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Water use efficiency threshold for terrestrial ecosystem carbon sequestration in China under afforestation

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ABSTRACT

Forests play a vital role in global carbon (C) cycling. Accordingly, afforestation engineering programs that promote increased terrestrial C stocks are an important means to help gradually decrease atmospheric CO_2 emissions. China, however, had increased its afforested area bordering hydroclimatic zones to 275.71 million hm^2 between 1949 and 2010. Ecosystem water use efficiency (EWUE) and plant water use efficiency (PWUE) provide data on ecosystem sensitivity to water availability across rainfall regimes. The water consumption cost of C sequestration (WCCC) is also an important parameter that gauges the cost of C sequestration under afforestation. However, abrupt changes in EWUE and PWUE (threshold values of 1.5 and 3.6 gC kg^{-1} H_2O, respectively) have been measured within the 400–500 mm precipitation climatic isoline boundary situated between semi-humid and arid zones. The threshold value of the corresponding WCCC was 1.0 kg H_2O gC^{-1}. Forest ecosystems in China typically generate high EWUE and PWUE values (2.80 ± 0.77 and 4.25 ± 1.02 gC kg^{-1} H_2O, respectively) but low WCCC values (0.52 ± 0.42 kg H_2O g^{-1} C), providing proof that afforestation is the best choice in increasing terrestrial C stocks. However, China's major afforestation engineering programs have concentrated efforts toward low EWUE and PWUE and high WCCC in the western region of the 400–500 mm precipitation isoline boundary, belonging to the arid and semiarid zones, which introduced potential environmental risks. Therefore, policies related to large-scale C sequestration initiatives under afforestation must first fully consider the statuses of WCCC and WUE.

1. Introduction

Total global forest ecosystem carbon (C) stocks are estimated at 861 ± 66 PgC. Consequently, forests play an important role in global C cycling as they do for the value of services they provide (Pan et al., 2011). Planting trees subsequently helps to reduce carbon dioxide (CO_2) emissions to the atmosphere, while increasing terrestrial ecosystem C stocks has long been considered an important measure of our ability to cope with global climate change (Gao et al., 2012, 2013). Owing to this, scientists have focused much attention on various ecological afforestation engineering programs to enhance C stocks with the aim to gradually decrease atmospheric CO_2 emissions. This has been especially true in China where from 1949 to 2010 total afforestation area has increased to 275.71 million hm^2, distributed alongside different hydroclimatic regions (Fig. 1) (BFC, 2010).

As research delved more deeply into the issue, scientists found that planting trees in regions with deficient water resources would give rise to risk factors related to environmental degradation, potentially impacting soil moisture content, hydrology, and vegetation coverage (Cao, 2011; Cao et al., 2011; Wang and Cao, 2011; Pongratz, 2013). Degraded land area in China increased alongside rapidly expanding afforestation between 1949 and 2010. Desertification expansion between 1976 and 1988 was 2100 km^2 yr^{-1}, but gradually exceeded 3600 km^2 yr^{-1} after 1998 (Yang et al., 2005). This took place because the overall survival rate of afforested trees since 1949 was only 15%, owing to deficiencies in adequate water resources during site selection (Cao, 2008). Water use efficiency (WUE) is a primary limiting factor on C sequestration under afforestation. For example, a region with a mean precipitation rate of <200 mm cannot sustain forest vegetation given an approximate potential evaporation rate of 2500–3000 mm yr^{-1}(Cao, 2008).

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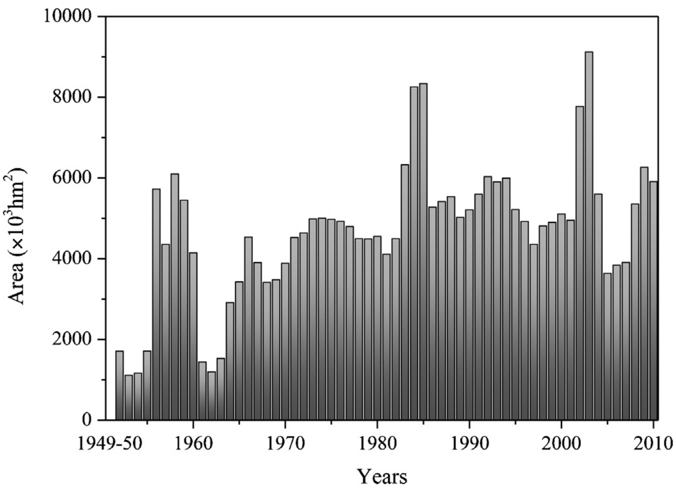

Fig. 1. Total area of afforestation in China between 1949 and 2010.

