LETTER

Reforestation enhanced landscape connectivity for thermal buffering in China

Anqi Huang, Runping Shen, Gensuo Jia* and Xiyan Xu*

1 School of Geographical Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, People’s Republic of China
2 Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: xiyan.xu@tea.ac.cn

Keywords: reforestation, connectivity, core forests, marginal forests, land surface temperature, thermal buffering

Abstract

Deforestation-induced landscape fragmentation causes habitat loss and isolation, modifies local climate, and therefore threatens biodiversity. While, on the contrary, how large-scale reforestation may improve the connectivity and thermal buffers of habitats is not well understood. We show that decades long large-scale reforestation in China has effectively increased the size and connectivity of forest patches by gradually filling gaps among isolated patches and creating more core forests. The core forests have a stronger capacity to cool the land surface, leading to a daily mean cooling effect of $-0.42 \pm 0.23$ °C relative to nearby marginal forests. Moreover, the core forests reduce diurnal range and seasonal variation of land surface temperature by $1.41 \pm 0.23$ °C and $0.42 \pm 0.55$ °C, respectively, relative to nearby marginal forests. The thermal buffering capacity of large size core forest ($>100$ km$^2$) is more than twice that of small size ($\leq 10$ km$^2$). Despite their relatively low thermal buffering capacity, the marginal forests contribute about 73% to the increase of forest area in China during the last two decades and create buffer zones for the core forests to resist external disturbances, maintaining the internal stability of the forest ecosystem. We highlight that improving the integrity and connectivity of the forests with ecological restoration and succession can further enhance potential of forests to buffer local thermal environment under the current reforestation efforts, and thereby providing better connected thermal habitats for species to survive under climate change.

1. Introduction

Deforestation is the removal of a forest or stand of trees from land and thus ruin related physical environment that is then converted to non-forest use. Global forests are experiencing severe deforestation and degradation (Giam 2017, Aleixandre-Benavent et al 2018, Houghton and Nassikas 2018). It is estimated that 420 million hectares of forest have been lost through conversion to other land uses since 1990 (Unep 2020). Deforested area is usually concomitant with fragmentation, in which continuous forests are divided into isolated patches (Laurance et al 2011), resulting in habitat isolation and loss. Forest fragmentation expands the edges of forest patches, exposing them to greater anthropogenic disturbances (Vieilledent et al 2018). The increasing edges among isolated forest patches tend to accelerate changes in local climatic conditions, leading to hotter, drier and more variable microclimate (Laurance et al 2002, Tuff et al 2016).

The connectivity of forest landscapes guarantees the dispersal success of species through the forest ecosystem, which in turn can affect biodiversity and ecosystem function (Pimm et al 2014, Cadavid-Florez et al 2020). In the context of global climate change, species in the forest ecosystem tend to experience more severe thermal stress, which is further amplified...
by edge effects (Barahona-Segovia et al 2019). Forest fragmentation decreases the connectivity within the forest ecosystem, reducing opportunities for species to migrate to habitats with buffered microclimate under thermal stress (Zhang et al 2012, de Frenne et al 2019). Considering that 20% of the world’s remaining forests are located within 100 m and 70% are located within 1 km of an edge, a large portion of species in world’s remaining forests is facing the threats of local extinction when local temperatures exceed their thermal tolerance limits (Pfeifer et al 2017).

Afforestation, forest conservation and restoration are considered as cost-effective nature-based solutions to climate change adaption and mitigation for removing carbon dioxide from atmosphere and provide habitats for species (Doelman et al 2020). The dynamic processes of reforestation not only affect the overall forest cover but also the spatial distribution of trees and forest patches (Taubert et al 2018), which has a great potential to change the spatial pattern of forest patches and create better connected forest patches, thereby buffering local microclimate change induced by forest fragmentation (Liu et al 2019). Furthermore, the increased forest cover after reforestation has direct impact on the local land surface and air temperatures through surface albedo, evapotranspiration and aerodynamic resistance (Duveiller et al 2018).

Reforestation is the process of re-creation of forest on a previously forested area, including natural regeneration, assisted restoration, enrichment planting, native tree plantations, commercial plantations, and agroforestry systems (Locatelli et al 2015). During the past four decades, China has initiated series of nationwide ecological restoration projects, aimed at forest conservation and reforestation (Lu et al 2018). Two of them, the Natural Forest Conservation Program and the Grain to Green Program, are the main ecological restoration projects for reforestation in China since the early 2000s because of their massive scales and potentially enormous impacts (Liu et al 2008). According to Ninth National Forest Resource Inventory Report of China (2014–2018), forest coverage in China increased from about 12% in the early 1980s to 22.96% by the 2018, a rise of about 10.96%. However, it is still unclear how much these national ecological restoration projects have modified the spatial distribution of forest patches, and to what extent enhanced the forest connectivity and buffered the local thermal environment.

