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Effects of soil moisture conditions on vegetative reconstruction with alfalfa on the northern Shaanxi Loess Plateau

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Vegetative reconstruction using alfalfa (*Medicago sativa*) has been effective in many areas to combat desertification. In arid regions of the China Loess Plateau water availability limits alfalfa productivity. Precipitation, runoff, soil moisture, and alfalfa biomass data from 2008 to 2010 on four distinct slopes representative of the Northern Shaanxi Loess Region, were collected. Relationships between precipitation, water availability, water use, and biomass were evaluated. Two methods - the Penman-Monteith-56 method and the water balance method, were used to estimate soil water carrying capacity for alfalfa and were compared. For alfalfa land on steep slopes, the relationship between water availability (Y_s) and precipitation (P) was $Y_s = 0.8003P + 2.8568$. Available water and alfalfa biomass had a linear correlation and alfalfa biomass and water use had a quadratic correlation. The Penman-Monteith-56 method estimated average annual water use of alfalfa to be 446.6 mm and peak alfalfa production to be 3992.2 to 4173.7 kg ha^{-1}. This method overestimated annual water use by 24.3 to 25.8% and biomass by 16.1 to 33.5%. Relationships between all measured parameters and recommendations for improving vegetative reconstruction are discussed.

Key words: Penman-Monteith-56 method, soil and water balance principle, *Medicago sativa*, water availability, desertification.

INTRODUCTION

Ecological environment of the Northern Shaanxi portion of the China Loess Plateau is extremely fragile. Soil erosion is serious, with annual soil loss of 16,000 tons km^{-2} (Zhu, 1990). Erosion from this region accounts for 56% of the total sediment load of the Yellow River. Moderately undulating slopes, ≥ 15°, characterized by broken and complex terrain with weak soil structure, high runoff, and low infiltration, account for 82% of the total area. Soil aridity is the most serious environmental challenge in the region and desertification is one of the top government initiatives (Zhu, 1990). Vegetative reconstruction, among other techniques, has successfully reversed the effects of desertification in many areas and is gaining wide-spread application in the Northern Shaanxi Loess Plateau.

However, soil moisture is one of the most important

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factors limiting vegetative reconstruction. Precipitation and average soil moisture in the region are decreasing, water consumption, evaporation, and transpiration are increasing (Bosch and Hewlett, 1982; Gardiol et al., 2003), and soil moisture in the region decreases with depth (Wang et al., 2008b).

Under-irrigation can cause slow and unstable growth which leads to reduced plant populations in times of drought, and there are serious economic constraints for vegetative reconstruction making over-irrigation economically untenable. To improve ecological and economic efficiency, vegetative reconstruction must have stable productivity which considers environmental constraints (Li, 2002; Zeide, 2004; Liu et al., 2010). Balanced irrigation management for vegetative reconstruction requires moderate production goals and prevents soil from reaching the wilting point.

Alfalfa (*Medicago sativa*) is drought resistant, grows quickly, fixes nitrogen, and has market value. Due to its high ecological and economic efficiency, it is a suitable option for soil conservation efforts and is currently the preferred species for slope vegetation reconstruction in the region. According to the Shaanxi Loess Plateau Research Institute (unpublished data), 15 to 25° slope gradient is suitable for alfalfa production in the Northern Shaanxi Loess Region, but slope variation, direction, and position significantly affect alfalfa growth.

