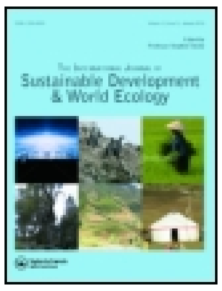

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Soil desiccation occurrence and its impact on forest vegetation in the Loess Plateau of China

Z. P. Shangguan[1,2]

[1]Institute of Soil and Water Conservation, Northwest A & F University, Yangling, Shaanxi, China
[2]Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, Shaanxi, China

Key words: Forest vegetation, Loess Plateau, soil desiccation, soil water content

SUMMARY

Soil desiccation is a major issue limiting development and sustainability of forest vegetation in the Loess Plateau of China. Better understanding of the mechanisms of soil desiccation in the Loess Plateau can help scientists and forest managers improve vegetation management practices. The arid soil layer is the ecological aftermath of intense soil desiccation due to disturbed plant succession and soil water reduction. The formation and types of arid soil layer in the Loess Plateau were investigated to determine major causes of soil desiccation and its impact on forest vegetation. The negative effects of soil desiccation on the ecological environment and forest vegetation mainly include drying microclimate, degrading soil quality, poor vegetation growth, difficult forest renewal from natural seed banks, making it even more difficult to reforest forest lands and grasslands following plant senescence. Low precipitation, high evaporation, soil and water losses, improper selection of vegetation types, and too high population density of trees are probably the major reasons for the arid soil layer. Proper selection of vegetation types, adjusting tree density and other management practices can reduce the negative effects of the arid soil layer on forest vegetation.

INTRODUCTION

The Loess Plateau in the hinterland of China is in the transitional zone from the humid monsoon climate in the southeast to the continental dry climate in the northwest of China, and covers the areas between warm temperate broadleaf forests and desert grasslands. The total area of the Loess Plateau is 62.85×10^4 km^2, ranged from 100°54′E to 114°33′E and between 33°43′N and 41°16′N, with elevations between 1200 and 1600 m above sea level (Figure 1). Severe soil erosion is a major issue in the Loess Plateau due to its topography, particularly the decline in height from south to north and poor vegetation cover. A soil erosion modulus of 1000~15000 tons km^{-2} yr^{-1} in the region has created criss-crossing gullies. The percentages of vegetation cover by tree and shrub forests are only 9.27% and 15.17%, respectively (Shangguan 2005). Therefore, scientists and regional communities now pay

Correspondence: Prof Z. P. Shangguan, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, Shaanxi, 712100, China, Email: shangguan@ms.iswc.ac.cn

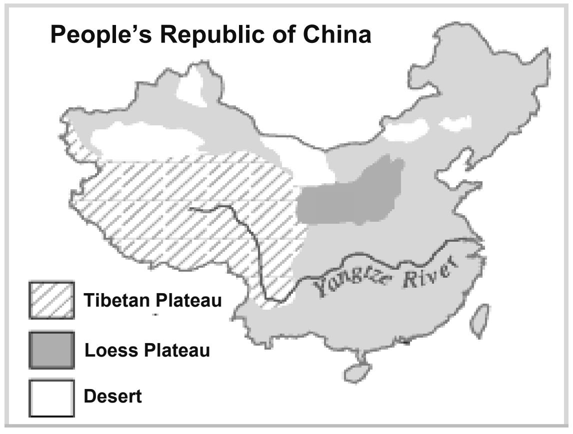

Figure 1 Locations of the North China Plain and the Loess Plateau

great attention to vegetation construction and the ecological environment.

