Species and spatial differences of vegetation rainfall interception capacity - a synthesis and meta-analysis in China

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Abstract

China has carried out many ecological restoration projects in the past. At present, there are large spatial differences in the hydrological effects of forest ecosystems in different regions of the country under heterogeneous conditions, which is not conducive to the macro guidance of ecological restoration projects. Canopy interception is an important link in the water cycle of the ecosystem. This paper attempts to use this index as a bridge to connect the research literature of existing ecological sites, so as to evaluate the differences in water resources distribution in different regions and vegetation ecosystems and analyze the main reasons for the differences. We combined canopy interception rate (I_0) and canopy water storage ability (I) to interpret canopy interception, and collected site related geographic, meteorological and ecosystem structure information simultaneously in the literature to build up an original dataset. Analysis on the database showed that the comprehensive interception capacity of vegetation in the south was generally higher than that in the north, which was dominated by shrubs, and that the tree species had interception advantages. Mixed forest showed the best comprehensive interception capacity, while pure tree forest had better interception potential than shrubbery due to its biomass advantage. The actual interception capacity of shrubbery was better than pure tree forest due to the advantages of stand density and the dry climate. Results from the evaluation of canopy interception ability using different indexes were not consistent, meaning that evaluating canopy interception with multiple indexes may be more objective. The study also highlights that the current structural characteristics of shrubby forests in northern China may be counterproductive to mitigating drought, reducing the structural density of a given stand will increase the opportunity for precipitation to reach the surface, thereby increasing the amount of water available to ecosystems in arid areas. Maintaining the healthy growth of mixed forests is still the right choice for humid areas in the south.

Key words: Vegetation restoration; Canopy interception rate; Canopy water storage ability; Water resources regulation.

1. Introduction

Since the reform and opening up, in order to improve the country's ecological environment, the Chinese government has adopted a series of policies and measures to promote afforestation project (Li, 2004; Wang et al., 2007). Entering the new century, Six Key Forestry Projects have been launched, which are described in Table 1. The rapid development of China's social economy in recent decades also has an important impact on the change of the ecological environment. As a result, the spatial distribution of vegetation in China presents a new pattern and the ecological functions carried by vegetation in different regions are also uncertain. Among many issues, the relationship between vegetation construction and water resources is controversial (Ellison et al., 2012). Some scholars believe that vegetation construction increases water resources (Calder,2002), while others believe that overplanting vegetation seriously consumes water resources in arid areas and aggravates the deterioration of ecological environment (Cao et al., 2011). These two viewpoints are mainly discussed on the basis of the water amount in the outlet of the ecosystem water cycle, namely the water yield of the ecosystem outlet, the consumption and loss of effective precipitation. Because these end-point water processes directly reflect or affect the water yield of the ecosystem. However, the amount of water flowing out of the water cycle outlet might also indirectly determined by the water source of an ecosystem, which is rarely considered in large-scale evaluation systems. Canopy interception, as an important component of precipitation distribution, is a suitable indicator for our traceability study.

Canopy interception is a phenomenon by which rainwater is stored by leaves under the action of leaf surface adhesion, supporting force, gravity, and cohesion of water molecules (Brauman, et al., 2010). Leaf surface interception occurs at the initial stage of rainfall, and increases continuously during the rainfall period until the maximum interception is reached. Water trapped in plant branches and on leaves falls to the ground when the weight of the droplets exceeds the surface tension. The interception process continues throughout the entire rainfall process, and the water is evaporated when the rainfall event ends (Klaassen, et al.,1998; Dunkerley, 2000). Canopy interception is an important link in the hydrological cycle, and affects the surface-atmosphere energy cycle and water balance (Sun, et al., 2018;). Canopy interception is also an important hydrological process which changes the quantity, duration, and spatial distribution of the water that is input and output in a given basin, and further affects soil erosion (Hanson et al., 2004; Cao et al., 2008). While it reduces the actual amount of rainfall that reaches the ground, reducing erosion (Calder, 2001), it also reduces the splash erosion of raindrops and the amount of disturbance they have on the thin layer of flow on slope (Williams et al., 2018), which is an important force driving slope runoff erosion.

