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# Differences in hydrological responses for different vegetation types on a steep slope on the Loess Plateau, China

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SUMMARY

Extensive vegetation restoration practices have been implemented to control soil erosion on the Loess Plateau, China. However, no strict guidelines are available to determine the most suitable plant species for vegetation restoration within a given area. The objective of this study was to quantify the changes of each component (soil water storage, surface runoff, and actual evapotranspiration) of a water balance model and soil loss over time under eight different vegetation types, and to further determine the optimal vegetation type for soil and water conservation and sustainable ecological restoration on the steep slopes (>25°) on the Loess Plateau. The results indicated that vegetation type substantially affected soil water storage and that the greatest soil water storage in both the shallow (0–2 m) and the deep soil layers (2–5 m) occurred under *Bothriochloa ischaemum* L. (BOI). Vegetation type also affected surface runoff and soil losses. The most effective vegetation types for reducing soil erosion were BOI and Sea-buckthorn (*Hippophae rhamnoides* L.), while Chinese pine (*Pinus tabulaeformis* Carr.) and Chinese pine + Black locust (*Robinia pseudoacacia* L.) were the most ineffective types. Soil water dynamics and evapotranspiration varied considerably among the different vegetation types. A soil water surplus was only found under BOI, while insufficient water replenishment existed under the other seven vegetation types. The higher water consumption rates of the seven vegetation types could result in soil desiccation, which could lead to severe water stresses that would adversely affect plant growth. This study suggested that both vegetation type and its effect on controlling soil erosion should be considered when implementing vegetation restoration and that BOI should be highly recommended for vegetation restoration on the steep slopes of the Loess Plateau. A similar approach to the one used in this study could be applied to other regions of the world confronted by the same problems of water scarcity along with the need for vegetation restoration.



## 1. Introduction

Soil erosion results in the removal of soil material by the processes of detachment and transportation by erosive agents causing on-site land degradation while deposition of the eroded material can cause negative downstream off-site impacts (Meyer and Wischmeier, 1969; Singh et al., 2006). Soil erosion is a worldwide issue of both social and environmental concern. The Chinese Loess Plateau is particularly susceptible to severe soil-erosion and the problems caused by this have received much attention, especially over the past several decades (Wei et al., 2007; Chen et al., 2010). Massive soil losses, due primarily to erosion by water, are principally caused by high-intensity storms, easily eroded loess soils, and poor vegetation cover that is often the result of inappropriate land use (Fu et al., 2005; Zhang and Liu, 2005). Consequently, the Chinese government has implemented a series of vegetation restoration projects to control soil erosion in the Loess Plateau region (McVicar et al., 2007, 2010; Jian et al., 2015). For example, the long-term, policy-driven "Grain for Green" project, implemented in 1999, had the main objective of controlling or preventing soil erosion from cultivated steep slopes. As a result, the cultivated slopes were either converted to forest or shrub land or were simply abandoned and allowed to gradually convert to native grassland through natural succession (Fu et al., 2005; Chen et al., 2010). This project has naturally led to great changes in the vegetation type and degree of cover, which in turn could potentially result in large changes to hydrological (Liu and McVicar, 2012) and erosion (Zhou et al., 2016) processes.

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Vegetation type is generally the most important factor affecting the intensity and frequency of soil erosion events, even exceeding the influence of rainfall intensity and slope gradient under certain conditions (e.g., large plant cover changes) (García-Ruiz, 2010; Li et al., 2015). Vegetation controls soil erosion by means of its canopy, roots and litter components (Mohammad and Adam, 2010). From a hydrological aspect, the canopy of vegetation reduces soil erosion by intercepting and diverting rainfall, providing physical protection to the soil by reducing raindrop impact energy and 'splash' effects, which also enhances infiltration; litter can play a similar protective role while plant roots can physically hold the soil in place, trap sediment and add organic substances to the soil, which can improve soil structure including the soil pore system (Gyssels et al., 2005; Bochet et al., 2006). Consequently, a number of studies have demonstrated the beneficial effects of vegetation in reducing surface runoff and soil erosion under different environmental conditions (Chaplot and Le Bissonnais, 2003; Kothyari et al., 2004; Wang et al., 2012). Sun et al. (2006) reported that runoff on the Loess Plateau following forestation had been notably reduced by more than 50%. Wei et al. (2007) found that shrub land was the best choice for controlling soil erosion when land use conversion was implemented, whereas pastureland was less effective. On the contrary, Wang et al. (2012) indicated that grassland has shown an important influence on flow deceleration and erosion control, while using minimal water. Mohammad and Adam (2010) reported that forests and natural vegetation dominated by *Sarcopoterium spinosum* could substantially prevent or decrease runoff and soil erosion, whereas removal of *S. spinosum* had a direct effect in increasing runoff and soil losses. Therefore, adapting the vegetation type to local conditions under appropriate land management can increase surface cover and, consequently, effectively reduce soil erosion. Conversely, vegetation destruction and/or inappropriate land management can have a negative effect on the dynamics of the surface water cycle and sediment deposition, which can lead to severe water and soil losses (Adekalu et al., 2006; Pan and Shangguan, 2006; Rulli and Rosso, 2007).

Vegetation type also considerably influences soil water dynamics and the hydrologic cycle on the Loess Plateau (Chen et al., 2010; Yang et al., 2012; Gao et al., 2014; Jian et al., 2015). The effect of vegetation on soil water is due primarily to its effects on infiltration rates, runoff intensity, and evapotranspiration (Cubera and Moreno, 2007; Zucco et al., 2014). There are two main effects of the vegetation on soil water due to its effects on evaporation and transpiration. By shading the soil surface, the vegetative canopy can reduce soil temperatures and evaporation rates and, hence, increase soil water contents (Suleiman and Ritchie, 2003). In contrast, higher water consumption rates through transpiration, especially of certain vegetation types, can cause soil desiccation and ecological degradation in arid and semi-arid regions (Chen et al., 2008). Li et al. (2009) found that changing the vegetation type from forest to grassland decreased soil water by 18.8% in an agricultural catchment on the Loess Plateau. However, Yang et al. (2012) showed that the soil water stored under grassland was greater than under forestland in both shallow and deep soil layers in a small watershed of the western Loess Plateau. Clearly, it is essential to investigate the changes in soil water storage as vegetation type evolves.

On the Loess Plateau, the thick loess deposits and very deep water table make rainfall the only natural water source by which to replenish soil water (Chen et al., 2010; Jian et al., 2015). Under these conditions, soil water has become the primary limiting factor influencing vegetation restoration in this region. Although the "Grain for Green" project of vegetation restoration has effectively reduced soil erosion (Fu et al., 2005), an incompatibility exists between the limited soil water availability and the greater water demands of the more extensive vegetation cover (Fu et al., 2012). For example, fast-growing tree and shrub species initially grow well but their growth and health are adversely affected when the stored soil water has been depleted (Chen et al., 2010). Wang et al. (2010) and Cao et al. (2011) both found that the soil became extremely dry in both shallow and deep soil layers when vegetation restoration was implemented. Jian et al. (2015) indicated that soil water replenishment by rainfall was not sufficient to recharge the soil water storage. This water over-use by vegetation has resulted in soil desiccation and the formation of dried soil layers (Chen et al., 2008; Fu et al., 2012). These phenomena have a detrimental effect on plant growth and natural vegetation succession and thus decrease ecosystem services and health (Chazdon, 2008; Wang et al., 2011; Jian et al., 2015). On the Loess Plateau, soil desiccation considerably affects plant evapotranspiration and growth (Fu et al., 2012). Soil desiccation has caused degradation of forest plantations that has resulted in the "small-aged-tree" phenomenon whereby mature trees have developed abnormally short trunks, as well as in the degradation of grasslands (Chen et al., 2010). Consequently, the water balance and soil and water conservation techniques should be considered when implementing vegetation restoration (McVicar et al., 2007). It is imperative to select the optimal vegetation type (McVicar et al., 2010) that not only effectively controls soil erosion, but can also balance soil water consumption and maintain sustainable vegetation restoration. However, there is a scarcity of research that determines distinct quantifiable effects of different vegetation types on the water balance for the Loess Plateau, and especially so for the steep slopes (>25°) where soil erosion is more severe. According to the soil erosion risk classification system used on the Loess Plateau (Fu et al., 2006), slopes are classified into three categories: gentle (0–15°), intermediate (15–25°), and steep (>25°).