Ecosystem water use efficiency (EWUE) is defined as the ratio of gross primary productivity (GPP) to evapotranspiration (ET) while plant water use efficiency (PWUE) is defined as the ratio of GPP to transpiration (T) (see Section 2). These values point to an intrinsic system sensitivity to water availability across rainfall regimes regardless of hydroclimatic condition, which provides further insight into associations between C and water cycles as well as providing an assessment of ecosystem response to climate change (Zhang et al., 2001; Niu et al., 2011; Campos et al., 2013). Effects of water deficiency and WUE are of considerable importance in the investigation of site-specific water cycles and drought effects on water balances and C sequestration (Law et al., 2000; Kljun et al., 2006; Krishnan et al., 2006). WUE also provides useful indexes for better understanding the importance of interactions between C and N and available water resources (Luo et al., 2004; Yu et al., 2008).

The rate of C uptake per unit of water loss integrates a suite of biotic and abiotic factors, which is important in quantifying how much water is used within an ecosystem relative to C sequestration. Therefore, a third index related to the water consumption cost of C sequestration was introduced (WCCC, the unit of C sequestration at the expense of the water rate, which is defined as the ratio between ET to GPP) to better understand WUE limitation on C sequestration under afforestation and to further assess if a region is suitable for C sequestration under such programs. EWUE and PWUE spatial distribution was investigated and WCCC was estimated as it pertains to large-scale hydroclimatic changes on afforested C sequestration.

2. Materials and methods

WUE includes EWUE, PWUE, and WCCC. Observed WUE was calculated by eddy covariance observations. WUE maps were drawn based upon geographical statistical relationships between observed WUE and the leaf area index (LAI) and altitude. For this study, WUE data were acquired from two sources: long-term monitoring data from the ChinaFlux monitoring network (the China Terrestrial Ecosystem Flux Monitoring Network, based upon the Chinese Ecosystem Research Network (CERN)) and results published in scientific literature between 1980 and 2010. For more detail on the 25 long-term flux monitoring stations, visit the ChinaFlux website (http://www.chinaflux.org/index/index.asp). Geographical statistical relationships between annual EWUE and LAI and altitude (acquired from ChinaFLUX and published literature) are as follows: $WUE = -0.035\ Al + 2.72\ LAI - 0.69\ LAI^2 + 0.98$, $R^2 = 0.83$, RMSE = 0.44, $n = 25$ (where Al denotes altitude). The EWUE map of China was then drawn using digital elevation model (DEM) data and yearly-averaged MODIS LAI data. Although observation sites covered most typical areas in China, lacking were observations for areas where altitude exceeded 4500 m, LAI exceeded 4.0, or LAI was less than 0.05. Therefore, when LAI was less than 0.05 or altitude exceeded 4500 m, EWUE was set to zero since only negligible vegetation would be present within such areas. When LAI exceeded 4.0, EWUE was set to the highest value (3.8 gC kg^{-1} H_2O) since high LAI may lead to a high EWUE (Beer et al., 2009; Liu et al., 2012).

Establishing the ratio between T to ET was necessary to obtain the PWUE value. Using the Shuttle worth-Wallace model, ET was subdivided into evaporation (E) and T, and then the ratio of T to ET was calculated (Hu et al., 2009). The logarithmic relationship between LAI and T/ET was investigated at this point. Logarithmic relationships and the yearly-averaged MODIS LAI data ($T/ET = 0.14 \log LAI + 0.54$, $R^2 = 0.63$) (Liu et al., 2012) provided the spatial distribution of T/ET. When yearly-averaged LAI was smaller than 0.05, T/ET was set to minimum. The spatial distribution of PWUE was generated using the spatial distribution of T/ET and EWUE. WCCC was the reciprocal of EWUE, and the spatial distribution of WCCC was drawn based upon the spatial distribution of EWUE.

