Biophysical feedback of forest canopy height on land surface temperature over contiguous United States

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Abstract

Forests are considered important in the mitigation of climate change. Biophysical effects of afforestation and deforestation on land surface temperature (LST) have been extensively documented. As a fundamental variable of forest structure, however, few studies have investigated the biophysical feedback of forest canopy height (FCH) changes on LST at large scale. This study is designed to investigate the impact of FCH changes on local land LST and clarify the biophysical processes controlling LST change from 2003 to 2005 over the contiguous United States, based on satellite observations. To this end, one satellite-based FCH product is selected, and the space-for-time approach, together with the energy balance equation, is applied. Results show that for different forest types, namely evergreen forest (EF), deciduous forest (DF), and mixed forest (MF), taller forests present a greater net cooling effect (0.056–0.448 K) than shorter forests at annual scale. The increase in net radiation and sensible heat flux was less than the increase in the latent heat flux when FCH classes converted from shorter to taller, resulting in annual net cooling effects. Furthermore, the cooling effect of EF is stronger than that of DF and MF, whether for tall, medium, or short FCH classes. Multiple regression analysis reveals that the changes in biophysical components can effectively explain the LST change during the growing season. Our findings provide a new insight for forest management decision-making with the purpose of mitigating climate warming.

1. Introduction

Through both biogeochemical and biophysical processes, forests play a crucial part in mitigating climate change (Arora and Boer 2010, Liao et al 2020). The biogeochemical process regulates climate by assimilating carbon dioxide (CO₂) absorbed from the atmosphere and storing it as carbohydrate in tree biomass and forest soils while the biophysical process influences climate through altering surface biophysical properties and modifying the exchange of energy and moisture between the land and atmosphere (Carvalhais et al 2014, Bright et al 2017, Abera et al 2019, Su et al 2021). In recent decades, research on the forest biophysical effect has received more attention than the biogeochemical effect due to its high spatial heterogeneity and complexity (Zhang and Liang 2018).

Forest canopy height (FCH) is acknowledged as a fundamental attribute of forest structure and primary driver of forest above-ground biomass, species diversity, and forest functions (Zhang et al 2014, Tao et al 2016, Xu et al 2018a, Potapov et al 2021). Investigating the biophysical effect of FCH changes is of great importance due to (a) forest height structures being continuously influenced by various natural and anthropogenic factors such as fires, water stress, deforestation, afforestation, as well as wood thinning and harvesting all around the globe (Koch et al 2004, Amiro et al 2006, van Mantgem et al 2009).
2009, Tao et al 2016); (b) the FCH changes significantly affecting the surface biophysical properties (Kumkar et al 2020), including albedo (primarily controlling the fraction of solar energy absorbed by surface), aerodynamic roughness (primarily regulated by the surface roughness length), and surface resistance (primarily regulated by water ability and vegetation structure), and hence directly impacting the partitioning of net radiation into latent and sensible heat fluxes and ultimately surface land surface temperature (LST) (Kuusinen et al 2014, Xu et al 2018b, Moon et al 2020). Therefore, the evaluation of the biophysical climate effects with different FCHs contributes to a better understanding of the feedback of forest on local climate.

Nowadays, research studying forest biophysical climate impact mainly falls into two categories: biophysical effect with and without land use and land cover change (LULCC). The biophysical effect of LULCC (e.g. afforestation) on local, regional, and global climate has been extensively explored using in situ measurements, satellite observations, and climate modeling techniques (Cao et al 2019, Li et al 2020, Zhang et al 2020, Zeng et al 2021). These studies agreed that afforestation in boreal zones increases the surface temperature due to the stronger albedo-induced warming effect than evaporative cooling effect, but the opposite occurs in tropical zones as a result of the stronger cooling effect of evapotranspiration (ET) (Li et al 2015). In temperate zones, the biophysical climate effect of afforestation is still ambiguous depending on the competing effects of albedo and ET (Huang et al 2018). Although the biophysical effect of land cover changes on local climate have been well studied, in contrast, there are still large knowledge gaps in relation to forest biophysical effects that do not involve land cover conversion.

Studies related to the biophysical impact of forests that do not involve LULCC focused primarily on forest management-induced changes in forest structural properties (e.g. FCH, leaf area index (LAI), and forest age) (Kumkar et al 2020, Zhang et al 2021). Changes in forest structure trigger significant changes in surface biophysical properties such as surface albedo, influencing surface energy balance, and hence the LST (Abera et al 2019). For example, Kumkar et al (2020) employed an offline model to simulate the impact of forest structure changes on local LST and attributed the contributions of biophysical components to LST change. They revealed that fully developed forests (i.e. highest LAI) decreased LST annually by 0.04 K due to a stronger evaporative cooling effect, whereas undeveloped forests (lowest LAI) increased LST by 0.14 K at annual scale owing to lower ET. Zhang et al (2021) investigated the biophysical effect of forest age changes on local LST using eddy covariance measurements from five paired AmeriFlux evergreen needleleaf forest (ENF) sites. They demonstrated that older ENF has an annual net cooling effect of 1.7 K more than younger ENF.

