ECOLOGICAL CHARACTERISTICS OF SOIL WATER AND ITS RELATIONS TO LANDFORM AND VEGETATION IN A SMALL SEMIARID WATERSHED IN A LOESS HILLY AREA

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Abstract
There is an urgent need to study soil water resources and eco-hydrological characteristics in depth so as to carry forward ecological environmental construction in the Loess Plateau. Soil moisture was measured to a depth of 5 m on 11 sites with different landforms and landuses in a transect of the Zhonglianchuan watershed during 2002. The watershed is located in the northern Yuzhong County, Gansu Province, and is part of a semiarid and loess hilly area. There were different types of soil moisture variations within the year of 2002 on the 11 sites. Soil moisture contents were low on all sites, and the averages of 2 to 5 m depth were usually lower than 10% by weight, in which the lowest water contents were in soils of the sloping land under the *Medicago sativa* and *Caragana korshinskii* vegetations. The dry soil layer is common in this area, not only under the planted vegetation but also under the natural vegetation. The soil moisture in a slope segment or area can be increased by collecting and harvesting surface runoff from upslope areas. One effective way to collect runoff is the level terraces alternated with sloping lands. The proportion of various grasslands, the proper acreage of alfalfa, and the sustainable development of the region should be further studied in order to successfully return cultivated land to grassland.

Additional Keywords: ecological environment; dry soil layer; rainwater harvesting technology; Gansu Province

Introduction
The main factor restricting ecological environment construction of the loess plateau is the shortage of water resources, especially in the semiarid loess hilly areas. The severely dissected landforms on the loess plateau formed thousands of small watersheds. A survey showed that there are more than 8000 small watersheds in China, and a greater portion of them is located in the loess plateau (Li, 1996). On top of the zoning distribution of rainfall, the rolling landform in small watersheds caused redistribution of rainfall, compounded by different landuse, resulted in various minor differences in soil moisture. Study of watershed hydro-ecology by taking account of the ecological characteristics of soil moisture with emphases on water behaviour in small watershed as well as ecological effects and its optimum control will help the reconstruction of the ecological environment through the development of thought processes, overall planning and optimization, and implementation of specific measures (Liu, 2000).

Researchers have studied, from various aspects, soil moisture in loess hilly areas for a long time. Yang *et al.* (1990), from the view points of soil physics and land characteristics, studied the effects of site conditions on soil moisture and seasonal changes of soil moisture as well as their relationships with landuse. Fu *et al.* (2001) developed mathematical models of spatial distribution of soil moisture on a hillslope in the hilly areas based on measured data and theoretical derivation by considering the major factors. Xu *et al.* (2003) analysed differences of the physical-geographical conditions, and explained the manifestation and intrinsic mechanism of the spatial distribution of the soil water by considering rainfall, heat, landuse, and topography. Soil water content and its profile distribution vary from region to region and from time to time. These spatial and temporal variations follow certain general laws, but the differences exist between regions and between time periods. Studying these differences through measurement and analysis will increase our understanding of soil moisture conditions and ecological characteristics of soil water in the loess hilly regions and even in the entire loess plateau.

General Situation of the Study Area
The study area is located in Zhonglianchuan watershed of loess hilly region in the northern Yuzhong County, Gansu province. Its climate type is semiarid, the main soil type is sierozem, and the native vegetation is warm temperate grass or steppe. The topography in Yuzhong is like a saddle (the compiling committee of Yuzhong

