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Short Communications

Vegetation greening in China and its effect on summer regional climate

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To mitigate the impacts of land degradation and achieve sustainable development, several large-scale conservation programs including the Key Shelterbelt Construction Program, Natural Forest Conservation Program, and the Grain to Green Program have been formulated into action in China since the late 1970s and 1998, respectively [1]. Recent satellite observations from 2000 to 2017 revealed a strikingly prominent greening in China due to these efforts [2]. Unraveling the influence of the greening on climate has become a new challenge in climate change research and adequate assessing of its environmental impact is imperative.

A number of studies using global Earth System models (ESM) with coarse resolutions have tested potential impacts of greening on surface temperature and terrestrial water cycle [3–5]. Satellite-derived leaf area index (LAI), which is a vegetation property representing the vegetation density, and forest area over either the globe or East Asia were the only vegetation variables that were changed in those studies. The global greening from 1982 to 2011 cools the global air temperature due to the increase in evapotranspiration, which mitigates surface warming [3]. The temperature and hydrological responses to the vegetation greening in China from 1982 to 2011 showed significant spring cooling and insignificant precipitation increase in North and Southeast China [4,5]. It is speculated that the weak climatic responses in summer to the vegetation greening were due to insignificant LAI changes in summer from 1982 to 2011 [4]. These studies also showed a few issues for concerns. For example, vegetation greening is expected to increase evapotranspiration, which may bring decrease in soil moisture [6], then induces a water resource problem. However, a study based on an ESM indicated that in North and Southeast China, the increased precipitation from vegetation greening, although statistically insignificant, may cancel out enhanced evapotranspiration, resulting in weak impact on soil moisture [5]. The regional responses of temperature, soil moisture, and precipitation to vegetation greening need to be further investigated. In addition, the previous studies only considered the greening associated with an increase in LAI and forest area but no fraction of vegetation cover (FVC) changes were included, which have been available since 2000 [3,4,7]. The 32% and 24% of the greening in China occurred in cropland and other land-use types [2], respectively. The lack of FVC change combined to the coarse resolution increased the uncertainty of the quantification on biogeophysical feedbacks of the observed greening in China on the East Asian regional climate.

This study intends to investigate the potential climatic impacts of the satellite-observed changes in both LAI and FVC in China by utilizing a high resolution (25 km) land–atmosphere coupled Weather Research Forecasting (WRF) regional climate model. The land surface model, Simplified Simple Biosphere model version 3 (SSiB3) coupled to the WRF, includes the influence of greening on surface albedo, canopy conductance, and aerodynamic properties of ecosystems, which affects surface energy and water balances, and interactions between the land surface and atmosphere [8]. In this study, we imposed the observed vegetation greening to the WRF/SSiB3 model, then conduct the experiments on different scenarios to assess the climatic responses to the observed greening. The NCEP/DOE Reanalysis 2 (R2) was utilized for the initial and lateral boundary conditions of WRF/SSiB3 in all cases. In the control scenario case, we imposed the specified monthly mean LAI and FVC based on the satellite LAI and FVC products from the "Global Land Surface Satellite" project [9] averaged for 2001–2005 over China to represent the vegetation condition before 2006. In the impact scenario case, the monthly mean LAI and FVC for 2013–2017 in China were used to describe the vegetation greening, while the other settings remained the same as the control scenario. The simulations were integrated from 28 April to 1 October for the 2006–2017. The results for June-July-August (JJA) means averaged over these years were analyzed.

Climate observations show that China had experienced remarkable warming in past decades [10]. The precipitation in China shows that southern China has undergone more rainfall while

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northern China is experiencing less precipitation since 1960 [11]. How the greening affects these climate anomalies in East Asia and related mechanisms are the major focuses of this paper.