FCH, as one of the most frequently used forest vertical structure variables, has received much attention regarding quantifying its affect on LST at city level (Zhang et al 2014, 2017, Yu et al 2018). Many in situ and remote sensing observational studies have demonstrated that LST is strongly negatively correlated with FCH (Yu et al 2018, Helletsgruber et al 2020, Vanneste et al 2020). However, these studies focused on urban or site scale. To our knowledge, few studies have been conducted to quantify the biophysical effect of forests with canopy height change on LST at broad geographical scales. Furthermore, the biophysical mechanisms of FCH change on LST have been rarely documented.

Recent advances in the development of global FCH satellite products provide the possibility of evaluating the biophysical impact of FCH changes on local climate at national scale. In this study, we used satellite-derived products and a space-for-time approach with the objective of investigating the biophysical impacts of FCH changes on surface energy balance and LST. Specifically, we classified FCH into three categories (i.e. tall, medium, and short) and aimed to address the following three questions: (a) What is the LST response among different FCHs from 2003 to 2005 over the contiguous United States (CONUS)? (b) How do the associated surface energy fluxes and biophysical properties change? (c) Can the changes in biophysical components explain the LST change?

2. Materials and methods

2.1. Remote sensing datasets

A large variety of remotely sensed datasets, including FCH, land cover, LST, albedo, emissivity, ET, surface incoming shortwave radiation, and elevation over CONUS were used in our study. Here, land cover was mapped using the 2016 National Land Cover Database (NLCD) product. Three different forest types including evergreen forest (EF), deciduous forest (DF), and mixed forest (MF) were extracted for further study. The distribution of EF, DF, and MF in CONUS is displayed in figure 1(a). The FCH product that we used is a global canopy height map with 1 km spatial resolution, which was developed by Simard et al (2011). In this study, we reclassify the FCH into less than 10 m, 10–20 m, and greater than 20 m to represent tall, medium, and short forest, respectively (figure 1(b)). Furthermore, to avoid the randomness of this classification, we also set another three categories: (a) less than 5 m, 5–15 m, and greater than 15 m; (b) less than 5 m, 5–20 m, and greater than 20 m; (c) less than 15 m, 15–25 m, and greater than 25 m. The detailed descriptions of the datasets used in this study are provided in Text S1. All of the remote
sensing data used in this study is summarized in Table 1.

2.2. Space-for-time strategy
A space-for-time approach (Yang et al 2020) was employed to quantify the impacts of FCH changes on local LST at 1 km resolution. The key point of this method is to compare the LST difference ($\Delta$LST) between tall forests and adjacent short forests. This method assumed that all adjacent tall forests and short forests pixels share a similar background climate so that local LST differences between tall forests and short forests can be attributed to FCH changes. Furthermore, since temperature is very sensitive to elevation variation, we controlled the elevation difference between adjacent tall forests and short forests within 50 m (Yang et al 2020). The process of this method includes three steps. Firstly, a square window with initial edge length (40 km) centered on a tall forest pixel is set. Secondly, we search for short forest pixels in this window. The short forest pixel with an elevation difference exceeding 50 m compared with central tall forests will be excluded. Thirdly, if the number of remaining short pixels in the window is larger than ten, the research will stop and $\Delta$LST will be calculated. Otherwise, the edge length of the square window will increase step by step. The maximum edge length of the window can not be greater than 100 km. If so, the window will be discarded. The workflow of this method is provided in figure S1 (available online at stacks.iop.org/ERL/17/034002/mmedia).

FCH was classified as tall, medium, and short in our study. Thus, the biophysical impact of FCH changes on LST was investigated using the following equation:

$$\Delta LST_{TS} = LST_{tall} - LST_{short},$$

$\Delta LST_{TM} = LST_{tall} - LST_{medium},$

$\Delta LST_{MS} = LST_{medium} - LST_{short}.$

where $LST_{tall}$, $LST_{medium}$, and $LST_{short}$ represent the surface temperature for tall, medium, and short forests, respectively. Negative $\Delta$LST denotes a cooling effect of taller forests.

2.3. Biophysical controls on LST changes
We used an energy balance equation to further illustrate the biophysical process leading to $\Delta$LST. The
land surface energy balance equation can be expressed as follows:

\[ R_n = R_{ns} + R_{nl} = (SW_{in} - SW_{out}) + (LW_{in} - LW_{out}), \]

where \( R_n, R_{ns}, \) and \( R_{nl} \) are net radiation, net shortwave radiation, and net longwave radiation, respectively. \( SW_{in}, LW_{in}, SW_{out}, \) and \( LW_{out} \) are incoming shortwave and longwave radiation and outgoing shortwave and longwave radiation, respectively. \( SW_{out} \) and \( LW_{out} \) can be further inferred as:

\[ SW_{out} = SW_{in} - \alpha, \]
\[ LW_{out} = \sigma \varepsilon LST^4, \]

where \( \alpha \) is albedo, \( \sigma \) is the Stefan–Boltzmann constant \((5.67 \times 10^{-8} \text{ W m}^{-2} \text{K}^{-4})\).