The overall goal of this study was to determine the optimal vegetation type for sustainable ecological restoration on steep slopes on the Loess Plateau. The specific objectives were: (i) to examine the soil water storage changes in different vegetation types; (ii) to quantify the effect of vegetation types on surface runoff and soil loss; and (iii) to compare the differences in water balance components under eight different vegetation types.

## 2. Study site and experimental design

### 2.1. Study site

The study was conducted in the Wangdonggou watershed (longitude 107°42′E, latitude 35°12′N; elevation 946–1226 m; area 8.3 $km^2$) of the Changwu Agro-ecological Experiment Station, Chinese Academy of Sciences (CAS) and Ministry of Water Resources (MWR) in the middle reaches of the Yellow River. The study watershed is located in the gully region of the Loess Plateau that has a continental monsoon climate with a mean temperature of 9.2 °C (1957–2014). The mean annual precipitation is 578 mm, more than 58% of which falls between July and September. The groundwater level is about 50–80 m below the soil surface, which precludes upward capillary flow into the root zone (Liu et al., 2010). Agricultural production on the tableland mainly depends on the rainfall alone with no irrigation. The soil texture at the study site is silty clay loams. Dominant plant species in this region include *Bothriochloa ischaemum* L. (BOI), Sea-buckthorn (*Hippophae rhamnoides* L.) (SEB), Chinese pine (*Pinus tabulaeformis* Carr.) (CHP), Chinese arborvitae (*Platycladus orientalis* L.) (CHA), and Black locust (*Robinia pseudoacacia* L.) (LOC).

### 2.2. Experimental design

In 2003, eight experimental runoff plots were established on a natural steep slope (35°). To avoid the influences of slope aspect and differences in original soil properties on soil erosion, all eight plots were established on the same slope with similar soil properties and, therefore, had the same aspects. The total area covered by the 8 plots was around 10,500 $m^2$ and the largest distance between any of the two plots was 150 m. Each plot was 20 m × 5 m with the longest side in the direction of the slope gradient. Each plot was surrounded by a cement wall that was 15 cm above the ground surface, which isolated plot runoff and sediment. At the lower end of each plot, two conjoined volumetric barrels (0.75 $m^3$ for each barrel and the potential maximum volume was 7.5 $m^3$ for both barrels) were established at the outlet of the plot in order to collect and measure surface runoff and soil losses. The cement walls and runoff barrels were maintained each year before the growing season.

The five dominant plant species mentioned in Section 2.1 were selected to be grown in the eight experimental plots. Four of the plots were assigned to mono-cultures of BOI, SEB, CHP, and CHA. The remaining four plots were assigned mixtures of SEB + CHP, SEB + LOC, CHP + LOC, and CHA + LOC. Detailed information about the experimental design is given in Table 1.

Land use change has occurred on the study slope since 1999 when the "Grain for Green" project was implemented. Therefore, a control plot could not be established under the natural vegetation conditions. After the experimental plots were established, the eight plant types grew well without any management practices applied, including weeding. During the study period, understory plants, which consisted mainly of different native grasses (such as *B. ischaemum*, *Arundinella hirta*, *Artemisia argyi*), covered around 8% of the soil surface under CHA, 25% under CHP and CHA + LOC, and 45% under SEB, SEB + CHP, and SEB + LOC (Abula, 2015).

Yang et al. (2016) measured soil properties in 2014, including soil bulk density (BD), saturated water content ($\theta_s$), saturated hydraulic conductivity ($K_s$), and soil organic matter (SOM), in the 0–20 and 20–40 cm soil layers in each of the eight vegetation plots. Their results, presented in Table 1, indicated that there were no significant differences in BD, $\theta_s$, or $K_s$ among the plots in either of the two soil layers ($P < 0.05$). However, the content of SOM was significantly higher under BOI than under the other seven vegetation types in both soils. The differences in SOM contents were attributed to the different vegetation types. It could be assumed that the environmental factors of topography, soil properties, and micrometeorology did not contribute to the observed differences in runoff, soil loss, and soil water content since all eight plots were located on the same slope and under similar environmental conditions. According to the soil classification system of the Food and Agriculture Organization, the United Nations Educational Scientific, and Cultural Organization (FAO-UNESCO), the soil has a silty clay loam texture (Huang and Gallichand, 2006), which is typical of the loessial soil group.

## 3. Methods

### 3.1. The LAI measurements

For each plot, leaf area index (LAI) was measured from April 2013 to October 2014 by a plant canopy analyzer (LAI-2000, LI-COR, USA). In total, 392 measurements of LAI were made. Vegetation properties (spacing, mean height and cover) were also recorded during this period (Table 1).

### 3.2. Soil water measurements

Three access tubes were installed at distances of 5, 10, and 15 m from the upper end of each plot along the midline in order to estimate volumetric soil water content to a depth of 5 m using a neutron probe (CNC-503B DR, ChaoNeng, China) that had been calibrated using standard methods (Huang and Gallichand, 2006; Fu et al., 2012). From April to November in 2013 and from May to October in 2014, volumetric soil water content was measured four times per month in the rainy season (July to September) and two times per month in the dry season, which occurred before and after the rainy season. Measurements were made at depth increments of 0.1 and 0.2 m in the 0–1 and 1–5 m soil layers, respectively. The mean soil water contents in the shallow (0–2 m), deep (2–5 m) and 0–5 m soil layers were all determined using depth weighting. The soil water storage (SWS) values (mm) of each vegetation type, $i$, at time, $j$, were calculated from $\theta(i,j,k)$ data where $k$ refers to the different soil depths. The respective SWS values for the 0–2, 2–5, and 0–5 m layers were calculated using the following equations:

$$SWS_{j(0-2m)}(i) = 100 * [\theta(i,j,0.1) + \theta(i,j,0.2) + \cdots + \theta(i,j,1.0)] + 200 * [\theta(i,j,1.2) + \theta(i,j,1.4) + \cdots + \theta(i,j,2.0)]; \quad (1)$$

$$SWS_{j(2-5m)}(i) = 200 * [\theta(i,j,2.2) + \theta(i,j,2.4) + \cdots + \theta(i,j,5.0)]; \quad (2)$$

and

$$SWS_{j(0-5m)}(i) = 100 * [\theta(i,j,0.1) + \theta(i,j,0.2) + \cdots + \theta(i,j,1.0)] + 200 * [\theta(i,j,1.2) + \theta(i,j,1.4) + \cdots + \theta(i,j,5.0)]. \quad (3)$$

**Table 1**
General description of the experimental plots.

| Vegetation type | Vegetation properties | | | Soil properties[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Spacing (m) | Mean height (m) | Cover (%) | *BD*[b] (g $cm^{-3}$) | | $\theta_s$[b] ($cm^3$ $cm^{-3}$) | | $K_s$[b] (m $s^{-1}$) | | Soil organic matter (g $kg^{-1}$) | |
| | | | | 0–20 cm | 20–40 cm | 0–20 cm | 20–40 cm | 0–20 cm | 20–40 cm | 0–20 cm | 20–40 cm |
| BOI | – | – | 100 | 1.17 | 1.22 | 0.496 | 0.462 | $3.83 \times 10^{-6}$ | $4.83 \times 10^{-6}$ | 13.6a[c] | 10.8b |
| SEB | 1 × 2 | 1.8 | 80 | 1.18 | 1.23 | 0.459 | 0.418 | $4.67 \times 10^{-6}$ | $1.50 \times 10^{-6}$ | 10.7b | 9.0c |
| CHP | 1 × 2 | 1.4 | 50 | 1.22 | 1.22 | 0.444 | 0.426 | $2.67 \times 10^{-6}$ | $2.50 \times 10^{-6}$ | 10.8b | 6.6c |
| CHA | 1 × 2 | 2 | 35 | 1.19 | 1.23 | 0.428 | 0.433 | $5.17 \times 10^{-6}$ | $2.67 \times 10^{-6}$ | 8.3c | 8.4c |
| SEB + CHP | 1 × 1 | 2.8 | 75 | 1.20 | 1.18 | 0.431 | 0.445 | $2.17 \times 10^{-6}$ | $3.00 \times 10^{-6}$ | 8.6c | 8.6c |
| SEB + LOC | 1 × 1 | 2.3 | 50 | 1.29 | 1.23 | 0.392 | 0.417 | $2.17 \times 10^{-6}$ | $0.83 \times 10^{-6}$ | 10.7b | 6.8c |
| CHP + LOC | 1 × 1 | 1.7 | 45 | 1.31 | 1.31 | 0.397 | 0.439 | $1.17 \times 10^{-6}$ | $2.67 \times 10^{-6}$ | 8.7c | 6.8c |
| CHA + LOC | 1 × 1 | 3.5 | 80 | 1.20 | 1.16 | 0.440 | 0.457 | $3.67 \times 10^{-6}$ | $6.83 \times 10^{-6}$ | 11.2b | 8.7c |