The summer LAI and FVC differences between 2013 and 2017 and 2001–2005 based on observation are displayed in Fig. 1. Overall, large parts of China have experienced a greening trend, with average increases of summer LAI and FVC over China being 0.084 m^2/m^2 and 1.12%, respectively [2]. The regions with the most substantial increase of LAI and FVC are found in Loess Plateau and Northeast China, larger than 0.8 m^2/m^2 and 20%, respectively. Fig. 1c, d shows model-specified difference between impact run and control run, respectively, to test potential impact of the greening.

Fig. 2 illustrates the impact of greening on the spatial distributions of the air temperature at 2 m (T-2m), precipitation, evapotranspiration, integrated moisture flux convergence, and wind vector at 700 hPa. The simulated T-2m is substantially reduced in the vegetation greening experiments in northern China (Fig. 2a). Fig. S1a (online) shows the observed differences in JJA T-2m between 2013 and 2017 and 2001–2005. Although there was a large scale warming in large part of China, there were no substantial temperature increases in many parts of North China

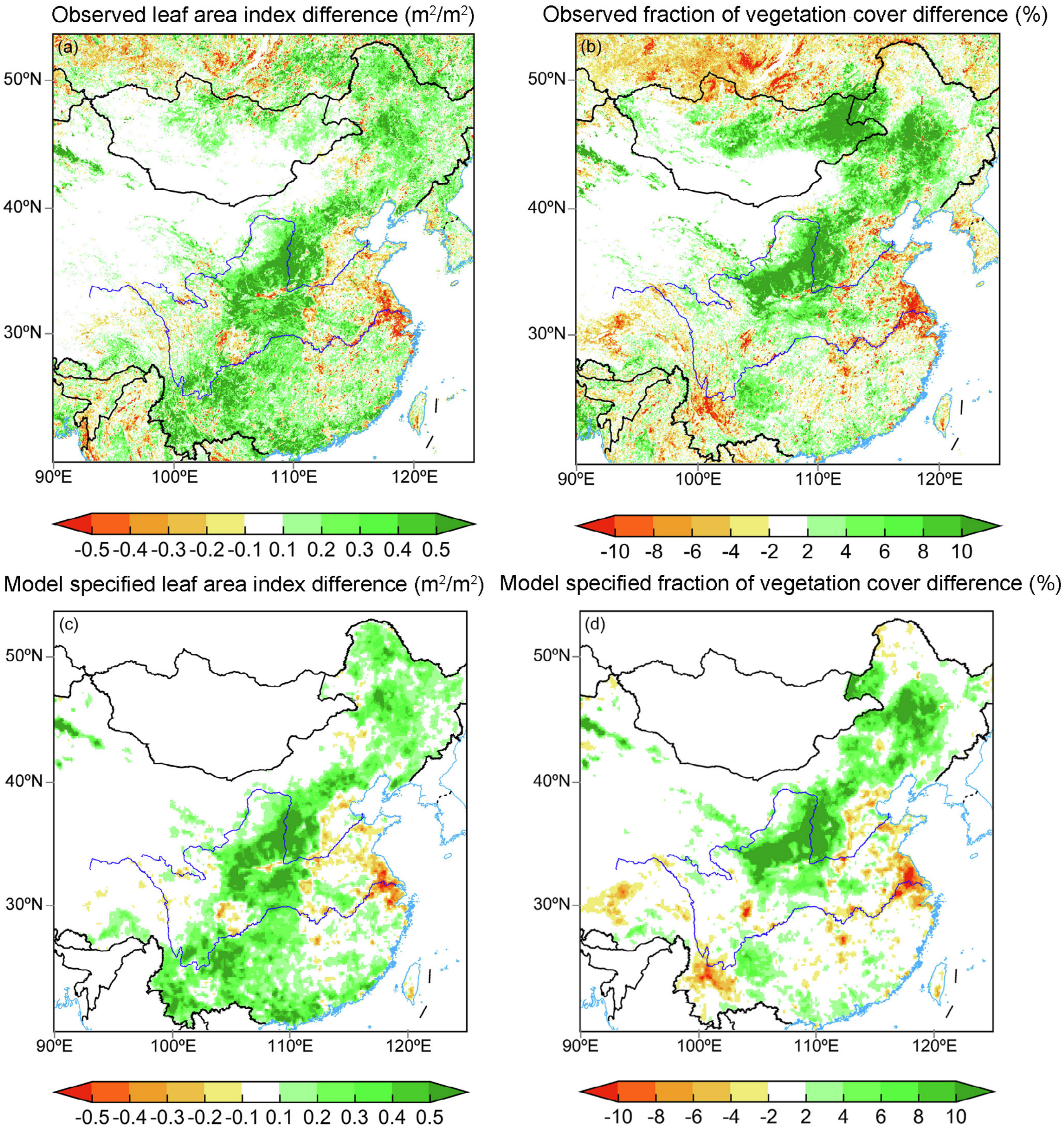

Fig. 1. The June-July-August (JJA) difference in leaf area index and fraction of vegetation cover between 2013 and 2017 and 2001–2005 in remote sensing observation (a, b) and model-specified difference between impact run and control run (c, d), respectively.