Spatial distributions of EWUE, PWUE, and WCCC were obtained using ArcGIS 10.0. Corresponding to the means from which EWUE and T/ET spatial variability was obtained, using mean observation values, the mean value of LAI between 2001 and 2010 was used to calculate EWUE and T/ET spatial distribution. This study mainly focused on EWUE, PWUE, and WCCC spatial variation; therefore, spatial distributions of EWUE, PWUE, and WCCC estimations were only apparent for long-term climate statuses where interannual variation was not taken into account. Total afforestation area in China between 1949 and 2010 and its subsequent expansion between 1999 and 2010 were obtained from the China Forestry Yearbook (1999–2010). Using EWUE, WCCC, and PWUE spatial distributions and vegetation maps (Editorial Committee of Vegetation Map of China, 2007), EWUE, WCCC, and PWUE values were calculated for different ecosystem types by the spatial analyst tools provided in ArcGIS 10.0. Two-Way ANOVA and the least significant difference (LSD) test at a 5% confidence level were carried out on each dependent variable, using SPSS 12.0.

3. Results

China was partitioned into different hydroclimatic zones according to precipitation and ET (Fig. 2a). From data pertaining to the significant precipitation and ET changes alongside climatic zones, EWUE and PWUE were found to gradually decrease from east to west. A distinct isoline boundary revealed that EWUE and PWUE abruptly declined in this direction. The isoline boundary for EWUE and PWUE was ascertained to be near to a 400–500 mm precipitation isoline hydorclimatic zone (Fig. 3), situated between semi-humid and arid zones. This is because natural precipitation is a key factor in supporting C sequestration sustainability and therefore determines the natural endurance of C sequestration. Given that the EWUE and PWUE isoline boundary could be the threshold value for the ratio of water loss to C gain, the isoline boundary itself has important implications on C sequestration potential under afforestation. EWUE exhibited significant longitudinal variation wherein the EWUE threshold value for the 400–500 mm precipitation isoline boundary was 1.5 gC kg^{-1} H_2O (Fig. 2b). The highest EWUE value was found within the cold temperate humid zone of northeastern China, a value in excess of 3.8 gC kg^{-1} H_2O, higher than the EWUE value in western China, which was lower than 1.5 gC kg^{-1} H_2O. Moreover, EWUE was higher in the temperate humid zone of northeastern China when compared to other zones. In addition, the partial pressure of CO_2 was lower in the temperate

