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ESTIMATION OF EVAPOTRANSPIRATION AND WATER USE EFFICIENCY OF THREE VEGETATION COMMUNITIES USING DRAINAGE LYSIMETERS IN THE TAIHANG MOUNTAINS, CHINA

Fan Yang[1,2]
Zhijun Liu[3]
Wanjun Zhang[2]
Yonghui Yang[2]

[1]Northeast Institute of Geography and Agroecology
Chinese Academy of Sciences, Changchun, Jilin Province, China
[2]Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang, Hebei Province, China
[3]Dynamic Solutions, LLC, Knoxville, Tennessee, USA

The objective of this research is to measure the evapotranspiration (ET) and water use efficiency (WUE) of three native vegetation communities to provide scientific information for vegetation recovery in the Taihang Mountains, China. They are a local grass, a local shrub and a mixture of the two. The ET and WUE were measured using level and slope lysimeters. The results show that the drainage lysimeter is an effective tool for estimating plant ET in mountainous areas. Generally, the measured ET was higher in the level lysimeters than the slope lysimeters because of loss of surface runoff from the slope lysimeter. The monthly ET peaked in August and had a close linear relationship with leaf area index. For all three communities, the dry weight and water use efficiency were higher in the level lysimeters than the slope lysimeters. For both level and slope lysimeters, the mixed vegetation community has a higher water use efficiency than grass or shrub alone. It is recommended that the mixed vegetation community be used for the vegetation recovery in the Taihang Mountains due to its higher WUE.

INTRODUCTION

The Taihang Mountains are one of the poorest mountainous areas of China. In this area, the majority of original forest was destroyed by cattle grazing, converting forest into cropland, and cutting forests to satisfy the needs for fuel from local residents. The original broad-leaved trees have been replaced by shrubs and grasses. The degraded ecosystem has adversely affected the soils and water resources of this region. The lack of vegetation cover causes serious soil losses during storm events, which in turn degrades the soil fertility and structure. In order to restore these impaired ecosystems, the State Council of the People's Republic of China passed the Regulations Concerning Grains in 2002. This law requires that all cropland cultivated on the mountainous areas with a slope higher than 15° be returned to forest or pasture lands. Understanding the water use efficiency (WUE) and hydrological functions of current vegetation communities is critical for successful vegetation recovery and sustainable development of the Taihang Mountains area. For example, Liu et al. (2003) estimated the seasonal evapotranspiration (ET) of pomegranate (*Pumica Granatum*) using the Bowen ratio method and proposed that two supplemental irrigations should be scheduled. This research has provided useful information regarding irrigation management for the local farmers in the Taihang Mountains areas.

As one of the most important hydrological components, evapotranspiration has received wide attention from all over the world (Ward, 1971; Mao et al., 2002). Methods for direct ET measurements include regional water balance, lysimeters, eddy correlation, and a controlled environment chamber. The regional water balance approach is capable of measuring the representative ET over a large scale, but cannot measure the ET for a specific vegetation community (Song et al., 2004b). The sensors used in eddy correlation are expensive and easily contaminated, which greatly limits their application in mountainous areas (Spittlehouse and Black, 1981; Yang, 2006). One of the disadvantages of the controlled environment chamber is that any small perturbations in the system state will cause inaccurate estimation of ET (Timlin et al., 2007). Lysimeters are the most commonly used approach to estimate the ET of vegetation communities in mountainous areas (Song et al., 2004a, b). Gee and Hillel (2006) pointed out that regional water balance models were suitable in use for irrigated agriculture but could inaccurately predict the ET in arid regions where plant cover is sparse and plants are subjected to seasonal water stress. They recommended that lysimetry and tracer tests be used for ET estimation in arid areas.

As a typical semiarid to semi-humid area, the Taihang Mountains have a low vegetation cover percentage of 20%. In addition, rainfall is distributed unevenly among the growth stages of local vegetation and plants often experience seasonal water stress. In this research, a lysimeter was selected as the ET estimation method. The first objective is to measure the ET from three local vegetation communities of the Taihang Mountains. These are a local grass community, *Themeda japonica* (referred to as TMgrass), a local shrub community, *Tanaka, V. negundo var. heterophylla Rehd* (referred to as TMshrub), and a community that is a mixture of the two. ET was measured using drainage lysimeters. The second objective of this research is to compare the ET of the three communities in level and slope lysimeters. The third objective is to calculate the WUE of the three vegetation communities. Findings from this research can provide useful information for vegetation recovery and sustainable development of forestry in the Taihang Mountains areas.