County Annuals, 2001). Cold and stony mountains, which are 2200-3673 m above the sea level, are in the south. The dissected valley lands are in the middle, with the altitude being 1500-2200 m above the sea level. The loess hilly areas, being 2000-2495 m above the sea level are in the north. The annual rainfall varies tremendously from the south to the north, ranging from 600 mm in the southern Xinglong Hill to below 300 mm in the northern yellow river valley. The average annual rainfall is 390.1 mm at the Yuzhong Weather Station (1951-2001) in the middle part. The average annual temperature is 6.6 ,and the annual evaporation from water surface is 1387.5 mm on average. In the northern Zhonglianchuan watershed the average rainfall and temperature are lower than those of the middle part (Yuzhong Agriculture Booklet, 1983). The average annual rainfall observed in the Yuzhong Weather Station in the period of 1999-2001 was 375.0 mm, and it was 275.6 mm in the Zhonglianchuan watershed. The rainfall amount in 2002 was 418.4 mm, which was much higher than the previous three years. Precipitation in May was over 100 mm, which differed considerably from other years. The monthly distribution of precipitation is showed in fig.1. The agriculture is under rain-fed conditions, main crops are spring wheat, pea, and potato, and cropping systems are annual summer crop-winter fallow.

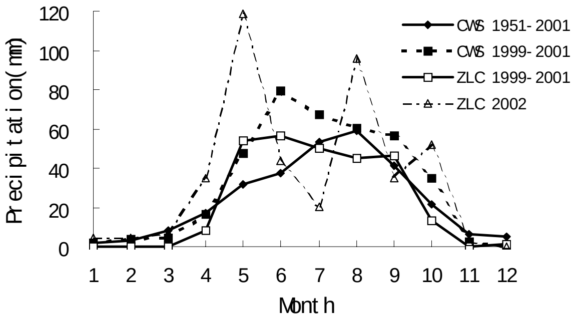

Figure 1. Monthly distribution of precipitation at the Zhonglianchuan watershed in the northern Yuzhong County (ZLC, N36°03′,E104°25′) and the County Weather Station in the Middle Yuzhong (CWS, N35°52′, E104°09′).

Materials and Methods

A transect was selected in the upper reach of the Zhonglianchuan watershed. The main stem at the transect runs from southwest to northeast. The relative relief between the hilltop (called Liang-mao in Chinese) and the gully bottom is about 150 m. The gullies, including some blind gullies in the watershed, are not fully developed, and there is no year-round running water in the main stem of the watershed. The local people call the hilltop of Liang-mao on the southeast "Nanchaliang" and its hillside "Nanchabang" (Figure 2), which is north-facing and northwest-facing slopes. The slopes on the northwest, called "Dayushan" by locals, are south-facing and southeast-facing slopes. Eleven sites were selected for the measurement according to the slope location, crop types, and land use. Soil water contents were measured every one or two months between April and December in 2002. The locations of selected sites are shown in fig.2. Soil moisture was determined by oven-drying and weighing method. Soil samples were taken with a soil auger at the 20 cm intervals to the 5 m depth. The landuse on the 11 sites included cropland, woodsland, bushland, and rangeland. Most croplands were located on the valley bottom, slope terraces (10º-20º), and level terraces of the Nanchabang. Grassland including steppe and some trees were grown on the Dayushan, which has steep slopes, ranging between 20º-35º. Trees such as poplar were grown on the gully bottom (Chuandao). Vegetation conditions including types, canopy cover, height, and biomass production were measured on the selected sites. In addition, five representative soil profiles (up to 100-150 cm deep) were selected along the transect for detailed analysis of soil physical properties. The measured physical properties included particle size distribution (pipette method) and bulk density (soil ring). Field capacity and wilting point were calculated from particle size distribution based on the relationship developed by Li *et al.* (1985).

Results and Discussion

Soil physical properties on different slope positions along the transect

From Nanchaliang along the transect (fig. 2), five slope positions including the hilltop, backslope, footslope, bottomland, and the backslope on the other side (Dayushan) of the watershed were selected for physical property analyses. Results showed that soil particle size distributions in each soil profile were fairly uniform, but differences existed between slope positions. Content of coarse particles was considerably higher on the hilltop and backslope than on the bottomland, while the opposite was true for the fine particles. Soil texture in the bottomland resembled that on the backslope of Dayushan (south facing slope). The coarse sand (0.02-0.05 mm) contents were

45.6, 44.2, 34.9, 60.0, and 55.2% for the hilltop, backslope, footslope, bottomland, and the backslope of Dayushan, respectively, while the silt contents (0.005-0.02 mm) were 25.6, 30.0, 32.1, 19.8, and 17.0%. The content of clay and fine silt (<0.01 mm) were 27.4, 26.3, 35.5, 25.7, and 25.1%. Nearly all profiles were light silt loam, except that all soil layers in the bottomland and the soil layer between 0-20 mm depth on the hilltop were medium silt loam soil. The soil bulk density was 1.01-1.23 g cm^{-3}; field capacity was 19.3-20.7%; and wilting point was 4.4-6.8%.