In China, the fraction of loess in soils has been used as an indicator of arid and semi-arid climates, and soil accumulation and has been characteristic of the drying tendency of the climate in north China from the epoch of early renewal to the epoch of late renewal (Liu 1985; Yang *et al.* 1998). The arid soil layer is predominant in all regions of the Loess Plateau, especially in hill and gully areas that have low-productivity and low-efficiency forests (Yang 1996). Because the arid soil layer often occurs beneath man-made vegetation on grasslands and forest lands, the relationship between grass and tree varieties and soil desiccation has attracted much attention. Yang and Shao (2000) reported that the arid soil layer was a special hydrological phenomenon under the semi-arid and semi-humid climatic conditions in the Loess Plateau, resulting in both climatic drought and soil desiccation. The arid soil layer is caused by extreme shortage of soil water, where the soil water content is close to or below wilting point due to long-term excessive consumption of soil water by forest and grass vegetation (Hou *et al.* 2000; Cameron 2001). Although several studies have mentioned the existence of arid soil layers in the region and their negative impact on vegetation (Yang 1996; Yang *et al.* 1998; Cameron 2001; Jayantha *et al.* 2002; Yang and Tian 2004), little is known about the mechanisms of the arid layer and the relationship between forest vegetation and soil moisture in the Loess Plateau. Better understanding of the mechanism underlying the arid soil layer in the ecological environment of the Loess Plateau will help scientists and land managers to make decisions for rehabilitating and reconstructing the forest vegetation and for improving the regional ecological environment. In this paper, we report factors causing the arid soil layer, effects of soil desiccation on forest vegetation and regional ecology.

SOIL DESICCATION IN THE LOESS PLATEAU

Water shortage in the top soil layer can be partly alleviated by rainwater during rainy seasons. The moisture of the deep soil layers will remain low in the long term without full soil water supplementation and thus the deep soil will become arid. The development of the arid soil layer negatively affects man-made forest and meadow vegetation of the Loess Plateau (Table 1). For lands without vegetation in the semi-humid loess high plain of Luochuan County in Shaanxi, soil moisture is often insufficient beyond rainy seasons (Figure 2). During the rainy season, rainfall can supplement soil water shortage in the top 0–2 m of soil, but sometimes there is less than 100 mm of water in the soil (Li 2001). Consecutive observations between 1983 and 1990 showed that land lacking vegetation in semi-arid hill and gully areas (Ansai County, Shaanxi) had insufficient moisture in the top 0–2 m of soil in all late rainy seasons, with an average shortage of 70.9 to 155.7 mm, and < 100 mm in 50% of the observed years (Yang *et al.* 1998).

According to research in semi-arid and hilly regions (Yang and Han 1985), 16-year-old *Robinia pseudoacacia* trees extended their roots to a depth of more than 5 m, with the highest water consumption layer between 3.0 and 4.5 m. The accumulative shortage of soil moisture under man-made *R. pseudoacacia* forests was 732.7 mm and the soil moisture 3 m below the soil surface was close to the wilting point. Man-made *Caragana korshinski* forests had a rooting depth of more than 5 m, with the greatest soil water consumption occurring between 2.5 and 4.0 m, and the accumulative shortage of soil water being 467.9 to 768.9 mm (Yang 2001). Therefore, afforestation in the Loess Plateau has intensified soil desiccation. This process of soil desiccation also occurs in areas covered by pure secondary *Sophora viciifolia* and 70-year-old *Platycladus orientalis* forests (Figure 3). Hence, although water content in the soil profile can be ameliorated by a relatively wet period of several years, high

Table 1 Depths of the arid soil layer in soil profile in different regions covered by man-made forests or grasses in the Loess Plateau

Research region	*Plant species*	*Semi-humid zone (cm)*	*Semi-arid zone (cm)*	*References*
Upper terraces of the Weihe River, Shaanxi	*Medicago sativa*			Li (2001)
	first year	210–250		
	third year	480		
	fourth year	> 500		
Ziwuling forest, at the boundary between Shaanxi and Gansu	Mixed forests of 40–50-year-old *Quercus liaotungesis* and *Betula platyphylla*	300–400		Wu and Yang (1998)
	Populus davidiana forests (20–30 years old)			
Hilly loess regions in north Shaanxi	*Robinia pseudoacacia* forests (1 year old)		Above 100–400	Yang and Shao (2000)
	Hippophae rhamnoides forests		Above 100–400	
	Astragalus adsurgens meadow (6 year old)		Above 100–700	
	Malus pumila forests		Above 200–300	
Hilly loess regions in northwest Shanxi	*P. hopeiensis* forests		Above 200–300	Wang and Li (2001)
	Caragana korshinski forests		Above 60–300	