The vegetative carrying capacity for soil moisture (VCCSM), which is the greatest population of a given plant that an ecosystem can naturally sustain through precipitation, is an important land reclamation assessment tool (Philip, 1966; Price, 1999; Guo and Shao, 2003b; SAUCA, 2005; Xia, 2008). Calculations of VCCSM include rapid mathematical model simulations (Raich et al., 1991; Aber and Federer, 1992; Zeide, 2004; Garcia-Quijano and Barros, 2005; Sun, 2004; Tian et al., 2009) and precise calculations based on the soil/water balance principle (Guo and Shao, 2003a; Ma et al., 2001). The former may save time and money, but can only generally reflect VCCSM of some plants in certain regions, and has limited application for the complex topographical conditions in the Loess Plateau. The latter is difficult and time-consuming, but is more precise and reliable. These methods can be combined so that the advantages of each can be exploited (Wang et al., 2008a). At present, VCCSM has been measured by plant thickness (Price, 1999; Guo and Shao, 2003a; Ma et al., 2001; Gao et al., 2002; Yan et al., 2001; Wang et al., 2005; Radersma et al., 2006), biomass (output), and leaf area (Tian et al., 2009; Xia, 2008). Since alfalfa output is the foundation of local animal husbandry development, biomass is the most suitable measurement option for this study, and also advantageous to the direct-viewing application in the production is its being easy to measure. Research which analyzes precipitation patterns, slope gradient, and subsequent effects on soil moisture, as well as moisture requirements for alfalfa, is crucial to sustainable vegetative reconstruction of the Loess Plateau (Verheyen et al., 2008; Xia, 2008). This will not only provide an important scientific basis for Loess Plateau land reclamation, but also has vital practical significance for sustainable ecological, economical, and social development of the region (Schneider et al., 1978) and can inform land reclamation research in other areas of the world as well. Considering the special characteristics of the Northern Shaanxi Loess Plateau Region, simulations using the Penman-Monteith-56 method and calculations of VCCSM using the soil/water balance principle were both measured on alfalfa. Implications for vegetative reconstruction are discussed.

MATERIALS AND METHODS

Study location

Observations were carried out at the Mizhi County Research Station of the Northwest Agriculture and Forestry University Loess Plateau Institute. This research station is located in the Mizhi County Donggou Basin, N 37° 40' to 38° 06', E 100° 15' to 110° 16'. The area is 4.1 km^2, soil suborder is Ustic Cambosols (CST, 2001), and soils have low fertility. Soil organic matter content is 2.29 g kg^{-1} and average pH is 8.9. Average annual temperature of the study area is 8.9°C; average annual precipitation is 420.2 mm; cumulative daylight hours is 2,716 h; frost-free period is 160 to 170 days; slope is 15 to 35°; and elevation is 951 to 1,029 m.

Experimental design

In the study area, alfalfa is generally grown on southern facing slopes because they receive more sunlight. On northern facing slopes, alfalfa is only distributed on down-slopes with smaller gradients. The experimental design considers this aspect of vegetative reconstruction management. The test was carried out on four site types. Seven 5 × 20 m runoff plots were constructed on south facing 15° slopes near the shoulder (uphill slopes) and south facing 23° uphill slopes. Alfalfa seeds were sown at a depth of 2 to 3 cm at densities of 5.5, 8.0, 10.5, 13.0, 15.5, 18.0, and 20.5 kg ha^{-1}. Five 5 × 20 m runoff plots were also constructed on mature, 6-year-old alfalfa land on south facing 15° slopes near the floodplain (downhill slopes) and north facing 15° downhill slopes. For treatment, 0, 20, 40, 60 and 80% of mature alfalfa plants were removed.

Data collection and analysis

Eight standard rain gauges were placed between plots. After each precipitation event, precipitation and surface runoff were measured. A neutron moisture meter system (CNC503B-DR) was used to measure soil moisture. Two neutron probes, 6.3 and 4.3 m in length, were inserted 10 m apart in the center of the field and at the sampling points. Moisture was determined monthly in the profile from 0 to 600 cm in 20 cm increments. Meteorological data from 2008 to 2010 was provided by the Mizhi County Meteorological Bureau. During the peak flowering period and in autumn, entire plots were harvested above the crown and fresh weights were recorded. Samples were dried and then weighed again and water content was calculated. Total biomass for each plot equals the sum of the weight of the two harvests.

The fate of precipitation can be summarized as four processes: interception at the alfalfa crown, evaporation, infiltration into soil,

Table 1. Precipitation (mm) from 2007 to 2010 in Mizhi County, Shaanxi.

