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Earth Surface Processes and Environmental Sustainability in China

Factors influencing soil moisture in the Loess Plateau, China: a review

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ABSTRACT: Soil moisture is a key issue for eco-hydrological research in arid and semi-arid regions, and is primarily concerned with water availability for vegetation. Shallow and deep soil moisture occurs according to the maximum infiltration depth. Soil moisture has three-dimensional characteristics: inter-layer variability, horizontal heterogeneity and temporal variability. Soil moisture is affected by various factors including terrain, soil characteristics, climate and vegetation, and the effects of these change with time (e.g., rainfall patterns) and space (e.g., soil depth). In arid and semi-arid regions, deep soil moisture is of particular importance to vegetation restoration and the evaluation of vegetation sustainability; however, accurate prediction of the spatial distribution of deep soil moisture in the Loess Plateau of China still faces numerous challenges. Therefore, future research should focus on the mechanisms, models and scale effects of soil moisture, particularly for deep soil moisture.

KEY WORDS: arid and semi-arid regions, deep soil moisture, landscape hydrology, restoration, scale, shallow soil moisture.

Soil moisture is an essential component in the hydrologic cycle. It has profound impacts on atmospheric, geomorphological, hydrological and ecological processes, and it is at the junction of disciplines concerned with these processes (Legates *et al.* 2011). Soil moisture in relatively deep layers connects shallow soil moisture with deep groundwater and acts as the soil water reservoir. It also affects vegetation growth and the atmospheric water cycle through water absorption and transpiration by vegetation (Yang *et al.* 2012a). Therefore, in arid and semi-arid regions, deep soil moisture is a major factor that limits vegetation growth and succession. It is also the key to the drought resistance of deep-rooted vegetation and plays vital roles in vegetation growth and ecosystem sustainability (Chen *et al.* 2008a).

The Loess Plateau in the upper and middle parts of the Yellow River basin (Fig. 1) in China has a dry climate (Zhao *et al.* 2012) with a much larger mean annual evaporation demand (>1000 mm) than mean annual precipitation (200–650 mm). Therefore, soil moisture in the shallow root zone is often lost via intense evapotranspiration during the dry season and is insufficient to support vegetation growth (Chen *et al.* 2007). The deep groundwater levels in the Loess Plateau of China are generally approximately 30–100 m below the soil surface and cannot be used by vegetation (Mu *et al.* 2003; Yang *et al.* 2012a). Thus, soil moisture in the deep layers located in the zone of aeration becomes an important water source for vegetation and is crucial to restoration, such as in the ‘Grain for Green Project’ (Lü *et al.* 2015a). Although the large-scale implementation of this project has gradually controlled soil erosion and restored vegetation in the Loess Plateau region, new challenges have also become apparent. Most species introduced to this region consume large amounts of water without considering the soil moisture carrying capacity. Consequently, the large-scale implementation of the Grain for Green Project has depleted most of the deep soil moisture over large areas, severely affecting the sustainability of vegetation restoration (Wang *et al.* 2010; Jia & Shao 2014). Artificially restored vegetation has begun to degrade in some areas, leading to the formation of ‘little old-man trees’ that are only 3–5 m high (Chen *et al.* 2008a). Traditional soil moisture research that focuses on the shallow active root zones can no longer meet the needs of sustainable vegetation restoration in this region. Due to these circumstances, soil moisture research in the relatively deep layers of the Loess Plateau has attracted the attention of numerous scientists (e.g., Qiu *et al.* 2001a; Chen *et al.* 2008b; Yang *et al.* 2012a; Wang *et al.* 2013b; Jia & Shao 2014).