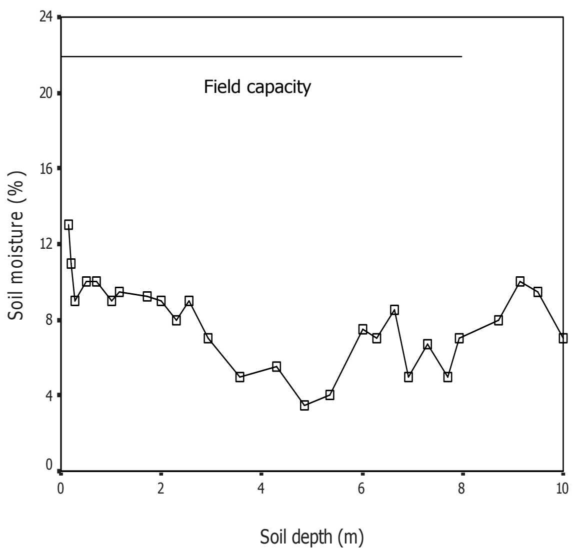

Figure 2 Soil moistures in deep soil layers in Jingbian County, Shaanxi, on 26 August 1982 (Wu and Yang 1998). Field capacity is 22%. There is a low soil moisture layer between 0 and 10 m, particularly 4 to 6 m below the soil surface

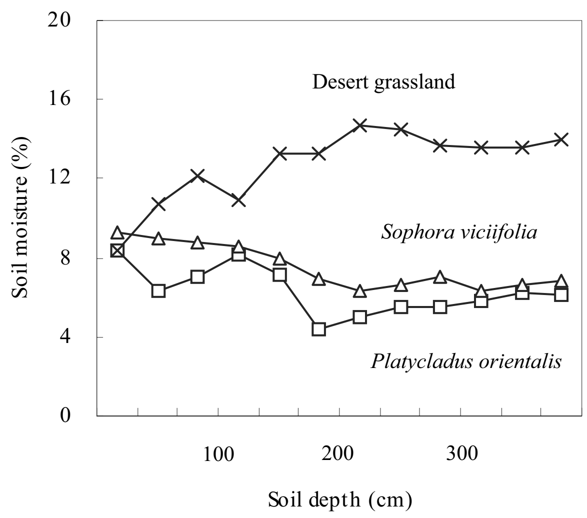

Figure 3 Soil moisture in pure secondary forests of *Sophora viciifolia* and 70-year-old *Platycladus orientalis* and a desert slope grassland, measured in Ansai County, Shaanxi, on 10 October 1982 (Wu and Yang 1998). Results indicate that man-made forest vegetation intensifies soil desiccation

precipitation cannot improve the environment because of the negative influence of man-made forests on the moisture content of desiccated soils.

Based on the mechanisms of soil desiccation in the Loess Plateau, the arid soil layer can be classified into two major types: those affected by evapotranspiration or those affected by evaporation. Evapotranspiration is caused by high water consumption by both plants and the soil surface. Evaporation is caused by strong soil surface water loss due to both atmospheric drought and water potential gradients. Evapotranspiration is widespread in the Loess Plateau (Wu and Yang 1998; Yang and Shao 2000; Li 2001; Wang and Li 2001).

Soil desiccation in arid and semi-arid regions is common and related to special hydrological conditions due to evaporation. The measurements in lands lacking vegetation, on the tops of ridges and mounds in hilly loess regions, indicate a low-moisture layer at soil depths of 0 to 10 m, but mainly 4 to 6 m below the soil surface (Wu and Yang 1998). Very dynamic upward evaporation of soil moisture, as well as low precipitation, results in low-moisture conditions, which are characterized by negative compensation of soil moisture. The arid soil layer in the Loess Plateau appears to be a special hydrological soil phenomenon under man-made vegetation and has three characteristics: (1) it occurs at depths between 0.4 and 2.0 m below the soil surface and can extend to 10 m; (2) it is relatively permanent; and (3) it occurs in a range of soil moisture conditions, with a lower limit below or equal to wilting point and an upper limit above or equal to the water content at which soil has a stable water content or soil capillary action breaks it up. In regions of dryland farming, a temporary low-moisture layer is formed in the upper soil profile due to water consumption by shallow crop roots, but precipitation on crop lands can compensate for insufficient soil moisture and return it to normal levels; therefore, the temporary low-moisture layer in cropped lands is not considered in the present paper.