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
2007	0	5.5	2.4	11.3	40.1	36	42.4	103.1	60.1	7.5	0	4.6	313
2008	12.3	5.2	0	12.2	60.3	81.3	168.3	91	42.3	15.7	12.3	0	500.9
2009	0.3	10.4	33.6	12	32.3	51	54.7	86.6	68.6	32	16.2	3.5	401.2
2010	14.5	5.8	12.5	35.2	6.1	50.4	31.6	59	95.2	25.2	1	0	336.5
Average	2.7	5	12.6	20.9	32.8	61.1	93.7	100.9	56.4	21.6	9.6	2.9	420.2

and runoff. Also, the water table level is ≥ 60 m (Li, 1983, 2002; Liu and Huang, 2002; Wang and Zhang, 2003) and no water is supplied by capillary action from the water table. Therefore, water availability for alfalfa was calculated as the difference between precipitation and surface runoff.

In the Loess Plateau arid and semi-arid areas, water availability determines vegetative productivity, especially for introduced varieties (Yang, 1996; Liu et al., 2010). Changes in upslope biomass affect runoff and water availability. In order to decrease the influence of precipitation and alfalfa production variation among years, weighted mean values for alfalfa biomass corresponding to precipitation were calculated prior to regression analysis.

Penman-Monteith-56 method

Estimating evapotranspiration using the Penman-Monteith-56 method (Allen et al., 1998) allows researchers to compare results to other studies across time, region, and soil and crop conditions. The Penman-Monteith-56 method was used in this study to calculate crop coefficients for alfalfa and evapotranspiration in the study area [Equation 1].

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \quad (1)$$

where, ET_o is reference evapotranspiration (mm day^{-1}), R_n is net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapour pressure (kPa), e_s - e_a is saturation vapor pressure deficit (kPa), Δ is slope vapor pressure curve (kPa °C^{-1}), and γ is psychrometric constant (kPa °C^{-1}).

The alfalfa crop coefficient (Kc) was calculated using monodromy analysis of the average computation recommended by FAO (Allen et al., 1998), and adjusted according to field generated data.

Estimation of light/heat potential (kg ha^{-1}), using crop radiation data and temperature, assumes that no other growth factors are limiting (Equation 2).

$$Y_{MP} = CL \times CN \times CH \times G \times \left[F \times (0.5 + 0.025 \times Y_M) \times Y_O + (1 - F) \times (0.05 \times Y_M) \times Y_C\right] \quad (2)$$

where, CL is the correct value of the leaf area index to the output, CN is the correct value of the material productivity, CH is the harvest index, G is alfalfa production period (number of days), F is cloud cover (%), Y_M is peak production under local climate conditions (kg ha^{-1} day^{-1}), Y_O is alfalfa production during cloud cover (kg ha^{-1} day^{-1}), and Y_C is alfalfa production during direct sunlight (kg ha^{-1} day^{-1}).

An alfalfa output index was calculated (Equation 3).

$$I_Y = 1 - K_Y \times \left(1 - ET_A / ET_M\right) \quad (3)$$

where, K_Y is the influence coefficient of water scarcity for alfalfa production, ET_A is actual water volume (mm) which alfalfa obtained in the duration period, under the specific quantity moisture supply situation; ET_M is alfalfa' water demand (mm) in the duration period. Under natural precipitation conditions, actual output (Y) for alfalfa is

$Y = Y_{mp} \times I_y$.

RESULTS

Regression of precipitation and available water

Annual rainfall data of Mizhi County from 1978 to 2010 reveals large variation, with 692.6 mm in 1980 and 239.4 in 1995. Additionally, precipitation within season is non-uniform (Table 1). Most precipitation occurs as high intensity rainstorms which account for the majority of annual rainfall. For example, on August 30, 2009, a single rainstorm event, with 77.7 mm precipitation, represented 15.5% of the annual precipitation. Concurrently, negligible precipitation (continuous 24 h precipitation with < 10 mm) was frequent. From 1978 to 2010, negligible precipitation was a cumulative 62,143 mm. Precipitation from January to March accounts for 4.8% of annual precipitation, and from April and May accounts for 5.0 and 7.8%, respectively. Precipitation is primarily concentrated from June to September, representing 74.3% of annual precipitation and precipitation from October to December accounts for 8.1% of annual precipitation.

Regression analysis of water availability (Y_s) with precipitation (P) reveals a strong linear relationship. As slope increases, surface runoff increases and water availability decreases. For the 15° gradient, $Y_s = 0.8003P + 2.8568$ ($r^2 = 0.987$,

Table 2. Precipitation and soil water supply (mm) on alfalfa in in Mizhi County, Shaanxi from 2008-2010.