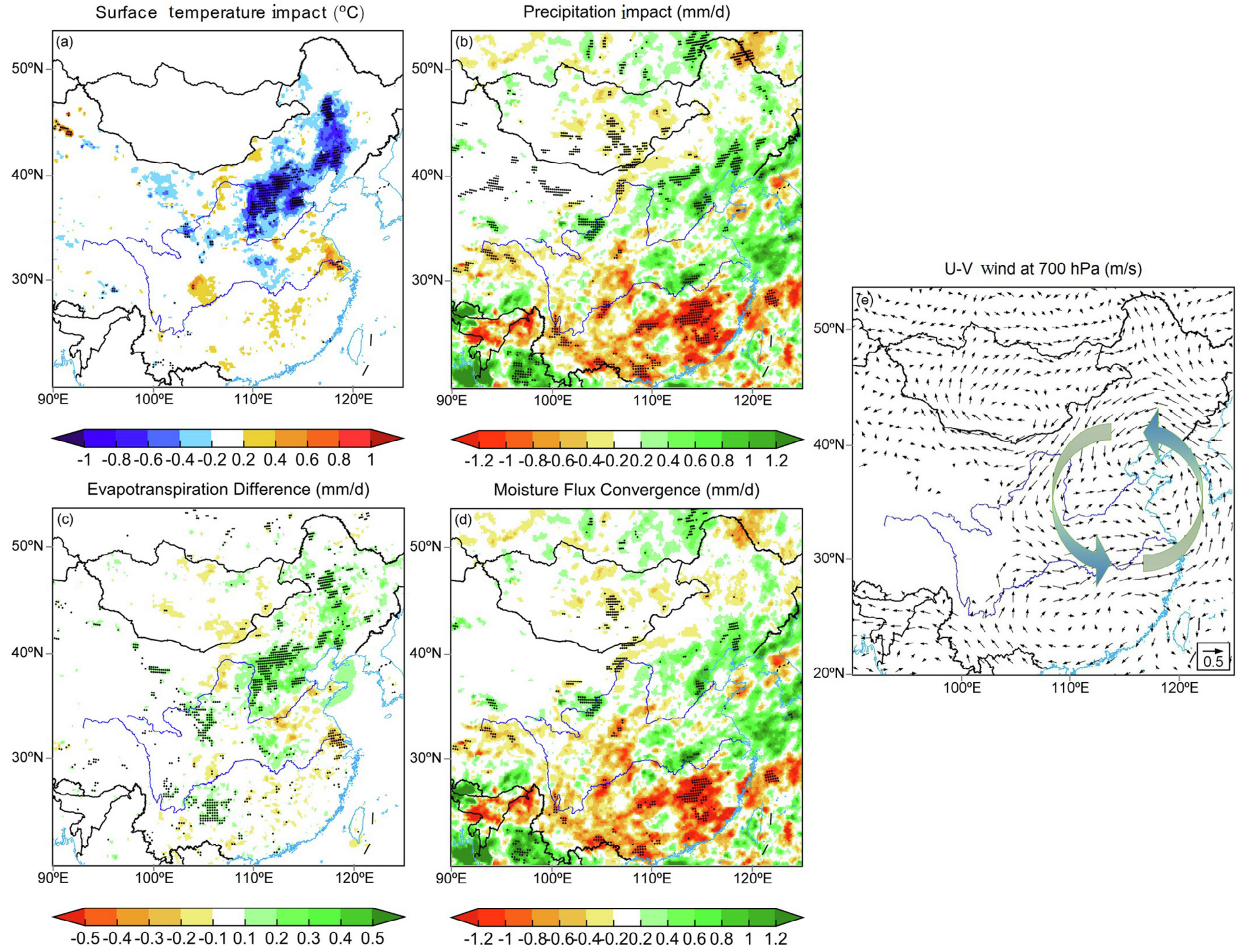

Fig. 2. June-July-August difference between the impact run and the control run in: (a) surface temperature (°C), (b) precipitation (mm/d), (c) evapotranspiration (mm/d), (d) integrated moisture flux convergence (mm/d) and (e) wind vector at 700 hPa (m/s). The stippled areas denote the areas statistically significant at $P < 0.10$ confidence level.

in observations where the impact run showed surface temperature reduction, suggesting that the greening lessened summer warming during our study period. The reduction of the T-2 m averaged from 37° to 43°N and 110°–127°E (referred to as North China in this paper) was 0.41 °C. Over the same area, the observed JJA T-2m difference between 2013 and 2017 and 2001–2005 is only 0.21 °C, much smaller than the average warming, 0.61 °C, over western China (90°–108°E, 27°–36°N, Fig. S1a, online).

The simulated rainfall significantly increased in the greening area in northern China, while decreasing to the south of the Yangtze River (Fig. 2b). A previous study with a hypothesized land cover change has reported that desertification in the Inner Mongolian grasslands would cause drying in northern China and increased wetness to the south [12]. Our study with observed greening in land condition and the state-of-the-art high resolution WRF tested the opposite process of land degradation, and the results were consistent with the desertification effects but with opposite signs and are more consistent with the observed climate anomalies (Fig. S1b). The simulation shows that with observed greening, the precipitation in North China increased by 0.34 mm/d, which is consistent with observed enhanced precipitation, 0.23 mm/d, between 2013 and 2017 and 2001–2005. China