Biogeophysical Forcing of Land-Use Changes on Local Temperatures across Different Climate Regimes in China[✉]

L. HUANG

Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

J. ZHAI

Satellite Environment Center, Ministry of Environmental Protection, Beijing, China

C. Y. SUN

National Climate Center, China Meteorological Administration, Beijing, China

J. Y. LIU, J. NING, AND G.S. ZHAO

Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

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ABSTRACT

Land-use changes (LUCs) strongly influence regional climates through both the biogeochemical and biogeophysical processes. However, many studies have ignored the biogeophysical processes, which in some cases can offset the biogeochemical impacts. We integrated the field observations, satellite-retrieved data, and a conceptual land surface energy balance model to provide new evidence to fill our knowledge gap concerning how regional warming or cooling is affected by the three main types of LUCs (afforestation, cropland expansion, and urbanization) in different climate zones of China. According to our analyses, similar LUCs presented varied, even reverse, biogeophysical forcing on local temperatures across different climate regimes. Afforestation in arid and semiarid regions has caused increased net radiation that has typically outweighed increased latent evapotranspiration, thus warming has been the net biogeophysical effect. However, it has resulted in cooling in subtropical zones because the increase in net radiation has been exceeded by the increase in latent evapotranspiration. Cropland expansion has decreased the net radiation more than latent evapotranspiration, which has resulted in biogeophysical cooling in arid and semiarid regions. Conversely, it has caused warming in subtropical zones as a result of increases in net radiation and decreases in latent evapotranspiration. In all climatic regions, the net biogeophysical effects of urbanization have generally resulted in more or less warming because urbanization has led to smaller net radiation decreases than latent evapotranspiration. This study reinforces the need to adjust land-use policies to consider biogeophysical effects across different climate regimes and to adapt to and mitigate climate change.

1. Introduction

As a primary anthropogenic activity, land-use changes (LUCs) influence regional and even global climates (Pielke et al. 2002; Feddema et al. 2005; Diffenbaugh

2009; Fall et al. 2010; Mahmood et al. 2010) through both biogeochemical (carbon cycle and atmospheric CO₂ concentration) and biogeophysical (physical properties of the land surface, such as albedo, roughness, and evapotranspiration) processes (Claussen et al. 2001; Pongratz et al. 2010; Jones et al. 2013a; Hallgren et al. 2013). By ignoring biogeophysical processes, which in some cases offset biogeochemical effects, policy makers cannot adapt the best climate solutions (Pielke et al. 2002; Bonan 2008; Anderson

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Corresponding author: J. Zhai, zhaij@lreis.ac.cn

et al. 2011; Anderson-Teixeira et al. 2012). For example, the cooling effects associated with vegetation removal as a result of the decrease in net radiation sometimes outweigh the warming effects caused by greenhouse gases (Betts 2000; Pan et al. 2011). Deforestation raises surface temperatures in the tropics but has the potential to cool the land surfaces at mid- to high latitudes by altering biogeophysical processes (Werth and Avissar 2002; Bala et al. 2007; Anderson et al. 2011; Hallgren et al. 2013), and this cooling effect increases northward of 45°N (Lee et al. 2011). Thus, ensuring effective climate protection through LUC requires considering combined biogeochemical and biogeophysical forcings (Pielke et al. 2002; Jackson et al. 2008; Diffenbaugh 2009), which are important for understanding observed and projected climate changes (Brovkin et al. 2006; Barnes and Roy 2008; Diffenbaugh 2009; Li et al. 2015). However, biogeophysical processes have not been considered in climate negotiations to date because of their uncertainties in sign and magnitude (Forzieri et al. 2017). Although many studies of the biogeophysical impacts of LUCs have been conducted using satellite measurements (Peng et al. 2014; Forzieri et al. 2017) or climate model simulations (Pitman et al. 2011), the impacts of LUCs on regional-scale climate remain uncertain.

Air temperature is controlled by land surface albedo and emissivity, incoming solar radiation, and the distributions of latent and sensible heat fluxes (Rotenberg and Yakir 2010; Peng et al. 2014). The net absorbed land surface radiation may be released into the atmosphere in the form of sensible or latent heat fluxes, which are presented as warming or cooling processes, respectively (Chapin et al. 2008). It has been suggested that net solar radiation plays a more prominent role in high-latitude regions, while the hydrological cycle is the dominant factor in tropical regions (Claussen et al. 2001; Bonan 2008). Forzieri et al. (2017) showed that widespread greening contributed to the warming of the boreal zones by reducing the surface albedo and contributed to evapotranspiration-driven cooling in arid regions. However, because of the lack of requisite field observations and high-resolution gridded datasets, the warming or cooling effects of LUCs resulting from the balance of sensible heat fluxes and the net radiation remains poorly understood (Peng et al. 2014). For example, cooling effects are associated with vegetation removal caused by the related decreases in net radiation (Betts 2000; Pan et al. 2011). Counteracting this effect, vegetation removal also reduces the surface evapotranspiration and the latent heat flux

(Anderson-Teixeira et al. 2012), because the energy usually used in evapotranspiration would heat the land surface instead (Pielke et al. 2002; Loarie et al. 2011). However, it is not known whether the intrinsic biogeophysical mechanisms of local-scale LUCs can change the temperature in a consistent manner (Rotenberg and Yakir 2010). In addition, quantitative analyses of the roles of LUCs across varied climate regimes are still elusive (Diffenbaugh 2009; Zhao et al. 2014).