MATERIALS AND METHODS

Study area description

Experiments were conducted at the Ecological Experimental Station of Taihang Mountains (EESTM), affiliated with the Chinese Academy of Sciences. The study area is located at the eastern Taihang Mountains, with geographic coordinates of E 114°15’55" and N 37°52'45". The study area has a typical semiarid to semi-humid continental climate. The annual mean precipitation is approximately 510 mm, 70% of which occurs during July to September. The annual average air temperature is about 13°. The typical shrubs and grasses are *Tanaka, V. negundo var. heterophylla Rehd* (TMshrub), *Themeda japonica* (TMgrass), *Z. jujuba var. spinosa Hu*, and *B. ischaemum (L.) Keng*. The artificially cultivated species include persimmon (*Diospyros kaki Linn.f.*), walnut (*J. regia L.*), Apricot (*Prunus armeniaca L.*), Zanthoxylum (*Zanthoxylum bungeanum*), and Jujube (*Z. jujuba Mill.*). In the flat areas, crops such as wheat and sweet potato are cultivated.

Lysimeter design

A total of 6 lysimeters were constructed. They were 260 cm in length, 160 cm in width, and 120 cm in height, as illustrated in Figure 1. The lysimeter is a tank placed in the ground that isolates the soil mass and vegetation so all water enters or leaves at controlled points. Three of them have a slope of 0°, and are referred to as the level lysimeters, and 3 of them have a slope of 25°, and are referred to as the slope lysimeters. The three vegetation communities, TMgrass, TMshrub, and the mixture of the two, were planted in both level and slope lysimeters. The walls of the lysimeters were made of brick and concrete with a thickness of 10 cm. In the bottom, there was a filter layer of 10 cm consisting of boulders, gravel and sand in order to help drain the water during heavy storm events. In the bottom, there was a pipe to collect deep drainage. The bottom was slightly tilted to the side with a drainage pipe in order to facilitate the water movement. The soil surface is 6 cm lower than the edge of the lysimeters.

In October of 2003, the representative vegetation communities of TMgrass and TMshrub were selected and transplanted into the lysimeters. The main stem of TMshrub was cut at a height above ground of 5 cm. For the mixed community, TMgrass and TMshrub covered 50% of the lysimeter area equally. Experimental measurements were conducted from May to October 2004.

Data collection

The measured parameters included precipitation, surface runoff, soil water content, deep drainage, soil water potential, biomass, plant height, root distribution in the soil, and leaf area index (LAI). The meteorological data were obtained from the automated weather station of EESTM. The precipitation, surface runoff, and deep drainage were measured using automatic rain gauges. The soil water content was estimated at soil depths of 30, 60, and 100 cm, using Time-Domain

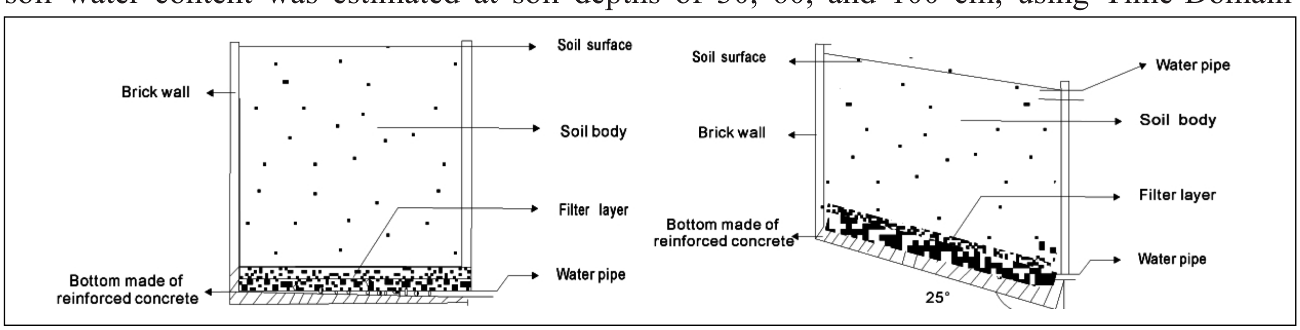

Figure 1. Illustration of constructed level and slope lysimeters.