has witnessed a summer northern drought with southern flood pattern in the past several decades [11]. The observed JJA precipitation difference over the Yangtze River Basin (108°–122°N, 28°–32°N) was very large, 1.5 mm/d (Fig. S1b online). The precipitation changes as shown in Fig. 2b suggest that the vegetation greening is likely to be the contributor for the increase of precipitation in relatively dry northern China while slightly mitigating the wet condition south of the Yangtze River Basin, by only −0.14 mm/d.

Vegetation greening affects both surface conditions and atmospheric circulation. It is expected to reduce surface albedo and aerodynamic resistance and to increase evapotranspiration [3,13,14]. Our simulated results showed a slight albedo reduction in North China, less than 0.01, which is also consistent with the remote sensing observation during the same time period. The downward shortwave radiation in the vegetation greening experiments was reduced by 4.11 W/m^2 over North China because of the increased cloudiness, which dominated the decreased outgoing shortwave radiation (by 1.6 W/m^2) due to the lower albedo. This result is consistent with other studies, which show that the albedo-climate feedback is weak in summer in China [3]. Because the lower surface temperature led to lower upward longwave radiation, the total net radiation has no substantial change (Fig. S2 online). The greening enhanced the vegetation transpiration and canopy interception while decreasing the soil evaporation, and, as a result, increased evapotranspiration by 0.13 mm/d over North China. The increased latent heat flux is largely balanced by the reduced sensible heat flux due to little change in the net radiation (Fig. S2 online).