Here, we first identified the changes in core forest which is defined as continuous forest interior fully surrounded by other forest with isolated or marginal patches (figures 1(a) and (b)) using moderate resolution imaging spectroradiometer (MODIS) land cover data from 2003 to 2018 (Sulla-Menashe et al 2019). Compared to the isolated and marginal forests, core forests tend to experience less outside natural and anthropogenic disturbances (Cao et al 2011). The core forests tend to have larger leaf area index (LAI) than the marginal forests (figure S1 (available online at stacks.iop.org/ERL/17/014056/mmedia)), indicating that core forests have higher vegetation abundance than marginal forests because the marginal forests are featured with edges of forests and isolated forest patches, which are newly restored or experienced more outside pressures than marginal forests. We then evaluated the changes of forest connectivity as a result of decade’s long reforestation efforts with landscape ecology approaches. We further evaluated the difference of land surface temperature (LST) between the core forests and nearby marginal forests, and how this difference relies on size of core forests.

2. Data and methods

2.1. Identification of core forests and marginal forests

The core forests are defined as the forests surrounded by other forests with marginal or isolated patches. Compared with fragmented forests, Core forests provide more stable and continuous habitats for species, thereby protecting biodiversity with less disturbance (Wang et al 2020). In order to quantify core forests and its surrounding marginal forests in China, we first used MODIS International Geosphere-Biosphere Programme land cover classification data (MCD12Q1 version 6) at 500 m spatial resolution from 2003 to 2018 to extract forest cover (Sulla-Menashe et al 2019), and then we applied morphological spatial pattern analysis (MSPA) to identify core forests and marginal forests. MSPA is a segmentation technique developed to identify spatial patterns of connected features (Vogt et al 2007). This method uses binary images consisting of foreground (forest) and background (non-forest) as input data. The foreground is further divided into core forest and marginal forest through morphological image processing technology (Vogt and Ritters 2017). Here we chose 500 m as the minimum possible size, which corresponds to the size of a MODIS land cover pixel. Therefore, the identifiable minimum core forest unit is composed of a 3 × 3 500 m pixels window. We delineated all core forest patches using eight-way connectedness, which permits connections through all horizontally, vertically, and diagonally adjacent pixels. The middle pixel of the window is identified as the minimum core forest pixel, while the rest of the forest areas are classified as marginal forest (figure 1(a)).

We assessed vegetation condition between the core forests and marginal forests within each 25 km window, in which climate background and variability are similar. Core forests are assumed to be with more stable ecosystem under the current climate state. Marginal forests are newly restored forests or have
experienced more natural and human disturbance than the core forests under the same background climate. We calculated 16 year (2003–2018) averaged LAI difference between the core forests and marginal forests within the same 25 km window with MODIS LAI dataset (MOD15A2H v006) of 500 m spatial resolution and 8 d temporal resolution (Yan et al. 2016), which was resampled to 1 km spatial resolution and corrected by Savitzky–Golay filter to remove outliers. On average, the core forests have shown higher LAI than marginal forests, particularly in low latitudes and in the growing season (figure S1).

### 2.2. Calculation of forest connectivity

Landscape connectivity defines the degree to which distinct patches of landscape are connected, which influences the movements of organisms and their genes among resources patches. We evaluated the landscape connectivity associated with the changes in core forests and marginal forests. The connectivity $C_i$ of forest pixel $i$ surrounded by $n$ other pixels is given by (Grantham et al. 2020):

$$C_i = \frac{\sum_{j=1}^{n} (F_jD_{ij})}{\sum_{j=1}^{m} (F_jD_{ij})}$$  \hspace{1cm} (1)

where $F_j$ is the forest extent, a binary variable indicating if forested (1) or not (0), $D_{ij}$ is the weight assigned to the distance between pixels $i$ and nearby pixel $j$, $n$ is the numbers of the pixels around the pixel $i$ in the current forest spatial distribution (numbered $j = 1, 2...n$) and $m$ is the numbers of the pixels around the pixel $i$ in the potential forest spatial distribution (numbered $j = 1, 2...m$). $D_{ij}$ uses a normalized Gaussian curve, with standard deviation ($\sigma$) equaling 500 m and distribution truncated to zero at $4\sigma$ for computational convenience. A small value of $\sigma$ captures landscape connectivity patterns operating at a local scale. Connectivity of forest in pixel $i$ was calculated using the current connectivity compared to the connectivity of potential forest without extensive anthropogenic modification, so that areas with naturally low connectivity, such as permanent waters and artificial surface, are not counted. The map of the potential forest cover was from a modified version of
Laestadius et al (2011). Note that the values of $C_i > 1$ were assigned a value of 1 to ensure that $C_i$ ranges from 0 to 1.

2.3. Temperature modulated by continuous forest

We compare the satellite LSR between core forests and marginal forests to evaluate the temperature modulated by forest expansion and increased landscape connectivity. We also compare the LST between core forests and croplands to infer the thermal buffer by forest relative to an open land. The LST between core forests and marginal forests and between core forests and croplands were calculated in the same 25 km window in which the LST differences were assumed to be caused by the forest fragmentation or land conversion to croplands.

In order to match the LST data of 1 km resolution, we converted the segmentation results of core forests and marginal forests into raster at 1 km resolution and then identified the pixels with 100% coverage of core forests, marginal forests and croplands. The differences in LST between core forests and marginal forests (or croplands) were calculated with core forests, marginal forests and croplands unchanged during the period between 2003 and 2018.