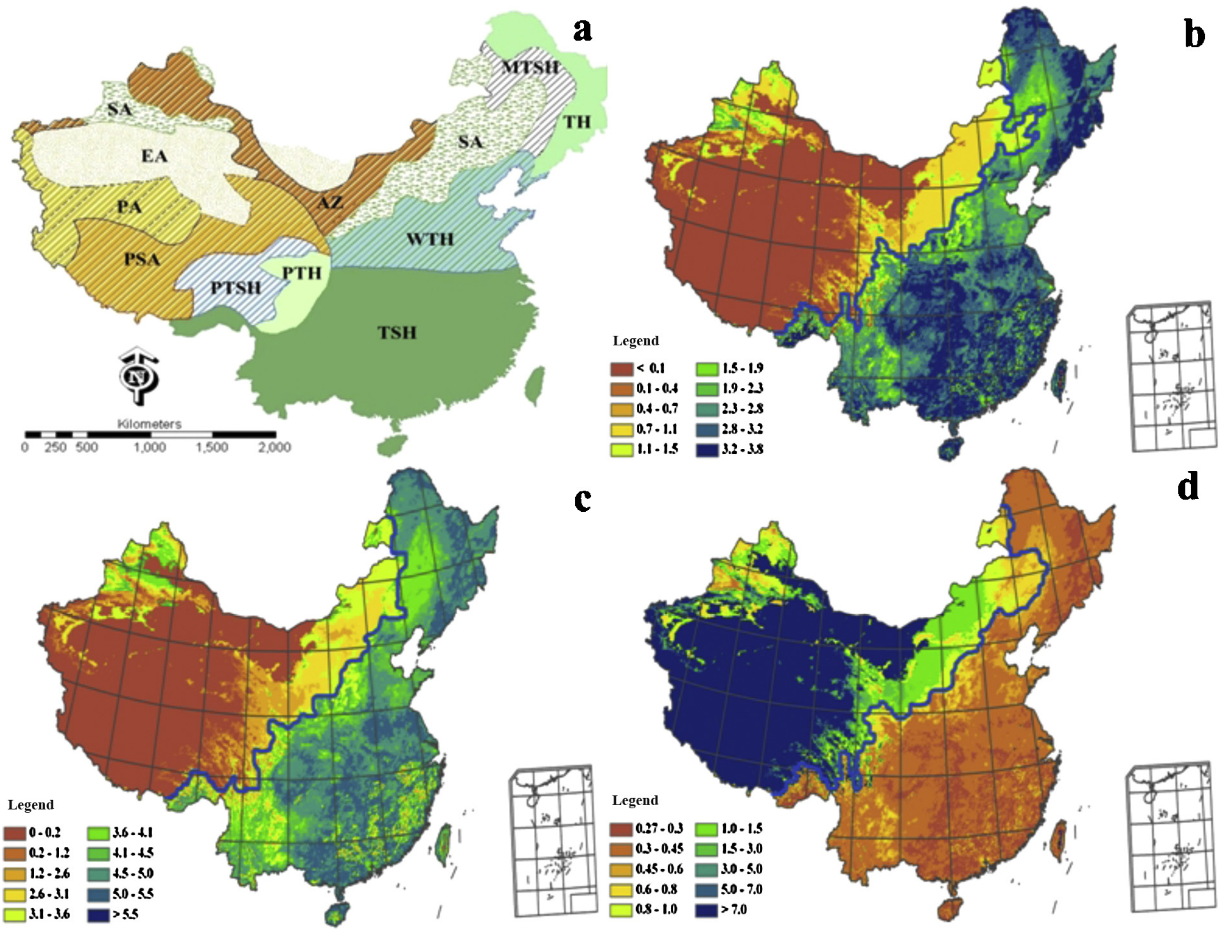

Fig. 2. (a) Depicts different climatic zones in China according to precipitation and evapotranspiration. TSH is the tropical/subtropical humid zone with an annual accumulated thermal temperature unit (ATU) >4500 °C and precipitation >800 mm; PTH is the plateau temperate humid zone with annual ATU <2000 °C and precipitation >800 mm; TH is the temperate humid zone with annual ATU <1600 °C and precipitation >800 mm; PTSH is the plateau temperate sub-humid zone with ATU <2000 °C and precipitation between 400 and 800 mm; MTSH is the middle temperate sub-humid zone with annual ATU between 1600 °C and 3400 °C and precipitation between 400 and 800 mm; WTH is the warm temperate humid zone with ATU between 3400 °C and 4500 °C and precipitation >800 mm; SA is the semiarid zone with precipitation between 200 and 400 mm; PSA is the plateau semiarid zone with annual ATU <2000 °C and precipitation between 200 and 400 mm; AZ is the arid zone with annual ATU <1600 °C and precipitation <200 mm; PA is the plateau arid zone with annual ATU <2000 °C and precipitation <200 mm; and EA is the extreme arid zone with precipitation <60 mm. Fig. 1b and c depicts EWUE and PWUE in China, respectively (unit: gC kg^{-1} H_2O). Fig. 1d depicts the spatial variation of WCCC in China (unit: kg H_2O gC^{-1}). Blue lines in b, c, and d are isoline boundaries for EWUE, PWUE, and WCCC, respectively.

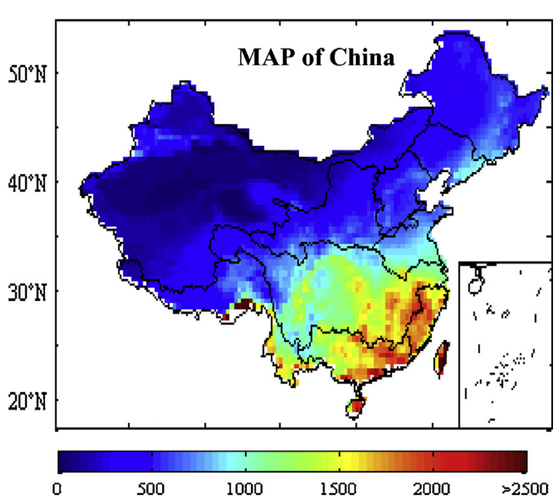

Fig. 3. Mean annual precipitation (MAP) of China (1962–2005) (unit: mm).

humid and subtropical humid zones due to their lower altitudes, resulting in a higher EWUE value once again. High altitudes and extreme arid conditions limit plant growth and lead to a decrease between the T and ET ratio. This explains why EWUE was found to be lower there compared to arid and semiarid zones.