Moreover, the \( R_n \) absorbed by land surface is approximately balanced by energy that is transferred out from land surface. Thus, \( R_n \) can also be calculated as:

\[ R_n = LE + H + G, \]

where \( LE, H, \) and \( G \) are latent heat flux, sensible heat flux, and ground heat flux, respectively. \( LE = ET \times 28.36 \text{ W m}^{-2} \text{ mm} \text{ d}^{-1}, \) \( ET \) in mm \text{ d}^{-1}, \) \( \) (Abera et al 2019). By combining (4)–(7), the land surface energy balance equation can be formalized as:

\[ (1 - \alpha)SW_{in} + LW_{in} - \sigma \varepsilon LST^4 = LE + H + G. \]

As the space-for-time approach assumes that the adjacent tall forests and short forests share a similar background climate, the difference in \( SW_{in} \) and \( LW_{in} \) can be ignored (Ge et al 2019). Moreover, the contribution of \( G \) was un conspicuous at monthly and annual scales compared with other components (Purdy et al 2016, Zhang et al 2021). Therefore, the terms of the energy balance equation can be formulated as follows due to FCH changes

\[ \Delta R_{ns} = -\Delta \alpha \times SW_{in}, \]
\[ \Delta R_{nl} = -\sigma \varepsilon_{\text{tall}} LST_{\text{tall}}^4 - \sigma \varepsilon_{\text{short}} LST_{\text{short}}^4, \]
\[ \Delta H = \Delta R_{ns} + \Delta R_{nl} - \Delta LE. \]

where \( \Delta(\cdot) \) signifies the difference of each component between different FCH classes, for instance, \( \Delta \alpha = \alpha_{\text{tall}} - \alpha_{\text{short}} \) is the difference in \( \alpha \) between tall forest and short forest. Similar to \( \Delta LST, \Delta \alpha, \Delta R_{ns}, \Delta LE, \Delta H, \) and \( \Delta R_{nl} \) were also obtained using the space-for-time method. The formulation above is the changes in surface energy fluxes of tall and short forest. The changes in surface energy fluxes of tall and medium forest, and medium and short forest are defined similarly.

3. Results

3.1. Feedback of FCH changes on LST

The spatial distributions of observed LST change showed that taller forests were generally cooler than shorter forests over CONUS at the annual scale, whether for EF, DF, or MF (figure 2). The probability density functions revealed that the pixels with negative values (cooling effect) were in the majority (figure 3).

Black vertical lines represent \( \Delta LST \) of 0 K and blue vertical lines represent the mean \( \Delta LST \).

Figure 4 shows that for EF, the annual mean LST difference between tall and short forests (\( \Delta LST_{TS} \)) is \(-0.448 \pm 0.004 \text{ K} \) (mean \pm 95% confidence interval, the same hereafter), between tall and medium forests (\( \Delta LST_{TM} \)) is \(-0.295 \pm 0.002 \text{ K} \), and between medium and short forests (\( \Delta LST_{MS} \)) is \(-0.290 \pm 0.002 \text{ K} \). For DF, the annual mean \( \Delta LST_{TS} \) is \(-0.118 \pm 0.002 \text{ K} \), \( \Delta LST_{TM} \) is \(-0.089 \pm 0.001 \text{ K} \), and \( \Delta LST_{MS} \) is \(-0.056 \pm 0.001 \text{ K} \). For MF, the annual mean \( \Delta LST_{TS} \) is \(-0.215 \pm 0.003 \text{ K} \), \( \Delta LST_{TM} \) is \(-0.118 \pm 0.002 \text{ K} \), and \( \Delta LST_{MS} \) is \(-0.069 \pm 0.002 \text{ K} \). For all forest types, the annual mean \( \Delta LST \) was larger than \( \Delta LST_{TM} \), indicating that medium forests were cooler than short forests. Moreover, the observed annual mean \( \Delta LST_{MS} \) also verified this result. The mild difference between \( \Delta LST_{TS} - \Delta LST_{TM} \) and \( \Delta LST_{MS} \) can be attributed to the discrepancy of pixels in the square window in the space-for-time approach. Overall, at annual scale, tall forests (EF, DF, and MF) produced the largest cooling effect, followed by medium and short forests. This conclusion was also applied to the growing season. However, for DF in the non-growing season, conversion from short DF to tall or medium DF led to a mild warming effect. The reason was detailed in section 4. Additionally, the cooling effect of taller forests was significantly higher during the growing season than the non-growing season. Specifically, conversion from short forests to tall forests obtained the highest mean \( \Delta LST \) for EF (\(-0.876 \pm 0.006 \text{ K} \)), DF (\(-0.449 \pm 0.002 \text{ K} \)), and MF (\(-0.463 \pm 0.005 \text{ K} \)) in the growing season. For different forest types, the cooling effect of EF is stronger than that of DF and MF, whether for tall, medium, or short FCH classes. The above results were based on the FCH of less than 10 m, 10–20 m, and greater than 20 m. The impact of FCH changes on LST based on the other three categories were displayed in figures S2–S4. In general, these results demonstrated that taller forests had a stronger cooling effect than shorter forests.

To further illustrate the impact of FCH changes on LST, the relationship between difference (\( \Delta \text{FCH} \)) and \( \Delta LST \) was established using correlation analysis.
Figure 2. Spatial patterns (aggregated on $0.1^\circ \times 0.1^\circ$ grid) of annual mean $\Delta$LST (K) between different canopy height classes for each forest type over CONUS. (a)–(c) represent $\Delta$LST between tall and short EF, DF, and MF, respectively, (d)–(f) represent $\Delta$LST between tall and medium EF, DF, and MF, respectively, (g)–(i) represent $\Delta$LST between medium and short EF, DF, and MF, respectively.