Under the enhanced land-use pressures resulting from economic development and growing populations and along with the increasingly urgent demand to mitigate and adapt to climate change, the quantification of biogeophysical forcing by LUCs will be essential. Here, we provide a simple analytical approach to quantify the biogeophysical cooling or warming effects arising from LUCs through a surface energy budget to evaluate how the most important LUCs have contributed to each climatic region's temperature changes based on observations from in situ stations and satellites and to define how useful land-use policies can be for mitigating and adapting to climate change in various regions of China. Satellite-derived LUC data, land surface temperature (LST) data, and biogeophysical products, such as albedo and emissivity together with in situ land surface radiation and hydrothermal measurements, were integrated using time-varying maps of land surface fluxes from the physically based Surface Energy Balance Algorithm for Land (SEBAL) model (Bastiaanssen et al. 1998) to analyze the impacts of three main LUCs (afforestation, cropland expansion, and urbanization) on the changes in the local temperatures of regions with various background climates and to discuss the spatial patterns of the regional-scale biogeophysical warming or cooling effects of LUCs.

2. Materials and methods

The methods used to estimate the LUC forcing on climates are usually applied to field observations or model simulation. However, applying only modeling approaches cannot accurately reproduce local effects, as field data measured in situ have limited coverage, and there are uncertainties in observations just from satellites (Li et al. 2015). To avoid these weaknesses when using a single approach, in situ field observations; meteorological, satellite, and reanalysis products; and modeling approaches were integrated to estimate the biogeophysical forcing of LUCs on the local temperatures of the 16 years from 2000 to 2015 (Fig. 1), when socioeconomic developments and ecological

FIG. 1. The flowchart of the methodology to determine the biogeophysical forcing and resulting temperature change over a particular region associated with a specific land-use change.

conservation movements drove the spatial and temporal variations of LUCs in China.

a. Biogeophysical forcing of LUCs on local temperature

According to a conceptual analysis of the biogeophysical effects performed by Lee et al. (2011), the actual temperature change depends on the surface radiation loading and energy redistribution through convection and evapotranspiration. Radiative forcing results from albedo changes, but it is always damped by energy redistribution, and the energy redistribution is decided by changes in the Bowen ratio and surface roughness.

It was assumed that the adjacent land-use types shared the same background condition, which was defined by the incoming solar radiation, the incoming longwave radiation, and the air temperature at the blending height above the ground (Lee et al. 2011). The impacts of the LUCs on local temperatures can be expressed as the temperature difference ΔT of one land-use type minus that of another nearby type. Positive (negative) ΔT indicates a warming (cooling) effect. Paired sets of mean air temperature data were used for analysis. Thus, we compared the

temperatures of the nearby typical land-use types of forest, grassland, cropland, and urban areas. The forest, grassland, cropland, and urban areas adjacent to each other were chosen for the pairwise comparison analyses.

A simple approach was proposed to quantify the biogeophysical forcing per unit area of LUCs. The land surface net radiation R_n determines the energy that could be provided for the latent heat flux LE, the sensible heat flux, and the soil storage flux. Therefore, the heat flux H provided from the land surface to the atmosphere was estimated using the mass balance $H = R_n - LE$, which assumes that the storage flux was negligible at annual time scales (Forzieri et al. 2017). Therefore, differences in LUC results $\Delta(R_n - LE)$ were averaged by unit at the pixel level and across climatological gradients. In addition, the spatial variations in the patterns of biogeophysical warming or cooling effects as a result of LUCs over the past 16 years from 2000 to 2015 were estimated per unit $\Delta(R_n - LE)$ and by the LUC area for each LUC type.

Then, we explored the relationships between the relative year-to-year variations of temperature (ΔT) and the terms of the surface energy budget $[\Delta(R_n - LE)]$ at the pixel level and across climatological gradients.

b. Land surface temperature datasets and meteorological observations

Air temperature data are usually obtained from measurements made at meteorological stations and provide only limited information regarding spatial patterns over wide areas. Therefore, the LST datasets were gathered at a 1-km grid over 8-day periods from 2000 to 2015 from the products of the Moderate Resolution Imaging Spectroradiometer (MODIS) (MOD11A2 and MYD11A2) and were used to derive the spatial and temporal patterns of local air temperatures over the past 16 years using simple linear equations, according to the work of Benali et al. (2012).