FACTORS AFFECTING SOIL DESICCATION IN THE LOESS PLATEAU

Dry climate and low precipitation

Loess and loess-like deposits are the most distinct features of the Loess Plateau. The climate of the plateau tends towards drought (Liu 1985), which greatly affects water conditions in loess soils. Precipitation is low and fluctuates year by year, ranging from 300 to 600 mm in most regions. However, evaporation varies from 623.8 mm (in Menyuan County, Qinghai) to 1254.0 mm (in Tongxin County, Ningxia) (Yang and Shao 2000). The lowest annual evaporation is higher than the highest average annual precipitation and thus will intensify soil desiccation. Therefore, the severity of soil desiccation is closely associated with the dry climate in the Loess Plateau and increases from southeast to northwest. Low precipitation, low relative humidity and high potential evaporation in the northwest result in a deeper soil desiccation layer compared to the southeast part of the plateau (Liu 1985).

Severe soil and water loss

The Loess Plateau suffers from severe soil and water loss and sand storms. Soil erosion is a major issue in approximately 145,000 km^2 of land, with an annual soil loss rate of more than 5000 ton km^{-2} (Shangguan 2000). Precipitation is concentrated and intense, resulting in severe soil and water losses. Average annual sediment load transported to the Yellow River is about 1.6 billion tons, mainly nutrient-rich eroded topsoil (Shi and Shao 2000). The sediment-carrying water runoff reaches 3.4 billion m^3, consequently intensifying water shortage and drought in the plateau.

Distinct regional physical properties of soil moisture

The physical properties of soil moisture in the Loess Plateau mainly refer to water-holding capacity, evaporation, stable moisture content, and water storage in deep soil layers. From southeast to northwest, soil water-holding capacity gradually decreases, soil evaporative capacity increases, stable moisture content becomes lower, and water storage in deep soil layers is reduced (Yang and Shao 2000). Thus, the natural regional vegetation distribution pattern from the southeast to northwest changes gradually into grassland (Yang 1996). Soil physical properties directly and severely affect soil water content and soil desiccation.

Incorrect selection of vegetation types

Because trees and shrubs have large root systems, they also have high water consumption, even in very deep soil layers. The water deficit due to vegetation water consumption cannot be maintained under continuous drought conditions, thus leading to soil desiccation and the arid soil layer. Therefore, in low-precipitation regions of the Loess Plateau, tree varieties with high evapotranspiration should be excluded and varieties with relatively less water consumption and strong capacity to retain soil should be grown. Zhang *et al.* (2001) noted the unfavourable effects of trees in regions where precipitation was less than 400 mm. In some regions, trees are planted for economic profits on lands that are more suitable for shrub growth, while rapidly-growing trees with high water-consuming capacity are planted on sites more suitable for xerophytic tree varieties, thus leading to more severe land degeneration and soil desiccation. Unsuitable trees will destabilize soils and eventually affect environments that cannot meet their water requirements. Therefore, appropriate vegetation types must be selected on the basis of major environmental variables, to reduce the gaps between vegetation water requirement and environmental supply.

High plant population density and productivity

Appropriate production for a plant population should lead to both high economic profit and great sustainability. In the Loess Plateau, profit-motivated practices cannot be sustained because they rely on excessive water consumption for high productivity, and thus soil desiccation and vegetation degeneration unavoidably occur. Between the 1970s and 1980s, a large area of *Astragalus adsurgens* was planted in some regions to enhance animal husbandry and reduce pressure on natural vegetation. Because proper measures were not used to control the high productivity of *A. adsurgens*, excessive soil water consumption led to soil desiccation, reduced plant population and yields, and other negative effects (Yang 2001). Correct control of population productivity is one of the most important measures to prevent soil desiccation and maintain sustainable development of vegetation in the Loess Plateau.