BOI: *Bothriochloa ischaemum* L.; SEB: Sea-buckthorn; CHP: Chinese pine; CHA: Chinese arbor-vitae; LOC: Black locust; *BD*: bulk density; $\theta_s$: Saturated water content; $K_s$: saturated hydraulic conductivity.
[a] Cited from Yang et al. (2016).
[b] Indicates that the differences in the BD, $\theta_s$, *and* $K_s$ among eight plots were not significant ($P < 0.05$).
[c] Means with the same letter are not significantly different at the 0.05 probability level.

### 3.3. Runoff and soil loss measurements

The surface runoff and soil loss from each experimental plot were measured for each rainfall event that produced runoff between May and September in the years 2010–2014. The surface runoff and soil loss were collected in clean barrels at the lower end of each plot. The contents of the barrels were thoroughly mixed before collecting a 1000-mL runoff subsample in a measuring cylinder. The sediment concentration was then determined by oven-drying the sediment at 105 °C. The total amounts of surface runoff and soil losses were also calculated. During the study period, 27 rainfall events that generated runoff were monitored. Meteorological parameters, such as rainfall amount and intensity, were recorded by a siphon rain gauge at the automatic weather station in Changwu Agri-ecological Experiment Station, which was 0.5 km away from the experimental plots. The statistical result for rainfall properties is shown in Table 2. The runoff coefficient was determined for each rainfall event as the ratio of total runoff to the total rainfall amounts.

### 3.4. Water balance model

The water balance in each plot is governed by an Input–Output process, which can be described by the following water balance model for the growing season in each of the study years (Chen et al., 2010):

$$\Delta S = P - R - ET \tag{4}$$

where $\Delta S$ (mm) is the change in the amount of soil water between the beginning and the end of the growing season that remains stored in the 0–5 m soil layer of the plot; $P$ (mm) is the total rainfall during the growing season, which is the only hydrologic input for the experimental plot; and the outputs are $R$ (mm), which is the surface runoff leaving the plot; and the actual evapotranspiration $ET$ (mm), which is the water leaving the plot via evaporation and transpiration into the atmosphere and can thus be calculated using Eq. (4). The change in the amount of soil water storage was used as an indicator by which to determine the most suitable plant species for soil and water conservation and vegetation restoration.

### 3.5. Statistical analyses

Descriptive statistical properties (i.e., minimum, maximum, mean, standard deviation, coefficient of variation, Kurtosis and Skewness) were calculated in order to explore the basic characteristics of the leaf area index (LAI), surface runoff, and soil loss data. Significant differences in the mean soil water storage, runoff, and soil loss among vegetation types were detected using a one-way analysis of variance (ANOVA) followed by the least significant difference (LSD) test ($P < 0.05$). Relationships between soil loss and runoff coefficients were analyzed by simple linear regression. All statistical determinations were made using SPSS 17.0 software (SPSS Inc., 2008).

**Table 2**
Statistical properties of rainfall events.

| Year | Minimum rainfall (mm) | Maximum rainfall (mm) | Mean rainfall ± SD[a] (mm) | Mean rainfall intensity ± SD (mm/h) | *n* |
|---|---|---|---|---|---|
| 2010 | 12.8 | 118.1 | 40.1 ± 39.3 | 3.64 ± 2.67 | 6 |
| 2011 | 19.6 | 53 | 42.3 ± 15.4 | 2.16 ± 0.69 | 4 |
| 2012 | 14.4 | 46 | 26.3 ± 5.7 | 5.21 ± 3.91 | 7 |
| 2013 | 17 | 120.8 | 47.5 ± 49.1 | 3.92 ± 4.87 | 5 |
| 2014 | 23.2 | 51.6 | 35.6 ± 11.5 | 1.66 ± 1.06 | 5 |

[a] SD: standard deviation.

## 4. Results

### 4.1. Leaf area index (LAI)

The statistical properties of the LAI for different vegetation types during the 2013–2014 experimental periods are presented in Table 3. It was clear that the LAI varied among the different vegetation types and that the vegetation type affected the LAI value. There were notable differences among the eight vegetation types in their minimum LAI values, which ranged from 0.25 to 1.82, and their maximum LAI values, which ranged from 2.09 to 4.62 (Table 3). The degree of variation in LAI for the BOI was the greatest (CV = 41.7%), while the LAI of SEB + CHP underwent relatively small changes (CV = 14.9%). According to the classification proposed by Nielsen and Bouma (1985), LAI demonstrated moderate variability ($10\% < CV \leqslant 100\%$) for all the vegetation types. In most cases (86%), the temporally-averaged LAI differed significantly among the different vegetation types ($P < 0.05$). Among the eight vegetation types, the mean LAI was the greatest (3.43) for CHP + LOC, and it was 1.36–3.01 times greater than those of the other vegetation types.

### 4.2. Soil water storage

Temporal soil water content dynamics at the various soil depths under different vegetation types are shown in Fig. 1. During the growing season, greater soil water contents occurred from July to October. In general, the changes in soil water content in the shallow soil layer for all vegetation types corresponded to the rainfall, increasing rapidly after rainfall events while decreasing more gradually over the periods without rainfall. This result was in agreement with the findings of Yang et al. (2012) and Zucco et al. (2014). In contrast, the soil water content of the deep soil layers was relatively stable due to lower rates of both rainfall infiltration and root water uptake. The soil water contents under BOI were notably higher than those under the other vegetation types at any given time within the growing seasons, and especially so in the 2–5 m soil layer.

Temporal variations in soil water content were less in the deep soil layer than in the shallow layer. In the deep layer the water content was relatively unaffected by the occurrence of rainfall events and showed greater temporal stability due to the insulating effect of the upper soil layer. However, similar temporal evolutions of soil water at all depths were found under the different vegetation types. This indicated that vegetation type had a relatively greater effect on spatial variations in soil water content but that the effect on soil water temporal patterns was almost negligible.

Vertical distributions of soil water content for different vegetation types are shown in Fig. 2. Vegetation type had a pronounced effect on water distribution within the soil profile. Under all vegetation types, the soil water content tended to increase in the 0–0.2 m layers at a greater rate than in the 0.2–1.0 m layers. The soil water contents under BOI exhibited small increases in the 1.0–2.0 m layer, while no obvious trend was exhibited under CHP, SEB + CHP, CHP + LOC, and CHA + LOC, and a slow decrease was observed under SEB, CHA, and SEB + LOC. In the deep soil layers, the soil water content under BOI, SEB, CHA, SEB + LOC, and CHA + LOC continued to exhibit slight increases with increasing soil depth, whereas no notable changes were observed under CHP, SEB + CHP, and CHP + LOC. This difference in the soil water content distribution patterns under the different vegetation types was probably caused by different vertical root distributions.

