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Comparative Analysis of Two Methods for Valuing Local Cooling Effect of Forests in Inner Mongolia Plateau

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Abstract: Studies have extensively examined the cooling effects of forests. Various methods exist for evaluating climate regulation at regional and global levels. Local-scale cooling effects and their valuing methods, however, remain poorly understood. In this study, the temperature difference and energy balance methods were compared to assess the value of cooling services of three forest types at a local scale. Using the window searching strategy, land surface temperature and sensible heat flux differences between forest and open land were compared. The average cooling temperature of broad-leaved forests was found to be 0.229 °C, significantly higher than that of coniferous forests, at 0.205 °C, while mixed coniferous–broad-leaved forests were not significantly different to the other two types. The average sensible heat flux differences in broad-leaved, coniferous, and coniferous–broad-leaved forests were found to be 0.23, 0.079, and 0.11 MJ/m^2/day, respectively. According to the correlation analysis, the sensible heat flux was significantly correlated with the cooling degree (R = 0.33, p = 0.05), suggesting consistency between the two approaches. However, the total cooling value calculated with the energy balance method was CNY 0.51 billion, significantly higher than the temperature difference method at CNY 0.11 billion. The main reason for the differences between the two approaches is the uncertainty in cooling volume and cooling time for the temperature difference method and energy balance method, respectively. The impact of vegetation on the microclimate depends on the vegetation type, topography, local climate, and other factors. It is also important to note that cooling services are not required at all times of the day, and energy differences can hardly be calculated based on the hour. However, surface radiation and evapotranspiration generally occur during the daytime, which is also when the surface temperature is high. Therefore, there is a certain coincidence with the time when cooling is needed. The energy balance method presented herein provides a novel alternative approach to assessing the cooling services of local-scale forests, offering advantages over the commonly used temperature difference approach, which is associated with large uncertainty.

Keywords: cooling effects; ecosystem services; forest; Inner Mongolia

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1. Introduction

With the global mean air temperature expected to rise, increasing attention has been paid to the climate regulation services of forests. Trees and forests affect the climate through both biogeochemical and biophysical processes [1]. Biogeochemical processes indirectly alter temperature by affecting the atmospheric carbon dioxide (CO_2) concentration, which is known as global climate regulation [2]. The biophysical process affects local air temperature directly through evapotranspiration, surface albedo, and shading [3]. Forests' climate regulation services vary depending on geography, climate, and other factors [4]. Observations of 32 cities in China indicate that the cooling effect of forests is insensitive to precipitation changes above a certain threshold [5]. Moreover, studies by Yu et al. (2018) [6] suggested that local climate conditions can affect the cooling effect of landscape components and configurations. Therefore, to address climate change, we should implement more accurate assessments of climate regulation services according to local conditions.

As urban heat islands have become a typical climate phenomenon, cooling services of urban forests and other vegetation have been widely studied [7]. For instance, studies demonstrated that Europe's urban vegetation is responsible for reducing the air temperature by 1.1 °C [8]. Among these, landscape pattern [9], patch size [10], and patch shape [11] are the main influencing factors of urban vegetation cooling services. However, the cooling service of forests in rural areas has received fewer assessments, although rural agriculture may be vulnerable to local climate change [2]. The forest can provide climate regulation services for surrounding farmland. For example, hot summers can result in lower crop production. If there are forests nearby, this may reduce food losses. There is evidence that climate change could affect soil organic carbon (SOC), nitrate (NO_3^-), and albedo, leading to a decline in crop yields [12]. Thus, climate regulation services of forests in rural areas must also be addressed.

Various methods have been used to evaluate the cooling effect of forests according to different scales, including field measurements, weather monitoring, remote sensing, and model simulations [7,13]. Field measurements are generally based on flux towers or thermal infrared cameras [14], which can obtain more accurate air temperature data. Forest cooling effects at small scales, such as urban parks [15] and urban green space [16], are widely studied using this method. However, as field experiments are time-consuming and labor-intensive, it is difficult to capture temperature data on a larger scale. Aside from that, data from weather monitoring can be used to assess the cooling effect of forests. For instance, Sun et al. (2017) [2] used meteorological data to assess forest cooling services for the farming area and built-up area in Fanggan village. Compared to field experiment data, meteorological data have time continuity, which could span a longer time period [17]. However, due to the limited number of meteorological stations, air temperature data often lack spatial representation [18] and cannot provide sufficient detail for climate research [5]. With the development of remote sensing, land surface temperature (LST) data from remote sensing satellite imagery are often used to quantify local and global climate change [19,20]. Through repeated and consistent observations from satellites, we can investigate the local effects of forests from a regional or global perspective [1]. Moderate Resolution Imaging Spectroradiometer (MODIS) satellites provide a range of data products with different spatial and temporal resolutions, which are crucial for evaluating LSTs in different regions [21,22]. There is evidence that LST can simulate sensible heat flux but cannot capture latent heat flux [7], which may lead to controversial results when analyzing the cooling effects of forests or other vegetation [4]. Su et al. (2019) [23] proposed a three-layered (canopy, forest air space, and soil [CAS]) land surface energy balance model to simulate air temperature within forest spaces and evaluate its biophysical effects on forest cooling. In addition, the E3SM Land Model is a state-of-the-art fully coupled model of the Earth's climate that includes important biogeochemical and cryospheric processes. The Community Land Model is the land model for the Community Earth System Model (CESM), which represents several aspects of the land surface, including surface heterogeneity, and consists of components or submodels related to land biogeophysics, the hydrologic cycle, biogeochemistry, and so on. Nevertheless, relatively few studies have combined LST with energy balance to analyze the cooling service value of vegetation [24].

Several indicators and methods have been established to evaluate the value of forest ecosystems for climate regulation, including the expert knowledge-based method [25,26] and the alternative market approach [27,28]. Based on expert knowledge, Costanza et al. (1997) assessed the climate regulation service value of different ecosystems but found that it was not possible to separate cooling services from climate regulation services [25]. The alternative market approach is widely used to evaluate the value of forest cooling services. According to Ouyang et al. (2013) [29], plant transpiration can absorb heat and be converted into energy-saving potential (ESP), which can reflect the monetary value of ecosystem services. In addition, Zhang et al. (2014) [16] and Zhao et al. (2018) [30] calculated heat absorption by urban vegetation by assessing temperature reductions in the urban vegetation and the volume heat capacity of the air. However, the volume of air cooled by forests varies depending on various factors [31]. Additionally, it is difficult to analyze the actual cooling processes of forests, such as evapotranspiration, surface reflection, photosynthetic activity, and so on [32]. In order to calculate forest cooling values, energy balance models that have been developed and widely validated for heat mitigation mechanisms can be useful.

In this study, we used the energy balance method to calculate the cooling service value of forests in Inner Mongolia and compared it with empirical estimates developed by Yang et al. (1994) [33] and Zhang et al. (2014) [16]. This study aims to address the following questions: (1) In Inner Mongolia, which forest type provides better cooling? (2) How does the empirical temperature difference differ from the energy balance method?

2. Materials and Methods

2.1. Study Site

The study area is Inner Mongolia, located in northern China (37°24′–53°23′E, 97°12′–126°04′N). The topography is long and narrow, stretching from the northeast to the southwest. The region's climate changes from semi-humid to semi-arid and dry, with a temperate continental monsoon climate. There is a noticeable gradient difference in precipitation between the northeast and southwest, with an average rainfall of 150 mm. The main ecosystem types of this region are forests, grasslands, farmlands, and deserts (Figure 1).