Reflectometry (Campbell Scientific Corporation model CS616). The sensors were connected to the CR10X automatic data collector. The communities were harvested in November, 2004, and the biomass was measured with an electronic scale. The soil water potential at soil depths of 10, 30, 60, and 100 cm, was observed using tensiometers. The leaf area was measured monthly to calculate LAI. The plant heights were measured monthly. After maturity in November, 2004, the root distributions in the soil profiles were investigated.

Data analysis

All the hydrological components were measured except ET. Hence, the ET can be estimated using the water balance Equation (1).

$$ET=P-R-\Delta S-D \quad (1)$$

where ET is the calculated evapotranspiration (mm); P is the measured amount of precipitation (mm); R is the surface runoff (mm); ΔS is the change of soil water storage (mm); and D is the deep drainage (mm).

The WUE for the three vegetation communities was calculated using Equation (2).

$$WUE=Y/ET \quad (2)$$

where WUE is the calculated water use efficiency (g/mm-m^2); and Y is the biomass of the vegetation communities (g/m^2).

Regression analysis was conducted to evaluate the relationships between monthly ET and LAI, and between the vegetation height and cumulative ET.

RESULTS AND DISCUSSION

Rainfall distribution

The observed rainfall distribution is shown in Figure 2. The 2004 water year was a humid year with annual precipitation of 706.4 mm, which exceeded the average annual rainfall of 510 mm. The water year exhibited the typical seasonal precipitation pattern of the Taihang Mountains. The majority of rainfall, approximately 76%, occurred in the summer season (June to August) (Figure 2). The winter season (December to February) had the lowest amount of precipitation, about 2%. The percentages of precipitation in Spring (March to May) and Fall (September to November) were 12% and 10%, respectively. There were two large storm events with a total amount of rainfall exceeding 100 mm. One event occurred during July 11 to 12, with a total precipitation of 152 mm. Another one was during August 9 to 14, with a total precipitation of 171.3 mm.

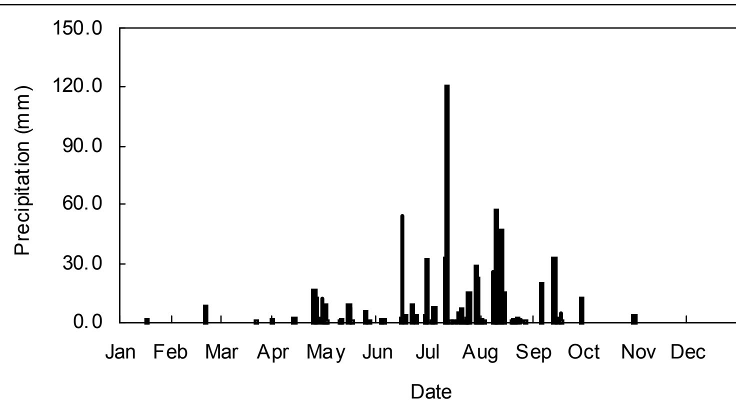

Figure 2. Observed rainfall of 2004 at Ecological Experimental Station of Taihang Mountains.

Growth characteristics of vegetation communities

Root distribution

The root distributions in the soil for TMgrass and TMshrub are shown in Figure 3. The majority of TMgrass roots, approximately 91.7%, were found in the soil depth of 0-40 cm (Figure 3). This indicated that TMgrass can only utilize the water in the surface soil. The TMshrub was able to absorb the water in the soil depth lower than 40 cm because 36% of TMshrub roots were distributed in this profile (Figure 3).

Vegetation height

The height growth curves of the three vegetation communities are shown in Figure 4. The growing season for these communities was from April to October (Figure 4). In April, the average air temperature was approximately 16.8°C, and the plants begin to turn green. However, the soil water content was very low at this time due to the low recharge from Winter and Spring rainfall (Figure 2). Hence, in April and May, plants grew very slow in Taihang Mountains areas. The rapid growth of TMshrub started from the beginning of June with an average growth rate of 1.4 cm/day. Even though the rainfall was very low in June, TMshrub can utilize the water in the deep soil to supply enough water. The rapid growth at this period prepared enough nutrients for the flowering stage of TMshrub (the middle of June). The TMshrub began to produce seeds during July to August with a lower growth rate of 0.8 cm/day. In the mature period of TMshrub, during September to