Figure 3. The probability density functions (pdf) of annual mean $\Delta$LST between different canopy height classes for each forest type. (a)–(c) represent pdf between tall and short EF, DF, and MF, respectively, (d)–(f) represent pdf between tall and medium EF, DF, and MF, respectively, (g)–(i) represent pdf between medium and short EF, DF, and MF, respectively.
Figure 4. The mean annual, growing season, and non-growing season $\Delta$LST between different forest canopy height classes for (a) EF, (b) DF, and (c) MF, respectively. The error bar on each panel denotes the confidence interval at 95% estimated by t test.

Figure 5. The relationships between $\Delta$FCH and annual mean $\Delta$LST for (a) EF, (b) DF, and (c) MF, respectively. (figure 5). As with $\Delta$LST, $\Delta$FCH was also calculated in a square window. The $\Delta$FCH that was less than 5 m and greater than 25 m was excluded due to an insufficient amount of pixels. The negative correlation between $\Delta$FCH and $\Delta$LST indicated the enhanced cooling effect with the increase in FCH.

3.2. Changes in biophysical components following FCH changes

The underlying biophysical mechanisms behind the observed changes in LST can be better clarified by quantifying the variations in the components of the surface energy balance. Here our analysis was also based on the FCH categories of less than 10 m, 10–20 m, and greater than 20 m. The spatial distributions of mean annual $\Delta$$\alpha$, $\Delta$Rns, $\Delta$LE, $\Delta$Rnl, and $\Delta$H are shown in figures S5–S9. The $\Delta$$\alpha$ values of EF, DF, and MF between different canopy height classes were all negative at annual scale (figures 6(a)–(c)), which confirmed that taller forests had a lower albedo than shorter forests. The $\Delta$$\alpha$ values between different canopy height classes for all forest types were lower in non-growing season than in growing season. Notably, conversion from short MF to medium MF slightly increased the albedo ($0.0036 \pm 0.0001$) during growing season (figure 6(c)). The probable reasons are further analyzed in section 4. For different forest types, the $\Delta$$\alpha$ between different canopy height classes of EF is obviously lower than DF and MF, whether at annual scale, during growing season or during non-growing season.

Contrary to $\Delta$$\alpha$, the albedo-induced changes in $\Delta$Rns for EF, DF, and MF between different canopy height classes were all positive at annual scale and growing season (figures 6(d)–(f)), which led to a warming effect of taller forests. This warming effect reached its highest in non-growing season due to a more remarkable difference of $\Delta$$\alpha$ in non-growing season than in growing season when FCH converts from shorter to taller. The latitudinal patterns of $\Delta$Rns were more heterogeneous between medium and short forests than the other two classes (figure S6). It is noteworthy that the magnitude of $\Delta$Rns between different canopy height classes for DF and MF was similar except for canopy height transition from short to medium, whether at annual scale, during growing season or during non-growing season. Annually, the magnitude of $\Delta$Rns for EF was almost twice that of DF and MF.

For $\Delta$LE, the values of EF and MF between different canopy height classes were all positive at annual scale (figures 6(g)–(i)), which demonstrated a cooling effect of taller forests. However, a mild warming effect occurred when medium DF was replaced by tall DF (figure 6(h)), which was mainly attributed to the cooling effect of LE in non-growing season counteracted by the stronger warming effect in growing season. Furthermore, the $\Delta$LE between different canopy height classes for all forest types were higher in growing season than in non-growing season, except for DF and MF when FCH transitioned from medium to tall. The lower LE of tall forest than medium forest in growing season led to this result.
Figure 6. The mean annual growing season, and non-growing season, change in biophysical components: (a)–(c) $\alpha$, (d)–(f) $R_{ns}$, (g)–(i) LE, (j)–(l) $R_{nl}$, and (m)–(o) $H$ between different forest canopy height classes for EF, DF, and MF, respectively. The error bar on each panel denotes the confidence interval at 95% estimated by $t$ test.

For different forest types, the $\Delta$LE between different canopy height classes of EF is larger than DF and MF at annual scale and in non-growing season. The similar magnitude of LE between tall and medium MF resulted in the largest $\Delta$LE between medium and short MF compared with EF and DF (figure 6(i)).

The $\Delta R_{nl}$, based on the surface energy balance equation, is contrary to the LST change patterns. Apart from a minor negative value that appeared when converting from medium DF to tall DF during non-growing season, the $\Delta R_{nl}$ values of EF, DF, and MF between different canopy height classes were all positive, whether at annual scale, in growing season or non-growing season (figures 6(j)–(l)), leading to a warming effect of taller forests. The consistent change patterns of $\Delta$LST and $\Delta R_{nl}$ between tall and short DF during non-growing season was mainly attributed to the impact of emissivity on LW$_{out}$.