Due to changes in altitude, mean annual temperature (MAT) and mean annual precipitation (MAP) drive EWUE and PWUE spatial variation mechanisms (Yu et al., 2008; Sheng et al., 2011). Similar to EWUE, PWUE spatial variation also exhibited a decreasing trend from east to west. The PWUE threshold value of the climatic isoline boundary was 3.6 gC kg^{-1} H_2O while PWUE spatial variation primarily acted in response to climate and altitude variation (Fig. 2c). The maximum PWUE value (in excess of 5.5 gC kg^{-1} H_2O) occurred in the plateau temperate humid zone of northern China. This zone was designated a temperate humid zone in the northeastern region of the North China Plain and the tropical/subtropical humid zone within the remainder of the region. In the mostly arid and semiarid zones of western China, PWUE did not exceed 2.6 gC kg^{-1} H_2O. Yu et al. (2008) reported that N deposition is the primary driver of EWUE and PWUE spatial variation mechanisms, but the impact of N deposition on EWUE and PWUE in the present study was primarily due to changes between the T and ET ratio (Caviglia and Sadras, 2001; Hobbie and Colpaert, 2004). Other studies have

Table 1
EWUE, PWUE, and WCCC statistics of a typical Chinese ecosystem between 2001 and 2010.

Types	EWUE (gC kg^{-1} H_2O)	PWUE (gC kg^{-1} H_2O)	WCCC (kg H_2O g^{-1}C)
Forest	2.80 ± 0.77^{a}	4.25 ± 1.02^{b}	0.52 ± 1.11^{c}
Grassland	0.84 ± 1.03^{b}	1.76 ± 1.80^{c}	5.03 ± 4.51^{b}
Farmland	2.46 ± 0.77^{ab}	4.33 ± 0.82^{b}	0.51 ± 0.67^{bc}
Wetland	2.57 ± 0.71^{ab}	4.39 ± 0.97^{a}	0.66 ± 1.50^{d}
Shrub	2.26 ± 1.16^{c}	3.55 ± 0.97^{d}	1.48 ± 2.84^{b}
Desert	0.19 ± 0.40^{d}	0.66 ± 1.33^{e}	8.17 ± 3.56^{a}
Mean	1.51 ± 1.33	2.63 ± 2.07	3.75 ± 4.43

Note: Different superscript letters denote a significant difference at a 5% confidence level.

suggested that an increase in MAT causes variation in EWUE and PWUE (Sheng et al., 2011).

A 400–500 mm precipitation climatic isoline boundary was also detected for corresponding WCCC spatial variation (1 kg H_2O gC^{-1}), which was more pronounced than WUE. The WCCC threshold value for the isoline boundary reflects the composite cost and water expense for providing sustenance to a tree. In this study, maximum WCCC (in excess of 7 kg H_2O gC^{-1}) was measured in plateau sub-arid and arid zones, which was greater than a magnitude of seven compared to WCCC measured within the isoline boundary. WCCC was found to be lower in tropical/subtropical humid zones than in other zones (Fig. 2d). Results from WCCC data reveal the existence of a potential environmental risk factor related to water availability and C sequestration under afforestation in arid and semiarid zones in the central western region of China. Available water resources cannot sustain ecosystem demand in these regions. Plateau temperate humid and tropical/subtropical humid zones in China have greater potential as C sinks because the plentiful water resources in these regions can sustain large-scale afforestation programs. In the temperate humid zones of northeastern China, slow plant growth resulting from low temperatures would counteract benefits from plentiful rainfall and would consequently have a negative impact on increases in C stocks. Therefore, the potential of C sequestration is higher in southern and southwestern China than in northeastern China. This differs from more traditional beliefs that assert that trees should be planted in subarid, arid, and sub-humid zones in the western and northern regions of the country.