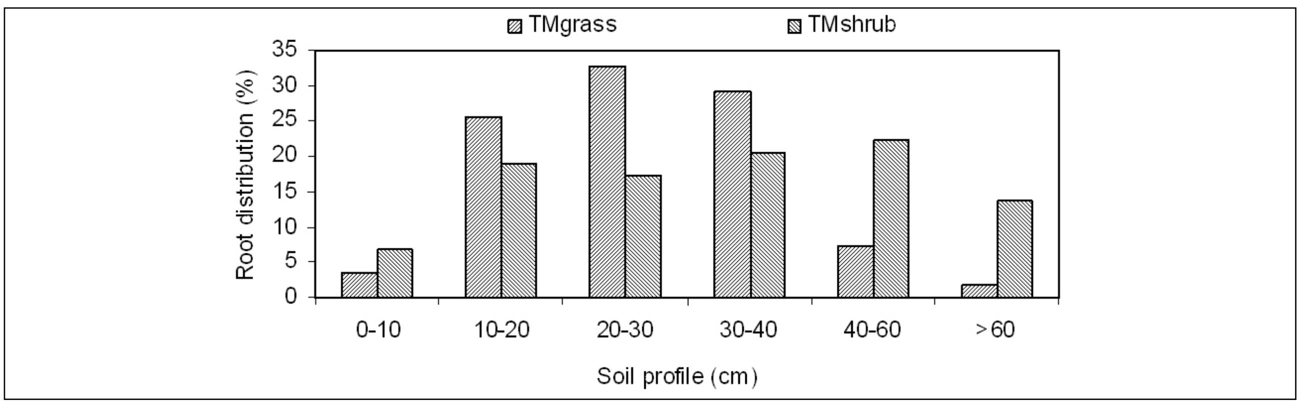

Figure 3. Root distributions of the TMgrass and TMshrub.

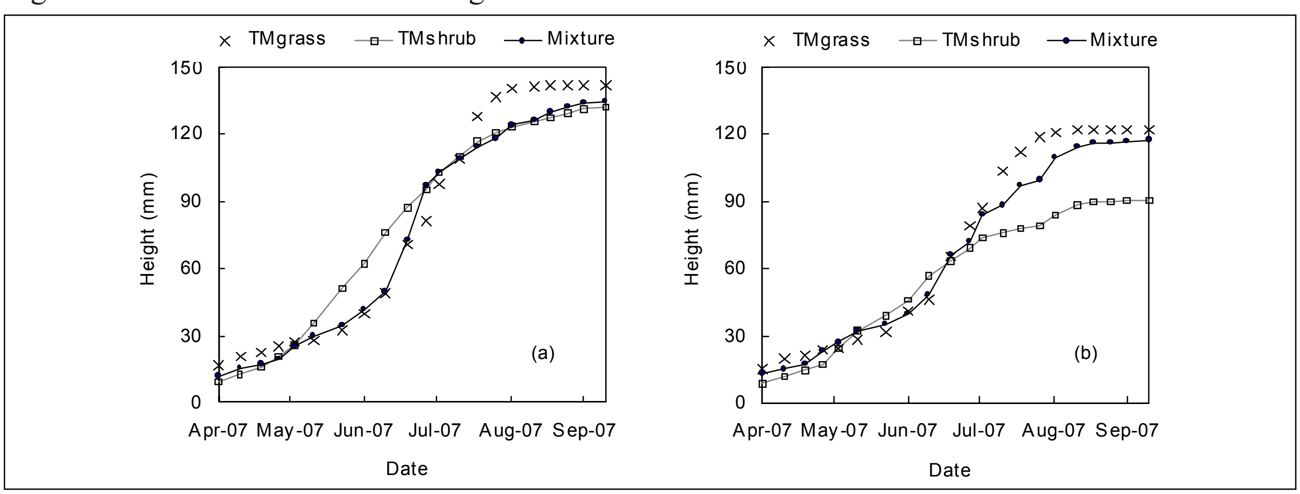

Figure 4. Measured heights of the vegetation communities. (a) is for level lysimeter; and (b) is for slope lysimeter.

October, the average growth rate was only about 0.3 cm/day (Figure 4). For the TMgrass, the rapid growth started from the beginning of July, when there is large amount of rainfall. This was followed by a slow growth period. In September, the TMgrass was nearly mature.