Compared with other surface energy fluxes, the $\Delta H$ presented clear spatial and seasonal variability (figures 6(m)–(o)). For example, the magnitude of $\Delta H$ was positive during growing season and negative during non-growing season when canopy height class converts from medium to tall. The $\Delta H$ between different canopy height classes overall is small ($-0.29 - 1.49$ W m$^{-2}$) due to a large spatial variability, ranging from a maximum value of exceeding 24 W m$^{-2}$ to a minimum value of lower than $-30$ W m$^{-2}$ over CONUS (figure S9). The $\Delta H$ showed an opposite overall pattern to $\Delta$LE for EF and DF between different canopy height classes at annual scale. This pattern is due to the surface available energy partitioning between $H$ and LE changes.
Figure 7. Multiple regression coefficient of ∆LST with ∆Rns, ∆LE, and ∆H between different forest canopy height classes for EF, DF, and MF at annual scale (a)–(c), during growing season (d)–(f) and non-growing season (g)–(i). Regression coefficient was statistically significant (P < 0.01). T–S: biophysical components of ∆Rns, ∆LE, and ∆H between tall and short forests; T–M: biophysical components of ∆Rns, ∆LE, and ∆H between tall and medium forests; M–S: biophysical components of ∆Rns, ∆LE, and ∆H between medium and short forests.

Table 2. The determination coefficient (R²) of ∆LST with ∆Rns, ∆LE, and ∆H for EF, DF, and MF following forest canopy height changes at annual scale, during growing season and non-growing season.

|           | Annual | Growing season | Non-growing season |
|-----------|--------|----------------|--------------------|
|           | T–S    | T–M            | M–S               | T–S    | T–M            | M–S               | T–S    | T–M            | M–S               |
| EF        | 0.48   | 0.71           | 0.48              | 0.75   | 0.91           | 0.71              | 0.44   | 0.57           | 0.49              |
| DF        | 0.15   | 0.17           | 0.27              | 0.71   | 0.69           | 0.8               | 0.09   | 0.1            | 0.16              |
| MF        | 0.27   | 0.29           | 0.23              | 0.63   | 0.74           | 0.58              | 0.17   | 0.18           | 0.17              |

3.3. Relation of LST change with net radiation, latent heat flux and sensible heat flux changes

To examine whether the changes in biophysical components can explain the ∆LST, the relation between ∆LST and ∆Rns, ∆LE, and ∆H following FCH changes was investigated using multiple regression analysis. Here the relationship between ∆LST and ∆Rns was excluded due to Rns being directly linked to LST. As shown in figure 7, the impact of ∆LE and ∆H on ∆LST was similar for different forest types, whether at annual scale or during growing and non-growing season, whereas the impact of ∆Rns on ∆LST varied depending on forest types and growing periods. For example, the impact of ∆Rns on ∆LST was up to ten times stronger than the ∆LE and ∆H effect on ∆LST when tall MF was compared with short MF during growing season. In contrast, the impact of ∆Rns on ∆LST was similar to the ∆LE and ∆H effect on ∆LST when medium EF compared with short EF during growing season. Obviously, the sign of the regression coefficient for ∆Rns was opposite in growing season and non-growing season. The determination coefficient (R²) of ∆LST with ∆Rns, ∆LE, and ∆H following FCH changes at different timescales is displayed in table 2. Notably, ∆Rns, ∆LE, and ∆H together explained 91% of the variation in ∆LST for EF when canopy height classes transition from medium to tall during growing season. To sum up, the biophysical components of ∆Rns, ∆LE, and ∆H together explained most of the variation in ∆LST for EF than DF and MF among different canopy height classes, whether at annual scale or during growing and non-growing season. The annual relatively low R² between ∆LST and ∆Rns, ∆LE, and ∆H for DF and MF was mainly attributed to the poor performance of these biophysical components in explaining ∆LST during non-growing season.
4. Discussion

Using satellite observations, we explored the biophysical climate effect of forests with different canopy height classes over CONUS. We further quantified the variations in the biophysical components leading to the observed local surface temperature change. Results showed that at annual scale, the values of $\Delta LST_{\text{TM}}$, $\Delta LST_{\text{MS}}$, and $\Delta LST_{\text{TSS}}$ for the three forest types (i.e. EF, DF, and MF, respectively) were all negative, indicating the cooling effect of taller forests. Moreover, our results also suggested that the cooling effect of EF is stronger than that of DF and MF, whether for tall, medium, or short FCH classes. The changes in biophysical components indicated that a decrease in the albedo in shorter forests to taller forests resulted in a positive radiative forcing. The surface energy fluxes of net radiation (i.e. $R_{\text{ns}}$ and $R_{\text{al}}$) and sensible heat flux dominated a warming effect while the latent heat flux regulated a cooling effect when FCH class converts from shorter to taller at annual scale. When FCH transferred from shorter to taller, the albedo-induced warming effect was due to smaller canopy gaps and there being less exposed underlying forest floor in taller forests (Ge et al. 2019, Alibakhshi et al. 2020). The LE had a cooling effect due to more vigorous ET on the leaf surface in taller forests (Xu et al. 2018b). Taller forests are more efficient in transferring water from the deeper soil to the atmosphere through deeper root systems than shorter forests. Yet this is not always the case in this study. For instance, LE led to a mild warming effect when medium DF was replaced by tall DF at annual scale (figure 6(h)). This may be associated with tall DF suffering from extreme climate (e.g. drought). Previous research demonstrated that the water transportation paths of taller forests are longer than that of shorter forests, leading to higher water demand (Nepstad et al. 2007). Therefore, the stomata of tall forests will close to reduce ET and regulate water loss once soil moisture is limited. Nevertheless, tall DF was cooler than medium DF in growing season even though the LE of medium DF was larger than old DF. This was largely attributed to the enhanced cooling effect of H (figure 6(n)). The rough surface of tall forest canopies provides a more efficient turbulent heat exchange with the boundary layer, such that convective cooling satisfies the need for strong evaporative cooling (Teuling et al. 2010). Moreover, the albedo of medium MF was larger than that of short MF during growing season (figure 6(c)).