The MOD11A2 and MYD11A2 comprise the 8-day LST products at 1-km spatial resolutions for *Terra* and *Aqua*, respectively. These products are calculated using a split-window algorithm that uses the emissivity from the MODIS bands 31 and 32. The four LST products of the *Terra* daytime, *Terra* nighttime, *Aqua* daytime, and *Aqua* nighttime were averaged for this analysis. The LST products were acquired and processed to correct for low-quality and bad-quality pixels resulting from cloud contamination and optical leak corrections using statistical outlier eliminations and gap-filling methods.

To retrieve the best estimations of the air temperature, air temperatures observed at 2422 national and local meteorological stations across continental China were collected (supplemental Fig. S1). For the meteorological data, 70% of the observed air temperatures were used for retrieval and 30% were used for validation. The validation results are presented in Fig. S2.

c. Estimation and evaluation of biogeophysical parameters

According to the SEBAL model (Bastiaanssen et al. 1998), the R_n can be expressed as the sum of the net shortwave radiation R_{ns} and net longwave radiation R_{nl} ,

$$R_n = R_{ns} + R_{nl}. \quad (1)$$

The R_{ns} can be calculated as the difference between the downward ($R_s^\downarrow$) and upward radiation ($R_s^\uparrow$) or as a combination of the downward radiation and land surface albedo α (Kim and Liang 2010),

$$R_{ns} = R_s^\downarrow - R_s^\uparrow = (1 - \alpha)R_s^\downarrow. \quad (2)$$

The monthly $R_s^\downarrow$ datasets on a $0.75^\circ \times 0.75^\circ$ grid from 2000 to 2015 were derived from reanalysis data collected from the European Centre for Medium-Range Weather Forecasts (ECMWF) with strict quality control (Dee et al. 2011). These data were then resampled to a 1-km grid.

The actual α is a combination of the albedo under a black sky α_{black} , and a white sky α_{white} , which was obtained by Román et al. (2010) as follows:

$$\alpha = S\alpha_{\text{white}} + (1 - S)\alpha_{\text{black}}. \quad (3)$$

The black-sky albedo (directional hemispherical reflectance) and white-sky albedo (bihemispherical reflectance) are collected from the MODIS standard albedo product (MCD43B3) every 8 days at a spatial resolution of 1 km from 2000 to 2015. The MCD43B3 albedo quantities are generated from the anisotropy models provided in MCD43B1 by combining both *Terra* and *Aqua* data. The models best describe the differences in radiation caused by the scattering of each pixel.

The quantity S is the sky scattering factor, which can be calculated using a simple exponential relationship (Long and Gaustad 2004)

$$S = a[\cos(\text{SZA})]^b, \quad (4)$$

where SZA is the solar zenith angle between the zenith line and the direction to the sun. It was provided by the MODIS reflectivity products and then monthly averaged during the period 2000–15. In typical midlatitudes, the values of a and b are 0.10 and -0.8 , respectively.

The R_{nl} can be calculated using the Stefan–Boltzmann equation as follows:

$$\begin{aligned} R_{nl} &= R_l^\downarrow - R_l^\uparrow = \varepsilon_s R_l^\downarrow(T_a, \varepsilon_a) - R_l^\uparrow(T_s, \varepsilon_s) \\ &= \varepsilon_s \sigma \varepsilon_a T_a^4 - \sigma \varepsilon_s T_s^4, \end{aligned} \quad (5)$$

where $R_l^\downarrow$ is the incoming longwave radiation, $R_l^\uparrow$ is the outgoing longwave radiation, ε_a is the air emissivity, ε_s is the land surface emissivity, T_a is the air temperature (K), T_s is the land surface temperature (K), and σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$). For the land surface emissivity, we used the 8-day MODIS product (MOD11A2). The broadband emissivity was estimated via conversions from the emissivity of individual bands according to the conversion coefficients from Jin and Liang (2006).

The MODIS snow product (MOD10A2) from 2000 to 2015 was applied to the filter to produce 8-day parameter datasets without snow cover.

The evapotranspiration/latent heat flux (ET/LE) product datasets [MOD16A2 (V005)] from 2000 to 2015 were collected from the MODIS Global Evapotranspiration Project (Mu et al. 2011). This dataset is a monthly composite product produced at a 1-km pixel resolution and applies an algorithm based on the logic of the Penman–Monteith equation.

