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Experimental analysis of the effect of forest litter cover on surface soil water dynamics under continuous rainless condition in North China

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Abstract

The forest ecosystem provides fundamental eco-hydrological functions, such as water retention capacity; while the eco-hydrological role of litter layer is often under-appreciated in forest systems. In this study, the effects of forest litter cover on surface soil moisture (θ_w) and soil water evaporation (E_s) under continuous rainless condition in Northern China were evaluated using the micro-lysimeters method. Five experimental groups were settled: the micro-lysimeters covered by Black locust litter /Chinese pine litter with the litter mass of 7.03 kg/m^2 (BL-I /CL-I for short separately), those covered by Black locust litter /Chinese pine litter with the litter mass of 10.54 kg/m^2 (BL-II /CL-II for short separately), and the control group (CG for short). The results indicated that: (1) The soil moisture of control group was less than that of treatment groups throughout the whole experiment period, indicating that the litter layer has a significant effect on the soil water retention capacity. While this effect is insignificantly influenced by the forest leaf litter types / litter mass. (2) The hourly soil water evaporation rates of all experimental groups showed the inverted "U" curve at the beginning of the experiment, but there were significant differences in the amount of hourly soil water evaporation rates and the occurrence time of maximum hourly soil water evaporation between the control group and the treatment groups. (3) The average diurnal soil water evaporation of treatment groups were less than 50% of that of control group during the first 9 days; while it was more than 2 times of that of control group during the 11th day to the 30th day. This result indicated that the diurnal soil water evaporation was mainly influenced by the meteorological factors when the soil moisture was greater than 1/2 of the field capacity. These results highlight the ecological services function of litter layer in forest systems, and it makes a more prominent role in forest management in Northern China.

Keywords: Black locust litter; Chinese pine litter; grey relational analysis; soil moisture content; soil water evaporation.

1. Introduction

As the most important terrestrial ecosystem, forests cover approximately one-third of the world's land surface and perform several important ecological services (Al-dousari *et al*., 2008; Bonan, 2008), such as the improvement of soil water regimes (Mohammed, 2002). Previous research indicated that the forest litter layer between canopy and tootzone layer in vertical structures played an important role in the forest hydrological processes (Sayer, 2006).

Generally, the forest litter layer supports water regulation functions in the following two aspects. First, the litter layer could dramatically increase the infiltration quantity by prolonging the flow retention time during the precipitation process (Putuhena & Cordery, 1996; Bruijnzeel, 2004). For example, Siriri *et al*. (2013) observed that the sesbania and alnus treatments increased mean soil moisture by 9~18% because of the mulching effect of greater litter deposition in Uganda. Huang *et al*. (2010) also observed the reforestation treatments increased infiltration rate of rainfall based on the six-year field experiments in Nü'erzhai catchment, Southern China. Petersen & Stringham (2008) proved that the soil infiltration rates were highly associated with the increase of surface litter during rainfall simulation in a western juniper (*Juniperus occidentalis* Hook.) watershed in south east Oregon. Second, the forest litter layer can effectively delay the soil desiccation process by increasing the surface resistance to soil evaporation (Murphy *et al*., 2004; Murphy & Lodge, 2001; Yao *et al*., 2014). For instance, Villegas *et al*. (2010) indicated that the existence of litter layer could influence the soil evaporation by attenuating radiation flux and resisting the water flux based on the field experiments in the Santa Rita Experimental Range, Arizona, USA. Baldocchi & Meyers (1991) observed that the forest litter surface imposed a significant resistance to water vapor transfer using the eddy correlation methodin the U.S. Department of Energy Reservation, Oak Ridge, Tennessee. Zhou *et al*. (2008) revealed that the litter cover exhibited an obvious inhibition on soil evaporation and this inhibition efficiency increased with litter cover thickness based on the experiment in the Tarim Desert Highway shelterbelt, China. However, impacts of leaf litter on soil eco-hydrological properties varied among litter type and mass, such as the precipitation interception and soil erosion (Li *et al*., 2014). Yoshinobu *et al*. (2004) found that the broad-leaf litter could intercept more rainwater than the needle-leaf litter, based on the experiment in the Research Institute of Kyushu University Forest. The role of litter layer in hydrologic cycle in forest ecosystem was often underestimated and related mechanisms still remain unclear.

