Asymmetrical cooling effects of Amazonian protected areas across spatiotemporal scales

Anqi Huang1, Xiyan Xu1,∗, Gensuo Jia2 and Runping Shen1

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

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Abstract
Amazonian protected areas (PAs) play an important role in maintaining the regional and global ecosystem services, biodiversity and climate change mitigation. The effects of Amazonian PAs on climate change mitigation mainly focus on the carbon sequestration benefits. The biophysical effects of PAs on regulating the local energy budgets, and hence changing local climate, however, are often ignored. Using multiple satellite observation datasets, we evaluated the effects of Amazonian PAs on land surface temperature (LST) and the biophysical mechanisms of PAs on surface albedo and evapotranspiration (ET). We showed that Amazonian PAs have a cooling effect on local LST in relative to nearby croplands and non-protected areas (non-PAs) with the same land cover as PAs. The asymmetrical cooling effects of Amazonian PAs between daytime and nighttime, and between the dry and wet seasons sustain lower diurnal and seasonal temperature ranges, respectively, than non-PAs and croplands. The protected forests have stronger cooling effects, and more effectively moderate the diurnal and seasonal temperature ranges than the protected savannas due to the higher effects on surface albedo and ET. The non-PAs show weaker cooling effect than PAs, indicating reduced thermal buffering effect in non-PAs. Our results highlighted the great potential of natural vegetation in PAs versus non-PAs and croplands in buffering local thermal environment and the necessity of natural vegetation conservation in Amazon region.

1. Introduction
Amazonian forests are the largest tropical rainforest in the world, which provide valuable ecosystem services (Feeley and Silman 2016), biodiversity (Barlow et al 2016), and climate buffering for the planet (Hannah et al 2007). Tropical forests with high evapotranspiration (ET) are an important source of atmospheric moisture that forms precipitation in Amazon (Zemp et al 2017, Xu et al 2022). ET of tropical forests not only contributes water vapor to the lower atmosphere but consumes a substantial amount of energy as latent heat of vaporization, thereby cooling the land surface (Li et al 2015). As one of the largest ecosystem carbon pools on Earth, Amazonian forests play an important role in mitigating global climate warming by storing around 150–200 Pg carbon in living biomass and soils (Fearnside 2012, Brienen et al 2015). If Amazonian forest carbon is released to the atmosphere, it would substantially enhance greenhouse effect and global warming (Espírito-Santo et al 2014).

Establishment of Amazonian protected areas (PAs) is intended to safeguard biodiversity and mitigate regional climate change (Hannah et al 2007, Kroner et al 2019). Compared with non-protected areas (non-PAs), PAs tend to experience lower human-made and natural disturbances. Amazonian PAs demonstrate the ability to curb deforestation, and the probability of deforestation is 7–11 times lower in PAs than that in surrounding non-PAs (Ricketts et al 2010, Nolte et al 2013). However, due to the political and economic situation, the establishment of Amazonian PAs has been
stagnant in recent years (Bernard et al 2014, Ferreira et al 2014). Amazonian PAs have been under serious threats from deforestation, wildfire, and cropland expansion (Ferrante and Fearnside 2019, Xu et al 2020, 2021).

Climate mitigation and biodiversity conservation are the main focuses of current scientific studies on the role of PAs (Sathler et al 2018, Campanharo et al 2019). The PAs sequester and store carbon from the atmosphere into ecosystem (Watson et al 2014). Conservation of tropical forests in Amazon increases the probability to limiting global warming below 2 °C above pre-industrial level between 2000 and 2050 (Walker et al 2014). In addition to modulating temperatures on a global scale by carbon sequestration, PAs of tropical forests moderate local thermal environment through regulating biophysical processes such as ET, surface albedo, and roughness on a local scale (Alkama and Cescatti 2016). Tropical forests have a cooling effect of more than 2 °C on the local land surface temperature (LST) compared to the open land outside the forests (Li et al 2015).

The land use changes and disturbances, e.g. deforestation, cropland expansion and urbanization as major threats to tropical forests in Amazon (Curtis et al 2018, Potapov et al 2022), reduce ET substantially, which causes a much drier and warmer local climate (Swann et al 2015, Xu et al 2022). These biophysical effects induced by land use changes surpass the effects induced by greenhouse gas emissions on the local thermal environment (Alkama and Cescatti 2016, Huang et al 2020), which challenges local biodiversity and its response to macroclimate warming (De Frenne et al 2019).