The stronger cooling effect of EF than DF and MF can be attributed to the following aspects. First, for the same FCH classes of EF, DF, and MF, the proportion of different heights that make up these categories is different. For example, the FCH differences between tall and short EF are larger than that of DF and MF, leading to a higher $\Delta LST$. Second, the climate effect of forests with different canopy heights may be influenced by the background climate or the hydrometeorological state (Pitman et al. 2011, Huang et al. 2018). The intensified cooling effect of taller EF occurred due to stronger ET in some regions of western United States, where mean annual precipitation is less than 400 mm. DF and MF are mostly located over the eastern United States, where mean annual precipitation is greater than in the western United States. Therefore, the cooling effect of taller DF or MF can be weaker because the precipitation tends to minimize increases of sensible heat flux and reduce the moisture stress limiting the latent heat flux (Zhang et al. 2020).

The relationship of $\Delta LST$ with biophysical components changes ($\Delta R_{\text{ns}}, \Delta LE$, and $\Delta H$) following FCH changes showed large spatiotemporal variations for different forest types. The poor explanation of $\Delta LST$ to these biophysical components changes for DF and MF during non-growing season was likely related to the background climate and environmental conditions (e.g. soil moisture content) and bare soil proportion (Abera et al. 2020b). For instance, the pattern of albedo-related $\Delta R_{\text{ns}}$ was opposite during
rainfall extreme periods such as drought and extreme wet events (Abera et al 2020b). The change of CO$_2$ concentration may affect the water use efficiency of forests and thus have an impact on ET (Hatfield and Dold 2019). These factors affected the partitioning of $R_{ns} + R_{al}$ into LE and $H$ and hence, in turn, influence the relationship of $\Delta$LST with $\Delta R_{ns}$, $\Delta$LE, and $\Delta H$.

Our results have implications for forest management in tackling climate change. First, it would be crucial for areas where space is limited and it is difficult to expand vegetation cover. An effective way is to consider the climate impact of vegetation height. Second, species of tall EFs with the strongest cooling effect would be preferable for afforestation or forest management to mitigate global warming. Our results are consistent with those studies in that tall vegetation is more efficient in decreasing local surface temperature (Ren et al 2018, Yu et al 2018, Li et al 2021a). Meanwhile, our study has gone a step further than previous studies in two aspects. On the one hand, compared with most studies focusing on the biophysical effect of land cover change (e.g. afforestation, reforestation, and deforestation) on LST, research concerning forest canopy structure changes on LST is reported less. This study quantified the biophysical climate impact of forest canopy structure changes on LST from the perspective of FCH, which can be considered to complement to related studies on biophysical climate effect. On the other hand, compared with studies aiming at urban scale, this study fills in the gaps on the biophysical effects of forests under natural conditions at the national scale. Besides, the underlying biophysical mechanism of FCH changes in influencing LST was clarified from the perspective of surface energy balance. Nonetheless, it should be noted that our study also has some limitations. Previous studies exploring the biophysical climate impact of land cover changes have proposed several energy balance-based decomposition methods such as the decomposed temperature metric and intrinsic biophysical mechanism to quantify the contributions of biophysical components on LST (Lee et al 2011, Luysaert et al 2014, Abera et al 2020a, Zhang et al 2020). These studies clearly illustrated the changes in energy fluxes (shortwave, sensible and latent heat fluxes), which were consistent with our study. However, this study was incapable of applying the above-mentioned physically-based attribution approach to elucidate the relative contributions of biophysical components to the FCH changes-driven local LST change. This was due to a lack of incoming longwave radiation and sensible heat flux products with high spatial resolution. Furthermore, the aggregation of land cover data and resampling of shortwave radiation and emissivity data might introduce uncertainty into our results. Last but not least, the approach this study used is space for time, which means FCH classes are constant over a period of time. In the future, with the development of the annual remote sensing dataset for long time series, it will be possible to investigate forests’ biophysical climate effect together with the ‘space and time’ strategy.

5. Conclusions

Using satellite observations from between 2003 and 2005, we investigated the biophysical effect of forests with different canopy height classes on local LST and illustrated the biophysical processes controlling LST change over CONUS. Our analysis was based on the space-for-time approach in combination with the energy balance equation. Moreover, multiple regression analysis was performed to examine whether the changes in biophysical components can explain the $\Delta$LST. Results showed that FCH has a significant impact on LST. For diverse forest types (EF, DF, and MF), taller forests are cooler than shorter forests at the annual scale. This annual cooling effect is mainly attributed to enhanced ET outweighing albedo and sensible heat flux changes when FCH classes convert from shorter to taller. Furthermore, the effect of FCH on LST is different among forest types. The cooling effect of EF is stronger than that of DF and MF, whether for tall, medium, or short FCH classes. This is perhaps due to DF and MF being mostly distributed over the eastern United States where the wet conditions tend to prevent moisture limitations to latent heat flux. The multiple regression analysis indicated that the biophysical components of $\Delta R_{ns}$, $\Delta$LE, and $\Delta H$ explain the variation of $\Delta$LST better in growing season than in non-growing season. The poor performance during non-growing season is mainly affected by background climate and environmental conditions. Our results highlight the necessity of considering FCH when studying forests’ biophysical climate effects. It also provides valuable theoretical guidance for forest management regarding tackling climate change.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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from https://doi.org/10.1029/2011JG001708 (Simard et al. 2011). The 2016 NLCD product can be obtained from www.mrlc.gov. The MODIS monthly ET product is available at http://files.ntsg.umt.edu/data/NTSg_Products/MOD16/. The month SIS product is available at http://doi.org/10.11888/Meteorol.tpdc.270112 (Tang et al. 2019).