We used MODIS 8 d Aqua LST (MYD11A2 version 6) at 1 km spatial resolution to quantify local LST (Wan 2014). The overpass time of Aqua is around 13:30 and 01:30 local time, which approximates to the time of daily maximum and minimum temperatures, respectively. We calculated recent 16 year (2003–2018) monthly mean LST to analyze the LST difference ($\Delta\text{LST}$) between core forests and marginal forests (or croplands) were calculated with core forests, marginal forests and croplands unchanged during the period between 2003 and 2018.

In the same 25 km window, we evaluated the $\Delta\text{LST}$ between the core forests and marginal forests, and between core forests and croplands,

$$\Delta\text{LST} = \text{LST}_{\text{CF}} - \text{LST}_{\text{MF (or CRO)}}$$

where $\text{LST}_{\text{CF}}$, $\text{LST}_{\text{MF}}$ and $\text{LST}_{\text{CRO}}$ are 13 year monthly mean LST in the same 25 km window for core forests, marginal forests, and croplands, respectively. Negative values thus reflect cooler temperatures in the core forests than marginal forests and croplands. The $\Delta\text{LST}$ at 13:30 and 01:30 local time were used to represent the daytime $\Delta\text{LST}$ ($D$) and nighttime $\Delta\text{LST}$ ($N$), respectively. The differences in daily mean LST ($\text{LST}_{\text{B}}$) between core forests and marginal forests (or croplands) were calculated as the mean of $D$ and $N$. The differences in diurnal LST range ($\text{LST}_{\text{B}}$) between core forests and marginal forests (or croplands) were calculated as the difference between $D$ and $N$ ($\text{LST}_{\text{B}} = D - N$).

In order to avoid the influence of elevation on the surface temperature, we constrained our analysis to windows where mean elevation differences between core forests and marginal forests (or croplands) were within ±500 m. Then for a specific window, we divided elevations into 100 m intervals, and calculated $\Delta\text{LST}$ in each same interval. Finally, we obtained the $\Delta\text{LST}$ of the window by calculating the average of the $\Delta\text{LST}$ of all intervals (Ma et al 2017). Here we used digital evaluation model from the shuttle radar topography mission as the elevation data (Farr et al 2007).

3. Results

3.1. Reforestation enhanced landscape connectivity

We showed that forest area increased by 169 500 km$^2$ in China over 2003–2018, in which the area of marginal forests increased from 515 100 km$^2$ in 2003 to 639 300 km$^2$ in 2018, a net increase of 124 200 km$^2$. As reforestation and conservation progressed, newly restored forests created buffer to original forest patches which transforms marginal forests to core forests, and some non-forest areas were gradually covered by core forests (figure 1(c)). As a result, the increase of core forests was lower and lagged behind marginal forests for about 5 years (figures 1(d) and (e)). The area of core forests increased from 347 300 km$^2$ in 2003 to 392 600 km$^2$ in 2018, a net increase of 45 300 km$^2$. About $8.82 \times 10^4$ km$^2$ of new core forests were established by filling the gaps around marginal forests. However, disturbance and land conversion still existed leading to about $4.29 \times 10^4$ km$^2$ of core forests transformed to marginal forests and non-forest areas.

The increased core forests and marginal forests by gradually filling gaps among isolated patches have improved landscape connectivity in China, and the core forests showed greater improvement than marginal forests. We quantified mean landscape connectivity around each forest pixel, which defines the degree to which forest landscape are connected. Landscape connectivity ranges between 0 and 1, implying fully isolated and connected landscape, respectively. The mean connectivity of marginal forests and core forests over 2003–2018 were 0.64 ± 0.01 (mean ± standard deviation, the same hereinafter) and 0.97 ± 0.01, respectively. Forests with high connectivity are mainly distributed in the northeast, central and southwest regions of China (figure 2(a)), where the main area of natural forests in China are present. Transformation from marginal forests and non-forests to core forests led to landscape connectivity increase by 0.15 ± 0.08 and 0.95 ± 0.04, respectively.Conversion from non-forests to marginal forests led to connectivity increase by 0.61 ± 0.07 (figure 2(b)). There was also slightly improved connectivity within marginal forests from 0.62 ± 0.09 to 0.67 ± 0.07. The proportion of forests

...
Figure 2. Forest connectivity in China. (a) Distribution of forest connectivity in 2018. (b) Spatial distribution of changes in forest connectivity due to the transformation from marginal forest (MF) to core forest (CF) between 2018 and 2003.

with high connectivity (>0.8) increased from 45.7% to 49.1% between 2003 and 2018.

3.2. Thermal buffering of forests with high connectivity
With increased connectivity, core forests enhanced cooling effects on land surface during daytime and warming effect at nighttime compared to marginal forests (figures 3 and S2). The daytime cooling is particularly pronounced throughout the year in the subtropical and temperate regions, as well as summer in the boreal regions. On the contrary, core forests tend to have warming effects during the night, particularly in the boreal winter. These asymmetrical effects of core forests during the daytime and nighttime lead to a lowered daily mean cooling effect of $-0.42 \pm 0.23 \, ^\circ C$ compared to marginal forests, which is dominated by daytime cooling effect. However, the nighttime warming of core forests dominated the daily mean effects of core forests in the winter above 40 °N.