The North China plain is one of the most water-stressed regions in China. Currently, the situation has been aggravated further by abrupt climate change and intensive human activities (Alley *et al*., 2003; Bates *et al*., 2008). Ensuring water security has become one of the dominant problems for both scientists and policy-makers in China (Piao *et al*., 2010; Xia & Zhang, 2008). Therefore, the eco-hydrological function of forest ecosystem has become one of the research hotspots, mainly focused on the water retention capacity (Li *et al*., 2013; Zhang *et al*., 2010; He *et al*., 2011; Yu *et al*., 2002).

The objective of this study is to investigate the effect of different leaf litter type and litter mass on the soil moisture content and soil evaporation rate under continuous rainless condition during the growing season in North China, and further analyze the main influencing factors of soil evaporation in the experiment. Specifically, we hypothesize that the forest litter layer would impose significant resistance to soil water evaporation, and this effect would change with the litter type and litter mass.

2. Materials and methods

2.1 Field site

The experiment was carried out in June and July, 2013 at the Daxing experimental station of China Institute of Water Resources and Hydropower Research (116°25' E, 39°37'N, approximately 31m elevation above sea level). The area features a temperate continental monsoon climate. Mean annual temperature is 12.1°C. Mean annual precipitation is 540 mm, mainly focused in July and August in the form of rainstorm, accounting for 81.2%. Mean annual potential evaporation is 1889 mm. According to the experimental results, the soil in the experimental plot is approximately 2.0% clay, 69.4% silt and 28.6% sand, which belongs to the category of silt loam. The average field capacity (θ_f) is 29.32±1.07% and the dry soil bulk density is 1.38±0.09 g/cm^3.

2.2 Experimental methods

2.2.1 Litter samples collection

Both the Black locust (*Robinia pseudoacacia* L.) and the Chinese pine (*Pinus tabuliformis* Carrière) have the advantage of high drought-tolerance, fast growth and barren resistance, which have been widely used in afforestation in North China. Therefore, in this study, we selected the above-mentioned two typical contrasting forest leaf litters: the Black locust litter (as the broad-leaf type) and the Chinese pine litter (as the needle-leaf type). The forest leaf litter samples were collected from two representative forest sample plots in the western hills of Beijing in May, 2013. Each of the sample plots was dominated by relatively pure forest of Black locust/ Chinese pine respectively. Both sample plots size was 10m×10m. The average litter thickness of the Chinese pine sample plot was 1.07cm, and that of the Black locust sample plots was 1.75cm, based on the measurement of five random sampling points in each sample plot. Ten quadrats with the area of 0.3m×0.3m were set randomly in each sample plot. The litter mass contained in the quadrat was collected and put into a plastic case, which was brought back for the laboratory analysis.

2.2.2 Experimental design

In this study, the experiment was carried out by employing the micro-lysimeters method. The micro-lysimeters were made by rigid polyvinyl chloride with a height, length and width of 15cm, 23cm and 16.5cm, respectively. The plastic rectangle pipes (23cm×16.5cm) were stuck into the soil with a depth 15cm, then the pipes with intact soil columns were dug out of the ground. The bottom of the soil columns had been flattened and sealed with a plexiglass plate. After drying at 105°C to a constant weight, the pipes with intact soil columns were placed in-situ at a distance of 30cm from each other. Meantime, the fundamental physical properties of soil were measured by experimental methods. The soil texture was measured by using one mixed soil sample of the pilot area according to the standard of Soil Testing Part3: Method for determination of soil mechanical composition (NY/T 1121.3 -2006). The field capacity and dry bulk density were measured by using six single soil samples of the pilot area according to the standard of Soil Testing Part 22: Cutting ring method for determination of field water-holding capacity in soil (NY/T 1121.22 -2010).