Field observation datasets were applied to evaluate and calibrate the satellite products and the outputs of

SEBAL. Several in situ fluxes of radiation, sensible and latent heat, air temperature, and evaporation were primarily obtained from the China Ecological Research Network, including 10 forest flux towers, 5 grassland flux towers, and 10 cropland flux towers (Fig. S1). These sites have a minimum of three years of observational data. Moreover, these data were processed for the evaluation of satellite-derived biogeophysical parameters.

The spatial and temporal variation patterns of the biogeophysical parameters in the 16 years from 2000 to 2015 were analyzed. The biogeophysical parameters involved include the land surface albedo, emissivity, net shortwave radiation, net longwave radiation, net radiation, and latent flux.

d. Land-use changes datasets from satellite images

LUCs datasets were obtained from China's national land-use and land-cover datasets, produced by the Chinese Academy of Sciences. The datasets were generated by interpreting the Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper Plus (ETM+) images acquired in 2000, 2005, 2010, and 2015 with a mapping scale of 1:100 000. The hierarchical classification systems include six aggregated classes: cropland, forest, grassland, wetland, desert, and urban area. These datasets were evaluated using the extensive files of survey materials from 10% of the counties of China, and the interpretation accuracies of the aggregated classes reached 94.3%, according to Liu et al. (2014). The primary LUCs in China during the 16 years from 2000 to 2015 are presented as accelerated urbanization, shifted land reclamation, and increased forest area. Therefore, the main LUC types addressed in our analysis are afforestation, cropland expansion, and urbanization.

The gridded land-use type data with a 1-km spatial resolution from 2000 to 2015 were extracted by calculating the area fractions of each grid. A pure grid is defined as a grid with more than 90% coverage by one land-use type. For example, a pure grid of forest means that the area of forest in the grid was large than 0.9 km^2 , and it did not change in 2000, 2005, 2010, or 2015. The pure grids of forest, cropland, grassland, and urban areas were further extracted. Based on the pure grids of the land-use types, the value ranges of each biogeophysical parameter for forest, cropland, grassland, and urban area were statistically extracted at the pixel level and across climatological gradients.

e. Impacts of LUC on temperatures and biogeophysical parameters

The impacts of LUC on the temperatures and biogeophysical parameters are the difference between the temperatures and biogeophysical parameters for the

“actual landscapes” and “potentially converted” land-use types. We compared the temperatures, albedo, emissivity, and other biogeophysical parameters of the typical land-use types found nearby, which were defined as primary land-use types when accounting for more than 90% of the grid. The forest, grassland, cropland, and urban areas adjacent to each other were chosen for pairwise comparison analyses. The sample windows were defined as squares containing 30×30 pixels with $1 \times 1 \text{ km}^2$ spatial resolution. Valid windows were chosen by overlap method to compare actual landscapes with the “previous landscape” nearby. Any two horizontally or vertically adjacent windows were overlapped by 15 pixels with each other. A window was valid if it has more than 5% pixels of actual landscapes and previous landscape.

Altitude is one of the important proxies for pairwise temperature comparisons. In the sample windows, if the altitude of actual landscapes and the nearby previous landscape were very different, then the temperatures of actual landscapes should be adjusted for altitude biases. We performed an altitude adjustment by subtracting the altitude-induced temperature change from the original temperature of actual landscapes. It could be presented as

$$T = T_o - 0.6 \times \Delta\text{ELE}/100, \quad (6)$$

where T is the adjusted temperatures of actual landscapes, T_o is the original temperature of actual landscapes, ΔELE (m) is the altitude difference between actual landscapes and the nearby previous landscape.

To examine the potential biogeophysical forcing of LUCs, we quantified the net radiations and latent heat fluxes of the three main LUC types (afforestation, cropland expansion, and urbanization) of the eight climatic regions [arid middle temperate (AMT), semiarid middle temperate (SMT), warm middle temperate (WMT), warm temperate (WT), northern subtropical (NS), southern subtropical (SS), middle subtropical (MS), and Tibetan Plateau (TP); Fig. 2]. The climatic regions of China were regionalized by Zheng et al. (2013), and the boundaries were delineated according to days with daily temperatures consistently above 10°C in January or July and their annual mean temperature as well as the annual aridity indices and annual precipitation.