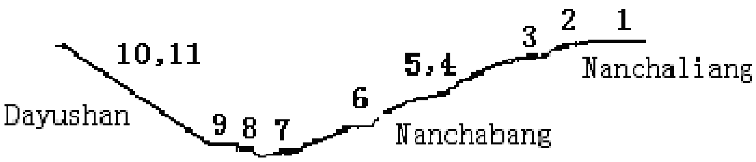

Figure 2. Sketch of soil moisture monitoring positions.

1, Level terrace on hilltop -- a community of *Stipa bungcana* + *Aucurolepidium dasystachys* + *Heteropappus altaicus*; 2, Gentle slope land on hilltop – a community of *Stipa bungcana* + *Potentilla chinensis*; 3, Sloping terrace on upper slope -- *Tritium aesirum*; 4, Sloping terrace on middle slope --*Pisum sativum*; 5, Sloping terrace on middle slope -- *Medicago sativa*; 6, Sloping terrace on lower slope -- *Tritium aesirum*; 7, Valley land -- *Populus simonii*; 8, River terrace -- *Medicago sativa*; 9, River terrace -- *Populus simonii*; 10, Middle-upper steep slope land – *Caragana korshinskii*; 11, Middle-upper steep slope land – a community of *Stipa breviflora* + *Artemisia frigida*

Soil water distribution and seasonal changes

The topography, landuse, and vegetation types in 2002 on the 11 sites along the transect from Nanchaliang through the valley to Dayusha are shown in Figure 2 and Table 1. The pea and spring wheat were harvested in late July and middle August, respectively. Average soil water contents in the entire 5-m profile on October 1 2002 for the 11 sites (from Nanchalian to Dayusha) were 7.1%, 8.0%, 10.3%, 7.7%, 4.4%, 8.5%, 6.8%, 8.5%, 6.9%, 4.7%, and 5.4%. The moisture content was the lowest (4.4%) in the alfalfa field on the sloping terraces, the second lowest (4.7%) under *Caragana korshinskii* vegetation on steep slopes, and the highest (10.3%) in the sloping terrace of harvested wheat field on the upper slope. It is common that soils growing alfalfa has low soil water content (Li, 2002). Spring wheat on the sloping terraces were reaped in the middle August, having a yield of 750 kg ha^{-1}. The soil moisture was recharged by rains during August and September, so its soil water content was relatively higher.

Table 1. Distribution of average soil water content per 100 cm depth under different site conditions on October 1, Zhonglianchuan, Yuzhong County, Gansu Province.

Depth (cm)	0-100	100-200	200-300	300-400	400-500	0-500
Level terrace on hilltop - grass	8.5	6.0	6.3	7.2	7.5	7.1
Gentle slope land on hilltop - grass	4.8	9.0	8.8	8.6	8.8	8.0
Sloping terrace on upper slope - wheat	10.8	9.5	10.7	10.1	10.3	10.3
Sloping terrace on middle slope - pea	7.2	7.0	7.5	8.3	8.5	7.7
Sloping terrace on middle slope - alfalfa	6.6	4.0	3.9	3.8	3.9	4.4
Sloping terrace on lower slope - wheat	11.0	10.8	7.8	6.4	6.8	8.5
Valley land - poplar	7.8	6.8	6.4	7.2	5.7	6.8
River terrace - alfalfa	12.2	11.1	7.0	5.8	6.3	8.5
River terrace - poplar	5.3	5.8	6.7	7.5	9.3	6.9
Middle-upper steep slope land - *Caragana korshinskii*	3.4	3.9	4.7	5.5	6.1	4.7
Middle-upper steep slope land - grass	4.4	4.7	5.5	6.0	6.4	5.4