The litter bag technique was used to guarantee the separation between forest litter and soil (Villegas *et al*., 2010). The litter bags were constructed from nylon netting with 60 mesh screen, and placed on the micro-lysimeters surface. The micro- lysimeters covered by the litter bags were assigned to treatment groups, including the Black locust litter-covered treatment (BL group) and the Chinese pine litter-covered treatment (CL group); while the others were assigned to the control group (CG group). For the treatment groups, two litter masses were setted: I= 7.03kg/m^2 and II = 10.54kg/m^2. Overall, there are five experimental groups, namely control group (CG), BL groups with the litter mass of 7.03 kg/m^2 (BL-

I), BL groups with the litter mass of 10.54 kg/m^2 (BL-II), CL groups with the litter mass of 7.03 kg/m^2 (CL-I), CL groups with the litter mass of 10.54 kg/m^2 (CL-II), and experiment was conducted for each group in triplicates. The initial soil moisture of all groups were treated under the conditions of simulated rainfall amounts of 90mm for 24h, which belong to the rainstorm grade (50mm≤R<100mm) in North China, by employing an artificial rainfall simulator, composed with water tank, micro air pump, sprinklers and connecting pipes. After the rainfall simulation, all groups were sheltered from natural precipitation by a plastic awning.

This experiment was stoped when the soil water content of all groups were less than 50% field capacity, which could significantly inhibit the normal physiology functions of plants (Shan *et al*., 2005; Yang *et al*., 2004). The micro-lysimeters without litter-bag were weighed at 19:30p.m. every day during the whole experiment period using an electronic scale with the precision of 1.0g, then the diurnal soil water evaporation was calculated according to the equation of water balance. Besides, the micro-lysimeters without litter-bag were weighed from 4:30a.m. to 20:30p.m. at one-hour intervals in the first sunny day after the simulated rainfall event and the hourly soil water evaporation was also calculated.

2.2.3 Meteorological data

Mean hourly/daily meteorological data, including air temperature (AT), relative humidity (RH), net solar radiation (SR) and wind speed (WS), were recorded by the Dynamet Weather Station in the open grass land of the Daxing experimental station, which was less than 20 meters from the experimental site.

2.3 Data analyses

Firstly, the one-way analysis of variance (ANOVA) was used to determine the differences with significance levels at P<0.05 (indicated by *) and P<0.01 (indicated by **) between the control group and the treatment groups. Secondly, the grey relational analysis method was used to analyze the correlative relations between diurnal soil water evaporation and its influencing factors.

The grey relational coefficient is calculated as following (Liu & Forrest, 2010):

$$\gamma(Y, X_i) = \frac{1}{n}\sum_{k=1}^{n}\gamma(y(k), x_i(k)) \tag{1}$$

Of which, $\gamma(y(k), x_i(k)) = \dfrac{\min\limits_i \min\limits_k |y(k) - x_i(k)| + \xi \max\limits_i \max\limits_k |y(k) - x_i(k)|}{|y(k) - x_i(k)| + \xi \max\limits_i \max\limits_k |y(k) - x_i(k)|}$

where, γ is the grey relational coefficient; y and x_i are the data series of the diurnal soil water evaporation and its influencing factors after normalisation, respectively; ξ is the distinguishing coefficient ranged between 0~1, which is taken as 0.5 herein.

All datasets were analyzed using SPSS 16.0 and the figures were processed using Origin Pro 8.0.

3. Results and discussion

3.1 Effect of forest litter on soil moisture content

There were significant differences in the soil drying curves between the control group and the treatment groups during the entire experimental process, which were presented in Figure 1. Overall, the soil moisture contents of treatment groups were greater than that of control group throughout the whole experimental period, though the difference between the treatment groups and control group did not reach the significant level of 5% in the first day. A similar conclusion was also drawn by Sharafatmandrad *et al*.(2010) from their study in an arid range land in Khabr National Park in south-eastern Iran.