Whether the PAs can provide a more suitable thermal environment for tropical biodiversity than non-PAs under the pressure of a changing climate and human activities is still unknown. Here, we used multiple satellite observations to quantitatively evaluate (a) how the PAs in Amazon and its surrounding regions moderate the local and regional LST and (b) what are the PAs impacts on local and regional albedo and ET, which explains the LST difference among PAs, non-PAs and croplands.

2. Data and methods

2.1. Amazonian PAs

International Union for Conservation of Nature World Database on PAs (WDPA) as of 2018 was used to extract PAs in Amazon region. We converted the WDPA vector data into raster at 0.01° resolution and then identified the pixels with 100% coverage of PAs. The 0.01° PAs were then masked with Moderate Resolution Imaging Spectroradiometer (MODIS) International Geosphere-Biosphere Programme land cover classification data (MCD12Q1 version 6) (Sulla-Menashe et al 2019) of 2018 at 0.01° spatial resolution. We delineated our study area within the geographic domain of 12.5° N–30° S and 90.0° W–30.0° W, including Amazon Basin and its surrounding regions, where tropical forests (mainly evergreen broadleaf forest) and savannas are the two major biomes (figure 1). Tropical forests are mainly located in the Amazon Basin, and savannas are mainly located in the Brazilian Cerrado region in the southeast of the Amazon Basin. The tropical forest and savanna PAs in this study area account for about 86.5% and 13.5% of the total studied PAs in this region, and for about 75.7% and 28.4% of the global tropical forest and savanna PAs, respectively.

We then identified pure non-PA and cropland pixels with MCD12Q1 at 0.01° resolution for forests and savannas within the same 0.25° window as PAs. We assumed that the background climate is similar in each 0.25° grid. Therefore, the difference of temperature and energy fluxes between PAs and non-PAs, and between PAs and croplands of 0.01° grids in the same 0.25° grid is caused by the disturbance to the non-PAs or land conversion to croplands. Each 0.25° grid with more than 5% areas of PAs and more than 5% areas of non-PAs (or croplands) is used for paired comparison. It is noteworthy that the number of 0.01° grids used to calculate the temperature and energy fluxes is different for comparison between PAs and non-PAs, and between PAs and croplands because it depends on the availability of non-PAs or croplands within a 0.25° grid.

2.2. LST and energy analysis

We used MODIS 8-day Aqua LST (MYD11A2 Version 6) at 1 km spatial resolution (Wan 2014) to quantify local climate moderation by Amazonian PAs. The overpass time of Aqua around 13:30 and 01:30 local time approximates to the time of daily maximum and minimum temperatures, respectively. We calculated recent five year (2014–2018) monthly mean LST to analyze the LST difference (ΔLST) between PAs and non-PAs (or croplands). In the same 0.25° grid, we evaluated the ΔLST between the PAs and non-PAs of the same biome, and between PAs and croplands, across the domain of Amazon Basin and its surrounding regions, where tropical forests (mainly evergreen broadleaf forest) and savannas are the two major biomes (figure 1). Tropical forests are mainly located in the Amazon Basin, and savannas are mainly located in the Brazilian Cerrado region in the southeast of the Amazon Basin. The tropical forest and savanna PAs in this study area account for about 86.5% and 13.5% of the total studied PAs in this region, and for about 75.7% and 28.4% of the global tropical forest and savanna PAs, respectively.

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\[
\Delta LST = LST_{P} - LST_{NP}(or C)
\]
regulates surface shortwave net radiation (SSNR). Here, we used MODIS albedo data (MCD43A3 Version 6), and Clouds and the Earth’s Radiant Energy System (CERES) energy balanced and filled (EBAF) Surface products from 2014 to 2018 to quantify SSNR change ($\Delta$SW) between the PAs and non-PAs of the same biome, and between PAs and croplands.