Core forests effectively reduced the diurnal range of LST because of asymmetric daytime and nighttime LST changes (figures 4(a)–(c)). The annual mean diurnal range of LST in core forests was $1.41 \pm 0.23 \, ^\circ C$ lower than that of nearby marginal forests. Compared with nearby marginal forests, 95.1% of the sample areas show the mitigation effect of core forests on the diurnal range of LST. The core forests reduced diurnal range of LST in all seasons. The mitigation tended to be greater in the higher latitude due to the cooling effects during daytime and warming effects during nighttime of IFs.

Furthermore, due to the seasonal asymmetry of the shortening effects of core forests, the seasonal variation in core forests tended to be lower.
Figure 3. LST difference between core forests and marginal forest. (a)–(d) The spatiotemporal patterns of monthly mean LST differences ($\Delta$LST) of daytime ($D$), nighttime ($N$), diurnal mean ($M$) and diurnal range ($R$) between core forests (CFs) and marginal forests (MFs). (e)–(h) The seasonal variations of regional-averaged $\Delta$LST of $D$, $N$, $M$ and $R$ between CFs and MFs. White intervals in (a)–(d) represent no value of $\Delta$LST because of lack of windows for calculation.

than that in marginal forests (figures 4(d)–(f)) by $−0.42 \pm 0.55$ °C, and 78.4% of the sample areas showed the mitigation effect of core forests on the seasonal range of LST. Core forests had much narrower seasonal temperature range in the higher latitude where core forests tended to be cooler in the summer and warmer in the winter than marginal forests.

The magnitude of thermal buffering of core forests depends on the size of core forests, i.e. larger patches of core forests led to stronger thermal buffering effects. We defined the core forests of different sizes, i.e. small core forests with area ≤10 km$^2$, medium core forests with area between 10 and 100 km$^2$ and large core forests with area greater than 100 km$^2$. In 2018, the number of core forests of the small, medium and large sizes were 7591, 2024 and 253, an increase of 26.9%, 23.2% and 17.7% relative to that in 2003, respectively (figures 5(a) and (b)). On average, the large size core forests buffered the daytime ($−1.32 \pm 0.68$ °C), nighttime ($0.15 \pm 0.47$ °C), daily mean ($−0.58 \pm 0.41$ °C) and diurnal range ($−1.47 \pm 0.53$ °C) of LST relative to marginal forests almost twice that of the small size core forests (figure 5(c)). The large core forests also showed a much lower seasonal range of LST ($−0.65 \pm 0.40$ °C) than marginal forests compared to negligible effects of small core forests ($−0.05 \pm 0.14$ °C).

Agricultural expansion is still one of the major drivers of land use change and habitat loss in China, which modified local climate greater than marginal forests. The daily cooling effect of core forests relative to marginal forests ($−0.42 \pm 0.23$ °C) was much weaker than that relative to croplands ($−1.12 \pm 0.23$ °C) (figure S3). The annual mean diurnal range of LST in core forests was $4.14 \pm 0.74$ °C lower than that of nearby croplands. Compared with nearby croplands, 99.1% of the sample areas showed the mitigation effect of core forests on the diurnal range of LST (figures S4(a)–(c)). Furthermore, the difference in seasonal range of LST between core forests and croplands was $−2.51 \pm 0.84$ °C, and 95.8% of the windows show the shortening effect of core forests on the seasonal range of LST (figures S4(d)–(f)). Although the thermal buffering effect of marginal forests is not as effective as that of core forests, marginal forests still have certain buffer effects on LST relative to croplands, with the daily cooling effect of $−0.98 \pm 0.35$ °C. Furthermore, the annual mean diurnal (seasonal) range of LST in marginal forests was $2.91 \pm 0.61$ °C ($−1.51 \pm 0.71$) lower than that of nearby croplands.
Figure 4. Differences in diurnal range and seasonal variation of LST between core forests and marginal forests. (a) LST differences ($\Delta$LST) of diurnal range between core forests (CFs) and marginal forests (MFs). (b) Frequency distribution histogram of annual average $\Delta$LST of diurnal range between CFs and MFs. $n$ denotes the number of 25 km windows in which the CFs were compared with MFs. Neg. and Pos. denote the fraction of negative and positive values of the $\Delta$LST, respectively. (c) $\Delta$LST of daytime ($D$), nighttime ($N$), diurnal mean ($M$) and diurnal range ($R$) between CFs and MFs. (d) $\Delta$LST of seasonal range between CFs and MFs. (e) Frequency distribution histograms of $\Delta$LST of seasonal range between CFs and MFs. (f) $\Delta$LST of summer (SM), winter (WT) and seasonal range (SM–WT) between CFs and MFs. The seasonal range of LST is calculated as the LST in summer (June–July–August) minus the LST in winter (December–January–February).