At present, the main indices that quantify the interception effects of the forest canopy on rainfall are the canopy interception amount *(I_m, mm)*, interception rate *(I, %)*, and storage capacity *(I_0, mm)* (Dunkerley & Booth, 1999; Dunkerley, 2000; Wang et al., 2012; Sun, et al., 2018). I_m and I refer to the difference between gross rainfall (GR) and the net rainfall (NR) which reaches the ground, and the proportion of the difference in gross rainfall, respectively (Attarod et al., 2015). In any single study, these two indicators generally appear only once, and can describe the average level of canopy interception at the event, monthly, seasonal, or yearly time scale (Zhang et al., 2017; Link et al., 2004; Deguchi et al., 2006; Komatsu et al., 2008).

Interception rates vary widely between ecosystems, ranging from 10% to 70% is possible (Carlyle-Moses and Gash, 2011; Attarod et al., 2015; Patricio et al., 2019; Sun et al., 2018) depending on multiple factors including the vegetation types, stand structure, canopy configuration, climate condition, and the rainfall characteristics (Gash et al. 1995; Xiao et al. 2000; Fleischbein et al. 2005; Toba and Ohta 2005; Deguchi et al. 2006; Staelens et al. 2008; Sun et al.,2018). Canopy storage capacity is defined as the interception amount of the saturated canopy in a single rainfall event when evaporation is negligible after rainfall and canopy drainage has ceased (Gash and Morton 1978; Gash et al. 1995). When compared to I_m, over a short period, I tends to be static in an ecosystem due to the stability of species characteristics, such as height, diameter at breast height (DBH), canopy density, leaf area index (LAI), chest height sectional area, leaf type, and leaf hydrophilic characteristics (Attarod et al., 2015; Crockford and Richardson et al., 2000).

Meteorological factors only change the rate of leaf saturation (Calder and Wright, 1986). Soto-Schönherr and Iroumé (2016) compared the annual interception amount of different vegetation and climate zones from 127 plot studies in Chile, and found that broadleaved forest stands (including native broadleaved and eucalyptus forests) generally presented higher interception losses than conifers, with higher interception losses in drylands than in humid regions (Soto-Schönherr and Iroumé, 2016). Patricio et al. (2019) compared the interception rate of different vegetation types in global drylands, and found that there was no significant difference between coniferous and broad-leaved forests (Patricio et al., 2019). Different measurement indexes may affect the consistency in estimates of vegetation interception performance, while the instability of the interception rate and the interception amount under varying meteorological factors may also reduce the comparability of samples. In contrast, I_0 is more reliable to use as a stable benchmark of vegetation interception ability. However, a synthesis analysis focusing on regional or global canopy saturation interception capacity has not yet been done due to a lack of measurements of I_0.

China is a big country in global forest resources. It has a total forest resources of 207.69 million hectares, with an average forest coverage rate of 21.63% (2009-2013) (http://www.forestry.gov.cn/data.html). It is also a vast country with a huge variation in spatial distribution of climate and terrain, forming diverse ecosystems. Excluding shrubs, there are more than 8,000 existing tree species in China (Sun et al., 2018). Long-term measurements on the hydrological function of forest ecosystems in China were initiated in the middle of the 20th century, but the most extensive work was done after the 1970s. Since the establishment of the Chinese Ecosystem Research Network (CERN) in 1988, a number of ecological forest stations have been established across the country, covering the boreal zone to the tropical zone and offering favorable conditions to study the characteristic hydrological functions of forest ecosystems across different physiographical environments (http://www.cern.ac.cn/0index/index.asp). These stations observe and measure forest hydrological processes in terms of rainfall interception, soil water dynamics, water cycle, water quality, and flooding and runoff, and also have a large amount of available hydrological data from case studies accumulated at each station over the decades. These efforts over the past 20 years provide a solid basis for making comparative and comprehensive analyses of forest hydrological functions at regional and national scales across China.