Year	Parameter	Slope	April	May	June	July	August	September	October	November
2008	Precipitation		11.3	40.1	36.0	42.4	103.1	60.1	7.5	0.0
	Runoff	15°	0.0	0.0	0.0	0.0	16.3	11.8	0.0	0.0
		23°	0.0	3.2	0.0	0.0	19.5	13.5	0.0	0.0
	Available	15°	11.3	40.1	36.0	42.4	86.8	48.3	7.5	0.0
		23°	11.3	36.9	36.0	42.4	83.6	46.6	7.5	0.0
2009	Precipitation		12.2	57.2	54.6	133.9	156.9	29.5	8.9	4.8
	Runoff	15°	0.0	1.9	3.8	29.9	25.9	0.0	0.0	0.0
		23°	0.0	2.2	4.2	33.5	28.5	0.0	0.0	0.0
	Available	15°	12.2	55.3	50.8	104.0	131.0	29.5	8.9	4.8
		23°	12.2	55.0	50.4	100.4	128.4	29.5	8.9	4.8
2010	Precipitation		12.0	32.3	51.0	54.7	86.6	68.6	82.0	1.2
	Runoff	15°	0.0	0.0	0.0	0.0	16.9	16.8	11.5	0.0
		23°	0.0	0.0	1.8	0.0	18.8	17.5	12.6	0.0
	Available	15°	12.0	32.3	51.0	54.7	69.7	51.8	70.5	1.2
		23°	12.0	32.3	49.2	54.7	67.8	51.1	69.4	1.2

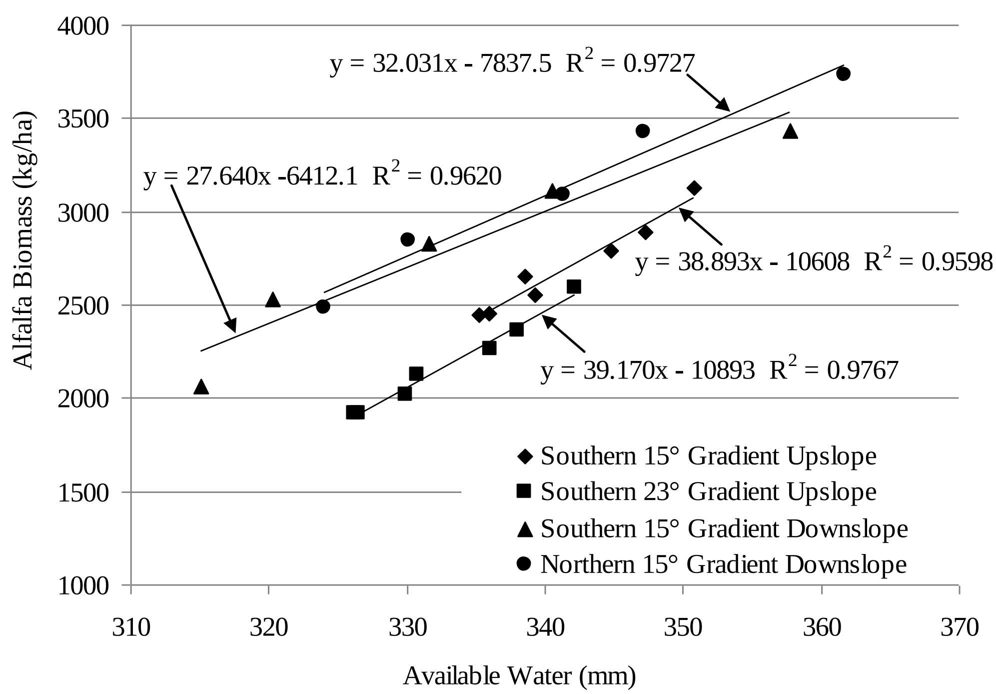

Figure 1. Regression of alfalfa biomass and available water on different slopes of the Northern Shaanxi Loess Plateau.

n = 33) and for the 23° gradient, $Y_s = 0.7771P + 3.0411$ ($r^2 = 0.985$, n = 33).