Table 1 gives the distributions of average soil water content per 100cm depth on the 11 sites on October 1 2002. These data generally revealed that soil water contents changed with the topographical locations and depths. Soil water content, as a state variable of water balance, was affected by utilizing condition, topographical location, soil type, and so on. Topographical conditions played a critical role in the reallocation of rainwater, especially in the shallow soil layer between 0 and 100-150 cm. Soil water contents in the 0-100 cm and 100-200 cm depths on the river terrace growing alfalfa were 12.2% and 11.1%, respectively, which were the highest because of the water inflow from side slopes and the great infiltration capacity under alfalfa. For the soil depths greater than 1 m, soil water contents, except for the sloping terrace-alfalfa site on the backslope, were higher than those on the slopes of the Dayusha.

Soil water in this area is mainly from rainfall (including reallocation of rainwater on soil surface), and the main consumption is evapotranspiration (ET), which is closely related to utilizing conditions and atmospheric evaporation demand. The authors calculated the long-term evapotranspiration potential of the area at the weather

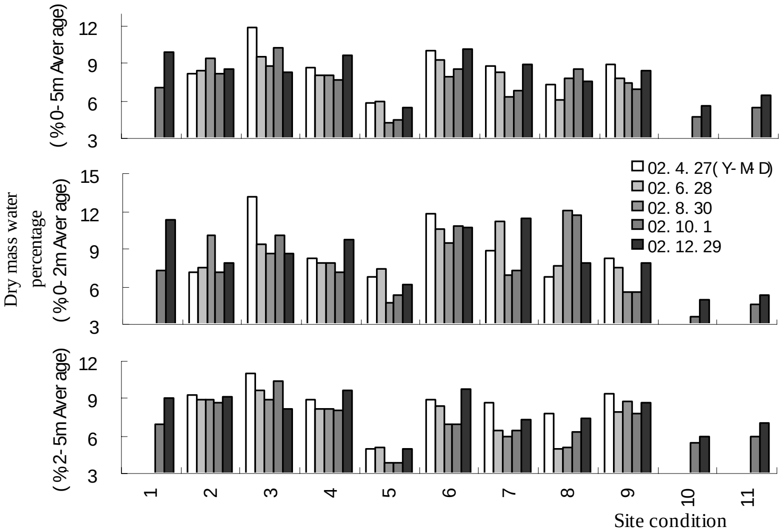

Figure 3. Seasonal variation of soil water content along the transect in the Zhonglianchuan watershed. Upper, average of 0-5 m; Middle, average of 0-2 m; Lower, average of 2-5 m.

station of Yuzhong County using penman formula. The greatest monthly ET occurs in June (129.1 mm), the next greatest appears in July, and then followed by May. The superimposition of seasonal precipitation changes, runoff redistribution on soil surface during and after rains, and seasonal ET changes dictates seasonal soil water dynamic. Seasonal dynamics of soil water content on the 11 sites between April and December with 5 measurements are shown in fig. 3. The upper panel is the average soil water content between 0 and 5 m depth, the middle panel is between 0 and 2 m, and the lower panel is from 2-5 m. Comparison between the soil water contents in the 0-2 m depth (middle) and those in the 2-5 m depth (lower) demonstrated that the most dynamic changes in the seasonal soil water contents occurred in the top soil layers. Seasonal soil water dynamics in the 0-5 m depth between April and December (upper) differed among the 11 sites, reflected the effects of site conditions, especially topography and landuse, on seasonal soil water balance. During the study period, the magnitude of soil water fluctuations was the smallest on the sloping terrace with peas; the lowest soil moisture contents occurred in the middle growing season on the sites of wheat field, sloping terrace-alfalfa, and valley land-poplar, while the highest moisture content was measured in the middle growing season on the gentle slope hilltop-grass. The seasonal soil dynamics between 0-2 m were similar to those between 0-5 m, but the magnitude in 0-2 m was much greater. Soil moisture measurements on the hilltop-level terrace-grass, upper steep slope-*Caragana korshinskii*, and upper steep slope-grass of Dayushan were initiated on October 1. The soil moisture contents on these sites increased between October 1 and 29. This is because 52-mm precipitation occurred in October as well as reduced ET in the month.