Under given circumstances, population density determines vegetation productivity as well as plant water consumption. An excessive population density leads to an over-consumption of soil water. This is one of the major factors causing soil desiccation in regions of the Loess Plateau with a dry climate and insufficient soil moisture. According to Yang and Shao (2000), the correct population densities of annual *Hedysarum scoparium*, *C. korshinski* and *Artemisia ordosica* should be 1700, 1800, 7700 plants km^{-2}, respectively, whereas their actual densities in the plateau are around 60000 plants km^{-2} (Li 2001). Such densities are much higher than the water capacity, resulting in excessive water consumption, soil desiccation and, finally, land deterioration and vegetation death. Because of inappropriate population densities, high productivity in most lands covered by man-made forests and meadows can lead to serious soil desiccation.

HYDROLOGICAL AND ECOLOGICAL EFFECTS OF SOIL DESICCATION ON FOREST VEGETATION

Local microclimate becomes dry

The arid soil layer due to soil desiccation is a consequence of a decrease in soil moisture. Soil moisture content plays an important role in climate change because it is closely associated with fluxes of induced heat, potential heat and longwave radiation transmitted from the land surface to the atmosphere. Climate change can cause changes in thermal and hydrological processes at ground level, which, in turn, affect fluxes from the surface to the atmosphere (Dobson *et al.* 1997; Jayantha *et al.* 2002). Soil moisture can change the reflective ratio of the land surface through changing soil colour, heat capacity, surface evaporation and vegetation growth, resulting in a realignment of surface energy and moisture, which further influence climate (Ma *et al.* 1999; Jayantha *et al.* 2002; Li *et al.* 2002). Chahine (1992) found that 65% of precipitation originated from land surface evaporation and 35% from the sea surface. Soil desiccation inevitably decreases evaporation and precipitation, causing further drying of the climate.

Soil quality degradation

Low soil water content in the top layer of loam and clay soils leads to development of a crust and increases soil compaction. In Xiji County, Ningxia, soil compaction of the top 90–100 cm of soil in man-made grasslands containing lush *Onobrychis viciaefolis* and *A. adsurgens* is 26.08 and 24.56 kg cm^{-3}, respectively. In contrast, the compaction of man-made grassland with relatively sparse *Medicago sativa*, natural meadow grassland, and fallow land are only 12.60, 7.30, and 2.17 kg m^{-3}, respectively. There is a 10-fold difference in soil compaction between the two vegetation systems

(Yang and Shao 2000). Soil desiccation under man-made vegetation results in deterioration of soil chemical and physical properties and a decease in soil quality.

Poor vegetation growth

Because of the arid soil layer, soil water capacity in the Loess Plateau is greatly decreased, leading to poor vegetation in forests and meadows and large areas of low-efficiency and low-yield forest. Small-leaf poplar (*Populus simonii*) trees usually grow more than 15 m tall under normal environmental conditions (Sun *et al.* 1998), but on arid soils, the growth rate is only 5–20 cm per year, one tenth to a quarter of the normal growth rate. On arid soils, a 20-year-old small-leaf poplar will be only 4–6 m high. The poorly developed canopies have small leaves, low leaf and shoot numbers, dark bark and suffer diseases and insect infestation, making them uneconomic. Generally, forest stands mature 2 to 4 years earlier on arid soils than on other land, and trees die due to lack of vigour and shallow root systems in extreme drought years. The effect of the arid soil on grassland seems to be more significant than on forest lands, e.g. *A. adsurgens* can survive in Wuqi County for 8 years, but only lasts 4–5 years in Yulin and 3–4 years in Guyuan. The great variation in survival is closely related to precipitation and arid soils (Yang and Yang 1989).