Using available hydrological data from case studies at existing ecological stations, this study collected characteristic values of vegetation interception in different regions of China and estimated the canopy storage capacity of different vegetation by using a widely used rainfall-interception semi-empirical model. Based on these data and the differences in vegetation interception characteristics in different regions, the different performances of canopy interception rate and canopy storage capacity were compared to ultimately evaluate vegetation interception ability across the country. Such comparative research may reveal new findings on vegetation interception ability and provide new policy suggestions for regional water resources management

2. Materials and methods

2.1 Literature review

Several search engines were used to find publications about canopy interception and rainfall partitioning studies in forest plots, which included searches in international journals, local journals, and theses until 2018. When selecting literature, the focus of vegetation type was on tree and shrub, while grass, crops, moss, and other vegetation were ignored because of the research methodology gap. The extracted data for explanatory variables, when available, was comprised of forest stand characteristics such as species, stand types, age, density, tree diameter at breast height (DBH), height, leaf area index (LAI), canopy cover, and various site characteristics and climate conditions such as location, elevation, potential evapotranspiration (PET), mean annual precipitation (MAP), and mean annual temperature (MAT). Snow interception has rarely been mentioned in previous literature, therefore, only interception from rainfall was considered in this study. The extracted data for explained variables fell into two categories: rainfall distribution ratio, including throughfall rate (Tf), stem flow rate (Sf) and interception rate (I); and the measured data sequence of gross rainfall (GR)-canopy interception (I_m) generated by multiple rainfall events in a short period. Linsley formula, which were described in section 2.2, was used to fit canopy water storage capacity (I_0) based on the data series of GR-I_m. The literature that contained the measured data sequence and fit I_0 well ($p<0.001$) was selected to be used in the analysis, while different articles from the same site and duplicated information were disregarded. Interception losses (I and I_0) were analyzed in terms of the stand characteristics and site variables as mentioned and compared across different administrative regions and tree species. Additional group analyses were performed by species (needle-leaved forests, broad-leaved forests, mixed forests, and shrubbery). All studies were conducted entirely during the growing season (April-October). Analyses in this study were based on the assumption that there was no significant change in the stand structure during the study period, and the influence of the discrete observation time on any changes in interception can be ignored.

2.2 Canopy storage capacity fitting

Two methods are generally used to estimate I_0: direct methods such as cantilever remote sensing, the ray-attenuation method, artificial wetting of vegetative surfaces and deflection method, (Garcia-Estringana et al., 2010; Aston 1979; Hancock and Crowther 1979; Herwitz 1985; Liu 1998; Keim 2003; Vegas Galdos et al. 2012), and indirect methods such as model optimization or graphical estimation (Leyton et al. 1967; Rutter et al. 1975; Gash 1979; Gash et al. 1995; Asadian 2007; Pereira et al. 2009; Sadeghi et al. 2014). Direct methods are not commonly used because of the complexity in calibration and cost (Keim 2003; Kume et al. 2008). In contrast, indirect methods are simple to apply (Kume et al. 2008), it is suitable for estimation of water storage capacity of vegetation canopy in large area. Exponential model is the most commonly used semi-empirical and semi-theoretical model for indirect prediction of I_0. This model was established and modified by Merriam (Merriam, 1960), the formula is as follows:

$$I_m = I_0\left[1 - \exp(-kP)\right] + CEt \qquad (1)$$

Where I_m is event interception, I_0 is the saturated canopy interception, P is event precipitation, C is the ratio of the surface area of tree branches and leaves to the projected area, E is the surface evaporation strength of branches and leaves, t is rainfall duration, and k is a constant which reflects the uniformity of the distribution of branches and leaves in the canopy. Wang et al. (1998) simplified the CE in the model into an α, the rainfall evaporation rate, based on the complex regional characteristics of China, and made the model widely used in China.

In this study, due to the short duration of the rainfall event and the small temperature difference and water vapor pressure difference, the evaporation is very small and can be ignored. In addition, the closed rainwater collection device also avoids evaporation. This means that *CEt* in Eq. (1) is equal to zero. Therefore, the above equation is usually simplified as:

$$I_m = I_0 * [1 - \exp(-kP)] \quad (2)$$

I_0 can be calculated by fitting the paired data of I_m and P obtained in the literature with Eq. (2). The specific fit results are shown in the Appendix (Table A), In addition, the Appendix (Table B) shows the canopy storage capacity (I_0) directly obtained from the literature, which was fit using the same model.