The variations in the soil water storage under different vegetation types in the various soil layers are presented in Fig. 3. In the 0–5 m soil layers, soil water storage differed significantly among the

**Table 3**
Statistical properties of the leaf area index (LAI) of eight vegetation types.

| Vegetation type | Minimum | Maximum | Mean | SD | CV (%) | Kurtosis | Skewness |
|---|---|---|---|---|---|---|---|
| BOI | 0.25 | 2.09 | 1.14e | 0.48 | 41.73 | −0.59 | 0.11 |
| SEB | 0.98 | 2.64 | 1.70d | 0.46 | 26.89 | −0.74 | 0.46 |
| CHP | 1.23 | 3.11 | 1.92c | 0.56 | 29.21 | −0.58 | 0.83 |
| CHA | 0.79 | 2.35 | 1.52d | 0.40 | 26.48 | −0.56 | 0.22 |
| SEB + CHP | 1.74 | 3.29 | 2.53b | 0.38 | 14.94 | −0.52 | 0.17 |
| SEB + LOC | 0.86 | 2.29 | 1.53d | 0.36 | 23.69 | −0.33 | 0.15 |
| CHP + LOC | 1.08 | 2.77 | 1.90c | 0.43 | 22.41 | −0.61 | 0.02 |
| CHA + LOC | 1.82 | 4.62 | 3.43a | 0.68 | 19.69 | 0.02 | −0.34 |

CV: coefficient of variation; SD: standard deviation.
Values within a given column followed by the same letter are not significantly different among vegetation types ($P < 0.05$, LSD: least significant difference).
BOI: *Bothriochloa ischaemum* L.; SEB: Sea-buckthorn; CHP: Chinese pine; CHA: Chinese arbor-vitae; LOC: Black locust.

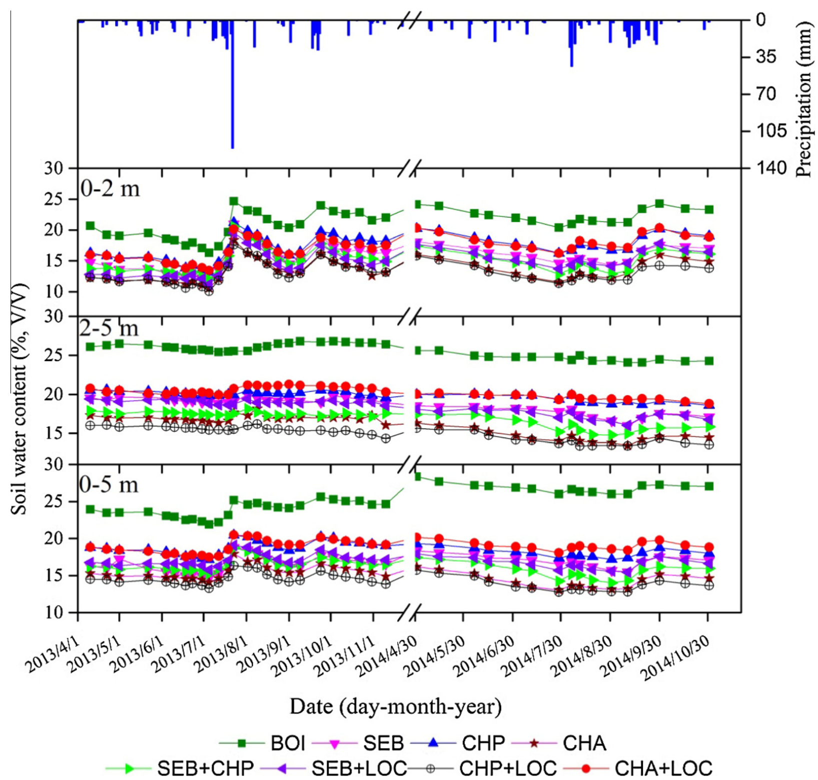


**Fig. 1.** Temporal variations of the depth-averaged volumetric soil water content under eight different vegetation types for three soil layers during two growing seasons. BOI: *Bothriochloa ischaemum* L.; SEB: Sea-buckthorn; CHP: Chinese pine; CHA: Chinese arbor-vitae; LOC: Black locust.

different vegetation types ($P < 0.05$). In the 0–5 m soil layer, the mean soil water storage under BOI (1190.9 mm) was the greatest among the eight vegetation types investigated, and was 1.37, 1.29, 1.59, 1.47, 1.4, 1.67, and 1.26 times greater than those under SEB, CHP, CHA, SEB + CHP, SEB + LOC, CHP + LOC, and CHA + LOC, respectively. In deep soil layers, soil water storage also presented significant differences among all of the different vegetation types except for those under SEB and CHP + LOC.

### 4.3. Surface runoff and soil loss

Table 4 shows the statistical characteristics of the annual total surface runoff from the plots under the eight vegetation types for the years 2010–2014. It was clear that surface runoff was strongly affected by vegetation type. For instance, in the study period of 2010–2014, the mean total annual runoff from the plots under BOI was the least (0.26, 0.35, 0.23, 0.40, and 0.39 mm for the five years, respectively) while that from the plots under CHA was the greatest (ranging from 2.11 to 3.31 mm). Runoff was considerably lower from the BOI plots than from the other plots. The lowest runoff values that occurred for the rainfall events within a given year from the BOI plots ranged from 0.08 to 0.22 mm, while those values for the CHA plots ranged from 0.38 to 1.66 mm. The maximum runoff also exhibited the same characteristics. This implied that the grass (BOI) was more effective in reducing surface runoff than the trees. Similarly, the CV of the runoff varied with vegetation type. Runoff from the CHP, CHA, and CHP + LOC plots exhibited moderate variability, while that from the plots of some of the other types exhibited strong variability (CV > 100%) in certain years (e.g. SEB in 2013 and SEB + CHP in 2014).

The mean surface runoff from a plot under a given vegetation type also differed in different years. Furthermore, the lowest and highest values of runoff under the different vegetation types were not synchronous in different years, a result consistent with the conclusion reported by Wei et al. (2007).

Similarly, the CV of the mean runoff values varied among different years. In 2011 and 2012, runoff from the plots under the eight vegetation types generally exhibited moderate variability but

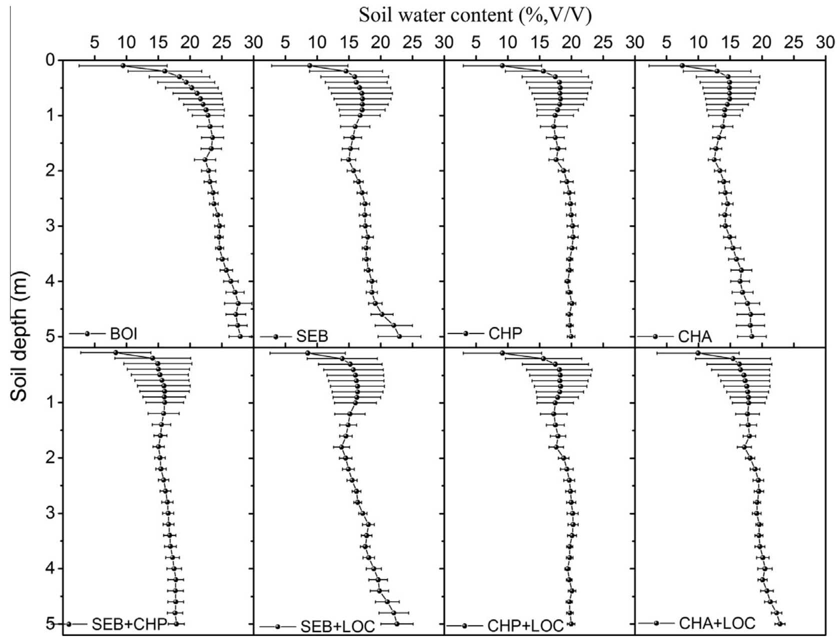


**Fig. 2.** Vertical distributions of the temporally-averaged volumetric soil water content (±1 standard deviation) for each vegetation type within a 5-m soil profile during the growing seasons in 2013 and 2014. BOI: *Bothriochloa ischaemum* L.; SEB: Sea-buckthorn; CHP: Chinese pine; CHA: Chinese arbor-vitae; LOC: Black locust.