MCD43A3 is produced daily using 16 day Terra and Aqua MODIS data at 500 m spatial resolution (Wang et al. 2018). It provides both directional hemispherical reflectance (black-sky albedo) and bihemispherical reflectance (white-sky albedo) for each of the MODIS surface reflectance bands. Actual clear sky albedo (blue-sky albedo) is calculated as the mean of black-sky and white-sky albedo because of their small differences and high correlation (Li et al. 2015). The daily albedo data were further aggregated to five year monthly mean and resampled to 0.01° spatial resolution to match the resolution of PAs, non-PAs and croplands. The albedo difference ($\Delta$Albedo) between PAs and non-PAs (or croplands) was calculated with MCD43A3 following the same way as LST,

$$\Delta \text{Albedo} = \text{Albedo}_P - \text{Albedo}_NP(\text{or C})$$

(2)

CERES EBAF Surface products provide monthly surface radiant fluxes (Kato et al. 2018, Loeb et al. 2018).

In this study, CERES downward shortwave radiation under clear-sky conditions at 1° spatial resolution from 2014 to 2018 was used and resampled from 1° to 0.01° spatial resolution by bilinear interpolation. The $\Delta$SW was calculated as,

$$\Delta \text{SW} = (1 - \text{Albedo}_P) \times S_{in} - (1 - \text{Albedo}_NP(\text{or C})) \times S_{in} = - \Delta \text{Albedo} \times S_{in}$$

(3)

where $S_{in}$ is the five year monthly mean downward shortwave radiation from CERES EBAF Surface products.

We used MODIS 8-day composite ET and latent heat flux product (MOD16A2 Version) at 500 m spatial resolution from 2014 to 2018 (Running et al. 2017) to quantify latent heat flux difference ($\Delta$LE) between the PAs and non-PAs (or croplands). MOD16A2 collection is retrieved based on the Penman-Monteith equation including inputs of daily meteorological reanalysis data with MODIS vegetation property dynamics, albedo, and land cover data. The 8-day MOD16A2 data were further aggregated to five year monthly mean and resampled to 0.01° spatial resolution. The $\Delta$LE was calculated following the same way as LST and albedo,
\[ \Delta LE = LE_P - LE_{NP(ORC)}. \]  

In order to avoid the influence of elevation, our analysis was performed in windows where mean elevation differences between PAs and non-PAs (or croplands) are within ±500 m. The we divided elevations into several 100 m intervals in each window. In each interval, \( \Delta \text{LST}, \Delta \text{SW} \) and \( \Delta \text{LE} \) were calculated, and then averaged over all the elevation intervals in a window (Ma et al. 2017).

We further calculated the seasonal differences in \( \Delta \text{LST}, \Delta \text{SW} \) and \( \Delta \text{LE} \) to evaluate the impact of land conversion from PAs to croplands on temperature and energy fluxes at seasonal scale. We distinguished the dry season from June to September and the wet season from December to March. These dry and wet seasons on average represent the seasonal climate pattern in Amazon, although the dry and wet seasons are not uniform across the forest ecosystem in the basin and to the southern savannas due to the magnitude and seasonality gradient of precipitation from the northwest to the southeast (Buarque et al. 2011).

### 3. Results

#### 3.1. Cooling effects of Amazonian PAs

LST of Amazon is generally higher in the dry season than that in the wet season, which is \( 23.93 \pm 1.12 \, ^\circ\text{C} \) (25.61 \pm 2.01 \, ^\circ\text{C}) for forests (savannas) in the dry season, and \( 22.73 \pm 0.71 \, ^\circ\text{C} \) (24.83 \pm 1.26 \, ^\circ\text{C}) in the wet season (figure 1(c)). Protected forests and savannas in Amazon have net cooling effects on land surface (\( \Delta \text{LST} < 0 \)) compared with non-PAs throughout the year (figures 2(a) and (c)). The cooling effect in the daytime is higher than that in the nighttime, which dominates the daily mean of \( \Delta \text{LST} \). The mean annual daytime \( \Delta \text{LST} \) between the protected forests (savannas) and nearby non-protected forests (savannas) is \( -0.51 \pm 1.14 \, ^\circ\text{C} \) (\( -0.98 \pm 1.51 \, ^\circ\text{C} \)). The mean annual nighttime \( \Delta \text{LST} \) between protected forests (savannas) and nearby non-protected forests (savannas) is \( -0.22 \pm 1.03 \, ^\circ\text{C} \) (\( -0.36 \pm 1.21 \, ^\circ\text{C} \)). The temperature differences between the protected and non-protected savannas are much higher than that between the protected and non-protected forests.
The mean ΔLST between PAs and croplands indicates significant cooling impact of protected forests and savannas on land surface in Amazon (figures 2(b) and (d)). Similar to the difference between PAs and non-PAs of the same biomes, PAs have stronger cooling effect in daytime than that in nighttime. Mean annual daytime ΔLST is $-5.17 \pm 2.47 \degree C$ ($-2.94 \pm 2.17 \degree C$) for protected forests (savannas), dominating the diurnal mean of ΔLST. Mean annual nighttime ΔLST between PAs and croplands is relatively low, i.e. $-0.61 \pm 1.24 \degree C$ ($-0.24 \pm 0.95 \degree C$) for forests (savannas). Compared with croplands, the protected forests and savannas have significant cooling effects in both the dry and wet seasons, although the mean cooling effect is stronger in forests than savannas (figures 2(e) and (f)). The daytime cooling effects are stronger in the dry season while the nighttime cooling effects are stronger in the wet season, which leads to a similar cooling in the wet and dry seasons for both forests and savannas.

