Carbon savings resulting from the cooling effect of green areas: A case study in Beijing

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A R T I C L E   I N F O

Article history:
Received 14 August 2010
Received in revised form 2 February 2011
Accepted 24 February 2011

Keywords:
Carbon savings
Cooling effect
Green areas
Beijing

A B S T R A C T

Green areas cool the climate of a city, reduce the energy consumption caused by the urban heat island (UHI) effect, and bring along carbon savings. However, the calculation of carbon savings due to the cooling effect of green areas is still not well understood. We have used a Landsat Enhanced Thematic Mapper Plus (ETM+) image of Beijing, to identify the cooled areas, compute the possible energy used to maintain the temperature differences between cooled areas and their surrounding heated areas, and calculate the carbon savings owing to the avoidance of energy use. Results show that a total amount of 14315.37 tons carbon savings was achieved in the study area and the amount was related to the biomass, the size and the shape of green areas. These results demonstrate the importance of carbon savings resulting from green areas’ cooling effect.

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1. Introduction

Increase in atmospheric temperature is thought by many to be resulted from increased atmospheric carbon dioxide (CO₂), which is largely attributable to fossil fuel combustion (about 75 percent) (McPherson et al., 1994). About two-thirds of the world’s total electric power is generated from fossil fuels (Dresselhaus and Thomas, 2001), of which about one-sixth is used to air-conditioning buildings in the United States. Of this one-sixth electricity, about half is used in cities classified as “heat islands” (Akbari, 2002). For example, Akbari et al. (1992) reported that 1 °C increase in temperature would increase peak electricity demand by 2–4% when temperature exceeded 15–20 °C. The same phenomenon occurred in China. According to the calculation of Beijing Electric Power Corporation, Beijing’s summer air-conditioning peak demand accounted for 40 percent of the total peak electricity load (Beijing Municipal Commission of Development and Reform, 2006). Air-conditioning demand is higher in urban areas than in the surrounding suburbs because temperature in urban areas is usually much higher than that of suburbs. Therefore, the cooling effect of urban green areas will decrease the emission of atmospheric CO₂.

In reducing atmospheric CO₂, urban green areas offer double benefits. First, trees in green areas directly sequester and store atmospheric carbon. Second, green areas cool local urban areas by trees’ transpiration and shade, reducing air-conditioning energy use and avoiding carbon emission, that is, carbon savings. Rosenfeld et al. (1995) estimated that 27 million tons of carbon emission reduction would be achieved if 20% of air-conditioning could be avoided in all US cities by cool surfaces and tree shade. US Environmental Protection Agency (EPA) (2008) recommended increasing the percentage of vegetated area as a common mitigation strategy of UHI. Rowntree et al. (1982) estimated that about 25–50% of the increased temperature attributed to urban heat island (UHI) could be mitigated via vegetation. Nowak (1993) estimated that carbon emissions avoided annually due to energy conservation from existing trees throughout the city of Chicago and the Chicago area of Cook and Dupage counties was approximately 12,600 tons. However, few studies have attempted to calculate the carbon savings resulting from the cooling effect of green areas on the park scale as a whole, which covers green areas and their surroundings. Only a few experimental investigations were performed on the carbon emission avoided of one or several trees (Akbari, 2002; Jo and McPherson, 2001), and the carbon savings that resulted from green areas’ cooling effect still remains unclear.

This paper provides an alternative holistic method, which is different from the method of measuring single trees and then by accumulation calculating the carbon savings resulted from urban
green areas’ cooling effect. Though urban green areas offer the double benefits of direct carbon storage and indirect carbon savings, the latter is the main concern of this paper.

Because the cooling extent of a green area goes beyond its boundary, and extends into its surrounding areas (Jauregui, 1991; Oke, 1982; Upmanis et al., 1998), calculation of the carbon savings caused by green areas’ cooling effect should not only take into account the green areas themselves, but also their extended cooled areas. By using ETM+, we first identified the cooled areas resulted from urban green areas’ cooling effect based on the land surface temperature (LST). The cooled areas consist of green areas and their extended cooled areas. Then we calculated the energy that would be used to maintain the temperature differences between the cooled areas and their surrounding urban heated areas. Finally, we calculated the avoided carbon emissions by accumulating the energy conservation of unit green areas to get the total carbon savings.