2.3 Site characterization

A total of 86 literature items were collected for this study that involved 47 different research sites in CERN across 21 provinces or municipalities in China. The study area was mainly distributed in areas with dense vegetation such as the Great Khingan, Changbai Mountains, Qilian Mountains and the hilly regions in the southwest, as well as arid and semi-arid farming-pastoral intersections ranging from northeast to southwest China (Table 2 and Fig.1). The studies are representative of a wide range of latitudes and longitudes, elevations, rainfall distribution, temperature, potential evapotranspiration and major vegetation types (Table 2).

The latitude and longitude of the research sites range from 23.05° to 52.83° N and 88.49° to 128.10° E. The elevations range from a minimum of 175.33 m in Tiantong, Zhejiang (Wang, 2008;

Peng and You, 2010; Hu et al., 2018) to a maximum of 4027.50 m in Tianlaochi, Gansu (Peng et al., 2014). Mean annual rainfall ranges from only 188.6 mm per year at the experimental station of Shapotou, Ningxia (Zhang et al., 2005; Liu et al., 2012; Zhang et al., 2015c) to a maximum of 1956.0 mm per year in the Zhaoqing, Guangdong (Yin et al., 2004). Among them, sites with average rainfall of less than 200 mm (arid regions) accounted for 2% of the total, and were located in Shapotou, Ningxia. Studies covering the 200–400 mm (semi-arid region) rainfall range represented 11 % of the total. Studies covering the 400–800 mm (sub-humid region) and >800 mm (humid region) rainfall range represented 51% and 32% of the total, respectively. Mean annual temperatures ranged from a minimum of -5.4 °C in the Great Khingan Mountains in Inner Mongolia (Tian, 2014) to a maximum of 21.4 °C in Zhaoqing, Guangdong (Yin et al., 2004). Mean annual potential evapotranspiration was not comparable between sites, as calculations of this variable were performed using different methodologies and varied widely, ranging between 773 mm (Wolong, Sichuan; Hao, 2007; He et al., 2008) and 2500 mm (Shapotou, Ningxia; Zhang et al., 2005; Liu et al., 2012; Zhang et al., 2015c). The vegetation studied involves needle-leaved forest, broad-leaved forest, mixed forest, and shrubbery.

2.4 Vegetation distribution

A total of 160 case studies were included from the 86 articles collected, with the most frequently studied regions of Chongqing (16%), Shaanxi (12%), Sichuan (10%), Qinghai (9%), Beijing (7%) Hebei (6%), Heilongjiang (6%) and Inner Mongolia (6%). The case studies were numerous and rich in vegetation types in Chongqing, while dominated by needle-leaved forest in Shaanxi (65%), Sichuan (57%), Beijing (60%), Hebei (78%), Heilongjiang (78%), Inner Mongolia (62.5%) and Xinjiang (67%). Shrubbery was the main vegetation type studied in northwest China (Qinghai (70%), Gansu (50%), and Ningxia (80%)) (Fig. 2). Of the studies examined, 43 species were involved, 83% referred to stands of trees and 17% to shrubs. Of the former, 57% studied needle-leaved forests, 20% broad-leaved forests, and 6% mixed forest. The tree species most frequently studied were *Pinus tabuliformis* (16.1%), *Cunninghamia lanceolata* (10.6%), *Larix gmelinii* (7.5%) and *Picea asperata* (6.2%) (Fig. 3).

Table 3 shows the stand characteristics of the forests studied as defined by tree density, age, height, DBH, canopy density and LAI. Of these variables, the most frequently found in the studies collected was canopy density (75% of the studies), followed by height (58.13%), and DHB (50.63%), then is density (38.75%) and age (36.88%), while the least available variable was LAI (19.38% of the studies). The stand density ranged from 209 trees ha^{-1} in an *A. fabri* forest in Sichuan (Diao et al, 2016) to 17,900 trees ha^{-1} in a *Q. aquifolioides* forest in Wolong nature reserve in Sichuan (He et al., 2008). The larch natural forest in Great Khingan was the oldest forest sample at 170 years old (Diao et al, 2016), while the *Q. aquifolioides* forest in Changbaishan was the youngest at 10 years old (Pei and Zheng, 1996). The height ranged from 0.6 m in two shrub lands in Shapotou, Ningxia (Liu et al.,