### 3.2. Diurnal and seasonal temperature ranges maintained by PAs

The PAs can effectively moderate the diurnal range of LST in Amazon region (figure 3). The mean annual diurnal range of LST is $7.72 \pm 1.25 \degree C$ and $12.72 \pm 2.69 \degree C$ for forests and savannas, respectively. The mean annual diurnal range of LST in protected forests is $-0.23 \pm 1.04 \degree C$ lower than that of non-PAs. The protected savannas, distributed mainly outside of the Amazon Basin, maintain even lower diurnal range of LST ($-0.39 \pm 1.34 \degree C$) than forests compared to their non-PAs. Compared with croplands, the mean annual diurnal range of LST is much lower in PAs ($-3.10 \pm 1.91 \degree C$). The mean annual diurnal range of ΔLST between protected forests (savannas) and croplands is about $-4.26 \pm 1.81 \degree C$ ($-2.73 \pm 1.61 \degree C$). Seasonally, the diurnal range of ΔLST between PAs and croplands is larger in the dry season than that in the wet season, indicating that PAs maintain a smaller variation of diurnal range of LST through the seasons (figures 2(e) and (f)). We noted that there are much fewer grids including both PAs and croplands in the same 0.25° grid inside than outside of the Amazon Basin, indicating the relatively low conversion of forests to croplands within the basin (figure 3(b)).

In Amazon, the LST of the dry season is higher than that of the wet season ($LST_{dry} - LST_{wet} > 0$) on average, although this seasonal difference is spatially heterogeneous (figure 1(b)). In the regions where the LST in the dry season is greater than that in the wet season, negative values of the difference in seasonal range of LST between PAs and non-PAs (or croplands) imply lower seasonal range of LST in PAs than in non-PAs (or croplands). The difference in seasonal range of LST between PAs and non-PAs is relatively low ($-0.01 \pm 0.38 \degree C$) (figure 4(a)), with $-0.03 \pm 0.26 \degree C$ for forests and $0.06 \pm 0.31 \degree C$ for savannas. However, compared with croplands, the PAs maintain a $0.17 \pm 0.12 \degree C$ lower seasonal range of LST on average (figure 4(b)). The seasonal range of ΔLST between protected forests (savannas) and croplands is about $-0.12 \pm 0.97 \degree C$ ($-0.54 \pm 1.01 \degree C$). The protected forests and savannas concentrated on the southeastern border of the Amazon Basin show strong capability of maintaining a lower seasonal range of LST.

### 3.3. Biophysical control of PAs

PAs in the Amazon region absorb more shortwave radiation ($ΔSW > 0$) than the non-PAs and croplands throughout the year (figure 5). The mean annual $ΔSW$ between the protected forests (savannas) and nearby non-protected forests (savannas) is about $0.73 \pm 2.90 \text{Wm}^{-2}$ ($1.50 \pm 3.02 \text{Wm}^{-2}$) with low seasonal variability. Protected forests and savannas absorb much more shortwave radiation than croplands. The mean annual $ΔSW$ between protected forests (savannas) and croplands is about
Figure 4. Seasonal temperature range moderated by protected areas in relative to non-protected areas and croplands. The differences in annual seasonal temperature range between protected areas (PAs) and non-protected areas (non-PAs) (a) and between PAs and croplands (b). The seasonal temperature range was calculated as the temperature difference between the dry season (June to September) and wet season (December to March).