The Loess Plateau in China is the primary study area for this paper; however, relevant worldwide studies on soil moisture are also referenced. This review discusses the soil moisture issues in the Loess Plateau with respect to the definition of

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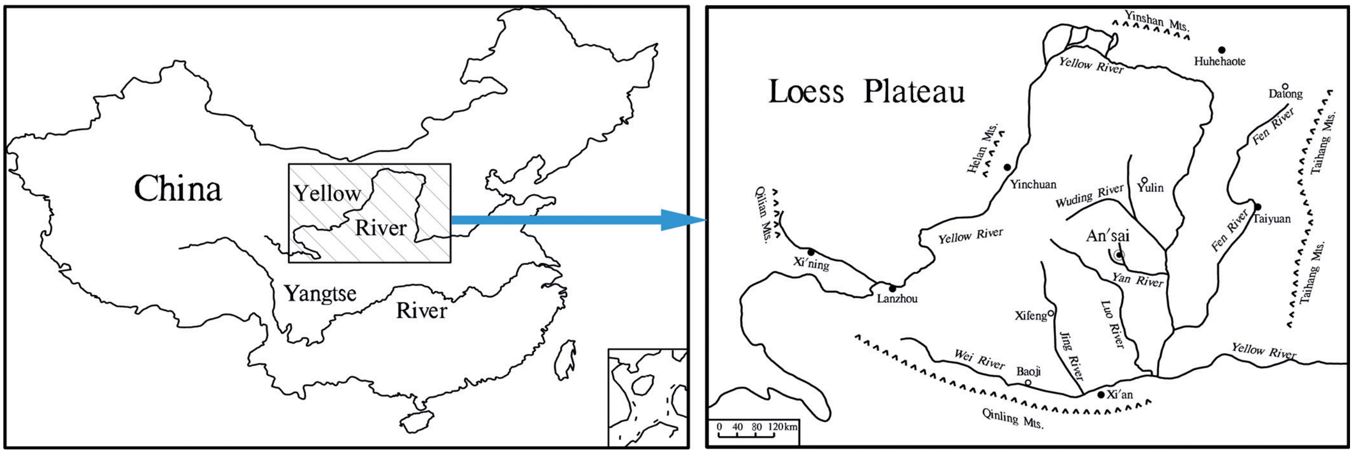

Figure 1 Location map for the Loess Plateau, China.

Table 1 Shallow and deep soil moisture depths.

Theoretical basis	Shallow soil moisture	Deep soil moisture	References
Soil moisture in all layers is referred to as deep soil moisture	–	0–75 cm	Qiu *et al.* (2001a)
	–	0–340 cm	Jia & Shao (2014)
	–	0–21 m	Wang *et al.* (2013a)
Soil moisture is classified into shallow and relatively deep layers	0–2 m	2–8 m	Yang *et al.* (2012a)
	0–60 cm	60–500 cm	Fang *et al.* (2016)
	0–30 cm	30–82.5 cm	Kurc *et al.* (2010)

soil moisture in different layers, the three-dimensional (3-D) characteristics of soil moisture and the factors and mechanisms affecting soil moisture. It also discusses future soil moisture research with the goal of supporting research in arid and semi-arid regions (e.g., landscape hydrology) and facilitating strategy designs for sustainable vegetation restoration.

1. Definition of soil moisture in different layers

Soil moisture refers to the water stored in different soil layers, from the surface layer to those layers above the groundwater interface (the water table); it is also known as the moisture in the unsaturated zone. For vegetation restoration and growth, soil moisture is defined as the moisture in the zone of aeration that can be absorbed and used by vegetation. Thus, soil moisture research often emphasises the practical significance and value of soil moisture, which can be classified as shallow and deep soil moisture. Shallow soil moisture is often one of the main factors that affects surface processes and vegetation growth (Tramblay *et al.* 2010; Song *et al.* 2013; Wang *et al.* 2013a), whereas deep soil moisture is more important for long-term moisture storage that supports sustainable vegetation restoration and rehabilitation (Fang *et al.* 2016; Zhang & Shangguan 2016).