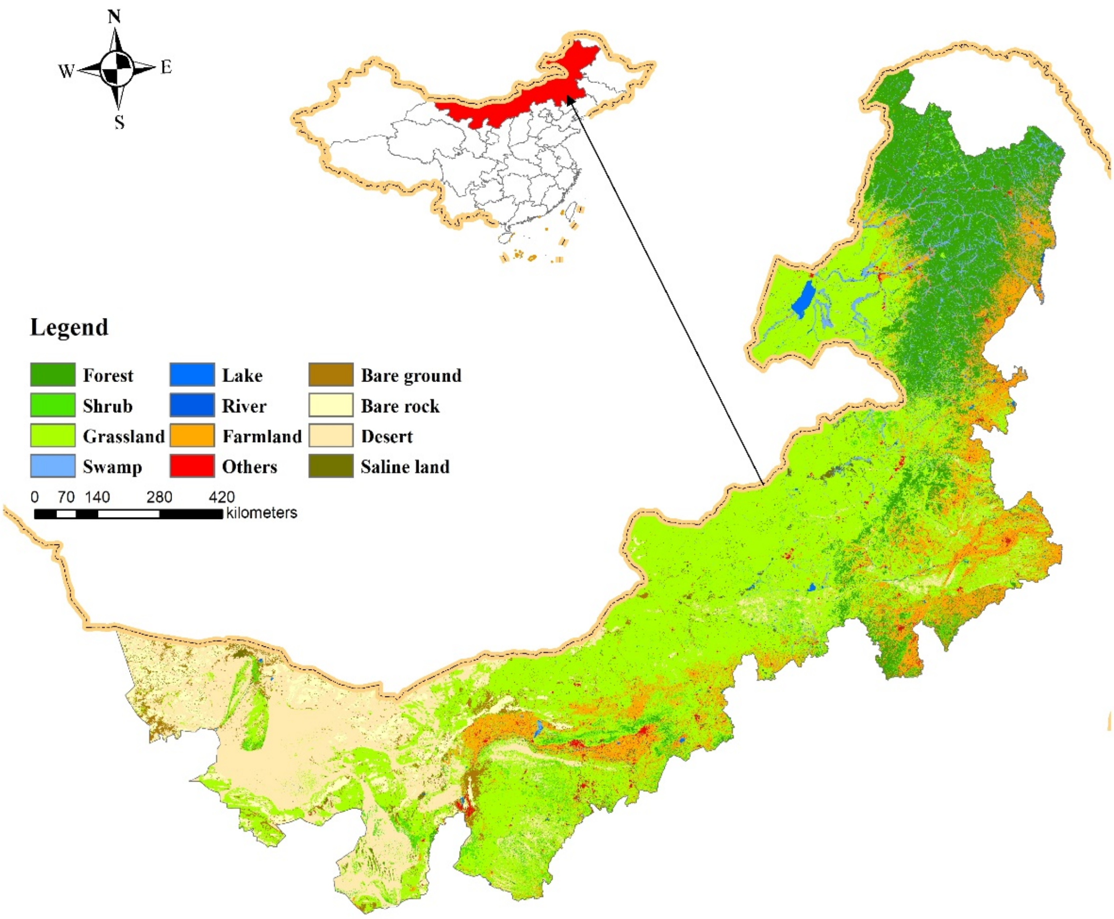

Figure 1. The location and land use of Inner Mongolia.

2.2. Input Data

We processed remote sensing spatial data on land use, LST data, net surface radiation, and monthly ET on the ArcGIS 10.6 platform (Esri, USA) for the analysis (Table 1).

Table 1. Sources of primary data.

Type of Data	Description of Data	Data Sources
Land use	This type includes cropland, forest, grassland, waters, construction, and unutilized land, with a spatial resolution of 30 m.	Resource and Environmental Sciences Data Center, Chinese Academy of Sciences (https://www.resdc.cn/ (accessed on 20 April 2024).
LST	A raster data set is retrieved from MOD11A1, with a spatial resolution of 1 km.	Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn (accessed on 3 February 2024).
Net surface radiation	A raster data set is derived from the National Earth System Science Data Center, with a spatial resolution of 1 km.	National Science and Technology Infrastructure of China (http://www.geodata.cn (accessed on 20 February 2024).
Monthly ET	Data for MODIS/006/MOD16A2, with a spatial resolution of 1 km.	From the National Aeronautics and Space Administration (NASA).

2.3. Research Methods

Figure 2 shows the flow chart of this study. In the first step, we extract data on land use to determine whether any forests or open lands exist. To screen control and experimental groups, the window searching strategy was employed. Using the temperature difference method (method 1), we compared LST between close cells, calculated their heat absorption difference, and converted it to electrical energy using Equation (1). The cooling service value was calculated using Equation (3).

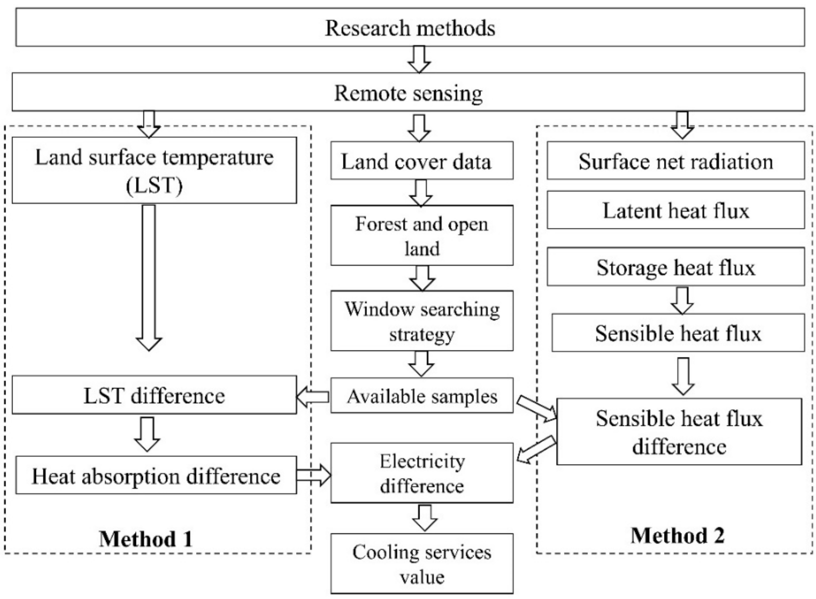

Figure 2. Study flow chart. Method 1 refers to temperature difference method; method 2 refers to energy balance method.

In the energy balance method (method 2), sensible heat flux between forest and nearby open land was compared. Using Equation (4), the sensible heat flux difference was converted into air conditioner energy savings. The cooling service value was calculated using Equation (3).

Window Searching Strategy

We compared land surface temperatures, surface net radiation, and other energy components across Inner Mongolia between forests and nearby open land (grassland and crops). As a proxy for non-forest land, open land represents the results of deforestation or lands suitable for afforestation or reforestation in the future. To find all available samples to compare forests with open land across the study area, we used a window searching strategy (Figure 3). In this study, surface temperature and other spatial data were processed with Python, including Rasterio, OS, Math, Pickle, Globe, and other native Python libraries. In order to read all the raster data, we created a step size of 3 times in the x-direction and 2 times in the y-direction.