Regression of available water and alfalfa biomass

Typically, alfalfa plants were diminutive, crown level was thin, and water interception quantity was small (Table 2). The results show a linear relationship between water availability (Y_s) and upslope biomass (W_{dw}) (Figure 1). These regressions show that as alfalfa biomass increases, surface roughness and water runoff interception increases and impact erosion decreases, causing an increase in water availability. As the slop

Table 3. Evapotranspiration, water use, and crop coefficients for alfalfa on the Northern Shaanxi Loess Plateau.

Item	April	May	June	July	August	September	October	November	Total
ET_0 (mm d^{-1})	3.25	3.25	9.05	8.88	7.43	3.35	2.4	1.65	
Calculating days (d)	30	31	30	31	31	30	31	15	229
Crop coefficient (K_C)	0.4	0.45	2.1	0.9	1.9	0.4	0.2	0.1	
Water consumption (mm)	39	59.3	151.2	57.1	99.2	28.8	10.2	1.8	446.6

gradient increases, surface runoff increases and water availability decreases, but slope position and slope direction have little effect on water availability.

Regression of water use and alfalfa production

Water requirements for alfalfa on steep slopes is 446.6 mm, but the annual available water on the 15 and 23° gradients were 338.0 and 331.3 mm, respectively, resulting in a major water deficit (Table 3). Although this method does not consider terrain and biomass, it is still a useful benchmark for rapid estimation of water availability under experimental conditions.

Our estimation of soil water retention adequately reflects field observations (Figure 2). According to the water budget principle, with the specific physical geography condition in the Northern Shaanxi Loess Region, the underground water supply quantity and the holard infiltrates the leakage and can be neglected, in certain time. The sample plot 0 to 5 m soil layer soil moisture content W_{t2} is the initial soil moisture (W_{t1}) + available water (Y_s) – water use (Y_c). Mean error is ≤ 9%, indicating that the soil moisture consumption simulation results are acceptable.

During alfalfa production, water use is directly related to terrain (slope gradient, direction, and position) and above ground biomass. If biomass cover is high, water competition is high, plant grow is affected, and aridity is exacerbated. If biomass coverage is low, impact erosion is more common but water use is lower. Regression of water use (Y_c) and alfalfa biomass production (W_{dw}) under the four local growth conditions from 2008 to 2010, revealed a quadratic relationship. The southern, 15° gradient, uphill slope is $Y_c = 0.0001\ W^2 - 0.4635\ W + 854.72$ ($r^2 = 0.960$); the southern, 23° gradient, uphill slope is $Y_c = 0.0001\ W^2 - 0.3836\ W + 659.16$ ($r^2 = 0.981$); the southern, 15° gradient, downhill slope is $Y_c = 0.0001\ W^2 - 0.4628\ W + 805.53$ ($r^2 = 0.973$); and the northern, 15° gradient, downhill slope is $Y_c = 0.0001\ W^2 - 0.5324\ W + 991.67$ ($r^2 = 0.951$). Biomass production and water use are positively correlated. Slope position has a direct affect on water use because solarization on the southern slope is intense.

Alfalfa production capacity

In the study area, light/heat estimation was 7115 kg ha^{-1}. The alfalfa output index for the 15° gradient and 23° gradient was 58.7 and 56.1%, respectively, and actual alfalfa output for the 15° gradient and 23° gradient was 4173.7 and 3992.2 kg ha^{-1}, respectively. Therefore, under the natural precipitation conditions, Northern Shaanxi Loess Region steep slope farmland can support 3992.2 to 4173.7 kg ha^{-1} y^{-1} alfalfa.

Assuming an ideal 100% use efficiency according to the Penman-Monteith-56 method, we can estimate the soil carrying capacity for alfalfa production under various local growth conditions. Ideal production for the southern, 15° gradient, uphill slope would be 6926.3 kg ha^{-1}; for the southern, 23° gradient, uphill slope would be 6716.1 kg ha^{-1}; for the southern, 15° gradient, downhill slope would be 6631.3 kg ha^{-1}; and for the northern, 15° gradient, downhill slope would be 6555.6 kg ha^{-1}. This also illustrates that active management of soil moisture with irrigation can enhance vegetative production.