Effects of topography and landuse on soil water

To illustrate the effects of topography and land utilization on soil water, it is necessary to hold other factors constant as much as possible. The river terraces, when planted alfalfa, although being a high water-consuming perennial, still maintained relatively high soil moisture with the water supply not only from in-suit rainfall but also from remarkable surface runoff from upper slopes and village roads; while the sloping terrace failed to meet the water consumption and resulted in large water deficit because soil water were supplied only by in-suit rainfall. Figure 4 shows the profile distributions of soil moisture at 20 cm intervals for the two topographical positions under alfalfa. The sloping terrace had an average water content of 6.6% within 1 m and 3.5-4.0% between 1 and 5 m. The average soil water contents on the river terrace were 5.6% within 0-1 m, 7.1% in 1-2m, and 2-3% in 2-5 m greater than those of the corresponding depths on the sloping terrace. Among the 11 test sites, two sites were under the same wheat but at different slope positions, namely the sloping terrace on the upper slope and the slope terrace (about 3 degree) on the lower slope. Under cropped conditions, factors affecting soil water became more complicated. The differences in rotation sequences and fertilizer inputs considerably affected soil water balance. The average water content in the upper slope is 1.8% higher than that of the lower slope. The lower slope is closer to the village and receives better fertilization. It was reported that the wheat yield on the lower slope, which reached 1050 kg/ha in 2002, was 300 kg/ha higher than that on the upper slope. Higher yield certainly consumed more water and therefore resulted in lower soil moisture. But concerning the 0-2 m layers, the water content on the lower slope was still 0.75% higher than that on the upper slope, or about 18-mm water depth greater. This was because the lower slope had more run-on water from upper slopes during the runoff-producing rains.

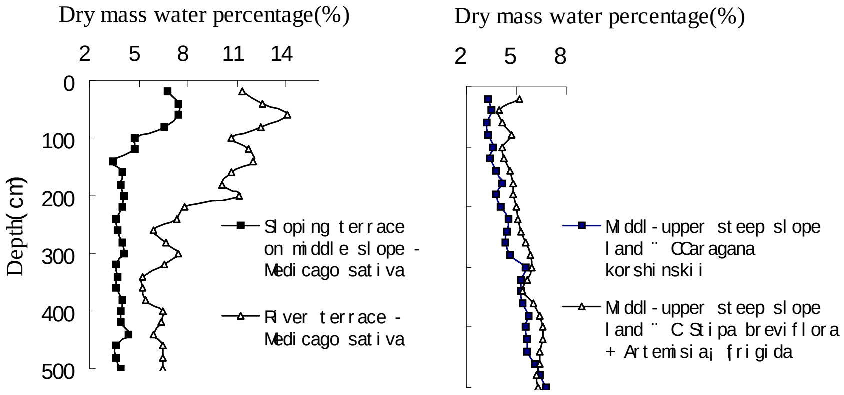

Figure 4. Depth-distribution of soil moisture.
Left, *Medicago sativa* on a sloping land and a river terrace; Right, *Caragana korshinskii* and *Stipa breviflora + Artemisia frigida* on middle-upper steep sloping lands.