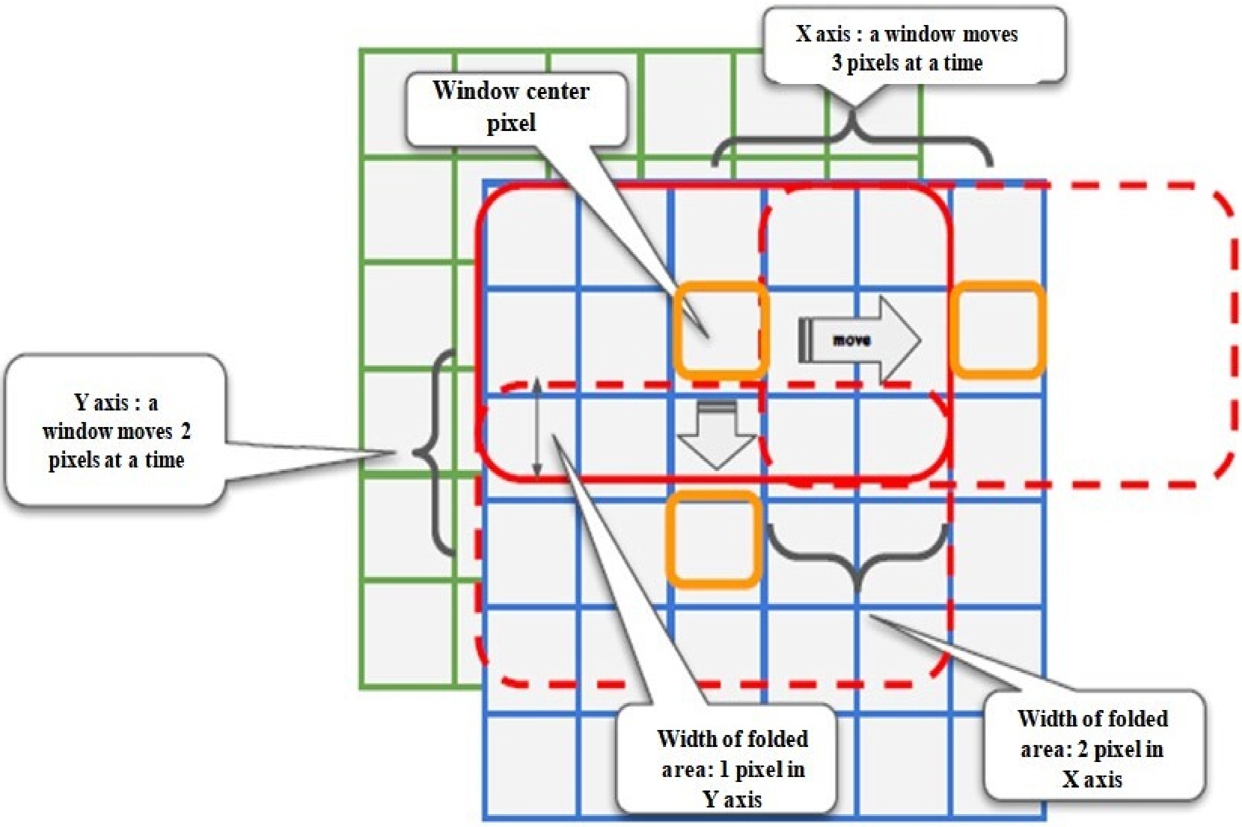

Figure 3. Schematic diagram of moving window method.

The search window size is 5 × 3 pixels (longitude × latitude), approximately equal to 5 × 3 km. Two adjacent windows are partially overlapping along both the longitudinal (3 pixels) and latitudinal (2 pixels) directions. Using this strategy, all nearby forests and open land that share similar climate background data were compared. Whenever both the forest and open land surfaces were greater than 0 in the same window, it was considered a staggered zone. We calculated the mean differences in land surface temperature and sensible heat flux in the staggered window. Data were excluded from sample plots with an altitude difference of more than 100 m compared to the control when considering the cooling effect of altitude.

2.4. Cooling Service Value Calculation

In this study, the temperature difference method (method 1) and energy balance method (method 2) were compared to calculate the cooling service value of forests in Inner Mongolia.

2.4.1. Temperature Difference Method

To calculate the heat absorbed by vegetation from the surrounding air, the empirical method proposed by Yang (1994) [33] is used to convert between temperature and heat. Based on his hypothesis, the mean height of the microclimate is 100 m, and the horizontal range is 10 m^2. Therefore, a theoretical air column with a 10 m^2 base and a height of 100 m could be considered a computational unit. In addition, the heat absorbed by vegetation (ΔQ) could be determined by temperature reduction (ΔT) and the volume heat capacity of the air (ρc) in Equation (1). Many studies have been conducted to assess the cooling service value of forests using the empirical model [16].

$$\Delta Q = \Delta T \times \rho c \times V_{air} \tag{1}$$

where ΔQ is the heat absorbed by vegetation, ΔT is the temperature reduction caused by vegetation, ρc is the volume heat capacity of the air, and V_{air} is the volume of air in the surrounding microclimate.

The difference in surface temperature between the paired forest and open land was calculated using the window searching strategy. The equation is as follows:

$$\Delta T = T_{forest} - T_{openland} \tag{2}$$

where ΔT is the land surface temperature difference between the paired forest and open land, T_{forest} is the land surface temperature of the forest, and $T_{openland}$ is the land surface temperature of open land.

An alternative method was used to calculate forest cooling service values. According to our hypothesis, forests are replaced by heat-absorbing air conditioners, so the forest's cooling value is equivalent to the air conditioning's electricity consumption:

$$V_{\text{forest}} = N_c \times E_C \times P \tag{3}$$

$$N_c = \Delta Q \div Qc \tag{4}$$

where V_{forest} is the cooling service value of the forest, N_c is the number of air conditioners needed to cool the air, E_C is the power consumption required for an air conditioner to work continuously for an hour, P is the electrovalence of the local area, and Qc is the heat absorbed by an air conditioner per hour.

2.4.2. Energy Balance Method

Land surface temperature changes are accompanied by variations in energy, particularly a reduction in the sensible heat fluxes (SHFs) [34,35]. Studies have shown that surface net radiation, storage heat flux, and latent heat flux are the main factors affecting surface temperature [1].

Sensible heat flux can be calculated based on the energy balance equation as follows:

$$Q_H = Q_{Rn} - Q_L - Q_S \tag{5}$$

where Q_H is the sensible heat flux of the ecosystem, Q_{Rn} is the net radiation of the ecosystem, Q_L is the latent heat flux, and Q_S is the storage heat flux. Due to the extremely low storage heat flux value, this indicator was not considered in the calculation.

The data on net radiation of the surface [36] are sourced from the National Earth System Science Data Center, National Science and Technology Infrastructure of China (http://www.geodata.cn (accessed on 20 February 2024).

$$Q_L = mr \tag{6}$$

where Q_L is the latent heat flux of the ecosystem, m is the mass of water vapor (kg), and r is the vaporization heat (kcal/kg).

The difference in sensible heat fluxes is accompanied by land surface temperature changes [37]. Therefore, we calculate the sensible heat flux difference between the paired forest and open land using the window searching strategy to assess the cooling service of the forest. The equation is as follows:

$$\Delta Q_H = Q_{Hforest} - Q_{Hbare} \tag{7}$$

where ΔQ_H is the sensible heat flux difference between the paired forest and open land, $Q_{Hforest}$ is the sensible heat fluxes of the forest, and Q_{Hbare} is the sensible heat fluxes of the open land. Forest cooling service values were calculated using Equations (3) and (4).