2012) and Qilianshan, Qinghai (Ma et al., 2017) to 39.49 m in an *A. fabri* forest in Wolong nature reserve in Sichuan (Hao, 2007), while the shortest tree was 2.80 m in a *Pinus tabulaeus* woodland in Shenmu, Shaanxi (Cheng et al., 2009). DBH varied between 0.19 cm in a *P. asperata* young forest located in Tianlaochi, Xingjiang (Peng et al., 2014) to 50.87 cm in a natural *A. fabri* forest located in Gonggashan, Sichuan (Diao et al, 2016). Canopy density ranged from 0.2 in *P. asperata* forest in Tianshan, Xingjiang to 0.95 in C. deodara and S. superba in Taian, Shandong and Tiantong, Zhejiang, respectively (Song, 2015; Wang, 2008). LAI varied from 0.67 in a shrubbery in Shapotou, Ningxia to 7 in a *C. lanceolata* forest in Huitong, Hunan (Sun et al., 2011b).

3. Results

3.1 Interception characteristics in different regions

Figure 4 shows the average canopy water storage capacity and rainfall partitioning in different regions, in descending order. The figure shows that the difference in canopy water storage capacity was large across the different regions, while the difference in canopy interception rate was small. The region with the maximum canopy water storage capacity was Guangdong (27.57%), followed by Zhejiang (23.57%). The region with the minimum canopy water storage capacity was Ningxia (3.67%), followed by Jilin (4.05%). The region with the maximum canopy interception rate was Qinghai (34.56%), followed by Inner Mongolia (29.45%), while the minimum canopy interception rate was in Shanxi (13.63%), followed by Ningxia (14.89%). Canopy water storage capacity and interception capacity were not consistent across the different regions. The regions with canopy water storage capacity and the canopy interception rate both in the top ten were Guangdong, Chongqing, Beijing, Jiangxi, Hunan, Sichuan, and Qinghai.

3.2 Interception characteristics of different species

Figure 5 shows the average canopy water storage capacity and rainfall partitioning of different species in descending order. Among them, the species with the maximum canopy water storage capacity were *S. superba* (34.59mm), followed by *Q. dentata* (20.49mm). The species with the minimum canopy water storage capacity were *G. axillaris* (0.59mm), followed by *C. fortune* (0.63mm). The species with maximum canopy interception rate was *M. squamosa* (47.56%), followed by *C. fortunei* (42.73%), while the species with the minimum canopy interception rate was *P. davidiana* (12.4%), followed by *R. pseudoacacia* (13.57%). As with results from regional differences, canopy water storage capacity and interception capacity were not consistent across different species. Species with canopy water storage capacity and the canopy interception rate both in the top ten were *M. squamosa* (S), *C. fortune* (N), *P. fruticose* (S), *C. jubata* (S), *B. diaphana* (S), and *C. parthenoxylon* (B).

3.3 Interception characteristics of different vegetation types

The data for interception rate and interception amount were grouped and analyzed. The results showed that the interception characteristics of different vegetation types varied greatly (Fig.6). When rainfall partitioning ratios were compared (Fig.6a), the overall proportion for throughfall rate was **70.77 ± 9.86% (n=64)**, which was the highest proportional component in rainfall distribution. The average value of different vegetation types was ranked in descending order as: B **(75.26 ± 8.61%, n=18)** > N **(71.36 ± 8.50%, n=27)** > S **(66.73 ± 11.20%, n=14)** > M **(63.61 ± 11.20%, n=5)**. Canopy interception was the main way for vegetation to intercept precipitation, with a general proportion of **25.48 ± 9.82% (n=76)**. The average canopy interception rate of different vegetation types was ranked in descending order as: M **(35.02 ± 10.5%, n=5)** > S **(29.04 ± 10.96%, n=17)** > N **(25.24 ± 8.30%, n=36)** > B **(19.93 ± 8.49%, n=18)**. The percentage of stemflow was the lowest, accounting for only **4.37 ± 4.66 % (n=57)** of gross rainfall. Although this proportion was small, it showed significant differences among different vegetation types, with the stemflow rate of shrubbery relatively high **(6.09 ± 3.29%, n=9)**, followed by needle-leaved forest **(5.89 ± 4.03%, n=36)**, broad-leaved forest **(4.86 ± 3.19%, n=17)** and mixed forest **(1.36 ± 2.20%, n=5)**.