Furthermore, green areas’ cooling extent is influenced by both the characteristics of the green area itself, such as its quality, size and shape, and those of the surrounding area, such as building density and height, and street direction (Lee et al., 2009; Upmanis et al., 1998). It is essential to identify the relation of carbon savings with these factors. However, until now few investigations have been made to reveal these relations.

To investigate what factors affected the magnitude of carbon savings, we systematically analyzed the relationship between carbon savings and the characteristics of green areas, such as biomass, size and shape. These factors affect the green area’s cooling effect and will also alter the amount of carbon savings. The results showed that there were significant correlations between carbon savings and the above-mentioned factors, which demonstrated: (1) more biomass would achieve better cooling effect and more carbon savings; (2) more small green areas would be better than fewer large green areas under the same sum of size; and (3) green areas of complicated shapes would perform better than simple-shaped ones of the same size.

This paper is organized into the following three sections. In Section 1, the study area and the methods are introduced, by which step-by-step calculation is outlined. The amount of carbon savings of the study area and its relation with the green areas’ characteristics are demonstrated in Section 2, and the results of carbon savings are analyzed and discussed in Section 3.

2. Study area and methods

2.1. Study area

Beijing (39°54′N, 116°23′E) is a metropolis located at the North China Plain. A branch range of the Tai-hang Mountains runs to the west of the city and the Yan-shan Mountains to the north. In 2009, Beijing’s residential population reached 17.55 million (Beijing Municipal Bureau of Statistics, 2010), with the population density being 1069 per km². Our study area covers 2268.89 km², whose boundary roughly coincides with the city’s 6th Ring Road (Fig. 1). Urban built-up areas, green belts, agricultural land, and water bodies are included in the study. According to official statistics, during the past ten years, the monthly mean temperature of the study area has been 21.3 °C in September, while the amounts of evaporation and precipitation have been 194.9 mm and 316.5 mm respectively.

2.2. Methods

2.2.1. Data preparation

First, land surface temperature was retrieved with moniwindow algorithm (as shown in the following equation) (Qin et al., 2001), and relevant parameters calibrated.

\[
T_s = \frac{a(1-C-D) + (b(1-C-D) + C + D)T_6 - DT_a)}{C} \quad (1)
\]

\[
C = \tau \epsilon \quad (2)
\]

\[
D = (1 - \tau)[1 + \tau(1 - \epsilon)] \quad (3)
\]

where \(T_a\) is the average atmospheric effect temperature, \(\tau\) is atmospheric transmission ratio, and \(\epsilon\) is land surface emissivity. We had \(T_a = 286.418\) K, \(\tau = 0.806903836\), and the land surface emissivity values of different underlying surface categories were as

Fig. 1. Location of Study Area.
2.2.2. Determine green area

Area Map of the Central City

satellite images of the study area according to reservoir and its surrounding catch basin. GAs were demarcated on underlying surfaces, ECAs were in fact the collecting areas around cores on the land surface, depending on different natures of the area (ECA) around GA. As GAs would form the lower-temperature MNDWI < 0.986 (Qin et al., 2001).

\[ \text{NDVI} = \frac{(\rho_{\text{NIR}} - \rho_{\text{Red}})}{(\rho_{\text{NIR}} + \rho_{\text{Red}})} \]  

where \( \rho_{\text{NIR}} \) is the reflection value of wave band TM4, and wave band TM3's is denoted by \( \rho_{\text{Red}} \); and

\[ \text{MNDWI} = \frac{(\rho_{\text{Green}} - \rho_{\text{MIR}})}{(\rho_{\text{Green}} + \rho_{\text{MIR}})} \]  

where \( \rho_{\text{Green}} \) is the reflected value of Green-light wave band, and \( \rho_{\text{MIR}} \) is that of mid-infrared wave band. We classified land cover based on the values of NDVI and MNDWI (Pixels with NDVI > 0.157 were treated as vegetation, while whose NDVI < 0.157 were divided into water bodies with MNDWI ≥ 0, and buildings with MNDWI < 0).