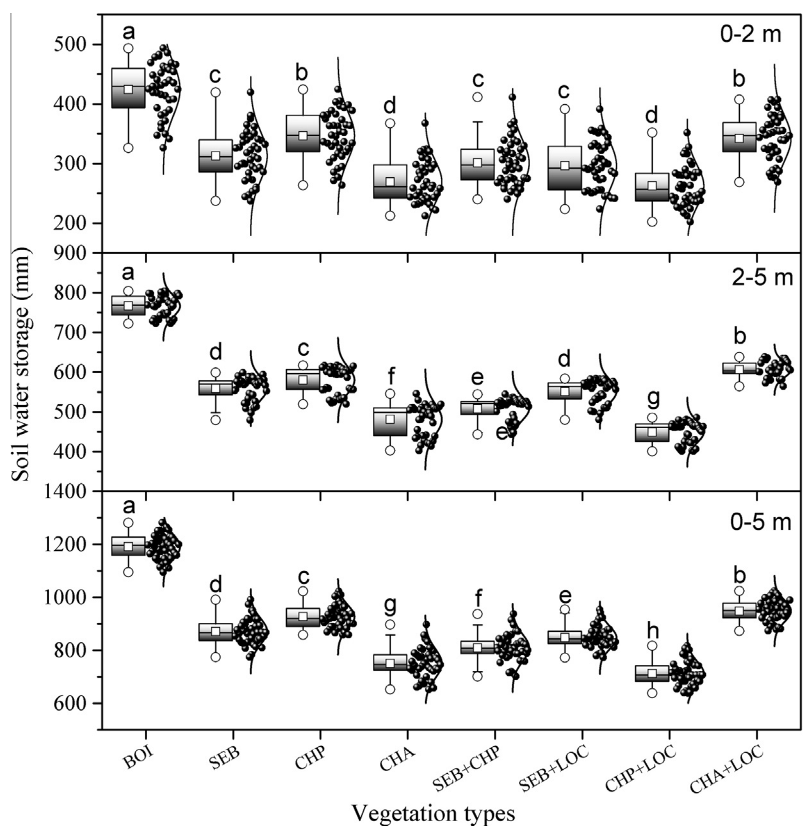


**Fig. 3.** Variations in soil water storage during the growing seasons in 2013 and 2014 of each vegetation type in different soil layers. A distribution curve is on the right side of each box plot and data points are represented by spheres. Different letters indicate significant differences ($P < 0.05$). BOI: *Bothriochloa ischaemum* L.; SEB: Sea-buckthorn; CHP: Chinese pine; CHA: Chinese arbor-vitae; LOC: Black locust.

under some vegetation types, such as SEB + CHP, it exhibited strong variability. These measurements indicated that runoff generation under different vegetation types could vary greatly for different rainfall event patterns.

Table 4 indicates that soil loss was greatly affected by vegetation type. The mean total annual soil loss varied among the plots with the different vegetation types and among the years. For instance, in 2010, the soil loss that occurred when LOC was grown

**Table 4**
Statistical parameters of annual surface runoff and soil losses for different vegetation types in the years 2010–2014.

| Year | Vegetation type | Runoff | | | | | | Soil loss | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min (mm) | Max (mm) | Mean (mm) | SD (mm) | CV (%) | *n* | Min (g m$^{-2}$) | Max (g m$^{-2}$) | Mean (g m$^{-2}$) | SD (g m$^{-2}$) | CV (%) | *n* |
| 2010 | BOI | 0.13 | 0.42 | 0.26 | 0.11 | 42 | 6 | 0.02 | 1.69 | 0.49 | 0.80 | 163 | 4 |
| | SEB | 0.15 | 1.12 | 0.54 | 0.39 | 72 | 6 | 0.36 | 1.15 | 0.72 | 0.34 | 47 | 4 |
| | CHP | 0.08 | 1.96 | 1.02 | 0.78 | 76 | 6 | 1.95 | 8.17 | 6.05 | 2.80 | 46 | 4 |
| | CHA | 1.31 | 5.13 | 3.31 | 1.62 | 49 | 6 | 1.72 | 335.88 | 119.51 | 155.88 | 130 | 4 |
| | SEB + CHP | 0.08 | 1.08 | 0.37 | 0.39 | 105 | 6 | 0.30 | 0.91 | 0.60 | 0.30 | 50 | 3 |
| | SEB + LOC | 0.21 | 2.08 | 1.06 | 0.78 | 74 | 6 | 0.81 | 8.62 | 3.10 | 3.70 | 119 | 4 |
| | CHP + LOC | 0.06 | 0.96 | 0.47 | 0.41 | 87 | 6 | 0.24 | 0.96 | 0.56 | 0.37 | 66 | 3 |
| | CHA + LOC | 0.50 | 1.91 | 1.11 | 0.64 | 57 | 6 | 1.79 | 3.03 | 2.21 | 0.58 | 26 | 4 |
| 2011 | BOI | 0.15 | 0.62 | 0.35 | 0.20 | 57 | 4 | 0.18 | 0.98 | 0.50 | 0.38 | 76 | 4 |
| | SEB | 0.56 | 1.08 | 0.73 | 0.24 | 33 | 4 | 0.51 | 3.51 | 1.34 | 1.45 | 108 | 4 |
| | CHP | 0.85 | 2.54 | 1.67 | 0.74 | 44 | 4 | 0.84 | 84.26 | 29.84 | 39.28 | 132 | 4 |
| | CHA | 1.66 | 4.02 | 3.20 | 1.11 | 35 | 4 | 4.69 | 568.48 | 170.70 | 269.20 | 158 | 4 |
| | SEB + CHP | 0.48 | 1.15 | 0.81 | 0.28 | 35 | 4 | 0.87 | 7.98 | 2.88 | 3.41 | 118 | 4 |
| | SEB + LOC | 0.69 | 1.42 | 1.02 | 0.31 | 30 | 4 | 0.71 | 12.62 | 4.30 | 5.64 | 131 | 4 |
| | CHP + LOC | 0.79 | 1.60 | 1.21 | 0.38 | 31 | 4 | 0.87 | 64.83 | 20.64 | 30.27 | 147 | 4 |
| | CHA + LOC | 0.60 | 1.73 | 1.17 | 0.49 | 42 | 4 | 0.99 | 18.83 | 5.61 | 8.82 | 157 | 4 |
| 2012 | BOI | 0.12 | 0.50 | 0.23 | 0.14 | 61 | 7 | 0.03 | 3.86 | 1.07 | 1.43 | 134 | 7 |
| | SEB | 0.19 | 0.52 | 0.29 | 0.11 | 38 | 7 | 0.01 | 7.23 | 1.16 | 2.68 | 231 | 7 |
| | CHP | 0.14 | 0.46 | 0.35 | 0.10 | 29 | 7 | 0.04 | 3.60 | 1.34 | 1.28 | 96 | 7 |
| | CHA | 0.38 | 4.30 | 2.73 | 1.73 | 63 | 7 | 0.47 | 43.61 | 21.62 | 19.76 | 91 | 7 |
| | SEB + CHP | 0.15 | 0.50 | 0.29 | 0.15 | 52 | 7 | 0.03 | 2.69 | 0.49 | 0.98 | 200 | 7 |
| | SEB + LOC | 0.19 | 0.92 | 0.41 | 0.25 | 61 | 7 | 0.06 | 3.21 | 0.91 | 1.17 | 129 | 7 |
| | CHP + LOC | 0.10 | 0.87 | 0.31 | 0.26 | 84 | 7 | 0.03 | 2.69 | 0.49 | 0.98 | 200 | 7 |
| | CHA + LOC | 0.30 | 1.68 | 0.69 | 0.46 | 67 | 7 | 0.04 | 47.13 | 7.52 | 17.48 | 232 | 7 |
| 2013 | BOI | 0.22 | 0.96 | 0.40 | 0.32 | 80 | 5 | 0.08 | 0.24 | 0.16 | 0.06 | 38 | 5 |
| | SEB | 0.12 | 1.81 | 0.56 | 0.70 | 125 | 5 | 0.10 | 0.45 | 0.22 | 0.14 | 64 | 5 |
| | CHP | 0.44 | 2.58 | 1.08 | 0.94 | 87 | 5 | 0.09 | 3.32 | 1.20 | 1.45 | 121 | 4 |
| | CHA | 0.38 | 4.02 | 2.11 | 1.79 | 85 | 5 | 0.77 | 57.39 | 21.48 | 25.00 | 116 | 5 |
| | SEB + CHP | 0.19 | 2.58 | 0.86 | 1.01 | 117 | 5 | 0.08 | 5.18 | 1.45 | 2.49 | 172 | 4 |
| | SEB + LOC | 0.23 | 2.48 | 0.78 | 0.96 | 123 | 5 | 0.05 | 1.31 | 0.56 | 0.54 | 96 | 4 |
| | CHP + LOC | 0.27 | 2.60 | 1.04 | 1.03 | 99 | 5 | 0.09 | 5.22 | 1.72 | 2.20 | 128 | 5 |
| | CHA + LOC | 0.25 | 3.37 | 1.19 | 1.31 | 110 | 5 | 0.09 | 5.32 | 2.19 | 2.14 | 98 | 5 |
| 2014 | BOI | 0.08 | 1.35 | 0.39 | 0.54 | 138 | 5 | 0.02 | 3.37 | 1.01 | 1.58 | 156 | 4 |
| | SEB | 0.17 | 1.31 | 0.51 | 0.46 | 90 | 5 | 0.07 | 2.80 | 0.94 | 1.28 | 136 | 4 |
| | CHP | 0.27 | 2.54 | 1.15 | 0.87 | 76 | 5 | 0.19 | 34.35 | 9.08 | 16.86 | 186 | 4 |
| | CHA | 0.38 | 4.85 | 2.20 | 2.07 | 94 | 5 | 0.23 | 286.14 | 90.20 | 133.81 | 148 | 4 |
| | SEB + CHP | 0.08 | 2.35 | 0.79 | 0.91 | 115 | 5 | 0.07 | 11.07 | 3.32 | 5.23 | 158 | 4 |
| | SEB + LOC | 0.08 | 1.58 | 0.56 | 0.59 | 105 | 5 | 0.10 | 5.05 | 1.66 | 2.30 | 139 | 4 |
| | CHP + LOC | 0.10 | 0.82 | 0.40 | 0.27 | 68 | 5 | 0.08 | 0.46 | 0.20 | 0.18 | 90 | 4 |
| | CHA + LOC | 0.18 | 2.76 | 0.99 | 1.06 | 107 | 5 | 0.07 | 15.47 | 4.65 | 7.30 | 157 | 4 |