4. Discussion

4.1. Reforestation enhanced landscape connectivity

In the past 20–30 years, China has carried out a series of reforestation and ecological restoration projects nationwide to combat deforestation and loss of biodiversity as consequences of rapid cropland expansion and urbanization. We obtained evidence of the impact of these reforestation projects on the spatial distribution of forests from satellite observations, and found out that the reforestation effectively increased the forest coverage and improved forest connectivity by the increased area and size of core forests surrounded by other marginal or isolated forests.

The dynamic formation of core forests mainly includes two processes: (a) new forests are added at the edges of the old core forests, expanding the existing core forest patches, and (b) the new forests appear in the form of isolated or marginal forests, and then gradually interconnected to form the core forests with natural vegetation succession. Therefore, the formation of core forests often has a time lag behind isolated or marginal forests, depending on the location of reforestation, the seedling and colonization of marginal forest patches into new territory, the evolution of marginal forest patches and the survival rate of trees (Cao et al. 2011), which explains that core forests are often established around 5 years later than that of marginal forests.

We found that most newly planted pioneer forests take years and even decades to fill canopy gaps to success to core forests, then the number of core forest patches have increased significantly. Considering core forests tend to experience less edge effects and anthropogenic disturbances which is suitable as a habitat for plants and animals, the increased number of the small-sized core forest patches has the potential to provide more stable habitats that meet the requirement of minimum habitat size (Vance et al. 2003, Whittaker et al. 2017). Meanwhile, the large-sized core forests tend to have relatively higher species richness and stronger thermal buffering ability relative to small size (MacArthur and Wilson 1963), indicating that increased number of the large-sized core forest
Figure 5. Core forest size and thermal buffering. (a) and (b) Distribution of core forests (CFs) with small size (area < 10 km²), medium size (10 km² < area ≤ 100 km²) and large size (area > 100 km²) in 2003 and 2018. (c) The LST difference between CFs and marginal forests with different CF size for daytime (D), nighttime (N), diurnal mean (M), diurnal range (R) and seasonal range (S). The error bars in (c) represent the standard deviation.

Landscape connectivity of the forest ecosystem, which influences the movements of organisms and their genes among resources patches, facilitates the migrating success of species through the forest ecosystem response to current and future climate change. We found the increased core forests and marginal forests have improved landscape connectivity in China, and core forests showed greater improvement than marginal forests. Considering that the formation of core forests has a time lag behind marginal forests, the connectivity of the existing marginal forests will continue to improve with a great potential to merge into core forest with increased connectivity under natural succession. Marginal forests, as the major contribution to the forest area increase, significantly improved the connectivity of non-forest areas and effectively increased the connectivity of old marginal forests.
4.2. Thermal buffering of forests with high connectivity

Core forests can effectively cool the land surface compared with nearby croplands, indicating their potential in buffering thermal environment change driven by anthropogenic land conversion (Li et al. 2015, Ma et al. 2017). The cooling effects of core forests are much stronger than that of marginal forests on LST. Core forests had a mean cooling effect of $-0.42 \pm 0.23 \, ^\circ\text{C}$ in relative to marginal forests on a national scale, with stronger effects in the tropical and subtropical regions. Compared to marginal forests, core forests show much greater potential to buffer local temperature change induced by forest fragmentation. Some studies have shown that warming impacts of deforestation on LST can surpass cooling impacts of reforestation in low latitudes where forest loss is far more extensive than forest gain (Sloan and Sayer 2015, Bright et al. 2017). As a possible mitigation solution to the above situation, improving the integrity of the forests by eventually integrating isolated patches of marginal forests into core forests may further enhance potential of forests to buffer local thermal environment change under the current reforestation policies and goals.

Climate change can lead to an increase in diurnal and seasonal temperature range, which can be further amplified by deforestation and fragmentation (Tuff et al. 2016, Lejeune et al. 2018, Chen and Dirmeyer 2019). The core forests cooled the land surface more efficiently during the daytime than the nighttime, which substantially reduces the daily variation of LST in southern China (south of $30 \, ^\circ\text{N}$). The low-latitude species have usually evolved to adapt to a narrow temperature range. These species are likely to be particularly sensitive to temperature range variation because physiological functions of many species have been developed to their optimal state within the relatively narrow temperature range (Wright et al. 2009). When the temperature range exceeds the optimal range, the performances of species organism decline rapidly, because they need more energy to maintain increased metabolic demand (Colinet et al. 2015, Verheyen and Stoks 2019). We showed that core forests in the low latitudes can effectively adjust the diurnal temperature range which alleviates the thermal stress caused by land conversion and forest fragmentation. The establishment of more core forests during the reforestation process can provide more thermal refuges for low-latitude species, which is essential for protecting low-latitude species diversity under climate warming.

The core forests had a slight cooling or warming effect in the north of $40 \, ^\circ\text{N}$ (mainly in northeast China). Compared with low-latitude forests, forests in the mid-latitudes have a lower cooling effect on LST, which may limit the mitigation potential of forests in this area (Li et al. 2015). However, temperate forests there reduce the diurnal and seasonal maximum temperature and increase the minimum temperature, thereby shortening the diurnal and seasonal range of temperature. Compared with low-latitude species, temperate species experience more pronounced diurnal and seasonal temperature range variation. The temperature reduction at night caused by land conversion, e.g. deforestation, poses a serious threat to species diversity in temperate and boreal regions (Sunday et al. 2019). Therefore, the warming effect in nighttime and cold season of core forests in northeast China has a thermal buffering effect, providing warmer habitats for species at night and cold seasons. Meanwhile, similar to low latitudes, the cooling effect of temperate core forests during the day and warm seasons can provide temperate species with cool habitats away from their upper thermal limit.