3. Results

3.1. Mapping LST and Heat Fluxes in Inner Mongolia

Remotely sensed LST is widely used for estimating surface heat fluxes at the regional scale in energy balance processes. The LST and heat fluxes have a strong spatial heterogeneity, which differed largely based on the land cover and geographical location. Figure 4 shows the distribution of mean LST and heat fluxes in Inner Mongolia from 2000 to 2015 in July. During the hottest period, the maximum LST ranged from 47.24 °C to 50.75 °C. The average temperature of the forest surface is 17.68 °C lower than the temperature of bare earth. The energy of surface net radiation (Q_{Rn}) shows a pattern of highs in the west and lows in the east. In the northwest, high values of Q_{Rn} can be found in forests with an average value of 21.6 MJ/m^2/day, while the low values can be found in deserts and grasslands with an average value of 20.9 MJ/m^2/day. Contrary to LST distributions, high-value areas of the evapotranspiration energy (Q_L) are concentrated in northeast Inner Mongolia, which mostly comprises forests and wetlands with average values of 7.1 MJ/m^2/day and 6.9 MJ/m^2/day, respectively, while open land only has an average value of 1.1 MJ/m^2/day. Sensible heat flux is higher in desert and open land, with average values of 21.8 and 21.5 MJ/m^2/day, respectively, while the lowest concentrations can be found in forests and wetlands, with 20.3 and 20.6 MJ/m^2/day, respectively.

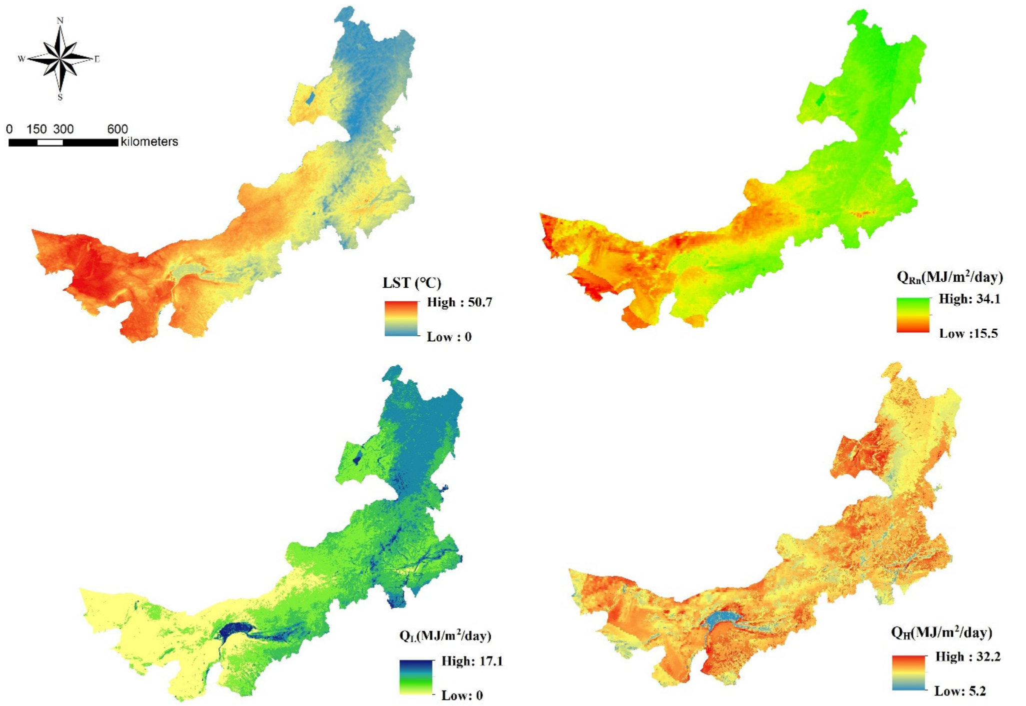

Figure 4. The average distribution of LST and heat fluxes in Inner Mongolia in July from 2000 to 2015. LST means land surface temperature; Q_{Rn} means the energy of surface net radiation; QL means the evapotranspiration energy; Q_H means the sensible heat flux of the ecosystem.

3.2. Forest Cooling Effect and Heat Fluxes

Based on the heat flux difference between forest and open land, the sensible heat flux difference is relatively small, whereas the latent heat flux difference is significant and is spatially similar to the cooling effect of forests (Figure 5). The cooling effect of forests varies depending on vegetation type. The average cooling temperature of broad-leaved forests is 0.229 °C, which is significantly higher than that of coniferous forests, 0.205 °C (Figure 6). The cooling effect of mixed coniferous and broad-leaved forests is not significantly different from that of other forest types. Similar spatial distributions can be observed for the cooling effect and the sensible heat flux difference. As for the sensible heat flux differences between forest types, the sensible heat flux difference in broad-leaved forests is 0.23 MJ/m^2/day, which is significantly higher than that of coniferous forests at 0.079 MJ/m^2/day and mixed coniferous–broad-leaved forests at 0.11 MJ/m^2/day (Figure 6).