CV: coefficient of variation; SD: standard deviation; Min: minimum; Max: maximum; *n*: number of runoff events.
BOI: *Bothriochloa ischaemum* L.; SEB: Sea-buckthorn; CHP: Chinese pine; CHA: Chinese arbor-vitae; LOC: Black locust.

with SEB (SEB + LOC) was greater (3.1 g m$^{-2}$) than when it was grown with CHA (2.2 g m$^{-2}$), or when SEB was grown with CHP (SEB + CHP; 0.6 g m$^{-2}$). However, this pattern of soil loss changed in 2013 when, under SEB + LOC the soil loss (0.6 g m$^{-2}$) was lower than under CHA + LOC (2.2 g m$^{-2}$), which was greater than under SEB + CHP (1.5 g m$^{-2}$). Moreover, substantially greater soil loss amounts were observed during 2011 in comparison with the other four years because the total precipitation was much greater in that year.

For comparison, the total annual surface runoff and total annual soil losses for the five years between 2010 and 2014 were averaged for each vegetation type (Figs. 4 and 5). During the five years, the mean annual surface runoff of the eight vegetation types ranked in order of CHA > CHA + LOC > CHP > SEB + LOC > CHP + LOC > SEB + CHP > SEB > BOI. However, the mean annual soil loss order was different to that of the annual runoff. The mean annual soil loss from the CHA plot was the greatest, just as the runoff amount was, and was 9–110 times greater than the soil loss from the plots with the other vegetation types. The second highest soil loss, occurred from the CHP plots, followed by the CHP + LOC and CHA + LOC plots, and then the SEB + LOC and SEB + CHP plots. The BOI plot exhibited the lowest mean annual runoff and soil

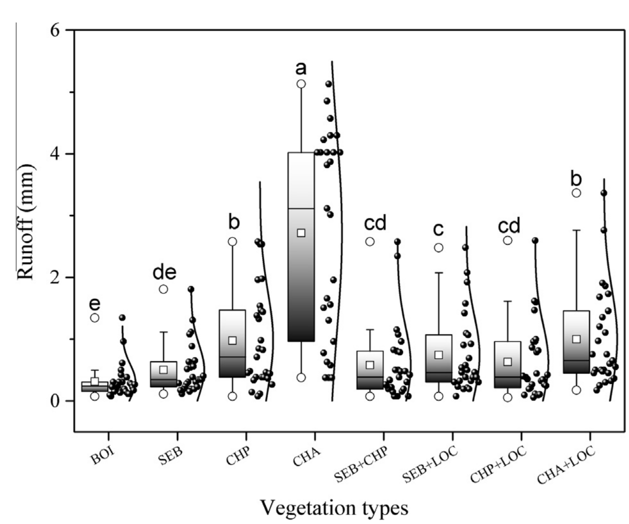


**Fig. 4.** Comparison of surface runoff among different vegetation types. A distribution curve is on the right of each box plot and data points are represented by spheres. Box plots with a letter in common indicate no significant differences between the surface runoff under two vegetation types ($P < 0.05$).

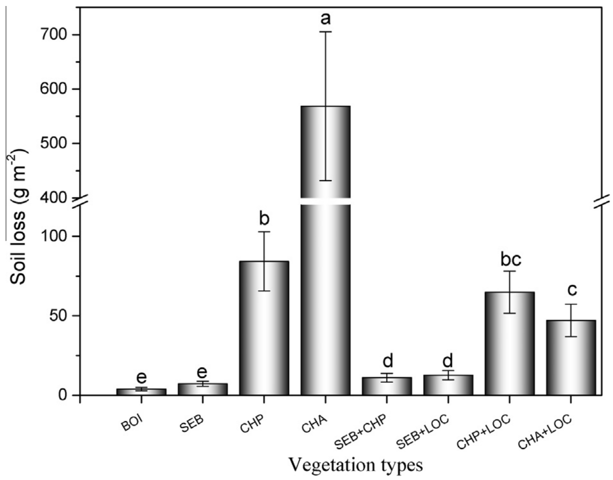


**Fig. 5.** Comparison of soil losses among different vegetation types. Error bars represent the standard deviation. Bars with a letter in common indicate no significant differences between the soil loss under two vegetation types ($P < 0.05$).

losses when compared to those from the plots under the other vegetation types.

The effect of runoff on soil loss depended on the vegetation type (Fig. 6). The slope of the regression equation describing the relationship between the runoff coefficient and the soil loss can be regarded as an indicator of the amount of soil loss produced by the runoff and also as a parameter with which to interpret the effect of different types of vegetation on soil erosion (Vásquez-Méndez et al., 2010). The slopes of the regressed linear lines were ranked in the order: CHA > CHP > CHP + LOC > CHA + LOC > SEB + CHP > SEB + LOC > SEB > BOI (Fig. 6). Since these slope values can be used as indicators of the effectiveness of different vegetation types in reducing soil erosion, it can be seen that they confirm that, in general, BOI and SEB, with the lowest slope values, were more effective in controlling erosion than the other vegetation types were.

### 4.4. Water balance components

The actual evapotranspiration in different vegetation types was calculated using the water balance model Eq. (4) and the results of the water balance during the growing season of 2013–2014 are presented in Table 5. In 2013, the actual evapotranspiration was higher than the rainfall (532.3 mm) for CHP + LOC (566.2 mm), while it was lower than the rainfall for BOI. For the other six vegetation types, the actual evapotranspiration values were approximately equal to the amount of rainfall during the growing season; the difference between those two parameters ranged from −7.4 to 2.6 mm. Different vegetation types had different effects on soil water dynamics. The soil water change in 2013 was positive in the BOI, SEB, CHP, SEB + LOC, CHA + LOC plots, whereas they were negative in the CHA, SEB + CHP, and CHP + LOC plots. In 2014, the actual evapotranspiration exceeded rainfall (464.4 mm) for all of the vegetation types with the exception of BOI, and the maximum difference was 63.2 mm for CHP + LOC. Hence, the soil water surplus during both growing seasons occurred under BOI, whereas soil water deficits occurred under all of the other seven vegetation types. Similarly, the mean actual evapotranspiration values for 2013–2014 were greater than the mean total rainfall (498.4 mm) during those two years for seven of the eight vegetation types (Zhang et al., 2016), with the exception being BOI, and the soil water changes were also negative under those seven vegetation types.

