Spatial-temporal variation of ecosystem water use efficiency in Beijing’s suburban region

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Abstract. Suburban ecosystem has multiple functions such as soil conservation and water regulation, which are critical for the welfare of human beings in the city. Water use efficiency (WUE) is an important indicator of ecosystem function that represents the amount of productivity per unit mass of evapotranspiration (ET). Improving WUE of suburban ecosystem is significant to climate regulation by carbon sequestration and water consumption, especially for cities with severe water shortage like Beijing, the capital of China. Based on remote sensing data, this paper examined the spatial and temporal variations in WUE in Beijing’s suburban region from 2002 to 2010. The results showed that the average annual WUE was 0.868 g C mm⁻¹ m⁻². It has large spatial variation with the minimum of 0.500 g C mm⁻¹ m⁻² in the Miyun District. During the study periods, the area with significant increasing trend of WUE was 63.2% of the total suburban region. In terms of ecosystem type, the value of WUE was following the sequence, deciduous coniferous forest (0.921 g C mm⁻¹ m⁻²) > mixed forest (0.887 g C mm⁻¹ m⁻²) > deciduous broadleaf forest (0.884 g C mm⁻¹ m⁻²) > shrubland (0.860 g C mm⁻¹ m⁻²) > evergreen coniferous forest (0.836 g C mm⁻¹ m⁻²) > grassland (0.830 g C mm⁻¹ m⁻²). As ET was similar among the ecosystems, the difference in WUE was mainly due to the discrepancy of NPP. We found that NPP significantly correlated with the diversity of ecosystem type (represented by Shannon-Wiener index). Our results suggest that ecological engineering construction, scientific ecosystem type selection, ecosystem diversity improvement and drought-resistant species cultivation are conductive to improve ecosystem WUE in Beijing’s suburban region.

1. Introduction
Socioeconomic development and population growth accelerated the urbanization process, while the neglect of ecological environment protection caused the deteriorating eco-environment [1]. Frequent urban environment problems, such as air pollution, water pollution, and etc., give serious threat to the sustainable development of cities [2]. Urban green space is an important part of urban ecosystem, which plays an instructive role in maintaining urban ecological balance and improving
eco-environment quality [3]. The development of green space in central city is restricted by the shortage of urban land, therefore, it is obviously important to construct suburban green space to protect urban ecological environment. In fact, green space needs to consume large quantities of water during the exertion of ecological function [4]. The fast development of suburban green space would aggravate contradiction between water deficient and green space water use [5]. Therefore, improving ecosystem water use efficiency in suburban region is contributed to relief urban water shortage.

Water use efficiency (WUE) is the amount of CO₂ fixed (or the amount of organic matter produced) by per unit mass of water consumption, which is an important indicator to evaluate the level of carbon and water coupling in urban ecosystem, and a quantitative indicator to assess the efficiency of water input and output in green space [6]. Researchers adopted different approaches to analyze the ecosystem WUE from multiple scales. The early research scale was primarily the leaf scales and vegetation scales, and researchers measured the transpiration rate and photosynthetic rate of leaf or vegetation to calculate the WUE by the experimental methods or measuring methods. The eddy covariance development advanced the WUE analysis in community scales and local scales. Using the eddy covariance technology, the data of CO₂ fluxes and evapotranspiration (ET) nearly the site can be measured, which can be intended for the WUE calculation. Meanwhile, the WUE analysis of region scales has been widely used with the development of remote-sensing technology. The investigators use the high precision remote-sensing date to assess the spatiotemporal dynamic of regional WUE [7]. The previous researches indicated that using the remote-sensing method can assess the regional WUE accurately, but study on the ecosystem WUE of suburban region is still in its relative infancy.

Deterioration of urban ecological environment has aroused the widespread attention of the community in Beijing. To solve the increasingly serious environmental problems, Beijing municipal government identifies the western and northern suburban region as the forest reserve [8]. The strengthening of forest protection has prompted the increased area of suburban ecosystems. The suburban ecosystems were 744.956 thousand hectares at the end of 2015, which has increased 125.713 thousand hectares comparing to 2005. The growth of suburban ecosystem contributed to the improvement of eco-environment quality, yet the water consumption of ecosystem has also increased significantly. Beijing is one of regions with severe water shortage in the world, and water safety problem has already restricted sustainability of the city. The improvement of water consumption of suburban ecosystem may have great influence on the water inflow of mountainous reservoirs [9]. The mountainous reservoirs are the most important water resource for Beijing, whose water storage may impact the amount of water available. Therefore, studying on spatial-temporal variation of ecosystem WUE in suburban region may help to understand the rule of ecosystem water consumption and then improve its water use efficiency.