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References

Abera T A, Heiskanen J, Pellikka P K E, Adhikari H and Maeda E E 2020a Climatic impacts of bushland to cropland conversion in Eastern Africa Sci. Total Environ. 717 137255
Abera T A, Heiskanen J, Pellikka P K E and Maeda E E 2020b Impact of rainfall extremes on energy exchange and surface temperature anomalies across biomes in the Horn of Africa Agric. For. Meteorol. 280 107779
Abera T A, Heiskanen J, Pellikka P, Rautiainen M and Maeda E E 2019 Clarifying the role of radiative mechanisms in the spatio-temporal changes of land surface temperature across the Horn of Africa Remote Sens. Environ. 221 210–24
Abbakshishi S, Naimi B, Hovi A, Crowther T W and Rautiainen M 2020 Quantitative analysis of the links between forest structure and surface land albedo on a global scale Remote Sens. Environ. 246 111854
Amiro B D et al 2006 The effect of post-fire stand age on the boreal forest energy balance Agric. For. Meteorol. 140 41–50
Anderson J R, Hardy E E, Roach J T and Witmer R E 1976 A land use and land cover classification system for use with remote sensor data (available at: http://pubs.er.usgs.gov/publication/pp964)
Arora V K and Boer G J 2010 Uncertainties in the 20th century carbon budget associated with land use change Glob. Change Biol. 16 3327–48
Bright R M, Davin E, O’Halloran T, Pongratz J, Zhao K and Cescatti A 2017 Local temperature response to land cover change driven by non-radiative processes Nat. Clim. Change 7 296–302
Cao Q, Wu J, Yu D and Wang W 2019 The biophysical effects of the vegetation restoration program on regional climate metrics in the Loess Plateau, China Agric. For. Meteorol. 268 169–80
Carvalhais N et al 2014 Global covariation of carbon turnover times with climate in terrestrial ecosystems Nature 514 213–7
Duman T, Huang C-W and Litvak M E 2020 Recent land cover changes in the Southwestern US lead to an increase in surface temperature Agric. For. Meteorol. 297 108246
Gates D M 1965 Energy, plants, and ecology Ecology 46 1–13
Ge J, Guo W, Pitman A J, De Kauwe M G, Chen X and Fu C 2019 The nonradiative effect dominates local surface temperature change caused by afforestation in China J. Clim. 32 4445–71
Hassel F J and Dold C V 2019 Water-use efficiency, advances and challenges in a changing climate Front. Plant. Sci. 10 103
Hellegersbrucher C, Gillner S, Gulyas A, Junker R R, Tanacs E and Hof A 2020 Identifying tree traits for cooling urban heat Islands-A cross-city empirical analysis Forests 11 1064
Huang L, Zhai J, Liu J and Sun C 2018 The moderating or amplifying biophysical effects of afforestation on CO2-induced cooling depend on the local background climate regimes in China Agric. For. Meteorol. 260 193–203
Koch G W, Sillet S C, Jennings G M and Davis S D 2004 The limits to tree height Nature 428 851–4
Kumkar Y, Astrap R, Stordal F and Bright R M 2020 Quantifying regional surface energy responses to forest structural change in Nordic Fennoscandia J. Geophys. Res. 125 e2019JD032092
Kuusinen N, Tomppo E, Shuai Y and Berninger F 2014 Effects of forest age on albedo in boreal forests estimated from MODIS and Landsat albedo retrievals Remote Sens. Environ. 145 145–53
Lee X et al 2011 Observed increase in local cooling effect of deforestation at higher latitudes Nature 479 384–7
Li H, Li Y, Wang T, Wang Z, Gao M and Shen H 2021a Quantifying 3D building form effects on urban land surface temperature and modeling seasonal correlation patterns Build. Environ. 204 108132
Li J, Tam C-Y, Tai A P K and Lau N-C 2012b Vegetation-heatwave correlations and contrasting energy exchange responses of different vegetation types to summer heatwaves in the Northern Hemisphere during the 1982–2011 period Agric. For. Meteorol. 296 106208
Li Y, Piao S, Chen A, Ciais P and Li X 2020 Local and teleconnected temperature effects of afforestation and vegetation greening in China Nat. Sci. Rev. 7 897–912
Li Y, Zhao M, Motesharreli S, Mu Q, Kalnay E and Li S 2015 Local cooling and warming effects of forests based on satellite observations Nat. Commun. 6 6603
Liao W, Liu X, Burakowski E, Wang D, Wang L and Li D 2020 Sensitivities and responses of land surface temperature to deforestation-induced biophysical changes in two global earth system models J. Clim. 33 8381–99
Luyssaert S et al 2014 Land management and land-cover change have impacts of similar magnitude on surface temperature Nat. Clim. Change 4 389–93
Moom M, Li D, Liao W, Rigden A J and Friedl M A 2020 Modification of surface energy balance during springtime: the relative importance of biophysical and meteorological changes Agric. For. Meteorol. 284 107005