Figure 6b shows the difference in canopy interception capacity of different vegetation types. According to the figure, the average canopy interception capacity of mixed forest was the highest **(25.98 ± 11.33mm, n=27)** with a variation of 43.62%, followed by broad-leaved forest **(10.33 ± 11.65mm, n=31)**, needle-leaved forest **(8.63 ± 9.00mm, n=92)** and shrubbery **(6.45 ± 4.95%, n=27),** with variations of 112.87%, 104.26% and 76.74%, respectively.

3.4 Factors influencing vegetation interception

The rainfall partitioning ratio and canopy water capacity were significantly affected by climate and vegetation characteristics, especially MAP, height, DBH, and LAI (Fig. 7). When considering the rainfall partitioning ratio, as mean annual precipitation increased, throughfall and stemflow showed a tendency to decline **(p=0.26 and p= 0.45)**, while interception increased **(p=0.13)** (Fig. 7a). Stemflow was the most sensitive component in rainfall partitioning to MAP with a slope of **-0.96**. As the tree height increased, throughfall increased **(p=0.17)**, while interception and stemflow declined **(p=0.36 and p=0.81)** (Fig. 7b). Throughfall was the most sensitive component in rainfall partitioning to height with a slope of **0.31**. As DBH increased, throughfall and stemflow showed insignificant decreases **(p=0.89 and p=0.38),** and interception increased negligibly **(p=0.49)** (Fig. 7c). In addition, throughfall and interception showed a significant increasing trend as LAI increased **($p=0.19$ and $p<0.05$)** while stemflow decreased **($p=0.54$)** (Fig. 7d). These results show that canopy water capacity is more sensitive to changes in climate and vegetation characteristics. As shown in the figures noted, the canopy saturation interception appeared to have a significant increasing trend as MAP, **($p<0.05$)** (Fig. 7e), average vegetation height (Fig. 7f-h), DBH, and LAI all increased **($p<0.05$, $p=0.23$ and $p<0.05$,** respectively).

4. Discussion

4.1 Spatial differences in vegetation interception

Previous studies have suggested that canopy interception is mainly determined by rainfall characteristics and vegetation types (Crockford and Richardson, 2000). Therefore, the interception ability of a given type of canopy may vary across different regions (Mao et al., 2011). In this study, canopy water storage capacity and canopy interception rate showed significant differences in different regions (Fig.4) when the combined performances of interception rate and water storage capacity were used to evaluate the comprehensive interception capacity of the canopy. As can be seen from the top ten provinces identified in this analysis, the regions with obvious advantages in comprehensive interception capacity were concentrated in the southern humid areas, while canopy interception was generally lower in northern arid areas (Fig.4). This difference was determined mainly by the differences in climatic conditions and vegetation (Morris et al., 2003; Maurer et al., 2014) between the arid and humid regions.

The northern areas of the Qinghai-Tibetian plateau, Loess plateau, and the Greater Hinggan mountains in China are typical arid and semi-arid areas, where rainfall events tend to be small and of short duration and the vegetation is dominated by shrubs, alpine, and desert vegetation (Fig.1, Table 1). In these regions, the stand structure of rare tree forest is also poor (Måren et al., 2015), meaning that the biomass in the north is low and the canopy water storage capacity is weak. The opposite is true in the south, where canopy interception capacity is significantly stronger than that in the north due to the abundant rainfall in the growing season and the huge biomass of the widely distributed tree species (Zhang et al., 2013). However, there are some exceptions. For example, Beijing and Qinghai provinces are both arid and semi-arid regions in the north, but the canopy interception rate and canopy interception capacity are ranked among the top in the sites analyzed in China, while canopy water storage capacity was ranked first. The research conducted in Qinghai province was dominated by shrubs (Table 1). While at the same site, the canopy interception amounts of trees were significantly greater than that of the shrubs due to the advantage of biomass (Garcia-Estringana et al., 2010), when the results are investigated from a cross-regional perspective, the reasons become more complex.