The *Caragana korshnskii* site and steep slope-grass site, which were located on the same slope position on the same steep slope (upper middle, southeastwards slope), can be used to illustrate the effects of landuse or vegetation type on soil water (Figure 4). The two sites are at the same altitude of 2400 m, have an exposure of E45°S and gradients of 32-35º. The steep slope-grass site was occupied by the community of *Stipa breviflora Griseb* and *Artemisia frigida Willd*, with the total coverage of 30-40%. The other species included *Ajania achilloides Poljaik . ex Grubov. Artemisia giraldii Pamp. ,Leymus Secalimus Tzvel., Potentilia tanacetifolia Willd. Ex Schlecht., Stemless Cinquefoil, Multicaulic Cinquefoil, Oxytropis bicolor Bunge, Heteropapus altaicus Novopok,* and so on. The *Caragana korshnskii* was planted in 1982 on narrow reverse-terrace (in two rows with 0.5-1.0 in-row spacing), which was alternated with 6-m slope. The total vegetation coverage of the slope was 30-40%. The two moisture distribution curves on the two sites converged and became similar below 3.5 m, and the soil moisture above the 4.8-m depth was higher in the grass site than in the *Caragana korshnskii* site, where the roots of *Caragana korshnskii* might have depleted soil available water. The average soil moisture in the 0-4.8 m depth was 4.6% in the *Caragana korshnskii* site and 5.3% in the grass site, and the difference was equivalent to 42-mm water depth. However, the soil moisture contents in both profiles were fairly low, and even on the grass site in which the average water moisture was only 5.4% within 0-5.0 m. This might be caused by high evaporation demand (south-east facing slope) and great surface runoff generation due to steep slopes.

Crop production, regional vegetation construction, and soil dry layers
Water scarcity has forced people to use water in a thrifty manner. This effort involves all aspects of the society including agriculture. It is the only choice to take the path of water-saving ecological agriculture when promoting ecological and economic development in the semiarid Zhonglianchuan watershed in the northern Yuzhong County. In the recent years, dryland farming, characterized by rainwater-harvesting agriculture, have made significant progress in the semiarid hilly region including the study area (Li *et al.*, 1999). Rainwater-collecting agriculture is to divert runoff from artificial or natural collecting areas to storage facilities such as cellars for supplemental irrigation later, or to designated areas to increase soil water storage and to improve pant water supply. Rainfall-collecting agriculture is a successful practice of combining water-saving dryland farming and water-saving irrigation agriculture in the conventional rain-fed agriculture region to enhance the efficient use of rainfall. Most lands in the Zhonglianchuan watershed, 0.33-0.40 ha per capita, are sloping terraces with severe runoff losses, low soil moisture, and poor yield. The peasants in the area have the inclination of conducting widespread cultivation with poor yield. It has been proved again and again that alternating slope and level terrace is a simple and effective measure to control redistribution of rainfall and to enhance soil water storage in loess hilly regions (Xu *et al.*, 2003). Surface runoff generated in the slope area is detained by the level terraces, and the additional water supply would increase crop yields in the terraces. The increased yield would compensate for the loss of reduced cultivation acreage, so some steep slope areas can be returned to native rangeland. With the help of water storage facilities like cellars and the adoption of alternating slope-level terrace, plus bottomland in the valley, the cultivated croplands can be reduced to 0.18-0.20 ha per capita in the watershed. Under this strategic plan, it is possible to return cultivated slope lands to native rangeland while maintaining self-sufficiency in grain production. This is an important step for eco-environmental reconstruction in the region.

Located in the typical grassland zone, the vegetation construction in the Zhonglianchuan watershed is mainly to return steep croplands to grassland or bushland. The main measures include closing hillsides or target areas to facilitate grass recovery or to plant grass and bushes if necessary. Harmonizing the relationship between ecological and economical grasslands is of importance. Raising livestock needs high quality and quantity forages, which will lead to excessive consumption of soil water. A survey showed that there is a large acreage growing alfalfa in the region. Soil water measurement in this study indicated that soil water contents in the alfalfa field, without runoff inflow from upper slopes such as on the sloping terrace, were the lowest, even in the deep soil layers. To better restore the native vegetation on the cultivated slope land, the effects of low soil water conditions on the grass productivity and sustainability should be further studied. When rainfall is less than potential ET and soil profile is very deep, such as in the semiarid to sub-humid regions on the loess plateau, excessive plant water uptake leads to soil water deficit in the entire soil profile, but limited rainfall cannot recharge the soil moisture in the deep soil layer. Thus, a relative dry soil layer, called dry layer, is formed between the maximum infiltrating depth and the maximum rooting depth. The dry layer was firstly reported in the 1970's (Li, 1983) In recent years, with the campaign of vegetation construction, researchers are paying more attention to the dry layer phenomenon and are studying it from various aspects (Li, 2002).