The marginal forests mainly consist of a large number of isolated patches and fragmented edges, which are susceptible to stronger edge effects and human disturbance. Fragmented forests with more edges are more likely to expose to climatic variability and extremes, reducing the ability of forests to buffer its internal thermal environment from background climate change (Ewers et al. 2013). Meanwhile, the fragmentation of forests can reduce forest connectivity which is important for species and genes to flow to more suitable habitats in the face of dynamically shifting climate (McGuire et al. 2016). However, we emphasized that the newly planted and restored marginal forests still play an important role in improving habitat, even before merged into core forests. Although the current buffering effect of marginal forests is weaker than that of core forests, the marginal forests still play important role in buffering thermal environment change and anthropogenic disturbances such as deforestation and urbanization. Marginal forests serve as a buffer zone for the core forests to resist external disturbances, maintaining the internal stability of the forest ecosystem. Therefore, strengthening the establishment of core forests, as well as the protection of marginal forests, can increase the potential of reforestation as a nature climate solution for mitigating local climate change and protecting biodiversity.

The core forests can buffer local thermal environment mainly through modification of surface energy budgets (supplementary S1). The albedo and turbulent heat differences between core forests and marginal forests (or cropland) vary during the day and night and among the seasons and latitudes (figures S5 and S6). Core forests with less canopy gaps have greater evapotranspiration, which enhances surface cooling by increased turbulent heat loss (Ringgaard et al. 2014). Compared with marginal forests (or croplands), core forests have lower albedo and thus can absorb more shortwave radiation in
daytime, which leads to a warming effect on surface. During nighttime, vegetation releases energy that stored during the daytime, which makes vegetation have a tendency to warm the surface (Li et al. 2015). This warming effect can be further amplified in the northern core forests during winter, due to the shading effect of tall canopy of core forests on snow, leading to albedo far lower than that of open land (Malle et al. 2021). The higher LAI in core forests than marginal forests results in lower aerodynamic resistance thereby enhancing the turbulent heat transfer (mainly sensible heat) from the land surface to the atmosphere and cooling the land surface (Chen et al. 2020).

Currently, global forest restoration has been recognized as an important natural-based solution to mitigate climate change, reduce biodiversity loss, and improve human well-being (Di Sacco et al. 2021). Reforestation is considered as the largest natural pathway of cost-effective natural climate solutions needed to limit warming below 2 \(^\circ\)C because of its high carbon sequestration ability (Griscom et al. 2017). Climate mitigations through biophysical processes of reforestation have not been considered in natural climate solutions to date. Several global restoration projects, such as the Bonn challenge and the 1 t.org platform, have set reforestation targets for hundreds of millions of hectares at the national and international scales (Seddon et al. 2021). However, the high costs of forest restoration in the implementation, maintenance, and long-term protection and monitoring restricted the fulfillment of current reforestation goals, thereby reducing the potential of forest restoration in global climate change mitigation (Brancalion et al. 2020). Therefore, it is necessary to formulate effective forest restoration plans that can maximize the role of forest in climate mitigation at a limited cost. Here, we provided observational evidences of local thermal environment buffering benefits of China’s reforestation projects in the past two decades other than carbon removal from atmosphere. Our findings provide useful references for forest restoration in other regions to create more core forests with high connectivity, which can maintain local species diversity in response to climate change and improve cost-efficiency of the current afforestation goals. How reforestation buffered thermal environment is interacted with forest composition, invasive species and even land degradation, however, needs further investigation.

5. Conclusions

We provide observational evidences to demonstrate that the ecological restoration efforts in China have effectively increased forest area in the last two decades. As reforestation and conservation progressed, newly restored forests created buffer to original forest patches that transforms marginal forest patches to core forests. The core forests with improved connectivity effectively buffer the LST and reduce diurnal range and seasonal variation relative to nearby isolated marginal forests. The marginal forests, however, are major contribution to the increase of forest area in China and create buffer zones for the interior forest to resist external disturbances, maintaining the internal stability of the forest ecosystem, despite their relatively lower buffer capacity at earlier succession stage. Considering that the formation of core forests has a time lag behind marginal forest, the existing marginal forests will have a great potential to become core forests. We highlight that improving the integrity and connectivity of the forests by creating more core forests, instead of marginal forests, can further enhance potential of forests to buffer local thermal environment change with continuous ecological restoration efforts.