Currently, there are two contrasting definitions of deep soil moisture: (i) soil moisture in the zone between the topsoil and the relatively deep soil layers; and (ii) soil moisture in the relatively deep layers only (excluding the shallow zone) (Wang *et al.* 2012; Table 1). The first includes soil moisture in both the shallow and deep zones, but does not reflect the differences between the two. In contrast, the second ignores soil moisture in the shallow zone, but fails to clarify at what depth soil moisture can be referred to as 'deep soil moisture'. For example, Qiu *et al.* (2001a) refer to deep soil moisture as moisture stored 75 cm below the surface. In contrast, many other studies consider 'deep' to be a depth below 2 m from the surface (Yang *et al.* 2012b; Jia & Shao 2014). Yang *et al.* (2012b) studied soil moisture in layers as deep as 8 m, and Wang *et al.* (2013b) investigated soil moisture in a layer 21 m below the surface. The disagreement on how to define shallow or deep soil moisture and how to distinguish them is a limitation requiring further research.

A more recent suggestion divides soil moisture into shallow and deep soil moisture based on the maximum precipitation infiltration depth: (i) soil moisture in the zone above the maximum precipitation infiltration depth (variable layers) or shallow soil moisture; and (ii) soil moisture in the zone below the maximum precipitation infiltration depth (stable layers) or deep soil moisture (Fang *et al.* 2016). The distinction of deep from shallow soil moisture based on the maximum precipitation infiltration depth reflects the infiltration and migration processes of soil moisture. Based on this concept, deep soil moisture studies should have the following characteristics. First, the investigated soil layer depth should exceed the maximum precipitation infiltration depth, which generally does not exceed 2 m in the Loess Plateau (Wang *et al.* 2011b). Second, the investigated soil layer depths should be determined based on the vegetation types and their root distribution. Third, when selecting soil layer depths for analysis, the scale of the study should be considered. Generally, for large-scale studies, the selected soil layer depths should encompass the primary depths that affect normal vegetation growth, whereas, for small-scale studies, the selected soil layer depths should include the maximum depth that affects vegetation growth.

2. 3-D characteristics of soil moisture

Soil moisture is affected by multiple interrelated factors and exhibits typical 3-D characteristics. In terms of its vertical dimension, soil moisture often exhibits notable inter-layer variability with soil depth. In terms of its horizontal dimension, soil moisture content, together with its influencing factors, varies significantly with the spatial scale of the study area and exhibits horizontal variability. In terms of its temporal dimension, the temporal stability of soil moisture also varies considerably with depth and region; thus, soil moisture also exhibits temporal variability.

2.1. Inter-layer variability of soil moisture

Soil moisture exhibits distinct inter-layer variability with soil depth. According to Fang *et al.* (2016), soil moisture can be classified as soil moisture in the variable layers and in the relatively stable layers demarcated by the maximum precipitation infiltration depth. Yet, both the variable and relatively stable layers are essential components of the regional hydrologic cycle through two interconnected processes. First, the variable layers can convert precipitation and surface run-off into soil moisture that can be absorbed and consumed by vegetation and is directly linked with atmospheric water through evapotranspiration. The relatively stable layers connect the variable layers with the deep groundwater and affect vegetation growth through water absorption via the deep-rooting systems of the plants, thereby connecting atmospheric water, water stored in vegetation, surface run-off, soil moisture and groundwater (Yang *et al.* 2012a, 2014a; Jia & Shao 2014). Second, the variable and relatively stable layers replenish and supplement each other. Under normal circumstances, soil moisture in the stable layers is primarily replenished by soil moisture in the variable layers due to soil moisture potential differences and seepage. Soil moisture in the relatively stable layers supplies water to the variable layers when precipitation is limited (Yang *et al.* 2012b; Wang *et al.* 2014). Hydraulic redistribution is the mechanism by which plants passively transport water from deep, moist layers to shallow, dry soil layers (Domec *et al.* 2010; Prieto & Ryel 2014).