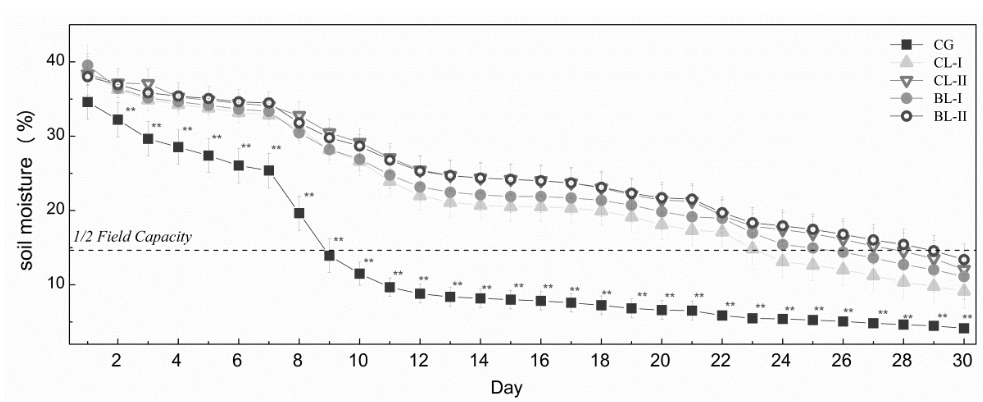

Fig. 1. Variation of soil moisture content during the entire experimental process for five treatment plots (CG, control group; CL-I, treatment group of micro-lysimeters covered by Chinese pine litter with the litter mass of 7.03kg/m^2; CL-II, treatment group of micro-lysimeters covered by Chinese pine litter with the litter mass of 10.54kg/m^2; BL-I, treatment group of micro-lysimeters covered by Black locust litter with the litter mass of 7.03kg/m^2; BL-II, treatment group of micro-lysimeters covered by Black locust litter with the litter mass of 10.54kg/m^2). Error bars represent standard deviation of soil evaporation rate. The bars with ** indicate statistically significant (P<0.01) differences of soil moisture content between the control group and treatment groups. The dashed line represent 1/2 of the field capacity in the experimental plot.

The soil drying curve of control group falls in a negative-exponential pattern. The entire experimental process can be divided into two stages: rapid decrease stage/ stage I (from day 1 to day 9) and steady decrease stage/ stage II (from day 10 to day 30). During stage I, the soil moisture content of control group fell from 34.60% to 13.92%, which was less than 1/2 of the field capacity. However, the soil moisture content of control group only decreased by 5.52% during stage II. While the soil moistures of both treatment groups were slowly and linearly decreased during the entire experimental process, which was less than 1/2 of the field capacity in the 30th day.The decreased rates of soil moisture content followed this order: BL-II > BL-I > CL-II > CL-I, but there were no significant differences among the treatment groups (P>0.05). The results demonstrated that the forest litter can significantly enhance water retention capacity of the soil and the effect would change with the litter types and litter masses. Compared to the needle-leaf type litter, the broad-leaf type litter has a stronger effect on the water retention capacity of the soil. Moreover, for the same litter type, the enhanced effect was improved with increasing litter mass.

3.2 Effect of forest litter on soil water evaporation

3.2.1 Effect of forest litter on hourly soil water evaporation

The average hourly soil water evaporation rates of all groups in the first sunny day after the simulated rainfall event showed the inverted “U” curve (Figure 2). The minimum soil hourly evaporation rates of all five groups were recorded at 6:00 a.m. while the peak values were recorded during 12:00a.m.~14:00 p.m.