2.2.2. Determine green area's cooling extent

Green area's cooling extent consists of two types of “sub-region-s”—one is green area (GA) itself, and the other is extended cooled area (ECA) around GA. As GAs would form the lower-temperature cores on the land surface, depending on different natures of the underlying surfaces, ECAs were in fact the collecting areas around GAs, or if described metaphorically such structure is analogous to the reservoir and its surrounding catch basin. GAs were demarcated on satellite images of the study area according to “the Present Green Area Map of the Central City” in the Master Plan for Beijing. In the meantime, ECAs were delineated by determining the catch basins of GAs on the land surface temperature map of the study area.

2.2.3. Calculate the possible energy used (energy conservation) to maintain the temperature differences

The temperature of a GA and its ECA is lower than their surrounding urban heated areas because of tree shade and evapotranspiration in the GA. To maintain these temperature differences, how much energy may possibly be used?

To calculate roughly the possible energy used to maintain the temperature differences, an ideal cylindrical model is established as follows (Fig. 2): imagine GA is a round-shaped zone, and its ECA forms an outer ring-shaped area surrounding GA. The latter's land surface temperature is lower than built-up areas. Starting from the centre of GA, land surface temperature increases roughly in a linear fashion outwards. Temperature differences start to disappear when reaching the outer edge of the ECA. If viewed from a vertical angle, when reaching the upper limit of the influence sphere of GA, the temperature difference will disappear accordingly.

To calculate the amount of energy needed to sustain the temperature difference of such a cylindrical area, integral method was used as shown in the following equation:

\[ Q = Q_{\text{GA}} + Q_{\text{ECA}} = C_p \rho \left( \int_0^{r_1} \int_0^H 2\pi \nabla T \, dh \int_{r_1}^{r_2} 2\pi \nabla T \, dr \right) \]

where \( C_p \) stands for specific heat under constant air pressure with a value of 1004.68 J kg\(^{-1}\) K\(^{-1}\), air density \( \rho = 1.2923 \text{ kg m}^{-3} \), vertical influence sphere of lower-temperature zone \( H = 70 \text{ m} \), temperature gradient \( \nabla T = \Delta T / \Delta r \), \( r_1 \) the radius of the cylindrical bottom surface (size equal to GA), and \( r_2 \) the radius of the bottom surface of the hollow cylindrical area (size equal to ECA).

2.2.4. Carbon savings and influencing factors

Urban GAs play the same role as the functioning of air-conditioner. Hence, the energy consumed by air-conditioners can be reduced or avoided by GA's trees shade and evapotranspiration. If the same effect is to be realized by employing electric measures, the amount of CO\(_2\) to be generated when producing the needed energy for air-conditioning will be just equivalent to what is to be saved by the GAs. Because vegetation can achieve the same cooling effect through its bio-chemical processes, the zero-consumption of electric energy will make CO\(_2\) emissions from power generation avoidable.

The amount of atmospheric CO\(_2\) emission of per unit energy (power) generation varies in different countries. In 2008, China's CO\(_2\) emission rate of coal-fired power was 863 g/kW h. According to
the Comparative Carbon Dioxide Emissions from Power Generation (World Nuclear Association), CO₂ emission rate of coal-fired power in the UK was 891 g/kWh in the year of 2006. The value of 863 g/kWh was used in our study to estimate carbon savings owing to the cooling effect of green areas on air-conditioning energy use by the assumption that the thermal power was generated by coal. Carbon savings was calculated by the avoided energy multiplying China’s CO₂ emission rate of coal-fired power.