Although the variable and the relatively stable layers are closely linked to one another, they can be distinguished according to several criteria (Yang *et al.* 2012a, 2014a; Wang *et al.* 2012). First, their differences are reflected in their respective effects on vegetation. The variable layers supply most of the water consumed by vegetation for growth and evapotranspiration, except during drought conditions when soil moisture in the variable layers is insufficient to maintain normal vegetation growth. During a drought, soil moisture in the relatively stable layers acts as a water reserve and is important for vegetation resilience in arid and semi-arid regions (Wang *et al.* 2012). Second, the variable and relatively stable layers have different response times to the influencing surface factors (e.g., precipitation, evaporation and run-off). Soil moisture in the variable layers responds rapidly and intensely to surface factors and has high temporal and spatial variability (Qiu *et al.* 2001a). However, the extents are much lower for the soil moisture in the relatively stable layers due to, for example, a lag effect. In addition, groundwater levels in the Loess Plateau range from 30 to 100 m below the surface and have a small effect on soil moisture (Chen & Hu 2004) because groundwater is not a viable supply for soil evaporation and/or plant transpiration (Yang *et al.* 2012a). Consequently, soil moisture in the relatively stable layers has a certain degree of temporal stability. Third, the mechanisms of water replenishment and consumption differ between the variable and stable layers. Soil moisture in the variable layers is (i) significantly affected by single rainfall events, (ii) replenished primarily by infiltration of each of those events and (iii) lost through evaporation and transpiration. In contrast, soil moisture in the stable layers is (i) related to the mean annual precipitation, (ii) replenished primarily by infiltration of water stored in the variable layers and groundwater and (iii) used primarily by vegetation through transpiration. Therefore, when studying soil moisture, it is necessary to design experiments based on the respective characteristics and relationships of the variable and stable layers. The variable and stable layers should not be considered as exactly the same, nor should they be completely separated.

2.2. Horizontal variability of soil moisture

Factors affecting soil moisture are correlated to one another to a certain degree, and they are scale dependent. Generally, studies of soil moisture patterns can be classified as large-scale (e.g., regions, watersheds and catchment) or small-scale (e.g., small watersheds, slopes and plots) studies. Entin *et al.* (2000) found that soil moisture patterns are primarily affected by soil type, terrain and vegetation on the small scale, whereas climatic factors, such as precipitation and evapotranspiration, are the dominant factors that affect soil moisture patterns on the large scale. Soil moisture patterns and their influencing factors have a certain scale effect. Small-scale research results cannot be directly applied to large-scale research because they require certain scaling.

The basic unit for small-scale hydrological research is the slope. Extensive research has been performed on soil moisture patterns and their controlling factors at the slope scale. Within one slope, soil types, vegetation factors and climatic factors are generally consistent. Therefore, horizontal variability in soil moisture is primarily determined by terrain factors (Gómez-Plaza *et al.* 2000; Bi *et al.* 2009; Zhu *et al.* 2014b). Within a small watershed, terrain factors, soil factors, vegetation and microclimate characteristics (e.g., received radiation on exposed slopes) can all affect the horizontal variability in soil moisture (Zhu *et al.* 2014b). In a large catchment, precipitation (e.g., intensity, volume and duration), soil factors (e.g., soil texture, soil chemical factors and soil physical factors) and vegetation (e.g., coverage, species and height) are the dominant factors that affect horizontal variability in soil moisture. On an even larger regional scale (e.g., the entire Loess Plateau), climatic, micro-terrain and vegetation factors are dominant. At all these scales, vegetation factors play a pivotal role in influencing the horizontal variability of deep soil moisture (Western *et al.* 2004).

2.3. Temporal variability of soil moisture

The temporal variability in soil moisture is related to numerous environmental and vegetation conditions (Jia *et al.* 2013). Soil moisture in the variable layers, including in the Loess Plateau, has poor temporal stability because it is directly and significantly affected by changes in environmental and vegetation factors (Entin *et al.* 2000; Cantón *et al.* 2004; Hébrard *et al.* 2006). Soil moisture in the stable layers of the vegetation restoration zone in the Loess Plateau exhibits relatively low temporal variability and a certain degree of temporal stability (Wang *et al.* 2012; Jia & Shao 2014; Yang *et al.* 2014a, 2014b), though, surprisingly, this soil moisture has relatively poor temporal stability under relatively wet conditions and relatively good stability under dry conditions. As vegetation consumes much of this deep soil moisture (with negligible precipitation impacts during dry years), soil moisture in the stable layers exhibits temporal stability (Chen *et al.* 2008a). Consequently, deep soil layers with low moisture content are generally observed in the regions where vegetation has been relatively well restored. In contrast, larger temporal variability is observed for deep soil moisture as a response to precipitation events, although there are time lags associated with such events (i.e., soil moisture in the relatively deep layers changes only after a certain amount of time following a precipitation event).