Data availability statements

Moderate Resolution Imaging Spectroradiometer (MODIS) International Geosphere-Biosphere Programme (IGBP) land cover classification data of 500 m (MCD12Q1 version 6), MODIS 8 day Aqua LST of 1 km (MYD11A2 version 6), MODIS 8 day leaf area index (LAI) dataset of 500 m (MOD15A2H v006), MODIS 16 day albedo of 500 m (MCD43A3 version 6), MODIS 8 day evapotranspiration of 500 m (MOD16A2 version 6) are available on Google Earth Engine where the data were analyzed. The monthly downward shortwave radiation data of 1° spatial resolution are from Clouds and the Earth’s Radiant Energy System https://ceres.larc.nasa.gov/data/. The Morphological Spatial Pattern Analysis is carried out using the freely public software GUIDOS https://forest.jrc.ec.europa.eu/en/activities/lpa/gtb/ . Potential forest cover is freely public available https://data.globalforestwatch.org/datasets/potential-forest-coverage.

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

Acknowledgments

Anqi Huang and Runping Shen are supported by National Key R&D Program of China (2018YFC1506602). Xiyan Xu and Gensuo Jia are supported by National Key R&D Program of China (2018YFA0606002).

Conflict of interest

The authors declare no conflicts of interest.
ORCID iDs

Anqi Huang https://orcid.org/0000-0001-9261-5966
Gensuo Jia https://orcid.org/0000-0001-5950-9555
Xiyian Xu https://orcid.org/0000-0003-2732-1325

References

Alexandre-Benavent R, Aleixandre-Tudó J L, Castelló-Cogollos I and Alexandre J L 2018 Trends in global research in deforestation. A bibliometric analysis Land Use Policy 72 293–302
Barahona-Segovia R M, Crespin S J, Grez A A and Veloso C 2019 Anthropogenic thermal gradient in managed landscapes determines physiological performance and explains the edge-biased distribution of ectothermic arthropods For. Ecol. Manage. 440 147–57
Brancalion P H, Amazonas N T, Chazdon R L, Melis J, Rodrigues R R, Silva C C, Serroni T B and Holl K D 2020 Exotic eucalypts: from demonized trees to allies of tropical forest restoration? J. Appl. Ecol. 57 53–66
Bright R M, Davin E, O’Halloran T, Pongratz J, Zhao K and Cescatti A 2017 Local temperature response to land cover and management change driven by non-radiative processes Nat. Clim. Change 7 296–302
Cadavid-Florez L, Laborde J and Mclean D J 2020 Isolated trees and small woodsy patches greatly contribute to connectivity in highly fragmented tropical landscapes Landscape Urban Plan. 196 103745
Cao S, Chen L, Shankman D, Wang C, Wang X and Zhang H 2011 Excessive reliance on afforestation in China’s arid and semi-arid regions: lessons in ecological restoration Earth Sci. Rev. 104 240–5
Chen C, Li D, Li Y, Piao S, Wang X, Huang M, Gentile P, Nemani R R and Myrneni R B 2020 Biophysical impacts of Earth greening largely controlled by aerodynamic resistance Sci. Adv. 6 eaba1981
Chen L and Dirmeyer P A 2019 Differing responses of the diurnal cycle of land surface and air temperatures to deforestation J. Clim. 32 7067–79
Colinet H, Sinclair B J, Vernon P and Renault D 2015 Insects in fluctuating thermal environments Annu. Rev. Entomol. 60 123–40
de Frenne P, Zellweger F, Rodriguez-Sánchez F, Scheffers B R, Hylander K, Luoto M, Vellend M, Verheyen K and Lemoine J 2019 Global buffering of temperatures under forest canopies Nat. Ecol. Evol. 3 744–9
Di Sacco A et al 2021 Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits Glob. Change Biol. 27 1328–48
Doelman J C et al 2020 Afforestation for climate change mitigation: potentials, risks and trade-offs Glob. Change Biol. 26 1576–91
Duveiller G, Hooker J and Cescatti A 2018 The mark of vegetation integrity Nat. Commun. 11 5978
Griscom B W et al 2017 Natural climate solutions Proc. Natl Acad. Sci. 114 11645–50
Houghton R A and Nassikas A A 2018 Negative emissions from stopping deforestation and forest degradation, globally Glob. Change Biol. 24 350–9
Laestadius L et al 2011 Mapping opportunities for forest landscape restoration Unasylu 62 47–48
Laurance W F et al 2011 The fates of Amazonian forest fragments: a 32-year investigation Biol. Conserv. 144 56–67
Laurance W F, Lovejoy T E, Vasconcelos H L, Bruna E M, Didham R K, Stouffer P C, Gascon C, Bierregaard R O, Laurance S G and Sampaio F 2002 Ecosystem decay of Amazonian forest fragments: a 22-year investigation Conserv. Biol. 16 605–18
Lejeune Q, Davin E L, Gudmundsson L, Winckler J and Seneviratne S I 2018 Historical deforestation locally increased the intensity of hot days in northern mid-latitudes Nat. Clim. Change 8 386–90
Li Y et al 2015 Local cooling and warming effects of forests based on satellite observations Nat. Commun. 6 6603
Liu J, Coomes D A, Gibson L, Hu G, Liu J, Luo Y, Wu C and Yu M 2019 Forest fragmentation in China and its effect on biodiversity Biol. Rev. 94 1636–57
Liu J, Li S, Ouyang Z, Tam C and Chen X 2008 Ecological and socioeconomic effects of China’s policies for ecosystem services Proc. Natl Acad. Sci. 105 9477–82
Locatelli B, Catterall C P, Imbach P, Kumar C, Lasco R, Marin-Spiotta E, Mercer B, Powers J S, Schwartz N and Uriarte M 2015 Tropical deforestation and climate change: beyond carbon Restor. Ecol. 23 337–43
Lu F et al 2018 Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010 Proc. Natl Acad. Sci. 115 4039–44
Ma W et al 2017 Multiple satellite-based analysis reveals complex climate effects of temperate forests and related energy budget J. Geophys. Res. Atmos. 122 3806–20
MacArthur R H and Wilson E O 1963 An equilibrium theory of insular zoogeography Evolution 17 373–87
Malle J et al 2021 Effect of forest canopy structure on wintertime land surface Albedo: evaluating CLM5 simulations with in-situ measurements J. Geophys. Res. Atmos. 126 e2020JD034118
McGuire J L, Lawler J J, McRae B H, Nuñez T A and Thoohrol D M 2016 Achieving climate connectivity in a fragmented landscape Proc. Natl Acad. Sci. 113 7195–200
Pfeifer M et al 2017 Creation of forest edges has a global impact on forest vertebrates Nature 551 187–91
Pimm S L, Jenkins C N, Abell R, Brooks T M, Gittleman J L, Joppa L N, Raven P H, Roberts C M and Sexton J O 2014 The biodiversity of species and their rates of extinction, responses to past and ongoing environmental change Nat. Ecol. Evol. 5 147–57
Rodrigues R R, Silva C C, Sorrini T B and Holl K D 2020 Multiple satellite-based analysis reveals complex climate effects of temperate forests and related energy budget J. Geophys. Res. Atmos. 122 3806–20
Ringgaard R, Herbst M and Friborg T 2014 Partitioning forest evapotranspiration: interception evaporation and the impact of canopy structure, local and regional advection J. Hydrol. 519 677–90
Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C, House J, Srivastava S and Turner B 2021 Getting the message right on nature-based solutions to climate change Glob. Change Biol. 27 1518–40
Sloan S and Sayer J A 2015 Forest resources assessment of 2015 and outlook to present: the MODIS collection 6 land cover product Remote Sens. Environ. 192 222–43
Sunday J, Bennett J M, Calosi P, Chueshi-Trullas S, Gravel S, Hargreaves A L, Leiva F P, Verberk W C E P, Olivera-Tárraga M A and Morales-Castilla I 2019 Thermal tolerance patterns across latitude and elevation Phil. Trans. R. Soc. B 374 20190036
Taubert F, Fischer R, Groeneveld J, Lehmann S, Müller M S, Rödig E, Wiegard T and Huth A 2018 Global patterns of tropical forest fragmentation Nature 554 519–22
Tuff K, Tuff T and Davies K F 2016 A framework for integrating thermal biology into fragmentation research *Ecol. Lett.* 19 361–74