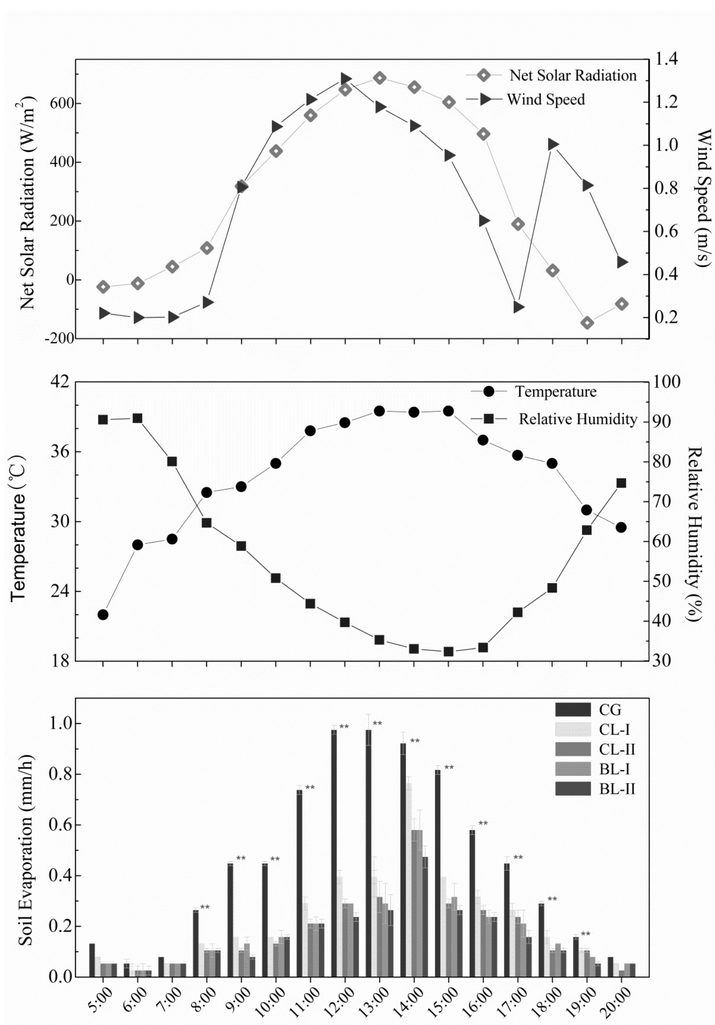

Fig. 2. Variation of the hourly soil evaporation rate (mm/h) and the meteorological factors durring the soil moisture content greater than 1/2 of the field capacity for five treatment plots (CG, control group; CL-I, treatment group of micro-lysimeters covered by Chinese pine litter with the litter mass of 7.03 kg/m^2; CL-II, treatment group of micro-lysimeters covered by Chinese pine litter with the litter mass of 10.54 kg/m^2; BL-I, treatment group of micro-lysimeters covered by Black locust litter with the litter mass of 7.03 kg/m^2; BL-II, treatment group of micro-lysimeters covered by Black locust litter with the litter mass of 10.54 kg/m^2). Error bars represent standard deviation of soil evaporation rate, and the bars with ** indicate statistically significant (P< 0.01) differences of soil evaporation ratebetween the control group and treatment groups.

There were significant differences in the daily variation process of soil water evaporation between control group and treatment groups. Firstly, the hourly soil water evaporation rates of treatment groups were significantly lower than that of contral group during 8:00a.m.~19:00p.m. (P<0.01). The average hourly soil water evaporation rate of control group ranged from 0.132 mm/h to 0.975 mm/h, with 0.588 mm/h on average, followed by the CL-I group with the average hourly soil water evaporation rate 0.294 mm/h. The average hourly soil water evaporation rates of CL-II group and BL-I group were equal to 0.228 mm/h, ranged from 0.105 mm/h to 0.580 mm/h. The average hourly soil water evaporation rate of BL-II group was the lowest among all groups, with the values of 0.195 mm/h, which was only 1/3 of that of control group. These results further proved that the forest litter could significantly restrain soil water evaporation, when the soil moisture is adequate during the growing season. Secondly, there was significant differences in the occurrence time of maximal hourly soil water evaporation rate between control group and treatment groups (P< 0.01). The peak values of control group were recorded both at 12:00a.m. and 13:00p.m., while the maximum hourly soil water evaporation rates of treatment groups were recorded at 14:00 p.m. The main reason was that, under enough soil water supply, the soil water evaporation rate of control group was controlled by the net solar radiation (Allen *et al*., 1998), as the aforesaid analysis, which reached a peak at noon. While the soil water evaporation rates of treatment groups were mainly influenced by the air/ soil temperature, the maximum of which were observed at 14:00 p.m. (Xu *et al*., 1997).