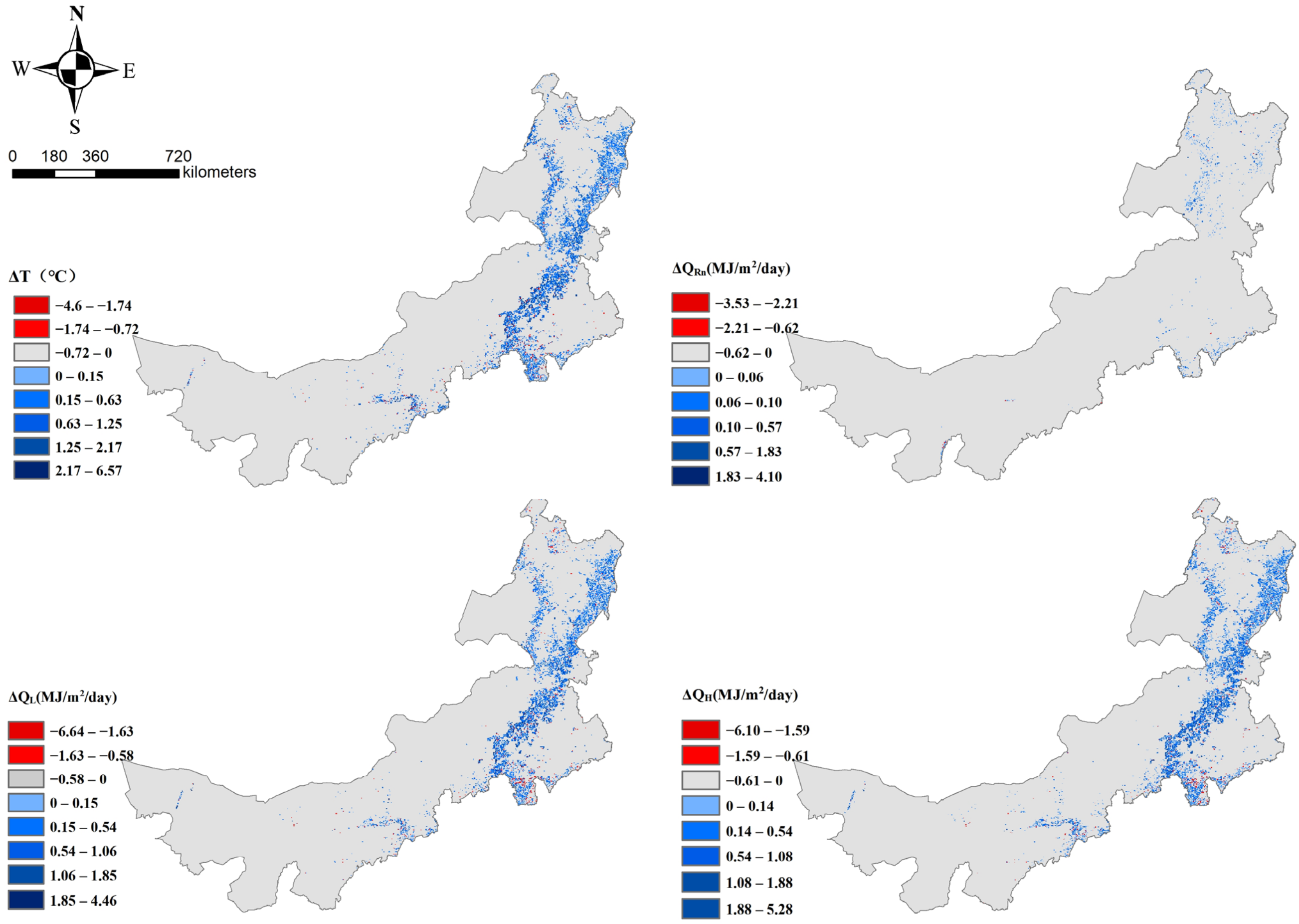

Figure 5. The difference in forest and open land's average long-term surface temperatures and heat flux in Inner Mongolia. ΔT means the difference in the forest and surrounding open land's average long-term surface temperatures in July between 2000 and 2015; ΔQ_{Rn} means the difference in the forest and surrounding open land's average long-term surface net radiation energy; ΔQ_L means the difference in the forest and surrounding open land's average long-term evapotranspiration energy; ΔQ_H means the difference in the forest and surrounding open land's average long-term sensible heat flux.

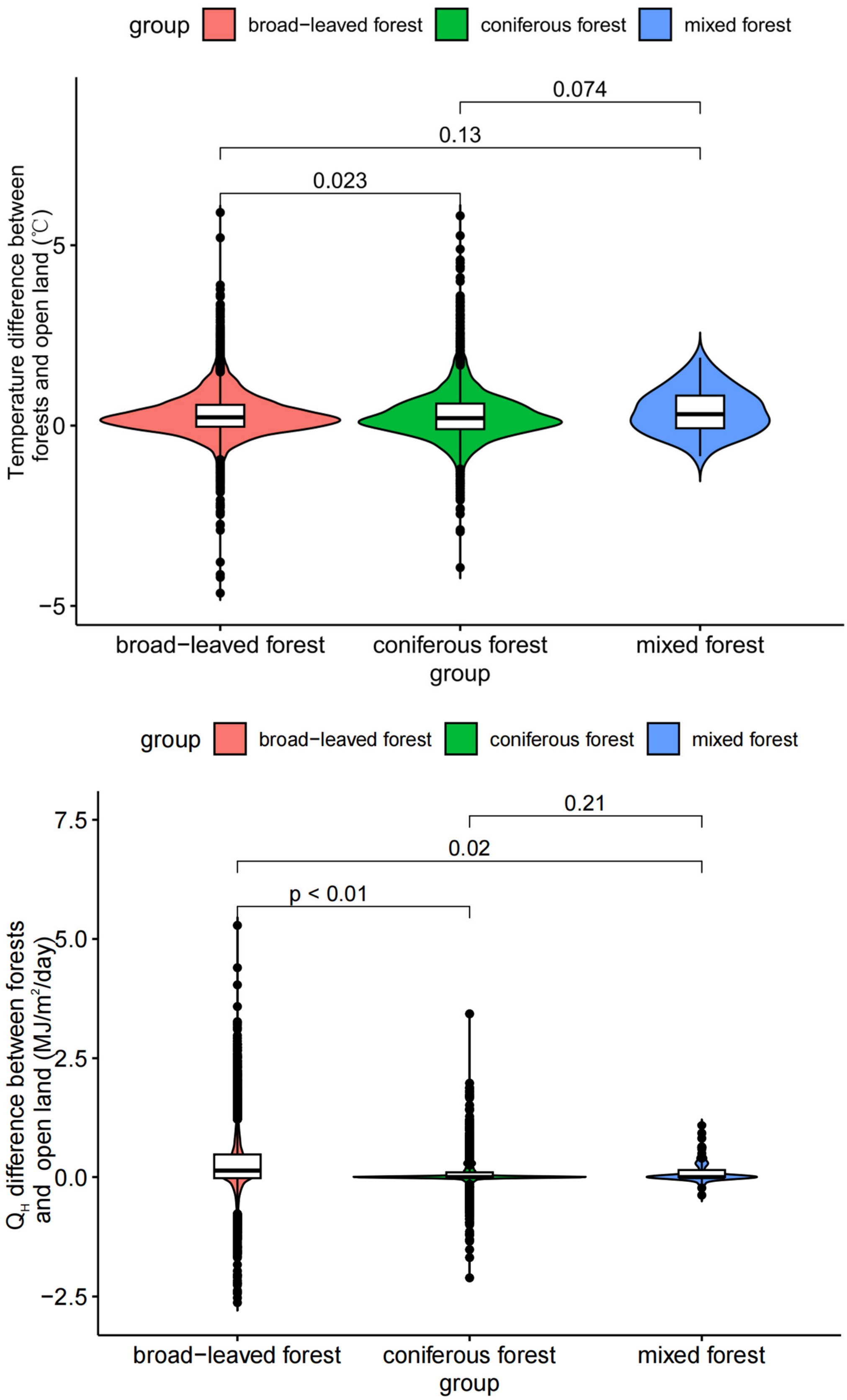

Figure 6. The average long-term differences in the cooling effect and sensible heat flux in different forest types in Inner Mongolia in July from 2000 to 2015. The cooling effect (°C) means the difference in the forest and surrounding open land's average long-term land surface temperature; the Q_H

difference (MJ/m^2/day) means the difference in the forest and surrounding open land's average long-term sensible heat flux in July from 2000 to 2015. The numbers on the graph indicate *p* values such as 0.023 and 0.13. A *p* value less than 0.05 indicates a significant difference between the two groups, and a *p* value less than 0.01 indicates an extremely significant difference.

The sensible heat flux (ΔQ_H) and latent heat flux (ΔQ_L) differences between the forest and open land are significantly correlated with their cooling effects. Similar correlations were found in broad-leaved, coniferous, and mixed forests. Therefore, the difference in surface energy significantly affects the cooling effect of the three forest types. Aside from sensible and latent heat flux differences, climate background, forest canopy structure, forest coverage, topography, and many other factors influence forest cooling. As a result, the R value is not very high, but it is statistically significant. Due to the small difference in net surface radiation between forest and open land, the difference in sensible heat flux depends primarily on the latent heat flux, indicating that the cooling effect is mainly determined by the difference in evapotranspiration between forest and open land. For coniferous, broad-leaved, and mixed forests, the correlation coefficient R for latent and sensible heat fluxes was 0.97, 0.95, and 0.97, respectively (Figure 7).

