012). The gradual changes refer to the trend component beyond the seasonal variation, slowly acting environmental processes (De Jong et al., 2012). Over time, these gradual changes in vegetation photosynthetic activity during the 1980s and 1990s may stall or reverse (Angert, Biraud, Bonfils, et al., 2005; Lotsch, Friedl, Anderson, & Tucker, 2005; Park & Sohn, 2010; Scheffer, Carpenter, Foley, Folke, & Walker, 2001; Wang et al., 2011; Zhao & Running, 2010; Zhao & Running, 2010). Most of these studies used time series of NDVI data from 1982 to 2006 or shorter. For example, De Jong et al. (2012) used NDVI data updated to 2008 and Wang et al. (2011) extended the study period to 2010 however only for China. In this study, we extended the study period until 2011 to analyze trend changes in vegetation photosynthetic activity using a 30-year long time series of NDVI data in the AP region. With the longest available NDVI series data, this study intends to answer the following three questions:

- How did the direction and rate of NDVI trend change temporally and spatially during the past 30-year period across the AP region?
- Are the previously observed trends in vegetation NDVI consistent with the trends during the last decade? For instance a reversal in the trend of vegetation NDVI in the late 1990s was found in Eurasia (Piao et al., 2011) and in the late 1980s/early 1990s in North America (Wang et al., 2011)?
- Is the global result that weaker greening in the SH while stronger greening in the NH (De Jong et al., 2012) applicable to the AP region?

To answer these questions, we analyzed changes in annual, growing season and monthly mean NDVI, and its annual standard deviation (s.d.) at a resolution of 8 km for the AA and NA regions.

2. Research area and dataset

2.1. Research area

We selected the AP as our research area (Fig. 1), which contains two subareas: the AA subarea (48°S–54°N, 73°–180°E) and the NA subarea (30°–72°N, 100°–168°W). The former covers much of East Asia, Southeast Asia and Australia, and the latter covers Alaska, Western Canada and Northwest USA. The AP contains almost all forest types on Earth, including tropical, sub-tropical, temperate and boreal forests, montane forests, and mangrove forests. The AP is predicted to be particularly vulnerable to climate change outcomes when compared to the rest of the world (Cruz et al., 2007; Hansen et al., 2010; USAID, 2010; Yao et al., 2008).

2.2. Dataset

In this study we used the Global Inventory Modeling and Mapping Studies (GIMMS) third generation NDVI dataset derived from the AVHRR sensors (NDVI3g) at a spatial resolution of 1/12° and 15-day interval, spanning from July 1981 to December 2011 (Myneni, Keeling, Tucker, Asrar, & Nemani, 1997; Tucker et al., 2005). This reanalysis improved AVHRR data quality in the northern parts of the world by using improved calibration procedures and calibrated using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data (Høgda et al., 2013). The GIMMS NDVI dataset has been corrected to minimize various deleterious effects, such as calibration loss, orbital drift and volcanic eruptions, and has been verified using stable desert control points (De Jong, Verbesselt, Zeileis, & Schaepman, 2013; Tucker et al., 2005; Xu et al., 2013; Zeng, Collatz, Pinzon, & Ivanoff, 2013).