3. Results

a. Dynamics of land surface biogeophysical parameters from 2000 to 2015

Figure 2 shows the trends of the land surface albedo, emissivity, net radiation, latent energy, and LST during 2000–15. The observed albedo was found to mainly

FIG. 2. The trends of the biogeophysical parameters from 2000 to 2015 in China. (a) Land surface albedo, (b) emissivity, (c) net radiation, (d) latent evapotranspiration (e) LST, and (f) ($R_n - LE$).

decrease in northern China, especially in the SMT region (Figs. 2a, S3a). This pattern could be largely explained by the vegetation restorations resulting from ecological restoration programs. Natural factors contributing to vegetation coverages, such as precipitation, showed slight decreases (Wan et al. 2014) or no significant change (Wang et al. 2017). In addition, significant albedo increases were also found in southern China (Fig. 2a). Changes in land surface emissivity were

observed in northern China and mainly presented decreasing trends, with partial increases observed in the AMT region (Fig. 2b). The net radiation over the past 16 years showed decreases in northern and eastern China, and increases in the SS region and over the Tibetan Plateau (Fig. 2c). Obviously, besides the Tibetan Plateau, the latent energy in southern, eastern, and north-eastern China decreased considerably (Figs. 2d, S3d). The LST decreased in most regions, especially in the WT

FIG. 3. The biogeophysical forcing (W m^{-2}) of afforestation in various climate zones: ΔR_{ns} (green), ΔR_{nl} (pink), ΔR_n (red), ΔLE (yellow), and $\Delta(R_n - LE)$ (blue).

and northern AMT regions (Fig. 2e). However, the LST increased in the northeastern WMT region, the northern SMT region, and over the southern TP region. The change of the LST could partially be a response to the variations of $(R_n - LE)$, especially in the TP, NS, and WT regions (Fig. 2f).

b. Impacts of afforestation on biogeophysical parameters

If we approximate the net radiation changes using the satellite-derived data, we arrive at the apparent local temperature sensitivities of all climatic zones. A conversion from cropland or grassland to forest leads to land surface albedo decreases of 0.017–0.059 and

0.004–0.102, respectively (Fig. S4). The annual average albedo changes by $-(11.6\%–33.17\%)$ when transitioning from cropland to forest and $-(3\%–48.3\%)$ when transitioning from grassland to forest. The changes in the surface albedos do not exceed 10% in subtropical regions (NS, SS, MS) (Figs. S4f,g,h). However, the changes in albedo are greater in the AMT and SMT regions (Figs. S4b,c). Hence, the albedo increases the net shortwave radiation at the forest surface by 2.92–9.13 W m^{-2} compared with those of the adjacent cropland and by 1.06–12.02 W m^{-2} compared with those of the adjacent grassland, with higher values in the temperate and arid regions and lower values in the subtropical regions and over the Tibetan Plateau (Fig. 3a).

Afforestation of cropland results in lower $\Delta\epsilon_s$ in all climatic regions but leads to lower $\Delta\epsilon_s$ in wet temperate and subtropical regions as well as higher $\Delta\epsilon_s$ in arid regions and over the Tibetan Plateau in the case of grassland (Fig. S5). Afforestation consequently increases the longwave net radiation in all climatic zones. In subtropical and temperate zones, the annual mean longwave radiation values that we observed in our cropland–forest and grassland–forest comparisons were 2.18–18.27 and 3.36–23.6 W m^{-2} , respectively, showing values that are generally equivalent in magnitude.

Compared to the aforementioned radiative effects, the hydrothermal processes show the opposite effects. In subtropical regions (Figs. 3f,g,h), afforestation increases the ΔR_n less than ΔLE ; thus, cooling was the net biogeophysical effect. Although an increase of ΔR_n could be completely compensated by an increase of ΔLE , this increase might cool the local climate indirectly as a result of enhanced cloud cover and consequently decrease the surface albedo. In arid and semiarid regions (Figs. 3b,c), afforestation increases the ΔR_n more than the ΔLE ; thus, warming was the net biogeophysical effect. In warm temperate regions (Figs. 3d,e), afforestation increases the ΔR_n more than the ΔLE ; thus, warming was the net biogeophysical effect.

In agreement with the previous studies of [Arora and Montenegro \(2011\)](#), [Betts \(2011\)](#), and [Peng et al. \(2014\)](#), the relative contribution of the biogeophysical forcing of afforestation to ΔT should depend on the local background climate. From northern to southern China, we can see that forest absorbs more solar radiation and simultaneously yields lower heat fluxes than the nearby grassland and cropland. Therefore, cooling will result when the afforestation increases both the absorbed incoming solar radiation and the dissipated evapotranspiration. Otherwise, afforestation will lead to warming in relatively arid regions.

c. Impacts of cropland expansion on biogeophysical parameters

Cropland expansion replacing forest or grassland results in higher surface albedo and $\Delta\epsilon_s$ in all climatic zones, consequently lowering ΔR_{nl} and ΔR_{ns} , especially in the arid regions. A comparison of grassland and cropland revealed that cropland expansion leads to increases of surface albedo by 5.11%–19.17% (Fig. S4) and consequent decreases of ΔR_{ns} by 3.34–6.93 W m^{-2} in subtropical and warmer temperate regions, but this transition leads to decreases of albedo by 10.34%–17.23% and increases of ΔR_{ns} by 3.95–13.89 W m^{-2} in the middle temperate regions and over the Tibetan Plateau. This transition also increases the $\Delta\epsilon_s$ and decreases the ΔR_{nl} by 2.14–12.31 W m^{-2} in all climate zones. Over the Tibetan Plateau, the changes in surface albedo and emissivity as a result of the LUCs from

forest or grassland to cropland are much more pronounced than those in other regions (Fig. S3).