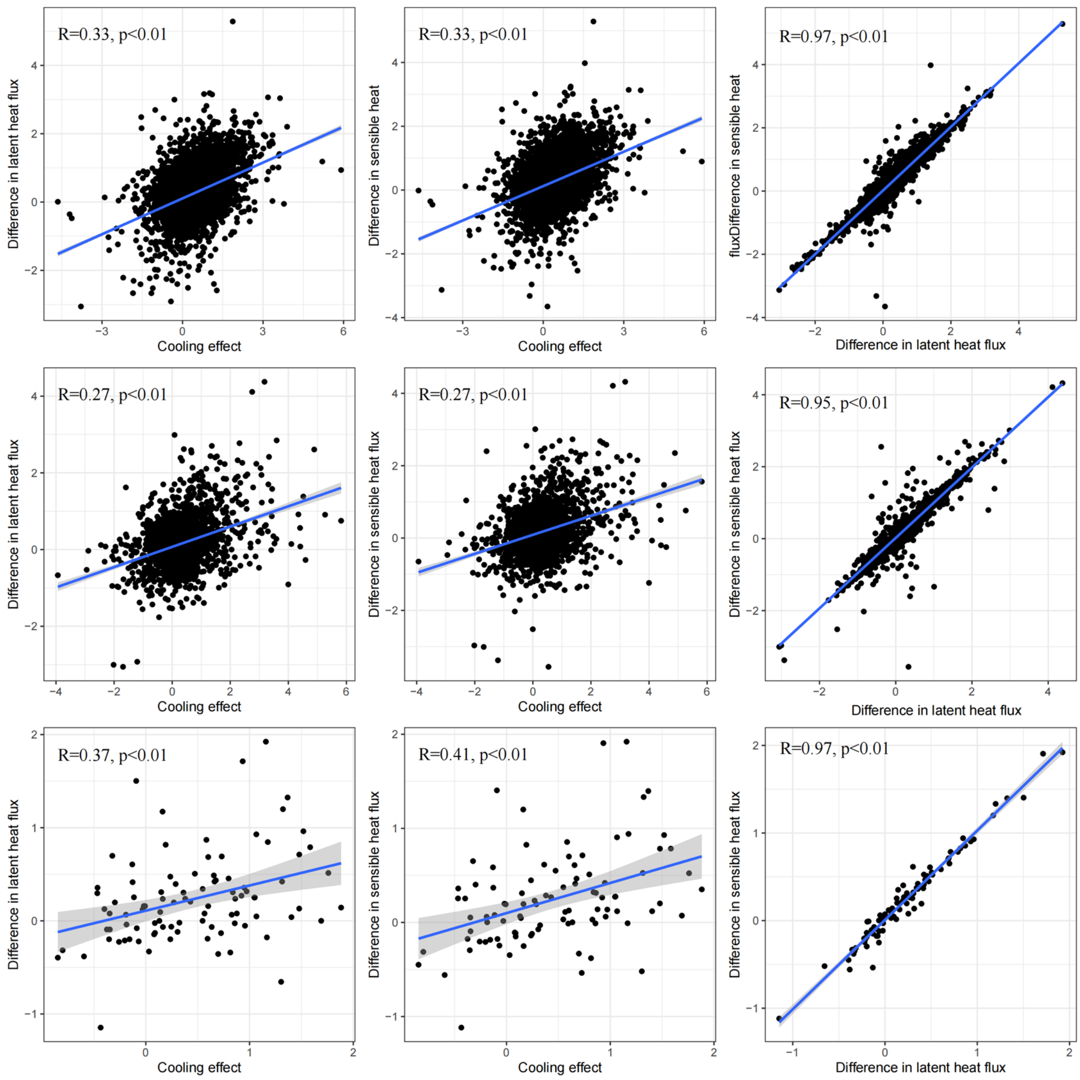

Figure 7. Correlation plots between cooling temperature, latent heat flux, and sensible heat flux for three types of forests in Inner Mongolia. The cooling effect (°C) means the difference in the forest and surrounding open land's average long-term land surface temperature; the difference in latent heat

flux (MJ/m^2/day) means the difference in the forest and surrounding open land's average long-term latent heat flux in July from 2000 to 2015. The difference in sensible heat flux (MJ/m^2/day) means the difference in the forest and surrounding open land's average long-term sensible heat flux in July from 2000 to 2015.

3.3. Cooling Service Value

3.3.1. Temperature Difference Method

Rising temperatures in the summer require people to consume more energy to maintain a comfortable environment. In this study, we assume that if the temperature exceeds 26 °C, humans require cooling, and the cooling effects of vegetation are therefore valuable. If it is lower than 26 °C, humans may not require cooling services. As a reference, the temperature of open land is used to measure the cooling effects of forests, while a reference temperature of 26 °C is used to determine whether the surrounding population requires cooling services.

Figure 8 shows the spatial interpolation results of the average daily cooling hours based on hourly temperature monitoring data collected from 116 meteorological stations in Inner Mongolia from July 2000 to July 2015. The cooling times vary, ranging from 1.82 to 7.76 h per day, unlike the constant value used in Zhang et al.'s study (2014) [16]. Since air temperature varies significantly with elevation, we removed plots and control data with altitudes greater than 100 m from the control set during plot screening.