It should be noted that the area over the south part of the Loess Plateau (33°–38°N, 108°–111°E), with the large increase in LAI and FVC, has only slightly increased the evapotranspiration because the decreased soil evaporation there due to the shelter from the vegetation counteracted most of the evapotranspiration enhancement from the canopy (Fig. S3 online). Another area, the area south of the Yangtze River, also showed large increase in LAI, but its impact there was not as substantial as that in North China. There is not much change in FVC. Moreover, in the southern China with abundant moisture in the atmosphere and on the surface, both the surface albedo and the evapotranspiration in JJA are not very sensitive to the LAI change.

The simulation results show that the enhanced evapotranspiration, 0.13 mm/d, is much less than the rainfall increase (0.34 mm/d) over North China in the impact runs. That said, the circulation change induced by the surface greening has to be evaluated. East Asian summer monsoon circulation dominates the summer precipitation pattern in China [11]. The JJA mean wind vector difference at 700 hPa between the impact and control runs (Fig. 2e) illustrates a strong cyclonic circulation in North China accompanied by an anticyclone in South China. Over North China, the increase of integrated moisture flux convergence associated with the cyclone explained about 60.3% of the variations in precipitation (Fig. 2d), indicating that the positive evapotranspiration combined with a cyclonic circulation has led to more convective precipitation there. Our previous desertification study [12] showed that the reduced evapotranspiration at the surface after land degradation decreased the heat release in the middle of the atmosphere, produced a relative cooling, generated subsidence and an anticyclone in northern China, and induced a cyclone to the south. The processes here with the surface greening show a reversal process.

The impact of land condition change on soil moisture is important for water resource management. There has been concern that enhanced evapotranspiration would cause a surface water deficit [6]. In this study, soil moisture differences at the surface layer showed a similar spatial pattern with the precipitation. With more rainfall to compensate for the enhanced evapotranspiration over North China, the volumetric soil water content in the surface layer actually increased by 0.007 there, which was consistent with previous study [6]. The soil moisture at the rooting zone only showed slightly changes across China (Fig. S4 online). However, in areas such as south of the Loess Plateau and South China with less moisture flux convergence to balance the increased evapotranspiration, the soil moisture at the root zone reduced by 0.01–0.03 (Fig. S4 online). While the soil moisture reduction in moist south China may not cause a problem, the effect of greening in semi-arid regions, such as the south Loess Plateau and Hulunbuir of Inner Mongolia, on soil moisture needs to be further investigated. Due to the relatively stable air condition, these areas are not conducive to the convergence of water vapor and rainfall forming [15]. Proper vegetation species with lesser water requirement may need to be selected for the vegetation plantation there.

This sensitivity study is the first to identify the significant summer regional climatic (precipitation and temperature) impact of the greening in China with two different vegetation conditions (with/without greening) and concludes that the observed greening in China caused significant summer cooling and enhanced the summer monsoon precipitation in North China, and slightly reduced precipitation to the south of the Yangtze River. This result indicates that the greening would counter some global warming effects and mitigate the consequence of the summer "north drought with south flood" anomalies in China. Our result further suggests that accurate representation of the full land cover change scenario and inclusion of all major feedback processes are essential to properly assess the effect of land use and land cover change. This study highlights the potential of land use management including reforestation and the agriculture green program in China to mitigate climate anomalies through biogeophysical feedbacks, which may have significant implications for environmental protection and future climate change projection.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Lingxue Yu made model simulation and data processing, and contributed to results analyses and paper writing. Yongkang Xue led this research. He designed the experiment and contributed to results analysis and paper writing. Ismaila Diallo contributed to model simulation and data processing.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2020.09.003.

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