In the slope lysimeters, the growth trend of the grass-shrub mixture community followed the trend of TMgrass over the entire growing season. In the level lysimeters, the growth trend of the mixture followed the trend of TMgrass in the early period, and then followed the trend of TMshrub.

Over the growing season, the plant heights of TMgrass and the mixture communities in the level lysimeters were slightly higher than those in the slope lysimeters (Figure 4). The peak heights of TMgrass, and the mixture were 128.9, and 127 cm, respectively in the level lysimeters, and 122.5, and 117.4 cm, respectively in the slope lysimeters (Figure 4). The plant height of TMshrub in the level lysimeter was much higher than that in the slope lysimeter. The peak heights of TMshrub in the level and slope lysimeters were 122, and 90.8 cm, respectively (Figure 4). For the slope lysimeters, the rainfall became both surface runoff and deep drainage, whereas in the level lysimeters there was only deep drainage. Compared with the slope lysimeters, there was more soil water in the level lysimeters available for ET, which resulted in the differences in heights of vegetation between the level and slope lysimeters. For example, over the growing season, the total water loss (surface runoff plus deep drainage) from TMshrub in the slope lysimeter was 173 mm, whereas the water loss of TMshrub from the level lysimeter was 83.9 mm. The higher amount of water loss from the slope lysimeters might cause water stress for vegetation growth.

Leaf area index

The calculated leaf area indexes for the three vegetation communities are given in Figure 5. The peak LAI of TMgrass occurred in August, whereas the peak LAI of TMshrub occurred in September (Figure 5). For the level lysimeters, TMgrass had a larger LAI than TMshrub before August, but lower LAI after August. For the slope lysimeters, TMgrass had a larger LAI than TMshrub over the entire growing season. As with the plant heights, at every stage of plant growth, the LAIs in the level lysimeters were higher than those in the slope lysimeters, which could be due to water stress the vegetation experienced in the slope lysimeters. Similar results have been reported where water

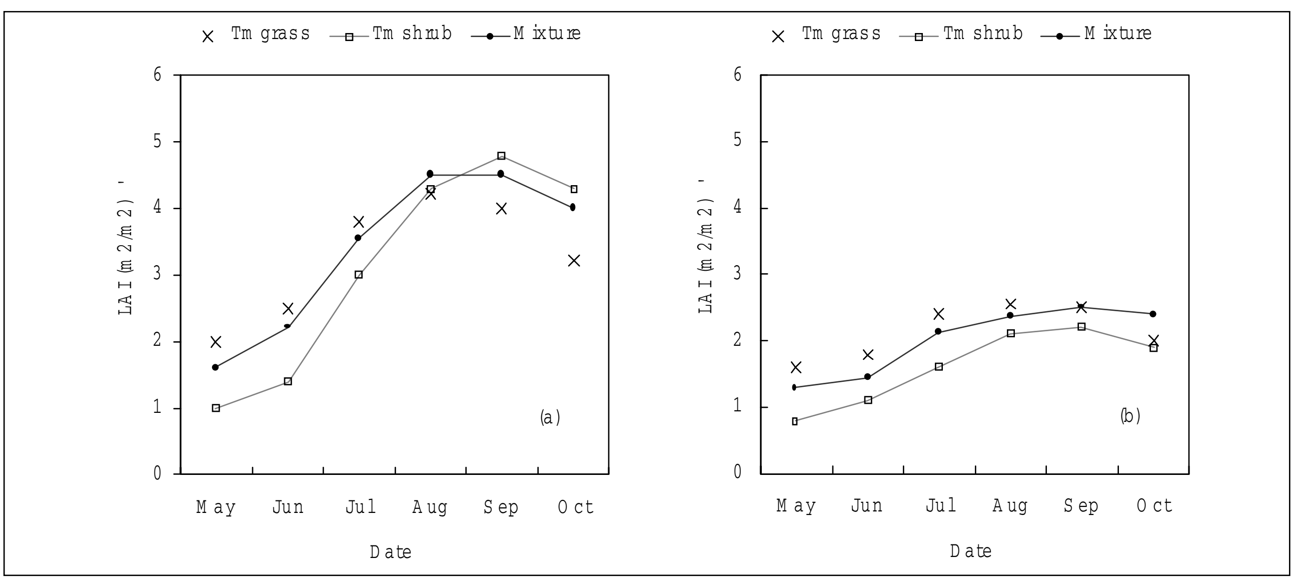

Figure 5. Calculated leaf area index for the vegetation communities. (a) is for level lysimeter; and (b) is for slope lysimeter.