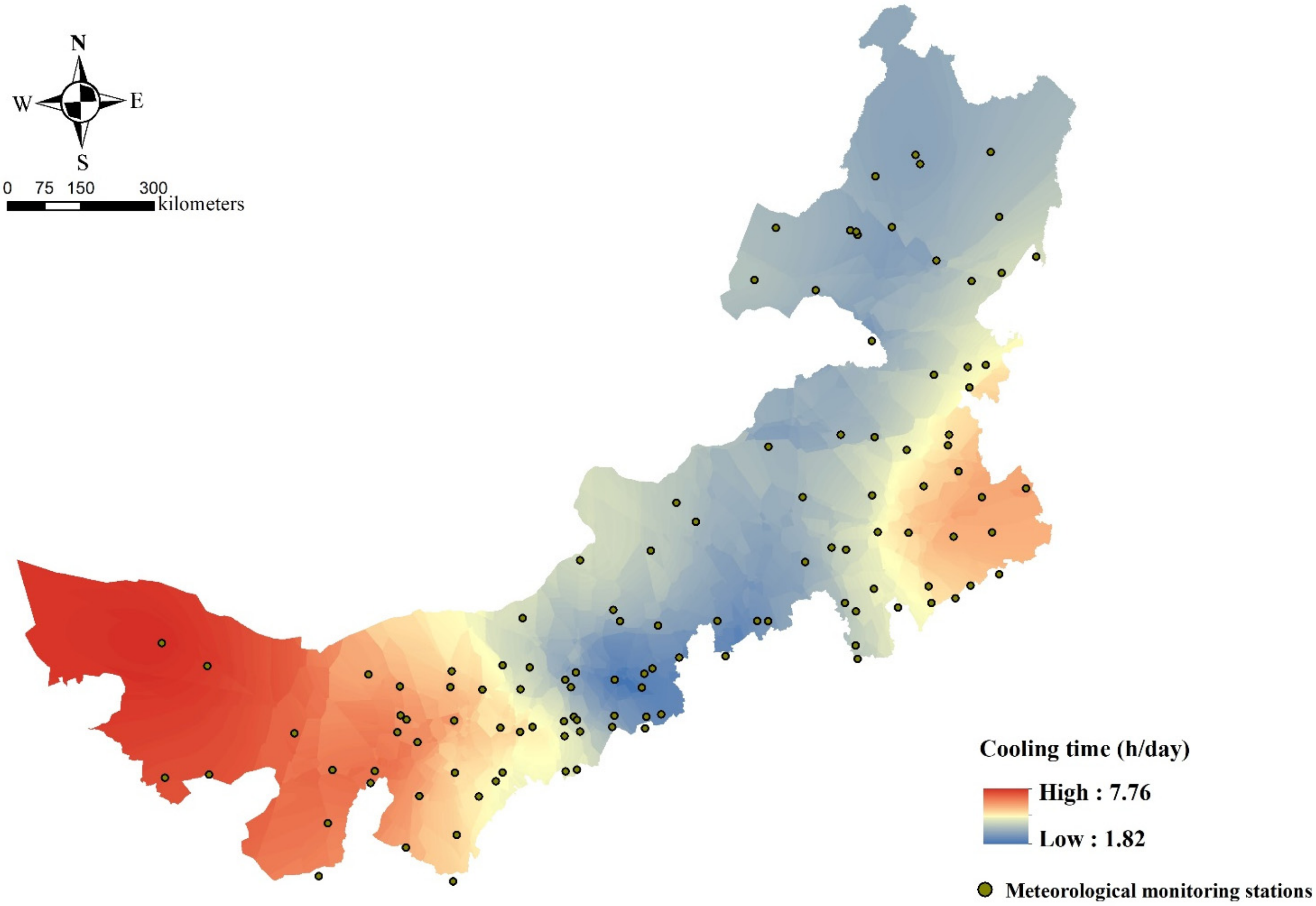

Figure 8. The average cooling length (in hours) per day in Inner Mongolia in July from 2000 to 2015.

According to the empirical method proposed by Yang et al. (1994), the microclimate of 1 m^2 of vegetation covers a base area of 10 m^2 and reaches a height of 100 m [33]. Therefore, 1 m^2 of vegetation will affect 1000 m^3 of the microclimate. In Inner Mongolia, forest patches are very large, and the forest microclimates overlap. It would be unreasonable to expand the range of horizontal microclimate based on Yang's method. Therefore, we assume that the forest area is the horizontal microclimate's influence range.

Forest cooling effects vary greatly depending on factors such as forest type, local climate, etc. We calculated the land surface temperature difference between paired forests and open land and the energy-saving cost using formulas 3 and 4 in Section 2.4.1. The total cooling value is CNY 0.11 billion in Inner Mongolia (Figure 8). If the cooling days are calculated based on 90 summer days, the average energy savings of the study area are 1768.7 kWh/(ha·a). This is based on the results of Jim and Chen's (2009) study in Beijing (1400 kWh/ha) [38], Nowak and colleagues' (2006) [39] study in Minneapolis (1111 kWh/ha), and Zhao et al.'s (2019) [30] study in Xiamen (949.30 kWh/ha). The average cooling effect of forests in Inner Mongolia is higher than that of Beijing, Xiamen, and Minneapolis because Inner Mongolia has an arid and semi-arid climate and lower rainfall, which leads to a large difference in evapotranspiration between the forest and open land. Furthermore, many studies have found that heat mitigation strategies by increasing green coverage were more effective in arid areas.

3.3.2. Energy Balance Method

The sensible heat flux is mainly determined by surface net radiation, latent heat flux, and soil heat flux. The difference in sensible heat flux between forest and open land represents the energy difference in the cooling service of the forest. Because the net radiation difference between forest and open land is small (Figure 5) and soil heat fluxes are extremely low, the difference in sensible heat flux is mostly determined by surface evapotranspiration. In addition, different forest types exhibit a similar pattern. There was a significant correlation between the sensible and latent heat flux differences between coniferous forest (CF), broad-leaved forest (BF), mixed coniferous and broad-leaved forest (CBF), and open land, with $R > 0.95$, $p < 0.001$ (Figure 7). According to the energy balance method, the average cooling service values of CF, BF, and CBF are 0.0055, 0.0143, and 0.0056 CNY/m^2/day, respectively (Figures 9 and 10). The total cooling value is CNY 0.51 billion. Compared with the temperature difference method, it has similar distribution characteristics in space, but the unit area values of CF, BF, and CBF are 64.1%, 102.1%, and 15.4% higher than those for the temperature difference method, respectively.

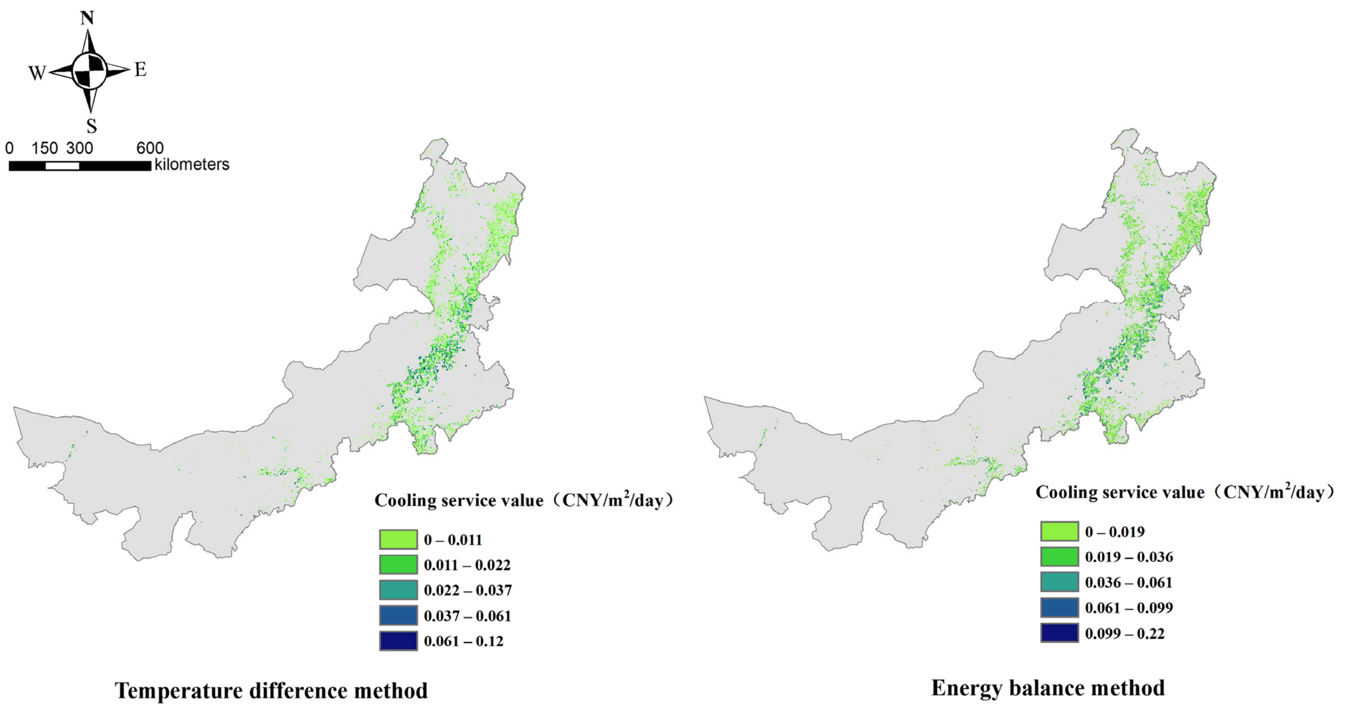

Figure 9. Forest cooling service value maps using the two methods in Inner Mongolia.