With higher albedo, cropland absorbs less incoming shortwave radiation, which probably results in cooling effects. However, the cooling is offset by lower latent heat losses, leading to warming effects. In the AMT region (Fig. 4a), cropland expansion over former forest causes decreases of ΔR_n that outweigh the decreases of ΔLE , while over former grassland, the increase of ΔR_n was less than the increase of ΔLE ; thus, cooling was the net biogeophysical effect for both. In the SMT region (Fig. 4b), the differences are not significant. In the WT region (Figs. 4c,d), cropland expansion over former forest also causes decreases of ΔR_n that outweigh the decreases of ΔLE , and over former grassland, this transition causes decreases of ΔR_n and an increase of ΔLE ; thus, cooling was again the net biogeophysical effect. In subtropical regions (Figs. 4e,f,g), the cropland expansion over forest or grassland showed warming of the land surface as a result of increases of ΔR_n and the decreases of ΔLE . Over the Tibetan Plateau (Fig. 4h), cropland expansion presents cooling effects because it causes the decrease of ΔR_n greater than the decrease of ΔLE over forest, and decreases of ΔR_n and increases of ΔLE over grassland.

d. Impacts of urbanization on biogeophysical parameters

In all climatic zones, the conversions from grassland, cropland, or forest to urban areas lead to much lower surface albedo. The decreases were higher over the Tibetan Plateau and in temperate regions than in subtropical regions. Urbanization consequently increases the net shortwave radiation by 6.98, 5.97, and 7.38 W m^{-2} for the conversions from grassland, forest, and cropland, respectively. Comparisons of the urban areas with grassland, forest, and cropland show that the emissivity decreases in all climate zones and that the average annual net longwave radiations decrease by 5.73, 16.3, and 10.34 W m^{-2} for the conversion to urbanization from grassland, forest and cropland, respectively. Therefore, urbanization warms the land surface as a result of the related increase of ΔR_n and decrease of ΔLE in all regions when changing from grassland to urban areas and because the decrease of ΔR_n is less than the decrease of ΔLE for the urbanization from cropland and forest in temperate and subtropical regions (Fig. 5).

e. Biogeophysical warming or cooling effects of LUCs

From 2000 to 2015, the forest area increased by $2.37 \times 10^5 \text{ km}^2$ in China, mainly in ecologically fragile areas, such as the Loess Plateau in the SMT region and the southern hilly area in the MS region, as result of the

FIG. 4. As in Fig. 3, but for cropland expansion.

implementation of key large-scale ecological conservation and restoration projects. The cropland decreased by $1.02 \times 10^6 \text{ km}^2$, and 55.4% of this decrease was attributed to the transition of cropland to urban area. In ecologically fragile areas, the main reason for cropland loss was ecological conservation, especially the “Grain for Green Program.” The urban area increased by $3.76 \times 10^6 \text{ km}^2$, mainly as a result of the accelerated urban expansion in the eastern parts of the WT region and the NS and SS regions. The grassland decreased by $1.89 \times 10^6 \text{ km}^2$, mainly as a result of cropland expansion into grassland in the AMT region (Fig. 6a).

During the 16 years from 2000 to 2015, the three important LUC types caused obvious spatial patterns of biogeophysical warming or cooling effects in terrestrial China (Fig. 6b). The warming effects of LUCs primarily occurred in eastern and

central China, with the intrinsic biogeophysical warming reaching 20 W m^{-2} , mainly as a result of urbanization (Fig. S6c). The cooling effects of LUCs primarily occurred in western and southwestern China, reaching approximately 15 and 10 W m^{-2} primarily as a result of cropland expansion (Fig. S6b) and afforestation (Fig. S6a), respectively.

f. Biogeophysical forcing of LUCs on local temperatures

The average annual mean ΔT change related to cropland-to-forest transition varied in different climate zones, with negative ΔT in WT, WMT, AMT and the three subtropical regions but positive ΔT in arid regions and over the Tibetan Plateau (Fig. 7). However, the ΔT changes related to grassland-to-forest transition were negative in the three subtropical regions and positive in the other regions. This

FIG. 5. As in Fig. 3, but for urbanization.

study finds that afforestation increases the temperatures in arid and semiarid regions and over the Tibetan Plateau, indicating warming effects, and decreases the temperatures in temperate and subtropical regions, indicating cooling effects.