## 5. Discussion

### 5.1. Leaf area index (LAI)

It is generally known that LAI has a significant influence on hydrological processes (Fu et al., 2012). Greater LAI is frequently associated with more evapotranspiration and reduced soil water infiltration because of canopy interception (Zimmermann et al., 2007; Fu et al., 2012). High evapotranspiration combined with low soil water infiltration can cause soil desiccation (Jian et al., 2015). If the LAI is lower, soil evaporation can be much higher within plots where exposure to light penetration is greater because this increases soil temperatures due to the reductions in shading by the overstory canopy. Furthermore, in such plots reduced levels of forest floor litter can also occur resulting in reduced protection from the increased light and air temperatures. Zhang et al. (2015) found that the optimal plant cover (expressed as the maximum LAI) was about 2.5 in this study area. The maximum LAI values of five of the vegetation types considered in this study were much greater than 2.5; i.e., those of SEB, CHP, SEB + CHP, CHP + LOC, and CHA + LOC. However, large values of LAI also generally correspond to greater amounts of water consumption that may lead to soil desiccation. From this aspect, a smaller maximum LAI value can reduce water consumption. Among the vegetation types investigated in this study, BOI had the smallest maximum LAI (2.09). Thus, achieving an optimal LAI is crucial for controlling soil desiccation.

### 5.2. Soil water storage

In this study, soil water storage was greatly affected by vegetation type and differed significantly among the eight different vegetation types, especially in the deep soil layer (Fig. 3). These results were in agreement with the findings of Wang et al. (2011) for the Loess Plateau, but differed to those of previous studies that indicated no significant differences were found between different vegetation types at depths below 2 m (Yang et al., 2012). Soil water storage in shallow soil layers varies seasonally and inter-annually depending on the amount of precipitation. Precipitation probably reduced the effect of vegetation type on soil water storage in shallow soil layers. The effect of vegetation type would be mainly due to its effect on root water uptake and would more clearly be observed in the soil water storage in the deep layers where rainfall had a smaller influence (Wang et al., 2010). Root uptake differed among different vegetation types (Fu et al., 2012; Jia and Shao, 2014). Han et al. (2007) and Yang et al. (2013) measured root distributions in soil profiles under CHP, SEB, LOC, and BOI in the study area, and found that the maximum root depth was about 4.5 m for CHP, SEB, and LOC, and 1.0 m for BOI. Their results also indicated that 86% of the BOI root system was in the 0–30 cm soil layer, 75% of the CHP and LOC root systems were in 40–80 cm layer, and 75% of the root systems of other plants were in the 10–40 cm layer. A greater number of plant roots present in the shallow soil layer can result in greater water consumption levels from that layer, while soil evaporation also contributes to lower water contents in that layer (Cheng et al., 2009; Fu et al., 2012; Yang et al., 2012). Hence, greater amounts of soil water stored in deep soil layers can be vital for plant survival and can be particularly important for the sustainable growth of vegetation (Chen et al., 2008).

In the deep layers, the root density of BOI was lower than any of the other vegetation types and, thus, had a lower root water uptake capacity from those layers. Consequently, the soil water storage in these layers was significantly greater under BOI than under the other vegetation types. Plant water uptake was considerably lower from the deep soil layers in the BOI plots than from those in the

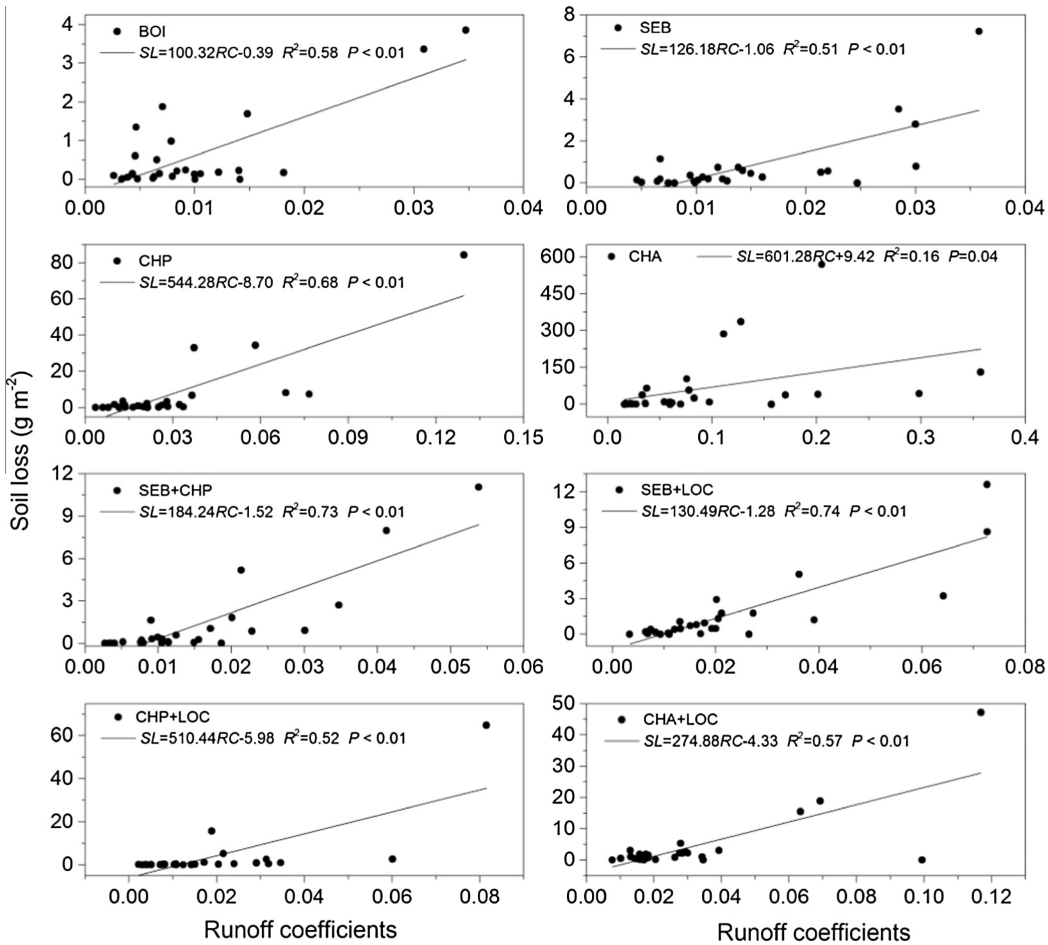


**Fig. 6.** Linearly regressed relationships between soil loss (SL) and runoff coefficient (RC) for each vegetation type represented by the lines with data points shown as black circles ($R^2$, coefficient of determination). BOI: *Bothriochloa ischaemum* L.; SEB: Sea-buckthorn; CHP: Chinese pine; CHA: Chinese arbor-vitae; LOC: Black locust.

other vegetation plots. This resulted in maintaining higher soil water contents that could also increase due to rainwater recharge of the deep soil layer under BOI. For high water consuming plants, low available soil water can not only constrain plant growth and aggravate soil water scarcity but also threaten the sustainability of vegetation restoration (Porporato et al., 2002; Yang et al., 2012). Thus, planting an optimal vegetation type is necessary in order to balance soil water consumption and the eco-environmental service performances of a vegetation restoration program (Cao et al., 2011). The successional planting can improve soil properties by gradually increasing soil organic matter and thus may result in more successful re-vegetation (Chen et al., 2007).