4. Discussion

4.1. EWUE, PWUE, and WCCC within different ecosystems

Forest ecosystems exhibited the highest EWUE and PWUE values after wetland ecosystems, attaining 2.80 ± 0.77 and 4.25 ± 1.02 gC kg^{-1} H_2O, respectively, but forest WCCC (0.52 ± 0.42 kg H_2O g^{-1}C) was significantly lower than the mean value of other ecosystems (Table 1). These results suggest that afforestation is the best choice in increasing terrestrial C stocks, which are higher in WUE and lower in WCCC. Furthermore, grassland, shrub, and desert ecosystems exhibited very low EWUE and PWUE and high WCCC values, indicating that increasing C stocks in these ecosystems would be more costly and would provide lower C sequestration efficiency compared to forest ecosystems. PWUE was higher than EWUE, and this discrepancy reveals similar trends in EWUE and PWUE measured in typical ecosystems.

4.2. Effects of WUE on afforestation in China

Results from this study suggest that EWUE and PWUE play important roles in regulating ecosystem C sequestration in response to climate induced changes taking place in the different ecosystems that comprise the climatic zones of China. Climate change initially affects hydroclimatic conditions and then alters C water balances on an ecosystem scale. In China, large-scale C sequestration afforestation policies need to fully take into account WCCC and the water resource statuses of different hydroclimatic zones. At the same time, appropriate species selection is crucial in improving PWUE values. Large-scale afforestation programs impact ecosystem function, those functions that include changes in ecosystem resilience in structural, biological, and chemical properties of soil as well as in vegetation structure, composition, biomass, and net primary productivity (NPP). If afforestation exceeds the carrying capacity of an ecosystem, degradation is inevitable.

When precipitation is lower than potential ET, available soil moisture typically cannot sustain forest vegetation, and under natural succession, xerophytic shrub or steppe species will replace forests to form a sustainable supplemental natural ecosystem in stable equilibrium with available water supplies (Cao et al., 2010). In the arid, semi-arid, or plateau temperate zones of China, soil moisture in planted forests is generally deficient due to low MAP values, leading to large-scale mortality after afforestation. Taking this into account, the implementation of large-scale afforestation initiatives in different climatic zones must consider topography, climate, and hydrology, all of which can affect EWUE, PWUE, and WCCC. In addition, different environments will support different plant communities. Therefore, increasing C stocks by afforestation