Figure 5. Differences in surface net shortwave radiation change ($\Delta SW$) between protected areas and non-protected areas or croplands. The mean monthly $\Delta SW$ between protected areas (PAs) and non-protected areas (non-PAs) for forests (a) and savannas (c), and between PAs and croplands for forests (b) and savannas (d). The shaded areas in (a)–(d) show the standard deviation of mean monthly for all the compared gridcells. $\Delta SW$ between PAs and croplands during wet and dry seasons were calculated for forests and savannas (e).

7.8 ± 4.75 Wm$^{-2}$ (5.91 ± 5.13 Wm$^{-2}$), with obvious seasonal variation. $\Delta SW$ between PAs and croplands in the wet season (8.68 ± 1.06 Wm$^{-2}$ for forests and 6.64 ± 0.89 Wm$^{-2}$ for savannas) is higher than that in the dry season (7.51 ± 1.24 Wm$^{-2}$ for forests and 5.63 ± 0.82 Wm$^{-2}$ for savannas), and $\Delta SW$ between protected forests and croplands (8.68 ± 1.06 Wm$^{-2}$ for the wet season and 7.51 ± 1.24 Wm$^{-2}$ for the dry season) is higher than that between protected savannas and croplands (6.64 ± 0.89 Wm$^{-2}$ for the wet season and 5.63 ± 0.82 Wm$^{-2}$ for the dry season).

The difference in latent heat between PAs and non-PAs (or croplands) has clear seasonal variations (figure 6). The mean annual $\Delta LE$ between PAs and non-PAs is relatively low, i.e. $-0.63 \pm 4.31$ Wm$^{-2}$ and $0.17 \pm 7.51$ Wm$^{-2}$ for forests and savannas, respectively. PAs release more latent heat than non-PAs during the season transitioning from the dry to the wet season, which is magnified during the dry season (June-November) in the savannas. Protected forests and savannas release much higher latent heat than croplands throughout the year (figures 6(b)–(d)). The mean annual $\Delta LE$ between protected forests (savannas) and croplands is about 27.28 ± 13.33 Wm$^{-2}$ (15.01 ± 8.19 Wm$^{-2}$) with obviously seasonal variation. On average, $\Delta LE$ between PAs and croplands in the dry season (31.36 ± 9.22 Wm$^{-2}$ for forests and 15.95 ± 5.22 Wm$^{-2}$ for savannas) is higher than that in the wet season (22.47 ± 5.87 Wm$^{-2}$ for forests and 12.42 ± 4.16 Wm$^{-2}$ for savannas). $\Delta LE$ between protected forests and croplands (22.47 ± 5.87 Wm$^{-2}$ for the wet season and 31.36 ± 9.29 Wm$^{-2}$ for the dry season) is higher than that between protected savannas and croplands (12.42 ± 4.16 Wm$^{-2}$ for the wet season and 15.95 ± 5.22 Wm$^{-2}$ for the dry season).
4. Discussion

Over the past 60 years, the total deforestation in Amazon has reached 20% of the forested areas, leading to regional ecological and climate crises (Nobre et al 2016). Establishment of PAs has potential to mitigate negative effects of deforestation in Amazon. Here, we obtained evidence of the PAs impact on local thermal environment from satellite observations. We found that PAs in Amazon and its surrounding areas can effectively alleviate local warming compared with adjacent croplands which represent zones with a full anthropogenic land conversion from forests and savannas to crops, indicating their potential in buffering thermal environment change driven by anthropogenic land uses. Currently, the deforestation driven by cropland expansion mainly occurs in the south of the Amazon Basin and the Cerrado region, while deforestation driven by commodity production mainly occurs inside the basin (Curtis et al 2018, Potapov et al 2022). Therefore, in our study the majority of pixels with PAs and croplands within the same pixel appear in the south of the Amazon Basin.