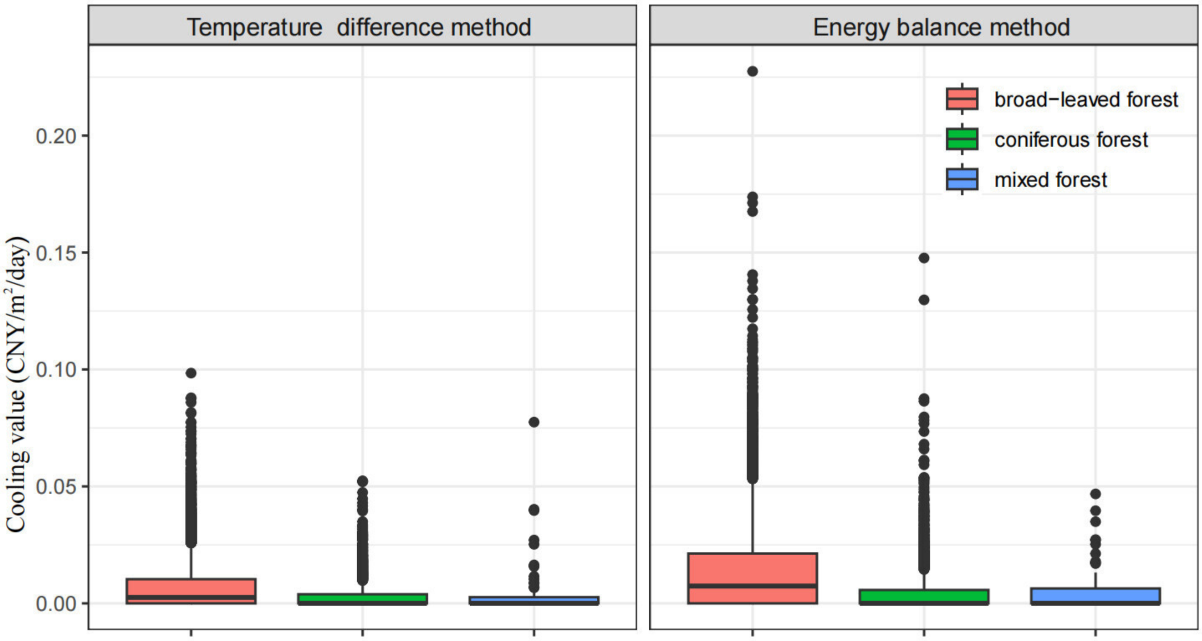

Figure 10. The cooling value of different forest types using the two methods in Inner Mongolia in July from 2000 to 2015.

4. Discussion

The estimated cooling service values of forests vary when different methods are used. Previous studies have used the heat absorbed by vegetation transpiration as the cooling effect of vegetation and converted the heat into the power consumption of air conditioners to calculate the cooling service value of vegetation [29]. However, key indicators that may affect cooling services were not considered in these studies, such as albedo and net surface radiation. In contrast to open land, forests have a lower surface albedo, which could absorb more shortwave radiation during the day, resulting in a warming effect. Meanwhile, the warming effect is offset by increased evapotranspiration, causing a cooling effect [1]. It has been demonstrated that higher evaporation in tropical regions can offset the impact of low forest surface albedo and has a significant cooling effect; an increased vegetation cover in frigid regions will increase surface temperatures to a certain extent [40]; and due to large differences in vegetation evaporation in temperate regions, the role of vegetation in regulating climate is still controversial [41]. Therefore, net surface radiation and evapotranspiration should be considered during the cooling value assessment. The limitation of the energy balance method is that the calculated energy difference between the net radiative and latent heat fluxes at the surface is in terms of days and cannot be refined to the hour. However, cooling services are not required at all times of the day, as shown in Figure 7, where the average daily cooling time in Inner Mongolia ranges from 1.82 to 7.76 h/day. Calculating the cooling value based on the daily energy difference may lead to overestimating the results. Nevertheless, the surface radiation and evapotranspiration processes generally occur during the daytime, which is also when the surface temperature is high, and there is a certain kind of coincidence with the time when cooling is needed.

Regarding the temperature difference method, Yang (1994) proposed an empirical method to convert between temperature and heat [33]. He hypothesized that one square meter of vegetation has a microclimate impact range of 10 square meters and that city buildings have an average height of 100 m. In this case, a theoretical air column with a base area of 10 m^2 and a height of 100 m was used as a computational unit. This 1000 m^3 air column's net reduction in heat flux from surface radiation and evapotranspiration might reduce surrounding air temperature ΔT. However, the cooling effect of vegetation varies based on its location, size, and spatial configuration [42]. According to Lee et al. (2009), the cooling radius of a park in the CBD of Seoul is 240 m [43]. Lin et al. (2015) analyzed

Landsat TM/ETM+ images of 24 parks in Beijing and revealed that cooling effects extend from 35 m to 840 m [44]. The areas of the park are closely related to its cooling extent. The threshold distance from urban forests in Seoul for the cooling effect was estimated to be roughly up to 300 m [43]. Due to uncertainty in the extent of the cooling effect, using the temperature difference method may result in deviations in the assessment of forest cooling services. Thus, assessing the actual cooling effects of the forest is crucial in understanding the forest's role in mitigating local heat waves.

Based on the comparison of the two methods, it was found that the forest cooling service value calculated by the energy balance method differs from the temperature difference method, primarily because of the uncertainty in the cooling volume in the temperature difference method. In this study, the expansion of forest microclimate on a horizontal plane was not considered due to the continuous distribution of plots. According to Yang et al. (1994), the microclimate height is 100 m, but the actual impact height depends on many factors such as vegetation, topography, etc. [33].

A significant limitation of the window searching method used in this study is that it can only calculate the cooling effects of forests with open land controls within a 5 km range, and there is no suitable open land around a considerable part of the forest. It has been shown that open land evapotranspiration is highly dependent on rainfall, temperature, wind speed, etc. In the future, the open land evapotranspiration and sensible heat flux can be predicted by meteorological factors such as rainfall, temperature, wind speed, etc. The cooling effect of all forests can be estimated via the simulation of evapotranspiration and sensible heat flux of open land.

5. Conclusions

A new method was used to assess the value of local-scale forest cooling services. The window searching method was used to obtain the surface net radiation and evapotranspiration of forest and open land in the window intersection area and calculate sensible heat flux differences. The cooling service value of the forest was calculated by using the substitution cost method of air conditioner cooling. In this method, the net surface radiation is added to the vegetation transpiration cooling method [29] to make it more consistent with the energy balance equation. The energy balance method avoids the microclimate volume uncertainty problem of the cooling value method. In this study, broad-leaved forests exhibited better cooling effects than coniferous forests, but the cooling effect of mixed coniferous and broad-leaved forests is not significantly different from that of other forest types. Further research should evaluate the cooling value of forests across a larger area by simulating evapotranspiration and sensible heat flux on open land using topographic and meteorological data without open land controls. The energy balance method is a useful tool for assessing the cooling service of local-scale forests.

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