The LUC from forest to cropland had the opposite impacts of afforestation on cropland, while the LUC from grassland to cropland resulted in increases in temperature in all regions. This study finds that cropland expansion over former grassland warms the land surface, which is a result that cannot be linked to the background climate. A comparison of the transitions of forest, cropland, or grassland to urban areas revealed that the average annual mean ΔT increased in different climate zones, which shows that urbanization warms land surfaces in almost every climate zone in China.

The relationship between the trends of temperature and surface energy budget ($R_n - LE$) is almost positive across the climate regimes. According to our analysis, the positive relations are obvious in arid and semiarid regions (Fig. 8a) and humid temperate regions (Fig. 8b), but they are not obvious in subtropical regions (Fig. 8c) and are more complex over the Tibetan Plateau (Fig. 8d).

4. Discussion

a. The biogeophysical effects of LUCs on temperature depend on local background climates

LUCs alter the land surface patterns of absorbed solar radiation and dispatched heat fluxes (Liu et al. 2016). Whether these changes result in cooling or warming effects depends on factors impacting the land surface

FIG. 6. The spatial variations of (a) afforestation, cropland expansion, and urbanization; and (b) their biogeophysical warming/cooling effects from 2000 to 2015 in China.

FIG. 7. The local temperature changes of afforestation, cropland expansion, and urbanization in various climate zones. I: cropland to forest, II: grassland to forest, III: forest to cropland, IV: grassland to cropland, V: forest to urban, VI: cropland to urban, VII: grassland to urban.

energy balance, such as the underlying reflectivity and soil water content, which are in turn determined by local climate factors (Betts 2011). For instance, the different biogeophysical effects for forest exhibit comparable strengths, making their net effects weak and more susceptible to other factors, such as land-atmosphere interaction and different temperature metrics, which can alter the relevant role of the biogeophysical effects (Li et al. 2015).

In concentrated areas of LUCs occurrences, the biogeophysical effects of LUCs on local temperatures can be much greater than the biogeochemical cooling effects resulting from the CO_2 uptakes of terrestrial ecosystems

because biogeophysical effects tend to occur on local to regional scales, while biogeochemical effects have global impacts. The spatial scales of climate forcing from LUCs differ from those of well-mixed greenhouse gases (Pielke et al. 2002; Jones et al. 2013b). At the global scale, the forcing requires that the climate sensitivity of different forcing agents be equal. However, the impacts and costs of climate change are experienced at the regional scale, where the stress of climate change is felt by humans (Jones et al. 2013b). Therefore, questions are raised by simulations regarding the regional and global climate impacts of LUCs (Feddema et al. 2005; Pongratz et al. 2010; Arora and Montenegro 2011). In addition,

FIG. 8. The relationships of temperature and the biogeophysical forcing of LUCs in various climate zones: afforestation (green), cropland expansion (yellow), and urbanization (red).

the biogeochemical and biogeophysical effects also have different temporal scales. For example, afforestation can lead to long-term carbon sink, which is associated with forest growth, and thus a long-term potential for cooling (Bonan 2008). Meanwhile, the biogeophysical effect has a host term effect, where once the trees have grown enough, they stop impacting the climate.

Consideration of the biogeophysical processes usually does not change the fundamental paradigm but instead changes the relative values of some ecosystems or even reverses them in some cases (Anderson-Teixeira et al. 2012). Some researchers found that the biogeophysical effects of LUCs may have cooled boreal regions and warmed some tropical regions (Lawrence and Chase 2010; Pitman et al. 2011). Our results show that the cooling or warming effects of LUCs generally depend on the local background climate regimes, which are seriously influenced by the concentration levels of CO₂ (Pitman et al. 2011). The importance of local background climate regimes in determining the degrees of

climatic disturbance degrees was also demonstrated in our results at the regional scale.

Ignoring the amplifying or suppressing feedbacks on CO₂-induced warming associated with LUCs that are not limited by moisture results in the incorrect attribution of the effects of these feedbacks to other climatic factors (Pitman et al. 2011). The limitation of water or precipitation on evapotranspiration results in varied effects of similar LUCs in different climate zones. In subtropical environments with substantial water, restoring vegetation increases evaporation and likely results in cooling effects (Anderson et al. 2011). However, in arid regions, restoring vegetation may reduce the land surface albedo (Field et al. 2007) and increase both the absorbed solar radiation and the energy emitted into the atmosphere. The increase of net radiation has typically outweighed the increase of latent evapotranspiration as a result of limited water and precipitation, thus biogeophysical warming was formed.