Generally, the lower limit of water content in the dry layer is the wilting point and the upper limit is the "stable soil water content". The field capacity and wilting point in the Zhonglianchuan watershed were 19.3-20.7% and 4.4-6.8%, respectively. Suppose the 60% of the field capacity is the stable water content, the water storage in the dry layer should be 11.6-12.4%. As are shown in Figures 3 and 4, soil water content were almost below the stable water content all sites in most of times, and therefore they all fell in the category of the dry layers. It was especially true on the sloping terrace-alfalfa site, steep slope-*Caragana korshinskii* site, and grassland site. As to the measurement results on October 1, soil water content between 2 and 5 m were less than or equal to 7.0% on seven out of 11 sites. The average soil moisture contents of the Caragana korshinskii and grassland between 0 and 5 m were 4.7 and 5.4%, respectively; and the average soil moisture contents between 2 and 5 m were 5.4% and 6.0% (Figures 3 and 5). Although the soil moisture content of the Caragana korshinskii site was less than that of the grassland, the difference was small and both were close to the wilting point. Thus, the dry layer can be developed not only under artificial vegetation but also natural vegetation, and is common in this area. In addition, some measured soil water contents were below the wilting point (4.4%). This doesn't mean that the soil moisture was less than the wilting point, because the wilting point was estimated from an empirical relationship using soil texture.

Conclusions

Soil water contents were measured five times on 11 sites along a transect in the small watershed. The relationships between soil moisture and landuse or vegetation cover were analyzed. The results fully reflected the soil water conditions and the ecological characteristics of soil water in the small watershed. Located at semiarid region in the northern Yuzhong County, Gansu province, the agricultural production in the Zhonglianchuan watershed is under rain-fed conditions, cropping systems are annual summer crop winter fallow, and the native vegetation is the typical drought-tolerant species. The results of soil water contents on the 11 sites showed that soil moisture in the watershed were generally low. The average soil moisture between 2 and 5 m were almost below the stable moisture content, and were generally less than 10% by weight. The sloping terrace-alfalfa site, Caragana korshinskii site, and the grassland site were the driest. The dry soil layer is very common in this area, and it is developed under not only artificial vegetation but also natural vegetation.

Rainwater-collecting agriculture is a new development and successful practice in the dryland farming agriculture in this area. Water-saving eco-agriculture is the inevitable choice for the sustainable development of regional ecological systems and economy. Turning sloping terrace into alternating sloping and level terraces, which allows runoff accumulation in the level terrace, can considerably change soil water conditions of the level terrace and increase crop yield. This practice will definitely speed up the pace of returning croplands to native grassland.

When changing steep croplands into Caragana korshinskii land, especially on the south-facing steep slopes, we must protect the existing wide-stripped Caragana korshinskii land and replant it in areas where the plant density is low. For establishing new Caragana korshinskii land, it can be densely planted in combinations of wide and narrow rows, which not only solve the water shortage problem but also make grazing easier.

In the campaign of returning croplands to grassland, alfalfa is the dominant species growing in the region. Grass millet and grass oats are also grown but in much small areas. Considering the grass productivity, grass may be grown on the valley bottomlands and some suitable level terraces, which normally have better soil water conditions. However, we must pay attention to area proportions of various grasslands, proper acreage of alfalfa, as well as the sustainable development of the region.

Acknowledgements

This research was supported by a project from the National Natural Science Foundation of China (No. 90202011) and a key project from the Knowledge Innovation Action of the Chinese Academy of Sciences (KZCX3-SW-421).

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