3.2.2 Effect of forest litter on diurnal soil water evaporation

The variations of diurnal soil water evaporation rates and its influencing factors are shown in Figure 3.

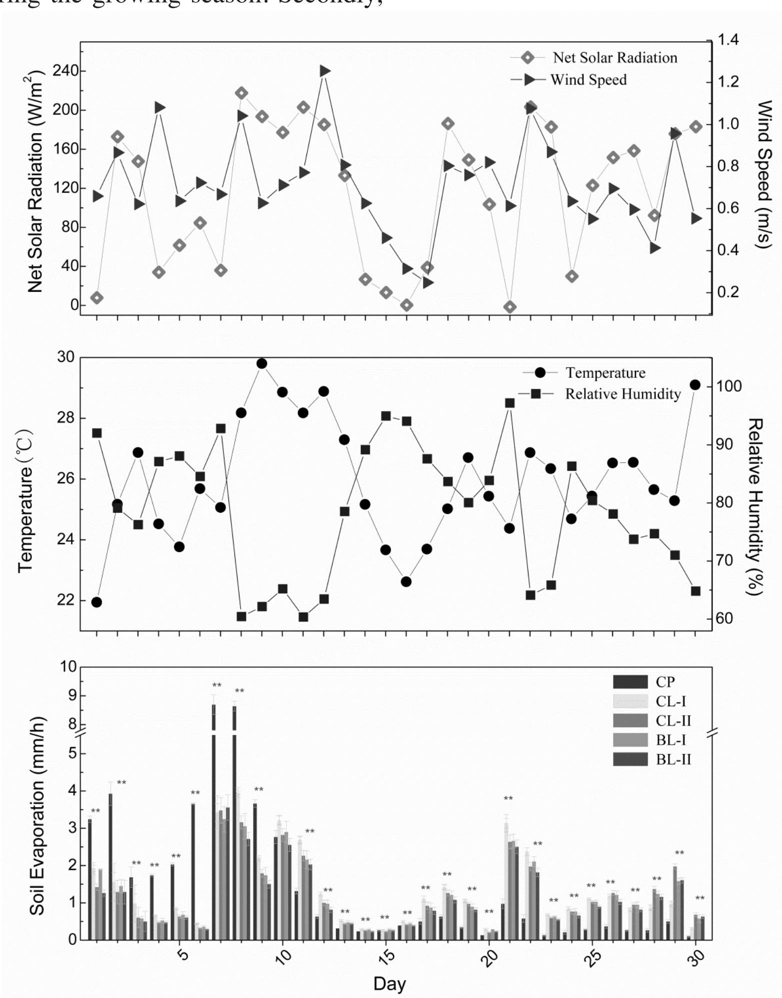

Fig. 3. Variation of the diurnal soil evaporation rate (mm/h) and the meteorological factors during the entire experimental process for five treatment plots (CG, control group; CL-I, treatment group of micro-lysimeters covered by Chinese pine litter with the litter mass of 7.03 kg/m^2; CL-II, treatment group of micro-lysimeters covered by Chinese pine litter with the litter mass of 10.54 kg/m^2; BL-I, treatment group of micro-lysimeters covered by Black locust litter with the litter mass of 7.03 kg/m^2; BL-II, treatment group of micro-lysimeters covered by Black locust litter withthe litter mass of 10.54 kg/m^2). Error bars represent standard deviation of soil evaporation rate, and the bars with ** indicate statistically significant (P<0.01) differences of soil evaporation rate between the control group and treatment groups.