Through statistical analysis, attempts were made to identify the main factors that might influence the carbon saving effect of GAs. These factors included: size, shape and biomass. Among them, the biomass factor was represented by the NDVI index. The shape index (SI) of GA was calculated by the ratio of its perimeter to area size.

By respectively analyzing the above characteristics of GAs and ECAs, we discovered not only the main characteristics that had affected the cooling effect of GAs, but also how and to what extent they had done so.

3. Results

3.1. Total amount of carbon savings

Total amount of carbon savings is the sum of carbon savings of each GA. Firstly we substituted the bottom surface radius and temperature gradient of the GA cylinder and those of ECA into the above Equation (6), and obtained the amount of energy used to maintain the temperature differences by each GA. Secondly, we added up the amount of energy of each GA in the study area, and obtained the total amount as 5.97 × 10¹⁰ kJ, which was equal to 16.59 MKWh.

If using electric equipment to replace GAs, the projected amount of CO₂ emission to achieve the above temperature differences would be 14,315.37 tons. Thus it could be seen that, in order to sustain a lower-temperature zone within the study area, when comparing the functioning of GAs’ cooling effect with artificial refrigeration, the former would not only save 16.59 MKWh of electric power, but also reduce 14,315.37 tons of CO₂ emission.

3.2. Relationship between carbon savings and NDVI (biomass)

NDVI is an indicator of a GA’s biomass. We first used all the GA samples to obtain the relationship between carbon savings and NDVI, and found that they seemed to be unrelated. After further analysis, we realized that the relation might be concealed by location and factors of size and shape, which should have been excluded in this process. Hence, we selected those GAs at almost the same location and with almost the same size and shape index, performed the regression analysis again, and found that there really existed a relationship between carbon savings and NDVI. Fig. 3 shows that carbon savings of GAs increases with the increasing NDVI by Equation (7). However, because it was difficult to find more samples at almost the same location and with almost the same size and shape, more general equation could not be concluded from our current investigation.

\[
Y = 15.14 X - 2.225 \quad (R^2 = 0.545) \quad (7)
\]

3.3. Relationship between carbon savings and size

3.3.1. Relationship between carbon savings and size of GA

Fig. 4 shows that both carbon saving amounts of GA and ECA change with respect to their size statistically. Fig. 4a demonstrates the relationship between amount of carbon savings and size of GAs by Equation (8). This result shows that carbon saving amount of GA is directly and significantly related to GA size. The slope of the trend line in Fig. 4a is steeper than that of Fig. 4b, which implies that an...
increase in the size of GA itself would have a bigger effect for carbon savings than the same size-increase in its ECA.

\[
Y = 75.80 - 1.679(X) \quad (R^2 = 0.992) \\
Y = 34.99 - 1.93(X) \quad (R^2 = 0.954)
\]

3.3.2. Relationship between carbon savings of ECA and size of GA

Fig. 4b illustrates similar relationship between amount of ECA carbon saving and GA size by Equation (9), showing that GA size has direct and significant influence on amount of ECA carbon saving. Fig. 5 shows that per unit-area carbon saving amount of ECA decreases with the increase in the size of GA, i.e. as far as the carbon savings of ECA is concerned, when the total GA sizes are equal, the effect of more small-size GAs will be superior to that of fewer large-size ones.

The scatter graph in Fig. 5 also depicts that when the size of a GA was smaller than 0.1 km², per unit ECA carbon savings will decline significantly with the increase of GA’s size; and while the GA’s size is larger than 0.10 km², changes in the per unit ECA’s carbon saving amount will not be that evident.

\[
Y = -14.1\ln(X) + 26.39 \quad (R^2 = 0.425)
\]

3.4. Relationship between carbon savings and shape

3.4.1. Relationship between carbon savings and shape of GA

To eliminate the influence of GA size on the relationship between carbon savings and GA shape, we used the factor of per unit-area carbon savings amount of GA and ECA instead of total carbon savings amount of GA and ECA to delineate the relation. Fig. 6 shows that GA’s per unit-area carbon savings decreases slowly with increasing of GA shape index by Equation (11), illustrating that shape index does have an effect on per unit-area carbon savings amount of GA, but its impact strength is relatively weak if compared with GA size.