### 5.3. Surface runoff and soil erosion

Since the soil properties were not significantly different among the eight vegetation plots (Yang et al., 2016), the differences in surface runoff and soil erosion for different vegetation plots were due to the effects of the different vegetation types. The lowest amounts of surface runoff and soil losses occurred under BOI due to the 100% cover that protected the soil surface. In contrast, the highest amounts of surface runoff and soil losses occurred under CHA due to a cover of only 35%, which was less able to protect the soil surface. Therefore, increasing surface cover is an effective means by which to reduce surface runoff and soil loss. For the same vegetation type, the surface runoff and soil loss exhibited large variations in different years and for different rainfall events (Table 4). This result suggested that surface runoff and soil loss were not only influenced by vegetation type but also by the characteristics of rainfall events, which include the amount of rainfall, rainfall intensity, etc., which led to a high degree of heterogeneity in surface runoff and soil loss (Wei et al., 2007; Mohammad and Adam, 2010).

The use of the runoff coefficient can normalize the surface runoff for different rainfall events (Wei et al., 2007; Vásquez-Méndez et al., 2010). To better reflect the influence of vegetation type on soil erosion, the relationship between the runoff coefficient and soil loss was derived for each vegetation type. Soil loss was significantly ($P < 0.05$) increased by increases in the runoff coefficient value, which was consistent with the findings of Mohammad and Adam (2010) (Fig. 6). The correlations between the runoff coefficient and soil loss for CHP, SEB + CHP, and SEB + LOC were strong and positive as indicated by the coefficient of determination ($R^2$) values of 0.68, 0.74, and 0.73, respectively. Compared with the other vegetation types, the soil loss from the CHA plot would be poorly estimated by the runoff coefficient since the $R^2$ value was only 0.16, even though the relationship between these two variables was significant (Fig. 6).

The presence of grass roots is an important factor that affects soil erosion by physically binding soil aggregates and particles within the soil matrix and by generating chemical exudates that are involved in bonding the soil that enhances soil stability and the soil's resistance to water erosion (Wang et al., 2014). They also play a crucial role in improving soil strength, thereby reducing soil erodibility (Knapen et al., 2007). Although CHP or CHP + LOC had greater LAI values than BOI, which might have suggested that their canopies would protect the soil surface from raindrop impact and

**Table 5**
Water balance components during the growing seasons of 2013 and 2014 for eight different vegetation types.

| Vegetation type | Year | Rainfall (mm) | ΔS (mm) | Runoff (mm) | Evapotranspiration (mm) |
|---|---|---|---|---|---|
| BOI | 2013 | 532.3 | 45.3 | 2.0 | 484.9 |
| | 2014 | 464.4 | 3.7 | 2.0 | 458.7 |
| | Mean | 498.4 | 24.5 | 2.0 | 471.8 |
| SEB | 2013 | 532.3 | 3.7 | 2.8 | 525.7 |
| | 2014 | 464.4 | −30.1 | 2.5 | 492.0 |
| | Mean | 498.4 | −13.2 | 2.7 | 508.9 |
| CHP | 2013 | 532.3 | 1.9 | 5.4 | 524.9 |
| | 2014 | 464.4 | −31.3 | 5.7 | 490.0 |
| | Mean | 498.4 | −14.7 | 5.6 | 507.51 |
| CHA | 2013 | 532.3 | −9.5 | 10.6 | 531.3 |
| | 2014 | 464.4 | −44.3 | 11.0 | 497.7 |
| | Mean | 498.4 | −27.0 | 10.8 | 514.5 |
| SEB + CHP | 2013 | 532.3 | −6.8 | 4.3 | 534.9 |
| | 2014 | 464.4 | −39.8 | 3.9 | 500.3 |
| | Mean | 498.4 | −23.4 | 4.1 | 517.6 |
| SEB + LOC | 2013 | 532.3 | 0.8 | 3.9 | 527.6 |
| | 2014 | 464.4 | −29.0 | 2.8 | 490.6 |
| | Mean | 498.4 | −14.1 | 3.3 | 509.1 |
| CHP + LOC | 2013 | 532.3 | −39.2 | 5.2 | 566.2 |
| | 2014 | 464.4 | −65.2 | 2.0 | 527.6 |
| | Mean | 498.4 | −52.2 | 3.6 | 546.9 |
| CHA + LOC | 2013 | 532.3 | 1.1 | 6.0 | 525.2 |
| | 2014 | 464.4 | −32.1 | 5.0 | 491.5 |
| | Mean | 498.4 | −15.5 | 5.5 | 508.3 |

Δ*S*: soil water storage change in the 0–5 m soil layer.
BOI: *Bothriochloa ischaemum* L.; SEB: Sea-buckthorn; CHP: Chinese pine; CHA: Chinese arbor-vitae; LOC: Black locust.

reduce soil erosion, the plots under these two vegetation types were actually the most susceptible to soil and water losses among the eight vegetation-type-plots. The large runoff and soil loss amounts were attributed to the lack of an understory layer. Very little grass existed near the soil surface since the canopy also reduced the amount of sunlight that could be utilized by understory plants (Jian et al., 2015). Chen et al. (2008) also found that favorable conditions for runoff and soil erosion under a forest were related to the prevailing bare soil conditions caused by decreased understory vegetation. Consequently, the grass plot (i.e., BOI) was less susceptible to soil erosion than the tree plots, especially that of CHP. This result was in accordance with the findings of Li et al. (2015), who reported that the erosion under woodland is 1.7 times greater than that under grassland. These results for surface runoff and soil losses in connection to the vegetation type would be useful when applied to soil and water conservation planning. From this aspect, planting SEB or BOI may be an excellent land management strategy by which to conserve both water and soil resources, while the use of CHP or CHP + LOC plantations would not be recommended for the semi-arid areas of the Loess Plateau.

### *5.4. Water balance components*

Vegetation types affect soil water dynamics and water balances by increasing evapotranspiration and/or by reducing runoff (Zhang et al., 2001; Sun et al., 2006; Oudin et al., 2008). The evapotranspiration capacity of the grassland species (BOI) was much lower than those of the other vegetation types (Table 5), and the surface runoff from the BOI plot was also the lowest among the eight vegetation plots. The soil water surplus that occurred under BOI during the growing season of 2013–2014 was due to it having the lowest LAI, which reduced its water requirement. However, soil water replenishment through rainfall could not meet the water requirements of the other seven vegetation types, which were relatively high due to the semi-arid climate. It is probable that the vegetation restoration strategy is limited by soil water availability (Chen et al., 2008; Cao et al., 2011). If these seven vegetation types, which are considered as the main species for soil erosion control, were to be used for vegetation restoration it would probably result in different degrees of soil desiccation on the Loess Plateau. Moreover, Wang et al. (2011) found that soil desiccation was more severe under forest than under grassland, and that dried soil layers under forest were more developed than those under grassland. Therefore, optimal vegetation type and its effect on soil water content must be considered in the selection of optimal vegetation restoration strategies for sustainable growth in this area (Chen et al., 2010; Fu et al., 2012; Zhang et al., 2015). Maintaining relatively more grassland as the start of successional re-vegetation strategy would be more appropriate for vegetation restoration (McVicar et al., 2010) on the steep slopes of the Loess Plateau.

## 6. Conclusion

This study investigated the water balance of eight vegetation types and determined the most suitable species for sustainability of vegetation restoration projects on the steep slopes of the Loess Plateau. Vegetation type had notable effects on LAI, soil water contents, and soil water storage. The BOI plot had the highest soil water contents and soil water storage, due mainly to having the lowest LAI and water requirements. In particular, vegetation type could lead to spatial variation in soil water but had a negligible effect on soil water temporal patterns. Surface runoff and soil loss was also considerably influenced by vegetation type. The BOI and SEB plots produced the lowest runoff and soil losses, while forest plots had higher water and soil losses. The CHP and CHP + LOC vegetation types were unsuitable for erosion control due mainly to an associated absence of an understory layer. Soil water dynamics and evapotranspiration varied greatly among different vegetation types. A soil water surplus only occurred under BOI, while soil water deficits commonly occurred under the other seven vegetation types. Such deficits would severely restrict plant transpiration and growth. Considering the water balance in relation to soil and water conservation practices, BOI can be highly recommended for vegetation restoration on steep slopes in semi-arid regions. A similar approach to the one used in this study could be applied to other regions of the world confronted by the same problems of water scarcity along with the need for vegetation restoration.


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