Based on the results of one-way ANOVA test, there were three periods. During the first 9 days, the diurnal soil water evaporation rates of treatment groups were remarkably less than that of control group ($P<0.01$), which indicated that the wet litter layer could reduce water. The average diurnal soil water evaporation rates of treatment groups ranged from 1.356 to 1.773 mm/d, of which the average diurnal soil water evaporation rate of CL-I group was greatest ($P<0.01$), followed sequentially by the BL-I, CL-II and BL-II groups, and not difference among these groups ($P>0.05$). While the average diurnal soil water evaporation rate of control group was 4.142 mm/d, ranged between 1.686~8.696 mm/d, which was more than 2 times of that of treatment groups. There were no significant differences in diurnal soil water evaporation rates among five groups in the 10^{th} day ($P>0.05$). However, during the 11^{th} day to the 30^{th} day, the average diurnal soil water evaporation rates of treatment groups were significantly greater than that of control group ($P<0.01$). The average diurnal soil water evaporation rate of control group was 0.423 mm/d, ranged from 0.105 to 1.318 mm/d. But the average diurnal soil water evaporation rates of treatment groups ranged between 0.939~1.084 mm/d, which instead were more than 2 times of that of control group. That was mainly influenced by the moisture supply at the evaporative surface. As the soil columns dried out, the water-potential gradient between soil surface and atmosphere increased and the upward water flux tended to balance the water loss of soil surface (Stewart & Howell, 2003). Affected by much less soil moisture contents of control group, the soil moisture contents of soil columns were not sufficient to maintain the upward water flux, and hence led to decrease of the soil water evaporation rate. Similar conclusions also have been obtained by Zhou *et al*. (2008) based on the experiments in the Tarim Desert Highway shelter belt, China.

Furthermore, the variation of relationship between the diurnal soil water evaporation rates and its influencing factors is similar, based on the grey relational analysis, which was shown in the Figure 4. During the first 9 days (Period I), the average wind speed had the highest grey relational coefficient in all groups, which was greater than 0.64, followed by the net solar radiation in the control group and the air tempreture in the treatment groups respectively. While the grey relational coefficient of soil moisture was the minimum in all groups, which was less than 0.5. The results indicated that the diurnal soil water evaporation variations of all groups were mainly influenced by the meteorological factors, rather than the soil moisture content, when the soil moisture content was greater than 1/2 of the field capacity. However, during the 11^{th} day to the 30^{th} day (Period II), the highest grey relational coefficient was the soil moisture in the control group, but that were still the wind speed in those treatment groups. The grey relational coefficient of soil moisture was third highest both in the CL-I and CL-II groups, but the last in the BL-I and BL-II groups. The results indcated that the effect of soil moisture on the diurnal soil water evaporation gradually increased with the decrease of soil moisture.