In this study, we aimed to improve the ecosystem WUE in Beijing’s suburban region by reasonable ecosystem collocation. Specifically, we attempted to explore following questions: 1) the temporal variation of ecosystem WUE from 2002 to 2010 in Beijing’s suburban region; 2) the influence of ecosystem type (deciduous coniferous forest, evergreen coniferous forest, deciduous broadleaf forest, mixed forest, shrubland and grassland) and ecosystem diversity on WUE.

2. Materials and methods

2.1. Study area

The suburban region of Beijing (39°26'-41°03'N, 115°25'-117°30'E) distributes in the western and northern of Beijing (figure 1), including 7 districts (Pinggu, Miyun, Huairou, Yanqing, Changping, Mentougou and Fangshan). The area of suburban region is 1041.750 thousand hectares, which accounts for 62% of Beijing’s total area [10]. The climate of Beijing’s suburban region is warm-temperate continental monsoon climate. The average temperature is 10℃-12℃ and average annual precipitation amount is 585 mm, and the precipitation is mainly concerned in July and September [6]. The typical ecosystem type in Beijing’s suburban region mainly includes deciduous coniferous forest, mixed forest, deciduous broadleaf forest, evergreen coniferous forest, shrub and
grass (figures 1(b) and 1(c)). The area of suburban ecosystem had increased nearly 5423.490 hectares from 2000 to 2010. The area of deciduous broadleaf forest (change area: 15459.390 hectares) and evergreen coniferous forest (change area: 1178.370 hectares) increased rapidly, while the area of shrubland (change area: 95059.220 hectares) and grassland (change area: 2214.360 hectares) decreased rapidly.

![Figure 1. The location (a) and land use/cover distributions in 2000 (b) and 2010 (c) of Beijing’s suburban region.](image)

### 2.2. Methods

The paper used the water use efficiency equation to calculate the ecosystem WUE [11,12].

\[
WUE_i = \frac{NPP_i}{ET_i}
\]

Where, \(WUE_i\) is the mean annual ecosystem water use efficiency (g C mm\(^{-1}\) m\(^2\)); \(NPP_i\) is the mean annual net primary productivity (g C m\(^2\)); \(ET_i\) is the mean annual evapotranspiration (mm); \(i\) is the study year, and 1 for 2002, 2 for 2003, …, and 9 for 2010.

Later, we used the ordinary least square (OLS) estimation to analyze the changing trend of ecosystem ET, NPP and WUE in each pixel from 2002 to 2010 [13]. In addition, a F-test method was used to test the significance level of changing trend.
distribution of land use (fig 1(a)) and NPP (figure 2), which was closely related to the spatial distribution of ecosystem type. By comparing the spatial distribution difference of WUE was mainly caused by different NPP. The ecosystem NPP was more than 1,000 g C m$^{-2}$ in Mentougou, Fangshan and central region of Yanqing, while the ecosystem NPP in Miyun was less than 0.500 g C mm$^{-2}$. The ecosystem WUE in Miyun was lower than 0.500 g C mm$^{-2}$, which caused WUE in these regions were higher than 1.000 g C mm$^{-2}$. Meanwhile, the spatial distribution difference of NPP was lower than 450 g C m$^{-2}$. Meanwhile, the spatial distribution difference of NPP was closely related to the spatial distribution of ecosystem type. By comparing the spatial distribution of land use (figure 1(b)) and NPP (figure 2(a)), the regions with the higher NPP (NPP ≥ 1,000 g C mm$^{-2}$) matched well with the results reported by Yu et al (0.853 g C mm$^{-2}$) and Xia, et al (0.873 g C mm$^{-2}$) [16,17]. The average annual WUE had obvious difference in spatial distribution. The ecosystem WUE in southwest region was significantly higher than the northeast region. The ecosystem WUE in Mentougou, Fangshan and central region of Yanqing were more than 1,000 g C mm$^{-2}$, while the ecosystem WUE in Miyun was less than 0.500 g C mm$^{-2}$. The ecosystem WUE in other regions mainly ranged from 0.500 g C mm$^{-2}$ to 1,000 g C mm$^{-2}$, and the ecosystem WUE in sporadic regions was more than 1,000 g C mm$^{-2}$.

Overall, the spatial distribution of ET had no significant difference, which mainly remained in the range of 550 – 700 mm (figure 2(b)) while the NPP had obviously different in spatial distribution, which basically coincided with the spatial distribution of WUE (figure 2(c)). It showed that the spatial distribution difference of WUE was mainly caused by different NPP. The ecosystem NPP was more than 550 g m$^{2}$ in Mentougou, Fangshan and Yanqing, which caused WUE in these regions were higher than 1,000 g C mm$^{-2}$. The ecosystem WUE in Miyun was lower than 0.500 g C mm$^{-2}$, which due to the regional NPP was lower than 450 g m$^{2}$. Meanwhile, the spatial distribution difference of NPP was closely related to the spatial distribution of ecosystem type. By comparing the spatial distribution of land use (figure 1(b)) and NPP (figure 2(a)), the regions with the higher NPP (NPP ≥
550 g C m$^{-2}$) mainly covered by deciduous broadleaf forest and mixed forest, while the shrubland mainly distributed in the regions with the lower NPP (NPP ≤ 450 g C m$^{-2}$).