Difficulties in forest renewal through natural seed

Forest renewal depends on seed availability to establish and increase numbers of trees and grasses and to maintain vegetation stability, but this process is impeded on arid soils. For instance, small-leaf poplar trees renew well through natural seed multiplication in gullies and ravines, but not on slopes of ridges and mounds (Yang 2001). There are many saplings of Chinese pine (*Pinus tabulaeformis*) in natural and man-made forests in Huangling, Fuxian and Yichuan Counties but no saplings can be found in Dingxi, Shenmu and neighbouring counties (Zhang and Shangguan 2002). Plants of *C. korshinski* are widely distributed in the Loess Plateau and are capable of producing a lot of seeds. However, saplings are rarely found in *C. korshinski* forests because of difficulties in its natural renewal (Shangguan 2005). This is directly associated with the arid soil layer, where soil water is insufficient for seed germination. Even though a few seeds germinate, their saplings cannot survive due to lack of water in the soil. Therefore, current stands in man-made forests only survive for one generation because of difficulties in regeneration. As a result, this kind of forest regresses with time to become barren mountains or rangelands.

Difficulties in reafforestation of forests and grasslands

Because of the arid soil layer, reafforestation on lands with senescent forest and grass vegetation is much more difficult than that on uncultivated land. An experiment was conducted on uncultivated and forest-removed lands to determine the effect of the arid soil layer on survival rate of planted tree seedlings (Hou *et al.* 2000). The two types of land were identical in soil texture, slope, year of transplanting, and afforestation method, but soil moisture differed considerably. The forest-removed land was originally covered with *M. sativa* and the canopy was removed one year before planting tree seedlings. The uncultivated land was assumed not to have an arid soil layer. The average water content at 3 m was 11.5% for the uncultivated land and only 4.0% in the forest-removed land prior to replanting (Table 2). Small-leaf poplar saplings were transplanted in 1993 and each plant was given 2 l of water. The percentage survival of saplings on the uncultivated land was five-times higher than on the forest-removed land. Soil limitation or the

Table 2 Survival rates on two types of land with the same stand, soil and slope conditions, and the same replanting dates and methods in hilly loess regions (Shenmu County, Shaanxi) (Hou *et al.* 2000)

Land type	*Soil*	*Slope condition*	*Soil moisture (%)*	*Afforestation dates*	*Afforestation method*	*Survival in planting year (%)*
Uncultivated land	Sandy loess	Semi-shade	11.5	1993–2004	Bench terrace planting	80
Medicago sativa land	Sandy loess	Semi-shade	4.0	1993–2004	Bench terrace planting	15

existence of a soil arid layer was a major factor affecting survival of saplings. Although water was applied to each sapling on the forest-removed land, the arid soil layer quickly absorbed the water and made it unavailable for the saplings, resulting in their low survival rates.

Because of low precipitation in the Loess Plateau, soil moisture in the arid soil layer cannot be normalized in a short time after senescence of forest and grass vegetation. Four years after *A. adsurgens* senescence, soil moisture increased by 2% 3.5 m below the soil surface (Yang 2001). Comparatively, soil moisture availability in the land with *A. adsurgens* is only one seventh of neighbouring natural grassland. It takes at least 20 years for soil moisture to return, at a rate of only 2% per year. These results suggest that, during the moisture recovery period, planting should be constructively controlled in the Loess Plateau.

CONCLUSIONS

In the Loess Plateau, the arid soil layer is typical, given the semi-arid and semi-humid climatic conditions. The interaction of drought and soil desiccation results in the formation of the arid soil layer. Factors inducing the arid soil layer vary depending on vegetation type. Evapotranspiration is a major factor in development of the arid soil layer in forests of semi-arid and semi-humid regions in the Loess Plateau because of great soil water loss through transpiration and soil surface evaporation. In areas where trees are not the dominant vegetation, soil evaporation, driven by atmospheric drought and the water potential gradient, results in arid soil. The occurrence mechanisms, classification and distribution of the arid soil layer require further investigation.

Soil desiccation is widespread under forest vegetation in the Loess Plateau. The formation of the arid soil layer in many regions of the plateau limits yield and forest efficiency and increases the risk of forest and grassland degeneration. Once the arid soil layer forms, it is difficult to restore soil moisture to the original level in a short time period, and this constitutes a threat to sustainable development of vegetation in the Loess Plateau. Because the arid soil layer causes many problems, construction of an ecological environment in the Loess Plateau is required to prevent and remove the arid soil layer.

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