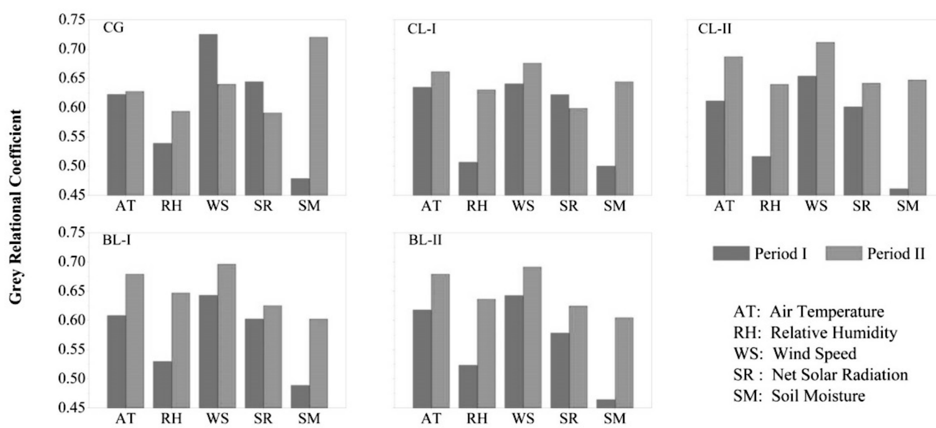

Fig. 4. Change of grey relational coefficients between the diurnal soil evaporation rates and its influencing factors between the first 9^{th} days (Dark grey bars) and the 11^{th} day to the 30^{th} day (light grey bars) for five treatment plots (CG, control group; CL-I, treatment group of micro-lysimeters covered by Chinese pine litter with the litter mass of 7.03kg/m^2; CL-II, treatment group of micro-lysimeters covered by Chinese pine litter with the litter mass of 10.54kg/m^2; BL-I, treatment group of micro-lysimeters covered by Black locust litter with the litter mass of 7.03kg/m^2; BL-II, treatment group of micro-lysimeters covered by Black locust litter with the litter mass of 10.54kg/m^2).

4. Conclusions

The experiment was carried out to investigate the effect of forest litter on soil moisture content and soil water evaporation under continuous rainless condition using the micro-lysimeters method in North China. Forest litter provides critical eco-hydrological functions in forest ecosystem, and has an important role in ensuring water security in Northern China. Significantly higher soil moisture contents were observed in treatments with forest litter. Impacts of forest litter on soil moisture depend on litter type and litter mass. Hourly soil water evaporation rate can also be altered by forest litters, while the impacts were highly dependent on soil moisture content. Better understanding of how forest litter impacts soil water properties is necessary and can help developing sustainable forest management measures using leaf litter as a tool.

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تحليل تجريبي لتأثير غطاء القمامة على ديناميكية مياه التربة السطحية تحت ظروف انعدام الأمطار في شمال الصين

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الملخص

يزود النظام الاقتصادي للغابات وظائف اقتصادية هيدرولوجية أساسية مثل القدرة على الاحتفاظ بالمياه وفي الغالب يتم تقليل تقدير الدور الاقتصادي الهيدرولوجي الذي تلعبة طبقة القمامة في نظام الغابات. في هذا البحث يتم استخدام طريقة ميكرو – ليسيمترز لتقييم تأثير غطاء القمامة على رطوبة التربة السطحية (Qw) وعلى تبخر مياه التربة (Es) تحت ظروف انعدام الأمطار في شمال الصين. تم الاستقرار على خمس مجموعات للتجارب. المايكروليسيمترز المغطى بقمامة بلاك لوكوست (BL-I) وقمامة شجر الخشب الأبيض الصينية بكثافة 7.03 كجم / متر مربع (CL-I) والمغطى بقمامة بلاك لوكوست (BL-II) وقمامة شجر الخشب الأبيض الصيني (CL-II) بكثافة 10.54 كجم / متر المربع إضافة إلى مجموعة التحكم (CG). تشير النتائج إلى التالي: (1) رطوبة التربة في مجموعة التحكم كانت أقل من نظيرتها في جميع المجموعات تحت الدراسة طوال مدة التجربة مما يوضح أن لطبقة القمامة تأثير واضح على قدرة التربة على الاحتفاظ بالمياه. بينما لا تتأثر هذه الخاصية بنوع القمامة. (2) معدل تبخر المياه في الساعة لجميع المجموعات تظهر منحنى ال U المقلوب في بداية التجربة لكن هناك فروق واضحة بين مجموعة التحكم والمجموعات محل الدراسة في كمية معدل التبخر في الساعة لمياه التربة وزمن حدوث القيمة العظمى لمعدل التبخر في الساعة لمياه التربة. (3) معدل التبخر في النهار لمجموعات الدراسة كان أقل من 50% من مثيله في مجموعة التحكم خلال المدة من اليوم الحادي عشر إلى اليوم الثلاثين. هذه النتيجة توضح أن تبخر مياه التربة في النهار يتأثر أساساَ بعوامل المترولوجيه عندما تكون رطوبة التربة أعلى من نصف سعة الحقل. هذه النتائج تلقي الضوء على وظيفة الخدمة الايكولوجية لطبقة القمامة في نظم الغابات وتصنع دور متقدم في إدارة الغابات في شمال الصين.