Of the six plants screened in Fig. 5, five are shrubs. As can be seen from Fig. 3, overall, the interception rate of shrubbery was higher than that of needle-leaved forests and broad-leaved forests, and second only to mixed forests. Although the biomass of shrubs was small, these results suggest that their interception ability was not less than that of trees. Similar conclusions have also been confirmed in integrated studies of global drylands (Garcia-Estringana et al., 2010; Patricio et al., 2019). Beijing's situation is different from that of Qinghai. As the capital, Beijing has innate policy advantages in ecological environment restoration. Therefore, although the precipitation is relatively small, the vegetation restoration construction over the past few decades has made the amount of forest coverage and biomass growth considerable (Qin et al., 2012; Li et al., 2016), which makes the interception capacity of the vegetation in this area stand out among arid areas (Fig.4). Regardless of policy factors, in the southern region, tree species are the main contributor to canopy interception, while in the northern arid region, the presence of shrub species is more advantageous. Vegetation suitability should be one of the primary principles considered in the optimal allocation of water resources and reforestation.

4.2 Interspecies differences in vegetation interception

There are many studies on the interspecies differences of vegetation interception (Fan et al., 2014; Xiao and Mcpherson, 2011; Wang et al., 2012; Wei et al, 2010), although it is difficult to draw general conclusions about the differences between species. Some studies have compared rainfall interception rates across different stand types. Huber and Iroumé's integrated study in Chile found that the spatial variability of interception losses from broad-leaved forests was greater than that of needle-leaved forests, but the interception rate of needle-leaved forests is higher than that of broad-leaved forests (Huber and Iroumé, 2001), which is consistent with Patricio et al' s research in global dryland forests (Patricio et al.,2019). Studies in southwest China (Wu et al., 2012) and north of the Yanshan mountains (Ji et al., 2013) showed opposite results, although few of these studies involved mixed forests and shrubs.

In this study, we compared both the canopy interception rate and canopy water storage capacity of four vegetation types. Mixed forests had the highest I and I_0 (Fig.6), which indicated that mixed forest was superior for precipitation interception. This might be because mixed forests usually contain a complete ecosystem, high level of biodiversity and have a thick canopy, which are all helpful to improve the interception of vegetation per unit area (Dickmann et al., 1985; Piotto et al., 2004; Piotto 2008). In contrast, pure forests often have a single stand structure, and long-term planting will affect soil nutrient structure and destroy soil physical and chemical properties, resulting in poor stand structure and low intercept ability (Lian and Zhang 1998; Schume et al., 2004; Piotto 2008). Interestingly, shrubbery showed a superior canopy interception rate compared to pure tree forest, and inferior interception capacity. Results indicated that although the interception potential of shrubbery is not large due to the small size of the plants, their interception ability is very strong during actual rainfall events. Wang and Zhang (2012) believed that this was due to the high density of shrubbery that is able to improve canopy storage performance per unit area. When compared across regions, spatial differences in rainfall quantity might play a bigger role in determining the interception function of trees and shrubs. Numerous studies have shown that the canopy interception rate decreases logarithmically as rainfall increases (Shou et al., 2016; Cao et al., 2008). In humid areas, a single rainfall event may be very intense (Ratan and Venugopal, 2013; Lu et al., 2014), leading the canopy to be more likely to approach the saturated state and allowing excess water to reach the ground, leading a lower interception rate (Hanson et al., 2004; Cao et al., 2008; Calder, 2001; Williams et al., 2018). Shrubberys in this study are mostly distributed in the arid and rainless areas in the north, where a single rainfall event is small (Ratan and Venugopal, 2013; Lu et al., 2014). The precipitation preferentially adheres to the shrub leaf surface, and the probability of reaching the ground is low, thus resulting in a high interception rate (Patricio et al., 2019; Wang et al., 2012; Owens et al., 2010). The rainfall pattern also impacts canopy interception, in which rainfall with high intensity and short durations present lower interception values than low intensity, long duration events. If the rainfall event was not continuous, even for short periods, higher interception values result (Crockford and Richardson, 2000). Therefore, it is necessary to consider the possible influence of the climatic characteristics of a given research site.