Water balance estimation

If soil moisture and biomass production are balanced, and water availability is properly managed, then, when the water use is equal to available water, plant density and biomass is at peak production. Under this assumption, we estimated available water needed for peak production under the four local growth conditions. For the southern, 15° gradient, uphill slope, 2849 kg ha^{-1} is needed, 31.7% lower than the estimated value; for the southern, 23° gradient, uphill slope, 2654 kg ha^{-1} is needed, 33.5% lower than the estimated value; for the southern 15° gradient, downhill slope, 3190 kg ha^{-1} is needed, 23.6% lower than the estimated value; and for the northern, 15° gradient, downhill slope, 3503 kg ha^{-1}, 16.1% lower than the estimated value.

DISCUSSION

Precipitation variation creates conditions for frequent floods and droughts and also causes large variation in agricultural production, which can be ten times higher in high production years than low production years. This is due to the effects of precipitation patterns on plant physiology. From January to April plants are dormant or emerging from dormancy. Precipitation in May and June is highly variable. In May, 2010, precipitation was 6.1 and

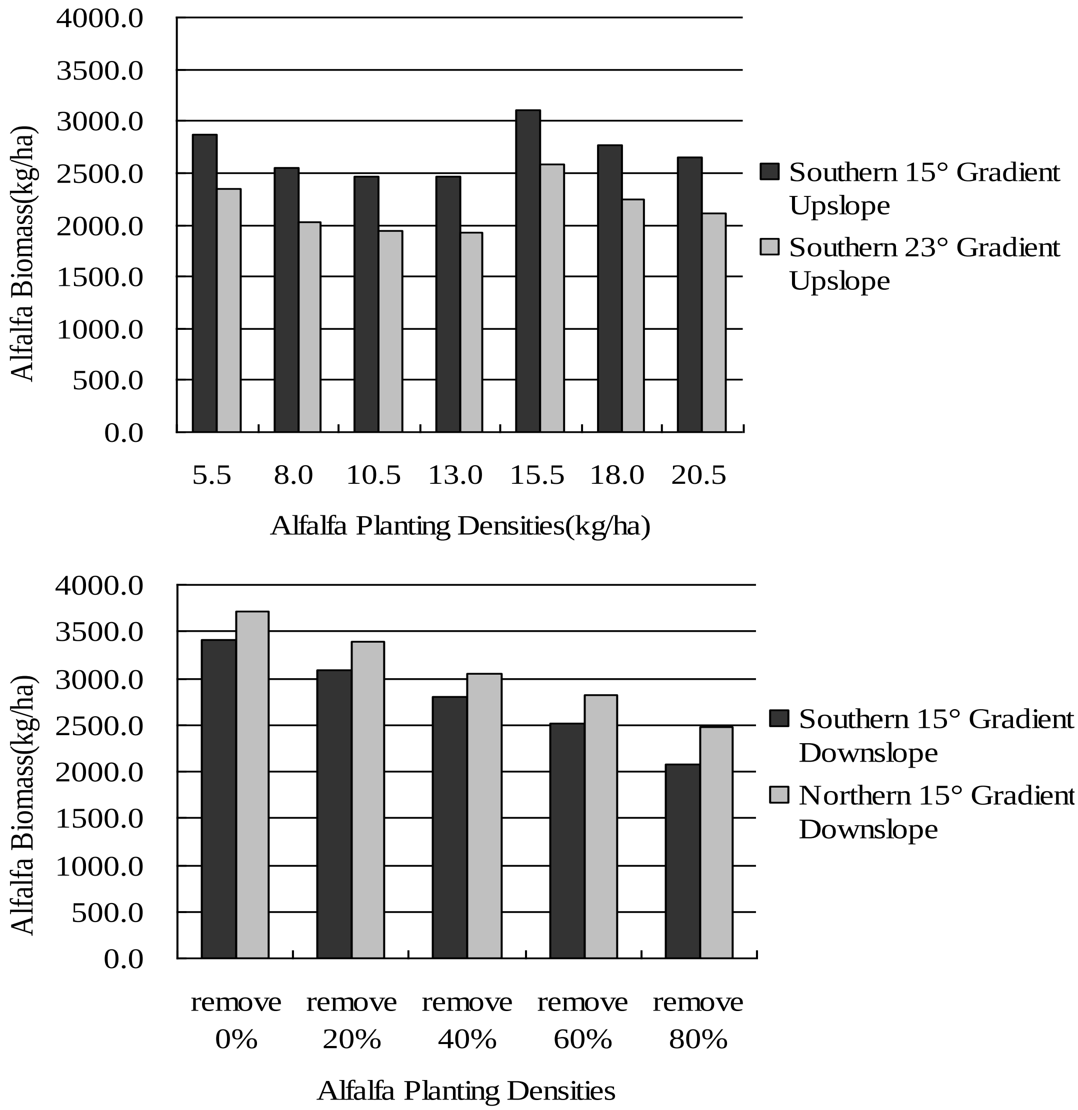

Figure 2. Effect of planting density and slope on alfalfa biomass in the Northern Shaanxi Loess Plateau from 2008 to 2010.

26.7 mm less than the monthly average. During this season, plants typically grow rapidly and water consumption increases correspondingly. Insufficient precipitation often restricts plant growth this time of year in the study area. The largest variation in precipitation occurs in July and August. In July 2009 precipitation was 168.3, 3.08 and 5.33 times higher than July 2008 and July 2010, respectively. Water availability at this time of year affects nutrient accumulation and plant reproduction. Moreover, temperature and evaporation are highest in this season and precipitation intensity, volume, and timing directly influence growth of mature plants. In September and October, precipitation variation is the smallest, and does not significantly affect plant physiology. Annual and monthly precipitation variation in November and December is also small and leaf drop and dormancy are the primary plant functions and are not greatly affected by precipitation patterns, but have some influence on plant root activity and the following years' germination.

Alfalfa is the most common artificial pasture in Loess Region in Northern Shaanxi, China. Precipitation and available water had a linear correlation and increased slope causes increased runoff and decreased water availability. Increased alfalfa biomass reduces erosion and runoff and increases water availability. Steeper slopes increase runoff and decrease available water despite slope position and direction (Liu et al., 2010).