stress strongly impacted the LAI of sunflowers (Sadras et al., 1991; Karam, et al., 2007). The peak LAIs of TMgrass and TMshrub were 4.2 and 4.9 m^2 per m^2 in the level lysimeters, and 2.6 and 2.1 m^2 per m^2 in the slope lysimeters (Figure 5). This could also be caused by differences in water balance between the level and slope lysimeters, as discussed before.

Measured ET for the vegetation communities

Weekly ET

The measured weekly ETs after May 1, 2004 for the three vegetation communities are given in Figure 6. Similar to the vegetation growth, the measured weekly ET showed a seasonal trend. At the beginning growth stage of plants, the weekly ET was lower than 20 cm and there were slight variations during the week. Starting from the middle of June, the weekly ET showed rapid increase, which coincided with the plant growth trend (Figure 4). In addition, the variations in weekly ET were very large at this time. The large variations in weekly ET could be due to the frequent storm events, which affected the environmental factors such as soil water content, soil temperature, cloud cover, and solar radiation. These environmental factors highly impact the dynamics of ET. For example, before and after the largest two rainfall events (as indicated by the two vertical lines of Figure 6), weekly ETs showed great variations. For the three vegetation communities, the peak weekly ET occurred in the first week of August. The peak weekly ET was higher in the level lysimeters than in the slope lysimeters (Figure 6). For example, the peak weekly ETs of TMgrass in the level lysimeter and slope lysimeter were 100.1 and 72.5, respectively. In October, the plants were mature, and the plants slowed in growth, and the weekly ET began to steadily decrease to less than 20 mm. It was also found that the cumulated weekly ET had a positive linear relationship with the vegetation height. The calculated correlation coefficients for TMgrass, TMshrub, and the mixture in the level lysimeters, were 0.96, 0.94, and 0.94, respectively.