\[
Y = -0.01\ln(X) + 0.006 \quad (R^2 = 0.167)
\]

3.4.2. Relationship between carbon savings of ECA and shape of GA

ECA’s carbon savings of per unit GA increases together with the increase of GAs’ shape indices—although such a positive correlation was not marked. The scatter graph in Fig. 7 depicts the relationship between GA’s shape index and ECA’s carbon savings of per unit GA. Results show that when a GA’s shape index is smaller than 0.055, the distribution of dots representing ECAs’ carbon saving amount is comparatively converging—as a result of shape changes; and while SI is larger than 0.055, the dots will show a dispersing trend, which is to say, when the shape of GA tends to be quite irregular, factors influencing its ECA’s carbon savings will be plural, and the shape index of GA alone—as a single factor—can no longer fully express its ECA’s carbon-saving effect.

\[
Y = -0.625X^{0.730} \quad (R^2 = 0.133)
\]

4. Discussion

4.1. Total amount of energy conservation

To maintain the temperature difference between the GAs’ cooled areas and their surrounding heated areas, the possible energy conservation by GAs is estimated to be $5.97 \times 10^{10}$ kJ. This

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Fig. 5. Relationship between GA’s size and per unit-area carbon saving amount of ECA.

Fig. 6. Relationship between GA’s shape index and its per unit-area carbon saving amount.

Fig. 7. Relationship between GA’s shape index and ECA’s carbon saving amount of per unit GA.
value is in line with previous studies conducted via other methods. For example, Chen et al. (1998) gave a value of $1.07 \times 10^{14}$ kJ per year for green areas’ transpiration cooling in Beijing’s built-up areas, which yielded $2.94 \times 10^{14}$ kJ per day. Our values are in the same order of magnitude as previous studies. In addition, when considering more evapotranspiration in the warm months than in the cold months of a year, the predicted value by Chen et al. should be greater and closer to our results.

When using electric facilities, it will consume 16.59 MKWh of electric energy to dissipate this amount of heat. Because there is no direct data on Beijing’s carbon emissions, we use instead electricity consumption to estimate the contribution of GAs’ carbon savings. In the year of 2007, Beijing’s total amount of electricity consumption was 67.51 billion kW h, and 185 MKWh per day (Beijing Municipal Bureau of Statistics, 2008). Therefore, the amount of electricity savings caused by GAs’ cooling effect accounts for 8.97% of Beijing’s total amount of electricity consumption in one day.

### 4.2. Carbon savings and biomass

Fig. 3 shows that carbon savings is directly relative to NDVI. It infers that more biomass will produce more carbon savings on account of the fact that more biomass will lead to more evapotranspiration and more tree shade, which will result in a lower-temperature compared with green areas of less biomass. This principle is proved by many micro-scale studies (Akbari, 2002; Gomez-Munoz et al., 2010; Grimmond et al., 1996; Simpson, 2002). Nonetheless, Pataki et al. (2009) suggested that doubling the density of tree planting on newly developed urban land would have negligible effects on total net CO2 emissions. Because planting on new urban land only represented a relatively small amount of tree biomass, and had less capability of direct carbon sequestration in the first 30 years of growth in their study in the Salt Lake Valley, Utah. However, they did not take into account the influence of altered albedo, shading, and latent heat fluxes on air temperature resulted from tree planting. Therefore, our investigation may be a useful complement for their further study on both the city and regional scales.

### 4.3. Carbon savings and size of GA

Our results demonstrate that the amount of carbon savings varies directly with the size of GA. In addition, when we divided the cooled area into two “sub-regions”, i.e. GA and ECA, both area sizes varied in direct relation to their carbon savings. These results are understandable because a larger GA contains more plants, and more plants produce more evapotranspiration and tree shade, which will lead to more intense cooling effect and larger amounts of carbon savings. This conclusion is compatible with previous studies conducted in the thermal environment fields (Clark et al., 2008; Franco, 2005; Kimura and Takahashi, 1991; Yu and Hien, 2006).