Water availability and alfalfa biomass had a linear correlation. Alfalfa biomass on steep slopes and water use had a quadratic correlation. As biomass production increased, moisture use also increased. Slope position affected solarization intensity and, thus, transpiration and water use.

The Penman-Monteith-56 method estimated peak alfalfa biomass production, based on available water on Northern Shaanxi Loess Region steep slope farmland to be 3992.2 to 4173.7 kg ha^{-1}. However, according to the water balance principle, that figure is 2600 to 3500 kg ha^{-1}, or 16.1 to 33.5% lower than that estimated by the Penman-Monteith-56 method. Under ideal moisture conditions, alfalfa production on steep slopes may be 6555.6 to 6926.3 kg ha^{-1}. The Penman-Monteith-56 method applies many meteorological factors, each of which includes inherent error which are compounded when combined. Therefore, results of the water budget principle seem to be more reasonable. Our research did not include water interception at the alfalfa crown; therefore actual alfalfa production may be slightly smaller than our results indicate.

Soil water carrying capacity for vegetation is a function of water availability and use. Therefore, any factors, environmental or anthropogenic, which affect water availability and use, also affect the vegetative carrying capacity. Environmental factors include rainfall distribution and intensity, temperature, solar radiation, soil conditions, terrain, and vegetative type. Anthropogenic factors include land-use and cultivation management. This study was conducted in one location, limiting the effects of environmental factors. Climate, soil, slope shape, vegetation, and management practices are fairly homogenous. The four selected slope positions, representative of most land in the Northern Shaanxi Loess Region, were isolated for study.

Soil moisture conditions are essential for plant growth and development. Under certain conditions, increased soil moisture recharge will increase plant production and growth (Verheyen et al., 2008). Effective vegetative reconstruction should conserve water, reduce runoff, promote infiltration, increase soil moisture recharge, and improve vegetative production. However, improving vegetative production also uses more water; therefore, improving water use efficiency is also an integral concern (Guidi and Labrecque, 2010; Li et al., 2008; Hsiao. et al., 2007). In order to reduce erosion and increase water availability, we recommend adjusting plant density, and managing the trade-off between productivity and water availability (Verheyen et al., 2008).

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