Our results concerning the impacts of afforestation on local temperatures showed strong cooling effects in the

subtropical regions, moderate cooling effects in the temperate regions, and increased warming in the high-latitude arid and semiarid regions. These distinctive latitudinal patterns are similar to a previous study by Peng et al. (2014). This study concluded that the cooling effects of afforestation decreased with increases in latitude, and the cooling even transitions to warming in high-latitude regions. The observed variation patterns of afforestation may also be primarily controlled by biogeophysical mechanisms in addition to the local background climate regimes via the land surface energy balance (Li et al. 2015).

Cropland expansion in parts of northern China should be considered as a climate regulation method under the background of food security, although the climatic impacts of tillage require further consideration. Jones et al. (2013b) showed that significant changes in temperature, precipitation, and the timing of climate changes occur when the negative forcing from agricultural expansion is approximately balanced by a radiatively equivalent increase in atmospheric CO₂.

Meanwhile, urbanization-related warming effects occur in almost every region without direct links to regional climate regimes. However, previous studies showed that the energy redistribution effects of urbanization can enhance the heat-island effect in humid climate or decrease temperatures in dry climate, mainly depending on whether the urban convection efficiencies are moderated or amplified (Peng et al. 2012, 2013; Clinton and Gong 2013; Zhao et al. 2014). Moreover, landscape planning during urbanization should focus on how to reduce and even avoid the related atmospheric warming effects.

Moreover, in addition to the local background climate, biogeophysical effects are also considerably impacted by various land-use management practices (Luyssaert et al. 2014; Li et al. 2015), such as the cooling effects of cropland irrigation (Kueppers et al. 2007; Fall et al. 2010) and forest harvesting or thinning. Therefore, land management measures to mitigate climate through LUCs should consider the regional background climate regimes. Afforestation may not be appropriate for all regions, especially for arid and semiarid regions.

b. Further research

Accurate simulations of snow-cover changes are required to model future biogeophysical changes related to land-cover and land-use changes (Pitman et al. 2011) because the presence of snow cover results in higher albedo and lower amounts of absorbed energy at the land surface. For example, the net warming effect of afforestation on the climate over the Tibetan Plateau is primarily caused by the increased absorption of solar radiation resulting from the lower reflectivity of dark

trees relative to that of snow cover. Extensive exposed snow cover reflects a considerable amount of solar radiation back into the atmosphere (Bonan 2008).

Currently, several land surface and atmospheric models are available that attempt to represent LUCs and their regional impacts on local climates. However, a large degree of uncertainties were observed when representing land surface dynamics. Thus, additional work is needed because of the importance of recognizing that land-cover change, LUCs, and mixed land use remain weak components in these models (Mahmood et al. 2010). Thus, continuous reassessment is necessary for the scientific community to understanding how well the true complexity of the land surface can be simulated by these models.

Land-cover and land-use changes must be expressed in more accurate projections of regional or even global climate changes (Pitman et al. 2009). Our results highlight the increasing impacts of LUCs in arid and semiarid regions, which reintroduce the anticipated merits of afforestation as a terrestrial CO₂ sink, and have been suspected as having triggered further warming (Betts 2000). Therefore, the challenge of forest land-use change is to identify those regions suitable for planting trees and to evaluate where afforestation will produce the greatest climate benefits while simultaneously providing other ecosystem services (Peng et al. 2014). Furthermore, whether the region is covered by snow is important. If snow cover is reduced over grassland and cropland, then afforestation in these regions may have a warming effect because of a concurrently reduced albedo and limited water, which will decrease or even reverse the values of these carbon sinks.

The large biogeophysical impacts of land-cover changes, LUCs, and land management changes suggest further expanding the dominating perspective of greenhouse gases to include biogeophysical effects (Mc Alpine et al. 2010; Luyssaert et al. 2014). Our results support the suggestion of Zhao et al. (2014), which calls for reducing warming via large-scale albedo management. Therefore, it is significant to consider how the biogeophysical impacts of LUCs can be incorporated into climate change mitigation strategies, and whether biogeophysical impacts should be adopted as an additional consideration for sequestration credits and management practices.

5. Conclusions

In concentrated areas of LUCs, the biogeophysical effects of LUCs on local temperatures can be much greater than the biogeochemical cooling effects resulting from the CO₂ uptakes of terrestrial ecosystems. However, the biogeophysical effects are dependent on

local background climate regimes. Afforestation may not be appropriate for all regions, especially in the arid and semiarid regions. Cropland expansion in parts of northern China should be considered as a climate regulation method under the background of food security, although the climatic impacts of tillage require further consideration. Moreover, landscape planning of urban areas should focus on how to reduce and even avoid atmospheric warming effects related to urbanization. Further studies will focus on the integrated impacts of LUCs, land-cover changes, and land management on regional temperatures, considering greenhouse gases and surface energy balances; the past and present scenarios of LUCs in regional climate modeling and the regional impacts of LUCs on precipitation; and will then incorporate the biogeophysical impacts of LUCs into the mitigation strategies addressing climate change.

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