The soil moisture response to precipitation events exhibits different characteristics at different depths. Soil properties, terrain and vegetation are all important aspects that determine the temporal variability of soil moisture. For example, Vachaud *et al.* (1985) determined that soil texture, particularly clay content, is the main explanatory variable for the temporal variability of soil moisture in variable layers. Jacobs *et al.* (2004) noted that soil moisture often exhibits temporal stability on a gentle slope and relatively poor temporal stability on a mound top or steep slope. Furthermore, some studies have determined that vegetation cover and management have significant impacts on the temporal stability of deep soil moisture (Martínez-Fernández & Ceballos 2003; Starks *et al.* 2006).

3. Influencing factors of soil moisture

Soil moisture, including in the Loess Plateau, is affected by several factors such as terrain (Qiu *et al.* 2001a), soil properties (physical, chemical and biological) (Zhu & Lin 2011), climate (Montenegro & Ragab 2012) and vegetation (Vivoni *et al.* 2008). From the perspective of restoration ecology, these influencing factors can be classified into two main types: environmental factors and vegetation factors, which may differ according to spatial scales.

3.1. Effects of environmental factors on soil moisture

In regions with little vegetation cover, environmental factors (terrain, soil and climate) often control the soil moisture distribution (Gómez-Plaza *et al.* 2001). Multiple terrain factors (e.g., slope position, slope surface, slope gradient, slope type and altitude) have different individual impacts on soil moisture redistribution and consumption (Zhu *et al.* 2014b). The response of soil moisture to a precipitation event varies at different slope positions in the variable layers (Zhu *et al.* 2014a). In general, the responses of soil moisture to a precipitation event are similar at the top and middle sections of the slope. Yet, the same precipitation event results in a lower soil moisture content in the top and middle sections compared to the lower part of the slope. This suggests that the change in soil moisture on a slope after a precipitation event, particularly in the variable layers, is primarily affected by lateral flows that favour the lower parts of the slope. However, Yang *et al.* (2012a) found that the location on a slope has relatively little impact on soil moisture in the stable layers and that there is no significant difference in the soil moisture content at different locations of the stable layers.

Because the amount of solar radiation received by soils on different slopes varies, evaporation rates and the subsequent soil moisture distribution also vary between different sloping surfaces. In addition, different types of vegetation are distributed on shady and sunny slopes. Different types of vegetation vary in water consumption capacity, thereby indirectly affecting soil moisture consumption (Yang *et al.* 2014a), which is primarily reflected in the soil moisture of the variable layers.

The slope gradient has significant impacts on soil moisture in both the variable and stable layers (Qiu *et al.* 2001b; Yang *et al.* 2012a). The soil moisture content is generally lower on steep slopes compared to gentle slopes, and the slope gradient negatively correlates with soil moisture (Kim *et al.* 2007). However, Ladson & Moore (1992) found no significant correlation between soil moisture and slope gradient, which was likely due to the uptake of soil moisture by vegetation.

In addition to typical terrain factors, micro-terrain factors (e.g., lateral evaporation from different sections of a gully) also have some impacts on soil moisture (Zhu *et al.* 2014a). The soil moisture increases with increasing distance from the gully boundary and decreases towards the edge. The extent of the lateral evaporation effects is determined by the shape and size of the gully and the local climate (Zheng *et al.* 2006).