Climate factors affect spatial differences in vegetation interception capacity, and the unique structure of each vegetation type adds to the complexity of these differences. Due to an incomplete data set, only three structural factors (Height, DBH, and LAI) with abundant samples were selected for analysis in this paper. From Fig.7d and Fig.7h, both I and I_0 showed significant positive correlation with LAI. This indicated that LAI would have good predictive ability for canopy interception (Crockford and Richardson, 2000). In fact, it is also one of the important parameters in many current models (Liang and Xie, 2008; Moeser, et al., 2015). Some studies suggest that the interception loss of vegetation will increase with the age of the forest (Huber and Iroumé., 2001), which is the most apparent in a coniferous forest, possibly because branches tend to be horizontal as the trees age, increasing the vertical projection area. Although no evidence of forest age was obtained in this study, it was found that the DBH of trees was positively correlated with canopy interception ability (Fig.7c and Fig.7g), which indirectly confirmed the influence of tree growth on interception. With increasing tree height, canopy water storage capacity increased significantly, which may also be the result of increased canopy biomass caused by tree growth, another important indicator for predicting canopy water storage capacity. In general, interception rate is the parameter dominated by climate factors (Crockford and Richardson, 2000; Magliano et al., 2019; Mao et al. 2011), which expresses the actual vegetation interception, but this metric is less comparable across vegetation types. Canopy water storage capacity is an interception parameter mainly determined by vegetation structure (Attarod et al., 2015; Kume et al., 2008), which reflects the potential interception and is therefore spatially comparable. Therefore, in the assessment of vegetation canopy interception ability, the comparison of any single parameter is one-sided, and only results combining the two parameters are more objective and accurate.

Vegetation traps precipitation through the canopy, and this part of the water cycle returns to the atmosphere in the form of evapotranspiration (Klaassen et al., 1998). For the humid areas in the south, high vegetation interception was expected, because it would be conducive to reducing floods and promoting atmospheric circulation. For arid and water-deficient areas in the north, it would be beneficial for humans and ecosystems if more precipitation reached the earth surface and was stored for future use. However, as the dominant vegetation in the north, shrubs even showed higher entrapment rate than tree species. This finding suggested that the current shrub structure may be detrimental to water conservation in some arid areas. The dense structure of shrubs was considered as an important factor that impacted its strong interception abilities. Therefore, in order to prevent the sparse precipitation from being trapped by vegetation to evaporate, and have more opportunities to enter into the surface, properly reduce the density of high density shrubbery might be a strategy for water resource management in northern China suffering from extended drought.

5. Conclusion

This study collected measured values of canopy interception rate and simulated values of canopy water storage capacity from 47 ecological sites across China based on data from scientific literature. For the first time, the spatial distribution characteristics of canopy interception capacity in China was described, and the canopy interception ability of different vegetation types was compared.

The study found that the dominant species of canopy interception in the southern region was tree, while in the north it was shrubs. The canopy interception capacity of vegetation in the southern region was generally higher than that in the north, although advantages conveyed through regional forestation policies may artificially reverse this feature. The comprehensive interception ability of mixed forest was the strongest among all the forest types. The interception potential of a pure forested canopy was better than that of shrubs, but the actual interception capacity of shrubs was stronger than that from purely forest. Differences in canopy interception rate and canopy water storage capacity were sensitive to meteorological factors and stand structure, which resulted in inconsistent results when evaluating vegetation interception. The study also highlighted that the current structural characteristics of the northern shrub regions may not be conducive to alleviating regional drought, while reducing the structural density of the stand may help to preserve more precipitation.

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Contributions

Qiufen Zhang participated in the collection, sorting and analysis of all data in the paper, and wrote the original manuscript. Guodong Jia and Ziqiang Liu assisted in the revision of the paper. Xinxiao Yu and Xizhi Lv supervised this work and contributed the same to this work.

Data Availability Statement

The data used to support the findings of this study are included within the article and supplementary materials.

Conflicts of Interest

The authors declare no conflict of interests. The funding sponsors had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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