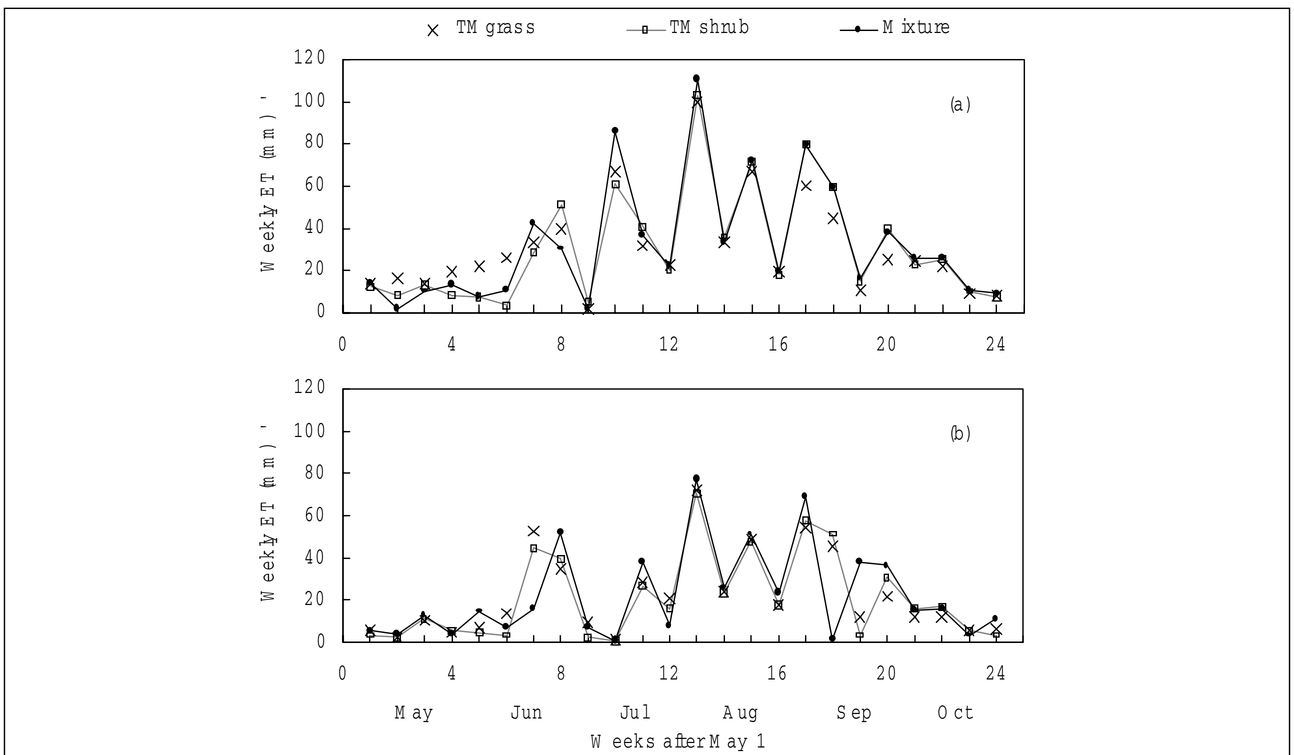

Figure 6. Measured weekly evapotranspiration for the vegetation communities. (a) is for level lysimeter; and (b) is for slope lysimeter.

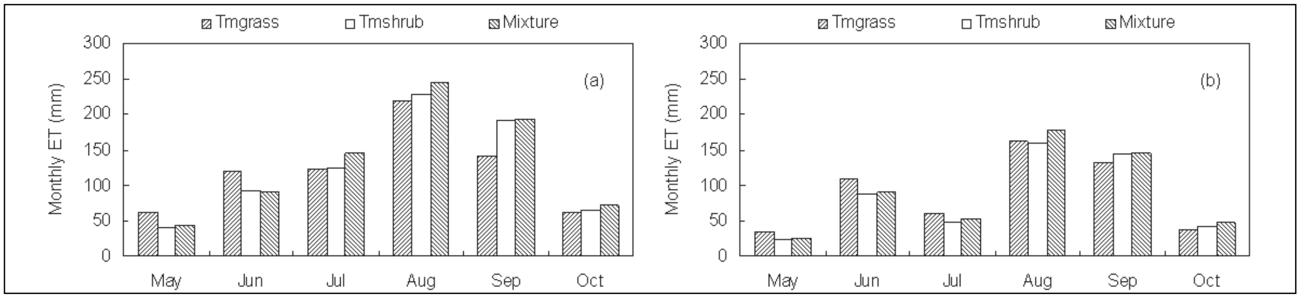

Figure 7. Measured monthly evapotranspiration for these three vegetation communities. (a) is in level lysimeters; and (b) is in slope lysimeters.

Monthly ET

The measured monthly ETs for the three vegetation communities are given in Figure 7. Generally, for all communities, the total ETs were higher in the level lysimeters than those in the slope lysimeters. The total ETs over the growing season for TMgrass, TMshrub, and the mixture were 730.4, 742, and 790.7 mm, respectively in the level lysimeters, and 535.5, 504.1, and 540.1 mm, respectively in the slope lysimeters. During May to August, the monthly ETs from the vegetation of the level lysimeters showed a continual increasing trend. However, in the slope lysimeters, the vegetation ETs of July were lower than those of June, even though there was much more rainfall recharge in July. The possible explanation was that compared with the level lysimeters, the plants in the slope lysimeters experienced worse water stress before early July. The plants in the slope lysimeters showed signs of wilting (visual observation). Hence, even though there is enough soil water in July, the plants still need some time to recover.

For all communities, the peak monthly ET occurred in August. The monthly ET showed a close linear relationship with LAI. In the level lysimeters, the calculated correlation coefficients between monthly ET and LAI were 0.72, 0.67, and 0.77 for TMgrass, TMshrub, and the mixture. In the slope lysimeters, the calculated correlation coefficients between monthly ET and LAI were 0.65, 0.67, and 0.53 for TMgrass, TMshrub, and the mixture. Li et al. (2003) also found that the maximum ET and peak value of crop LAI occurred at the same time period in the semiarid area of North China. Since the use of lysimeters is very expensive, LAI could be used in the future to estimate the ET from these vegetation communities.