The soil property effects on soil moisture are primarily reflected by different soil types having different water-conducting and water-retention properties that affect the migration, storage and evapotranspiration of soil moisture (Western *et al.* 2004). The hydrological properties of the topsoil (e.g., infiltration rate and saturated hydraulic conductivity) directly determine the capacity of the soil to convert precipitation to soil moisture and, thus, have significant impacts on the soil moisture content of both the variable and stable layers (Martínez García *et al.* 2014). Soil water retention properties (e.g., soil porosity and field moisture retention capacity) determine the amount of water that can be retained in the soil and significantly affect the soil moisture content in regions that receive ample precipitation (Gómez-Plaza *et al.* 2001). Ojha *et al.* (2014) determined that the soil clay proportion has a significant impact on moisture content, and soil layers with high clay content have a relatively large moisture content. The saturated water conductivity is related to the soil moisture conditions, and it impacts the soil moisture variation under relatively wet conditions, whereas the correlation between the saturated water conductivity and the soil moisture variation is relatively weak under relatively dry conditions (Martínez García *et al.* 2014). There have been numerous studies on the effects of soil properties on soil moisture at various depths; however, these primarily focus on topsoils. Therefore, it is necessary to investigate the effects of soil properties on soil moisture at various depths because soil properties generally vary with depth.

The effects of climatic factors on soil moisture are reflected by differences in water infiltration and evapotranspiration resulting primarily from precipitation and solar radiation (Savva *et al.* 2013). The effects of precipitation and solar radiation on soil moisture in the variable layers are observable and rapid; however, they are less so in the stable layers due to a lag effect. Therefore, soil moisture variation in the stable layers is determined by the water budget resulting from the long-term regional climate and vegetation characteristics (Chen *et al.* 2008b). With such characteristics, future replenishment of deep soil moisture in the Loess Plateau will be challenging because the area is projected to become warmer and drier during the summer (Qin *et al.* 2002; Yao *et al.* 2005; Qin & Stocker 2014). By analysing the meteorological and soil moisture data from the past 30 years, Pu *et al.* (2007) determined that soil moisture content in the Loess Plateau had decreased considerably with decreasing precipitation and increasing temperature. Consequently, there will be greater stress on the regional soil moisture due to intense evapotranspiration because soil moisture in the stable layers (i.e., >2 m below the surface) in most areas of the Loess Plateau cannot be directly replenished by precipitation, even during periods with typical precipitation rates (Chen *et al.* 2008b).

Additionally, the macroclimatic differences generated by different vegetation types, soil factors and terrain factors (Wang *et al.* 2013a; Zhu *et al.* 2014a) will lead to large-scale differences in soil moisture conditions. Macroclimate effects also have significant impacts on soil moisture patterns under certain circumstances. For example, given vertical variability, both precipitation and temperature vary with altitude in a mountainous environment. These variations may represent key factors that affect soil moisture patterns.

3.2. Effects of vegetation factors on soil moisture

The effects of vegetation on soil moisture are multifaceted, yet understanding the complex vegetation-related ecosystem factors on soil moisture is important for vegetation restoration in arid and semi-arid regions. The soil moisture in the root zone affects vegetation growth and succession (Vivoni *et al.* 2008), and vegetation affects the soil capacity for storing, transporting and evaporating water through the canopy (Zhang *et al.* 2016). Vegetation can redistribute precipitation through canopy interception and stem flow to affect infiltration processes after rainfall (Yuan *et al.* 2016). The vegetation can also alter the amount of net radiation through the canopy and reduce soil moisture evaporation from the variable layers by producing litter on the surface (Famiglietti *et al.* 1998; Vivoni *et al.* 2008; Yuan *et al.* 2016). Vegetation systems can further alter the physical and chemical properties of soil and, consequently, its water-conducting and water-retention capacities (Venkatesh *et al.* 2011; Fang *et al.* 2016). Root growth and organic matter decomposition increase soil porosity, prevent the topsoil from hardening, reduce bulk density and promote infiltration (Domec *et al.* 2010; Gao *et al.* 2013; Prieto & Ryel 2014). In general, well-developed topsoil has a relatively high water-retention capacity, as litter and humus retain more precipitation that will subsequently infiltrate into the soil and replenish soil moisture (Qiu *et al.* 2001b; Zhu & Lin 2011).