Compared with open land (e.g. croplands), PAs are demonstrated to have a asymmetrical cooling impact between the daytime and nighttime, and between the wet and dry seasons. The reduced diurnal and seasonal temperature ranges within PAs tend to provide suitable habitats for protecting tropical biodiversity because vegetation growth depends on daily and seasonal temperature extremes and variabilities (Lindvall and Svensson 2015). The asymmetrical diurnal and seasonal cooling impacts of PAs are mainly driven by albedo and ET, the two competing biophysical mechanisms to modulate LST (Gibbard et al 2005). Compared to croplands, protected natural vegetation has lower albedo and therefore absorbs more shortwave radiation, leading to a warming effect. However, PAs have higher ET than croplands, which causes higher latent heat loss that completely overcomes the warming effect of albedo change and dominates the local cooling effect (Li et al 2015).

Here, we found that the cooling effect of PAs on LST is much stronger than that of non-PAs, especially in the daytime. PAs had a mean cooling effect of $0.51 \pm 1.14 \degree C$ ($0.98 \pm 1.51 \degree C$) in relative to nearby forests (savannas) without protection on a regional scale. Many studies showed that all categories of PAs established under local laws in Amazon have shown better protection capability, and the probability of deforestation is 7–10 times lower in PAs than in that in surrounding non-PAs (Soares-Filho et al 2010, Ricketts et al 2010). However, as restrictions of deforestation are applied within PAs, logging pressure is transferred to their adjacent non-protected forests (Bode et al 2015). Therefore, non-protected forests tend to expose to more human disturbances, reducing the ability of forests to buffer its thermal environment from background climate change (Fuller et al 2020). Although the buffering effect of non-protected forests is weaker than that of protected forests, the non-protected forests have the potential to serve as a buffer zone for the protected forests to resist external disturbances (Huang et al 2022).

On average, the tropical forests showed higher cooling effect on LST than savannas. Although tropical forests have a lower albedo and therefore a higher warming effect than savannas, the higher canopy coverage of tropical forests with greater ET leads to greater cooling effect, which is more pronounced in the dry season. The southeastern border of Amazon is the ecotone where forests transit to savannas. Previous research has shown that savannas are very susceptible to natural and anthropogenic fires, and fires in savannas are easy to spread and cause tree mortality...
nearby (Hoffmann et al. 2012). Therefore, strengthening the management of protected savannas has the potential to maintain the stability and sustainability of the Amazonian forest ecosystem, mitigating changes in local thermal environment.

Currently, PAs have been recognized as an important natural-based solution to mitigate climate change and reduce biodiversity loss (Roberts et al. 2020). However, due to the political and economic goals, the local governments prioritize agriculture and commodity development, ignoring the importance of PAs in recent years (Bernard et al. 2014, Ferreira et al. 2014). Here, we found the benefits of Amazonian PAs in buffering local thermal environment. Our findings provide implications for climate governance and biodiversity protection in Amazon regions. Compared to recent extensive and cost forest restoration projects in Amazon (Nunes et al. 2020), strengthening the protection of Amazonian forests through the establishment of legal PAs is expected to be a low-cost and effective climate mitigation solution under the current policies and goals.

5. Conclusions

In this study, we provided observational evidences that Amazonian PAs have an effective cooling effect on local surface temperature in relative to croplands and non-PAs. The cooling effects of PAs are asymmetrical between the daytime and nighttime, and between the dry and wet seasons, which moderate the diurnal and seasonal temperature ranges, respectively, than that of croplands. Protected forests, mostly within the Amazon Basin, have stronger cooling effects and maintain lower diurnal and seasonal temperature ranges than protected savannas in the southeast of the basin. The cooling effects of PAs are due to competing effects of PAs natural vegetation on surface albedo and ET. Tropical forests with higher coverage are more effective in ET that dominate the stronger cooling effects than savannas, and the cooling effects are stronger in the dry season when the contrast of canopy is larger between forests and savannas. The non-PAs show weaker cooling effects than PAs, which indicates reduced warming mitigation potential without protection in non-PAs. Our results highlighted the potential of natural vegetation in PAs versus non-PAs and croplands in buffering local thermal environment and providing habitats with proper thermal environment for conservation of tropical biodiversity.

Data availability statement

The World Database on Protected Areas (WDPA) as of October 2018, 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 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-degree spatial resolution are from Clouds and the Earth’s Radiant Energy System https://ceres.larc.nasa.gov/data/.

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

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Conflict of interest

The authors declare no conflicts of interest.

ORCID iDs

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

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