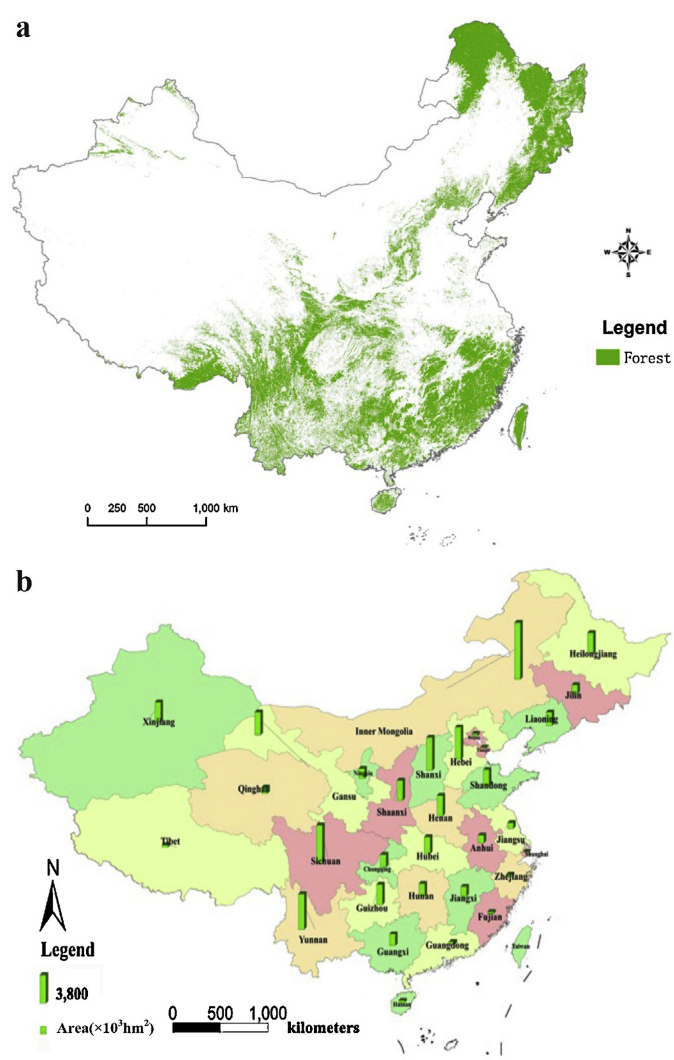

Fig. 4. Forest resource spatial distribution in China (a) and distribution of the increase in afforestation area in China between 1999 and 2010 (b).

Table 2
Increases in afforestation area for different Chinese provinces between 1999 and 2010.

Province	Area ($\times 10^3$ hm^2)
Beijing	321.30
Tianjin	89.50
Hebei	4284.49
Shanxi	4415.37
Inner Momgonia	7614.89
Liaoning	1803.02
Jilin	1178.82
Heilongjian	2759.82
Shanghai	70.84
Jiangsu	782.77
Zhejiang	279.11
Anhui	1057.21
Fujian	291.69
Jiangxi	1300.30
Shandong	2199.17
Henan	2696.76
Hubei	2265.07
Hunan	1713.13
Guangdong	353.56
Guangxi	1571.71
Hainan	316.32
Chongqing	1716.51
Sichuan	5127.33
Guizhou	2737.94
Yunnan	4763.39
Xizhang	309.50
Shanxi	5165.10
Gansu	3084.34
Qinghai	829.74
Ningxia	1362.03
Xinjiang	2683.38

is not an appropriate choice for all areas. Moreover, C sequestration under afforestation applying inappropriate plant choices will produce an unstable equilibrium with available water resources.

Since the founding of the People's Republic of China in 1949, afforestation area has rapidly increased by an average of 4595×10^3 hm^2 yr^{-1} (Fig. 1), but a decreasing trend may be inevitable considering that arid, semi-arid, or plateau temperate climatic zones have been proven unsuitable for C sequestration under afforestation because of their inherent low WUE values. In China, forestry resources have primarily been distributed from tropical/subtropical humid and temperate humid/sub-humid zones in the east of the 400 mm precipitation climatic isoline boundary (Fig. 4a), which has a huge potential in C sequestration under afforestation due to its suitable MAT and MAP levels. However, this study found that the main focus of afforestation engineering in China after 1999 concentrated on arid, semi-arid, semi-humid, or plateau temperate climatic zones (Table 2) where more than half of the increase in afforestation area is west of the EWUE, PWUE, and WCCC isoline boundary (Fig. 4b). Historically, forested areas in China have been distributed east of the 500 mm precipitation isoline, which defines the boundary between China's humid and semi-humid regions (Liu, 2005). This study also found that due to optimal EWUE, PWUE, and WCCC, the boundary having the greatest C sequestration potential under afforestation is the 400–500 mm precipitation isoline boundary situated between the semi-humid and arid zones.

Chinese governments have often ignored differences between reforestation initiatives used to restore degraded forests in regions that originally supported forest vegetation and afforestation initiatives used to generate forests on land where the natural climax community is an altogether different vegetation type (Cao et al., 2010; Cao, 2011). Moreover, governments have also often ignored potential groundwater redistribution, including transferring water between different provinces and deep groundwater recharges. As a result, potential changes in the depth of the groundwater table would heighten water shortages to some degree in certain regions of the country.

Furthermore, afforestation policies also need to consider local nutrient statuses due to N and water use co-optimization schemes used to maximize C gain. N can limit plant production by reducing photosynthetic rates in many terrestrial ecosystems (Elser et al., 2007). By reducing photosynthetic rates, N limitation has the potential of lowering stomatal conductance and T, thereby increasing runoff (Felzer et al., 2011). The benefit of WUE is that it reflects a compromise between biomass gain and water loss during growing seasons (McMurtrie et al., 2008; Dewar et al., 2009). Although there are plentiful water resources in southern China, a general lack of N in this region would also restrict large-scale C sequestration afforestation.

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