3.2. The trend of change in WUE

The temporal variation of ecosystem WUE from 2002 to 2010 was showed in figure 3(a). There were nearly 63.19% of ecosystem WUE increased during the study period. Through the significance test of variation coefficient, 6.21% of ecosystem experienced a significant WUE increase (P < 0.05). The ecosystem that experienced an extremely significant increase of WUE (P < 0.01) accounted for 1.22% of the total ecosystem cover. The ecosystem WUE in Miyun and the western region of Pinggu showed a significant increasing trend, and the regions of Huairou and Mentougou’s western region experienced a non-significance increase of WUE (P > 0.05). In addition, the regions experiencing the decrease of WUE were mainly distributed in the northern region of Yanqing, the western region of Changping and Fangshan, yet decreased trend was not significant (P > 0.05).

The temporal variation of ecosystem ET and NPP led to the WUE variation. During the study, the ecosystem with the decreasing ET accounted for nearly 73.03% of the total ecosystem (figure 3(c)), and the ecosystem with the increasing NPP was nearly 28.19% (figure 3(d)). The decreasing ET and increasing NPP caused the WUE experiencing an increased trend in most regions. The variation of ET
and NPP may be influenced by the increase of CO$_2$ concentration and the human protection activities [18,19]. The CO$_2$ emissions was more than 150 million ton, which rose by about 15% compared with 2002 (nearly 121 million ton) in Beijing. The rapidly increasing CO$_2$ emissions caused the improvement of CO$_2$ concentration, which directly affected the ecosystem NPP increase. The projects of Conversion of Cropland to Forest Program (CCFP) and Sand Control Program for Areas in the Vicinity of Beijing & Tianjin (SCP) were carried out in Beijing suburban regions since 2002, which may advance the restoration of natural hydrological balance and then contributed to the decline of ET. In addition, the regions with significant increase WUE may closely related to NPP increased. Comparing with the figures 3(b) and 3(d), we can find that the regions with the significant increase WUE mainly have the significant increase NPP ($NPP_{slope} > 5.0$).

![Map](image-url)

**Figure 3.** The temporal variation (a) and significant test (b) of WUE, the temporal variation of ET (c) and NPP (d) from 2002 to 2010 in Beijing’s suburban region.

### 3.3. The difference of WUE among ecosystem types

Based on the analysis of spatial-temporal of ecosystem WUE, the paper calculated different ecosystem WUE. The average annual WUE of each ecosystem type was different (figure 4). The maximum average annual WUE occurred in the deciduous coniferous forest (0.921 g C mm$^{-1}$ m$^{-2}$), yet the minimum average annual WUE was found in the grassland (0.830 g C mm$^{-1}$ m$^{-2}$). The average annual WUE of other ecosystem types were respectively 0.887 g C mm$^{-1}$ m$^{-2}$ (mixed forest), 0.884 g C mm$^{-1}$ m$^{-2}$ (deciduous broadleaved forest), 0.860 g C mm$^{-1}$ m$^{-2}$ (shrubland) and 0.836 g C mm$^{-1}$ m$^{-2}$ (evergreen coniferous forest). Result of sorting each ecosystem WUE was consistent with the other regions in the
same latitude [20, 21].

The difference among each ecosystem WUE was caused by the ET and NPP. Each ecosystem NPP was in the range of 500 – 520 g C m⁻² except grassland. Ecosystem ET made the WUE different in each ecosystem types. Deciduous coniferous forest had the physiological characteristic of defoliation and smaller LAI, which made the ET (567.7 mm) lower than other ecosystem types. Due to high LAI, the ET of mixed forest and deciduous broadleaf forest were higher than deciduous coniferous forest, which caused the mixed forest WUE and deciduous broadleaf forest WUE were lower than deciduous coniferous forest. Although evergreen coniferous forest LAI was same as deciduous coniferous forest, the physiological characteristic of evergreen made it had higher ET in spring, which directly resulted in the lower WUE. Grassland WUE was lower than other ecosystems WUE due to the lower NPP. Grassland ET (582.66 mm) was same as mixed forest (579.12 mm), yet the NPP (480.054 g C m⁻²) was significantly lower than other five ecosystem types. In addition, the WUE was smaller than 1.000 g C mm⁻¹ m⁻² because the average annual NPP of each ecosystem types was significantly lower than the ET. Thus, the improvement of ecosystem NPP was of great importance for regional WUE in Beijing’s suburban region.