UNEP F 2020 The state of the world’s forests 2020. Forests, biodiversity and people (FAO)

Vance M D, Fahrig L and Flather C H 2003 Effect of reproductive rate on minimum habitat requirements of forest-breeding birds *Ecology* 84 2643–53

Verheyen J and Stoks R 2019 Temperature variation makes an ectotherm more sensitive to global warming unless thermal evolution occurs *J. Animal Ecol.* 88 624–36

Vieilledent G, Grinand C, Rakotomalala F A, Ranaivosoa R, Rakotoaririana J-R, Allnutt T F and Achard F 2018 Combining global tree cover loss data with historical national forest cover maps to look at six decades of deforestation and forest fragmentation in Madagascar *Biol. Conserv.* 222 189–97

Vogt P, Riitters K H, Estreguil C, Kozak J, Wade T G and Wickham J D 2007 Mapping spatial patterns with morphological image processing *Landscape Ecol.* 22 171–7

Vogt P and Riitters K 2017 GuidosToolbox: universal digital image object analysis *Eur. J. Remote Sens.* 50 352–61

Wan Z 2014 New refinements and validation of the collection-6 MODIS land-surface temperature/emissivity product *Remote Sens. Environ.* 140 36–45

Wang Y, Brandt M, Zhao M, Xing K, Wang L, Tong X, Xue F, Kang M, Jiang Y and Fensholt R 2020 Do afforestation projects increase core forests? Evidence from the Chinese Loess Plateau *Ecol. Indic.* 117 106558

Whittaker R J et al 2017 Island biogeography: taking the long view of nature’s laboratories *Science* 357 6354

Wright S J, Muller-Landau H C and Schipper J 2009 The future of tropical species on a warmer planet *Conserv. Biol.* 23 1418–26

Yan K, Park T, Yan G, Chen C, Yang B, Liu Z, Nemani R, Knyazikhin Y and Myneni R 2016 Evaluation of MODIS LAI/FPAR product collection 6, Part 1: consistency and improvements *Remote Sens.* 8 359

Zhang X, Shi M-M, Shen D-W and Chen X-Y 2012 Habitat loss other than fragmentation per se decreased nuclear and chloroplast genetic diversity in a monoecious tree *PLoS One* 7 e39146