Dry weights and WUE

The calculated dry weights and WUEs for the different vegetation communities are given in Figure 8. For all communities, the dry weight and WUE were higher in the level lysimeters than the slope lysimeters. Especially for TMshrub, the dry weight and WUE showed a great difference between the level and slope lysimeters. The dry weight of TMshrub in the slope lysimeter (133.5

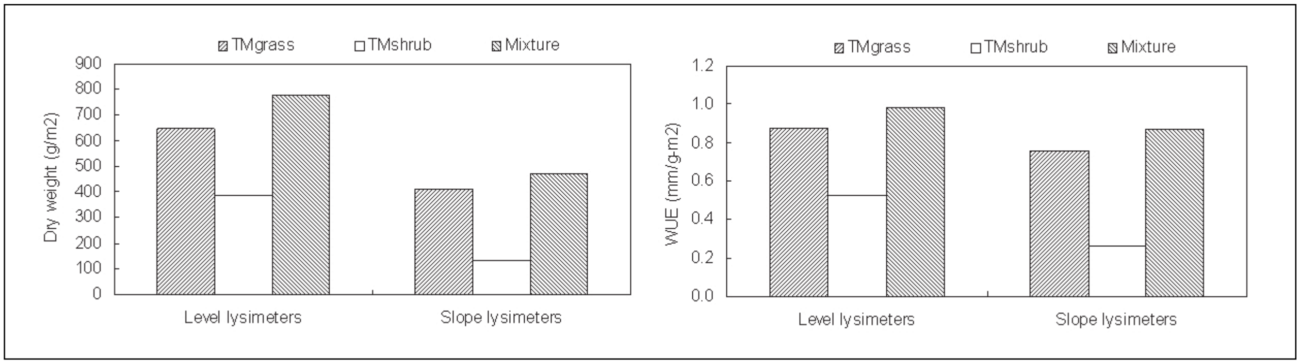

Figure 8. The calculated dry weight and water use efficiency of different vegetation communities.

g/m^2) was 34.4% of that in the level lysimeter (388.0 g/m^2). The WUE of TMshrub in the slope lysimeter (0.26 g/mm-m^2) was 49.1% of that in the level lysimeter (0.53 g/mm-m^2). Also the decrease of dry weight and WUE in the slope lysimeters may be due to the effects of water stress on plant growth. For both level and slope lysimeters, the grass-shrub mixture has a higher water use efficiency than both TMgrass and TMshrub. It is recommended that the vegetation community of the mixture be applied for vegetation recovery in Taihang Mountain, China, because it can make the full use of the limited water resources.

CONCLUSION

The major objective of this research is to measure the ET and WUE of local vegetation communities using level and slope drainage lysimeters. The ET was estimated using the water balance equation. The study was conducted during April to October 2004. The results from this research can be used to support the current large-scale vegetation recovery efforts in the Taihang Mountainous area of China. The major conclusions are summarized as follows.

The drainage lysimeter is an effective means to estimate the ETs of selected vegetation communities in mountainous areas. Over the growing season, the total ETs of TMgrass, TMshrub, and the mixed community, were 730.4, 742, and 790.7 mm, respectively in the level lysimeters, and 535.5, 504.1, and 540.1, respectively in the slope lysimeters.

For all vegetation communities, the monthly ET peaked in August, and had a close linear relationship with LAI. For each vegetation community, the measured ET was higher in the level lysimeter than the slope lysimeter due to water loss by surface runoff in the slope lysimeters. For all communities, the dry weight and WUE in the level lysimeters were higher than those in the slope lysimeters. The measured WUE of the mixture is higher than the TMgrass and TMshrub in both level and slope lysimeters. Hence, the grass-shrub mixture community is recommended for revegetation efforts in the Taihang Mountains area.

Even though the drainage lysimeter is an effective tool to measure ET in the mountainous area, it was found that lysimeters blocked the horizontal movement of soil water, as indicated by Howell et al. (1991). Hence, the soil water content inside the lysimeters was higher than that outside the lysimeter, which might result in the overestimation of the vegetation ET in natural conditions. Another limitation of this research was that ET was measured in a humid water year. It is recommended that measurement of ET in the normal and dry years be conducted in future research.

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ADDRESS FOR CORRESPONDENCE
Fan Yang
Northeast Institute of Geography and Agroecology
Chinese Academy of Sciences
3195 Weishan Road
Changchun 130012, Jilin Province
China

Email: yangfan@neigae.ac.cn