![Figure 4](Image)

**Figure 4.** The difference of WUE among ecosystem types in Beijing’s suburban region.

3.4. The correlation between ecosystem diversity and NPP

The Shannon-Wiener index indicated the degree of ecosystem diversity in study objectives. The range of Shannon-Wiener index in each pixel was 0 – 2.624, which showed that the degree of ecosystem diversity had certain difference in Beijing’s suburban region. However, the Shannon-Wiener index in nearly 37.786% of pixel was 0, which indicated that the distribution of ecosystem types was relatively simple in most regions. The previous researches had demonstrated the ecosystem diversity affects the level of ecosystem utilization resources and the ability to adapt to environment changes. Therefore, increasing the degree of ecosystem diversity was of great significance to the construction of regional ecological environment.
Figure 5. The relation between Shannon-Wiener Index and ecosystem NPP in Beijing’s suburban region.

The ecosystem NPP was the key influencing factor of WUE and the foundation of ecosystem service function, which was closely related to ecosystem diversity [22]. Through the analysis of correlation coefficients and fluctuation trend, we found that the Shannon-Winner index and ecosystem NPP had strongly positive correlation. The correlation coefficient of Shannon-Winner index and ecosystem NPP was 0.704 (P < 0.01), which showed that the ecosystem NPP might be impacted with the ecosystem diversity level. Meanwhile, figure 5 showed that ecosystem NPP and Shannon-Winner index were fitted by the second order polynomial, and the relationship expression was $y = 14.654x^2 - 17.038x + 513.13$. The results showed that the improvement of ecosystem diversity could help increase ecosystem NPP, and then increase ecosystem WUE.

3.5. The measures of improving suburban ecosystem WUE

Although WUE of Beijing’s suburban ecosystem region remains consistent with mean WUE of eastern China, improving suburban ecosystem WUE is imperative with water resource crisis serious in Beijing. Therefore, the study puts forward some measures about improving the ecosystem WUE based on the above analysis. Firstly, the management departments should continue to promote ecological engineering construction and strengthen ecological protection in Beijing’s suburban. The ecological engineering construction will contribute to improve the suburban ecosystem cover rate. Meanwhile, the ecological protection will reduce the behaviors of excessive deforestation and blind land reclamation. Secondly, forestry departments should take the ecosystem WUE in consideration in the process of selection and cultivation of ecosystem types. The ecosystem types with high WUE should be developed gradually, such as deciduous coniferous forest and mixed forest. However, grassland areas should be dropped because grassland WUE is obviously lower than other ecosystem types. Thirdly, management departments should improve the structure of ecosystem and realize reasonable ecosystem collocation. The results showed the ecosystem diversity had positive impact on ecosystem WUE, so the management departments should optimize the allocation proportion of arbor-shrub-grass and construct the arbor-shrub-grass compound land. Lastly, scientific institutions should accelerate the process of drought-resistant species cultivation, which may effectively reduce the water consumption of ecosystem and then improve suburban ecosystem WUE.

4. Conclusion

This paper studies ecosystem WUE in Beijing suburban region from 2002 to 2010. WUE has obvious difference in spatial distribution, with the northeast region was lower than the southwest region, which was consistent with the spatial distribution of NPP. The mean WUE gradually increased during the study period, with 63.19% of area had significant increasing trend. The result of sorting the WUE values according to ecosystem type was that deciduous coniferous forest > mixed forest > deciduous broadleaf forest > shrubland > evergreen coniferous forest > grassland. As ET was similar among the
ecosystem types, the differences in WUE was mainly caused by that of NPP. The further analysis between NPP and ecosystem diversity index showed that diverse ecosystem types were facilitated to have higher NPP. Therefore, the study proposed some measures of improving WUE based on the above results, including the construction of ecological engineering forest, scientific selection of ecosystem types, improvement of ecosystem diversity and cultivation of drought-resistant species. This will be helpful for improving water conservation function of suburban ecosystem and relieving urban water shortage in Beijing.

Acknowledgments

Financial support for this research was provided by the Project of Social Science Youth Foundation of Beijing Municipal (Grant No. 15JGJC148), the Project of the General Program of National Social Science Foundation of China (Grant No. 15BGL130), and the Project of Humanity and Social Science Youth Foundation of Education Ministry of China (Grant No. 13YJCZH131). Feng Mi, Qin Zhang and Xuanchang Zhang conceptualized the article, conducted background research, and edited the content. Shibao Yuan, Nan Lu and Nana Yan provided the ETWatch data and edited the content.

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