Furthermore, those ECAs adjacent to GAs contribute more to energy saving because more human activities take place there. Hence, increase in the size of ECAs will reduce air-conditioning utilization and increase carbon savings. In our investigation, it was statistically found that ECA’s carbon saving amount of per unit GA would decrease with the increase in the size of GA. This result suggests that when the total area sizes are the same, more small GAs perform better than less large GAs. The reason for this finding is that more small GAs have longer boundaries, through which more heat will ‘flow’ into the cooled GAs, and result in a larger size of ECAs and larger amounts of carbon savings. In contrast, fewer large ones behave the opposite. This result appears to be contradictory to the principle of Conservation Biology, which suggests that fewer but large protected areas should be better than more small ones for the conservation of wild lives (Fiedler and Jain, 1992). However, if considering the fact that conservation needs more internal protected spaces whilst cooled effect concerns more external extended areas, the two explanations are not in contradiction to each other.

### 4.4. Carbon savings and shape of GA

Results in Fig. 7 show that per unit-area carbon savings in the ECAs varies directly but slightly with the GA’s shape index. From the tendency of carbon savings increasing slowly with the shape index, we can infer that more complicated shapes would have a longer boundary for per unit GA, so that more heat will ‘flow’ into the cooled GAs through these boundaries. This process will result in larger size of ECAs and larger amount of carbon savings. From Fig. 6 we also find that there exists a turning point on the curve describing the relationship between GA’s shape and its per unit-area carbon saving amount, however, whether the position of the turning point is general, and the reason for this merits further consideration.

Apart from shape, the flowing of heat into a cooled GA may be influenced by other complicated conditions in the surrounding built-up areas. For examples, as Lee et al. (2009) pointed out, the difference between high-rise commercial buildings and low-density single family residential area would lead to different extents of cooling areas, and so would their carbon savings. Zoulia et al. (2009) suggested that street direction, street height/width ratio, and existence of trees would affect the local temperature differences at a micro-scale, and hence affecting the amount of carbon savings. These influence factors are worthy of our further investigation.

### 5. Conclusion

Theoretically, the effects of green areas on global carbon balance consist of two aspects. One is green plants directly capturing carbon dioxide from the atmosphere through photosynthesis, which is a process of long-term storage of carbon in the plants to mitigate accumulation of carbon dioxide in the atmosphere. It acts on the carbon sink in global carbon cycle. The other aspect is that green plants cool the living environment by evapotranspiration, reduce the energy consumption, and cut down carbon emissions. It involves the carbon source in the global carbon cycle by way of carbon saving. Both carbon capture and carbon saving are important in global carbon balance. Our study on the carbon savings of green areas will improve the understanding of the contribution of green plants to carbon balance.

Practically, a new method of computing the amount of carbon savings resulted from green areas’ cooled effect is put forward, and the relationship of carbon savings with various features of green areas is statistically examined. Results show a strong correlation between biomass, size and shape of green areas and carbon savings. Based on this study, green areas with different biomass, size and shape could be compared with each other, and it becomes possible to seek for more effective ways to design and build green areas. Results also infer that, for carbon savings under the same sum of area sizes, more small green areas perform better than fewer large green areas, and this could be a good reference for the combination of several urban green areas.

Nonetheless, apart from the influence of green area characteristics on carbon savings, the cooling extent of a green area is also affected by the features of its surrounding areas, such as the density of buildings, the height/weight ratio and direction of streets, and...
the existence of plants. These factors are not examined in this study and worthy of our further investigation.

Acknowledgments

The authors would like to thank Prof. Yin Zhi and Ms. Zheng Xiaojin for their support throughout this study and Mr. Jiang Wenyu for his valuable comments on an earlier version of this manuscript. The work is financially sponsored by Beijing Tsinghua Urban Planning & Design Institute.

References