Nepstad D C, Tolley I M, Ray D, Moutinho P and Cardinot G 2007 Mortality of large trees and lianas following experimental drought in an amazon forest Ecology 88 2259–69
Pitman A J, Avila F B, Abramowitz G, Wang Y P, Phipps S J and de Noblet-ducoolre N 2011 Importance of background climate in determining impact of land-cover change on regional climate Nat. Clim. Change 1 472–5
Potapov P et al 2021 Mapping global forest canopy height through integration of GEDI and Landsat data Remote Sens. Environ. 253 121165
Purdy A J, Fisher J B, Goulden M L and Famiglietti J S 2016 Ground heat flux: an analytical review of 6 models evaluated at 88 sites and globally J. Geophys. Res. 121 3045–59
Ren Z, He X, Pu R and Zheng H 2018 The impact of urban forest structure and its spatial location on urban cool island intensity Urban Ecosyst. 21 863–74
Richardson A D, Keenan T F, Migliavacca M, Ryu Y, Sonnentag O and Toomey M 2013 Climate change, phenology, and phenological control of vegetation feedbacks to the climate system Agric. For. Meteorol. 169 156–73
Ryu Y, Baldocchi D D, Ma S and Hehn T 2008 Interannual variability of evapotranspiration and energy exchange over an annual grassland in California J. Geophys. Res. 113 D09104
Simard M, Pinto N, Fisher J B and Baccini A 2011 Mapping forest canopy height globally with spaceborne lidar J. Geophys. Res. 116 40404
Stuenzi S M and Schepanski-Strub G 2020 Vegetation trajectories and shortwave radiative forcing following boreal forest disturbance in Eastern Siberia J. Geophys. Res. 125 e2019JD035395
Su Y et al 2021 Aerodynamic resistance and Bowen ratio explain the biophysical effects of forest cover on understory air and soil temperatures at the global scale Agric. For. Meteorol. 308 106615
Tang W, Yang K, Qin J, Li X and Niu X 2019 A 16-year dataset (2000–2015) of high-resolution (3 h, 10 km) global surface solar radiation Earth Syst. Sci. Data 11 1905–15
Tao S, Guo Q, Li C, Wang Z and Fang J 2016 Global patterns and determinants of forest canopy height Ecology 97 3265–70
Teuling A J et al 2010 Contrasting response of European forest and grassland energy exchange to heatwaves Nat. Geosci. 3 722–7
van Mantgem P J et al 2009 Widespread increase of tree mortality rates in the Western United States Science 323 323
Vanneste T et al 2020 Contrasting microclimates among hedgerows and woodlands across temperate Europe Agric. For. Meteorol. 281 107818
Wang Z-H and Bou-Zeid E 2012 A novel approach for the estimation of soil ground heat flux Agric. For. Meteorol. 154 214–21
Xu C, Manley B and Morgenroth J 2018a Evaluation of modelling approaches in predicting forest volume and stand age for small-scale plantation forests in New Zealand with RapidEye and LiDAR Int. J. Appl. Earth Obs. Geoinf. 73 286–96
Xu P, Zhou T, Zhao X, Luo H, Gao S, Li Z and Cao L 2018b Diverse responses of different structured forest to drought in Southwest China through remotely sensed data Int. J. Appl. Earth Obs. Geoinf. 69 217–25
Yang Q, Huang X and Tang Q 2020 Irrigation cooling effect on land surface temperature across China based on satellite observations Sci. Total Environ. 705 135984
Yu Q, Acheampong M, Pu R, Landry S M, Ji W and Dahigamwua T 2018 Assessing effects of urban vegetation height on land surface temperature in the City of Tampa, Florida, USA Int. J. Appl. Earth Obs. Geoinf. 73 712–20
Yuan W, Liu S, Liu H, Randerson J T, Yu G and Tieszen L L 2010 Impacts of precipitation seasonality and ecosystem types on evapotranspiration in the Yukon River Basin, Alaska Water Resour. Res. 46 W02514
Zeng Z et al 2021 Deforestation-induced warming over tropical mountain regions regulated by elevation Nat. Geosci. 14 23–29
Zhang C, Ju W, Chen J M, Li D, Wang X, Fan W, Li M and Zan M 2014 Mapping forest stand age in China using remotely sensed forest height and observation data J. Geophys. Res. 119 1163–79
Zhang Q et al 2020 Reforestation and surface cooling in temperate zones: mechanisms and implications Glob. Change Biol. 26 3384–401
Zhang Y and Liang S 2018 Impacts of land cover transitions on surface temperature in China based on satellite observations Environ. Res. Lett. 13 024010
Zhangle Y, Yao Y, Wang X, Liu Y and Piao S 2017 Mapping spatial distribution of forest age in China Earth Space Sci. 4 108–16
Zhang Z, Zhang F, Wang L, Lin A and Zhao L 2021 Biophysical climate impact of forests with different age classes in mid- and high-latitude North America For. Ecol. Manage. 494 119327