Although the vegetation impacts on soil are mostly positive, not all types of vegetation are ideal for restoration in the Loess Plateau. In vegetated areas, more water is lost via evapotranspiration compared to bare areas where only evaporation occurs (Savva *et al.* 2013). Because plant roots occur at various depths, different species have different water consumption characteristics. The rooting systems of plants in natural grasslands, for example, are primarily distributed at depths of 0–50 cm (Han *et al.* 2009). The rooting systems of annual crops in farmland are primarily at depths of 0–40 cm (Feng *et al.* 2007), although perennial crop roots (e.g., alfalfa or *Medicago sativa*) can extend down to 3 m. The rooting systems of shrubs (e.g., *Caragana microphylla*) are primarily distributed at depths of 0–1 m and can reach 6 m (Wang *et al.* 2010; Yang *et al.* 2014b). Therefore, most water consumption on farmland and natural grassland occurs in the variable layers, while the most water consumed on restored shrubland occurs in both the variable and stable layers (Fu *et al.* 2003; Wang *et al.* 2010). Hydraulic redistribution allows passive water transport from deep, moist layers to shallow, dry soil layers (Domec *et al.* 2010; Prieto & Ryel 2014), providing moisture for shallow-rooted species. Shallow-rooted vegetation can reduce the impact of short-term environmental changes on deep soil moisture and increase the stability of deep soil moisture (Vivoni *et al.* 2008). Therefore, it is necessary to investigate not only the vegetation effects at the individual level but also the effects of vegetation structural characteristics at the community level for successful and sustainable restoration (Ferreira *et al.* 2007).

3.3. Scale effects of the factors affecting soil moisture

The influences of environmental factors on soil moisture have a distinctive scale effect that may vary at different spatial scales. At a transect scale, land use and topography are the main influencing factors of soil moisture because other factors, such as atmospheric and soil properties, are similar within small areas. The vegetation type dominating certain land uses is, therefore, critical and may determine the soil moisture of the landscape. On the Loess Plateau, the deep soil moisture in most shrub or forest land is so depleted that its heterogeneity is lower than that in the grassland (Yao *et al.* 2012). The slope (position, length and gradient) primarily affects the lateral flow of soil moisture, and lower positions or gentle slopes typically have a higher soil moisture content than higher positions or steep slopes (Famiglietti *et al.* 1998; Kim *et al.* 2007; Qiu *et al.* 2007; Zhu *et al.* 2014a).

At the catchment scale, the factors that influence soil moisture vary with soil depth (Qiu *et al.* 2001b), although both shallow and deep soil moisture are affected by vegetation. Shallow soil moisture is primarily determined by topography and rainfall, while deep soil moisture is more affected by climate, topography, soil physical properties and land management. Land management, planting density and litter-water-holding capacity may improve deep soil moisture, while the high water consumption capacity of some deep-rooted-system vegetation may offset some of those benefits to deep soil moisture (Fang *et al.* 2016).

At the regional or larger scales, the effects of topographic factors are not evident (Zhang *et al.* 2017), although vegetation still has significant effects on soil moisture. Other factors such as precipitation, temperature and soil characteristics (field capacity and bulk density) also contribute to soil moisture variability (Yao *et al.* 2012; Liu *et al.* 2016; Zhang *et al.* 2016). Bulk density most significantly affects soil moisture in the shallow layers, whereas field capacity has greater effects on deep soil moisture (Zhang *et al.* 2016). For large-scale vegetation restoration on the Loess Plateau, precipitation and vegetation type are equally important factors (Liu *et al.* 2016). With introduced species, the sensitivity of soil moisture to changes in precipitation and soil water content is greater than when only local species are present (Yang *et al.* 2012b; Fang *et al.* 2016). For the same type of vegetation, soil moisture in areas with annual averages of 370–440 mm is more sensitive to precipitation than soil moisture in areas with other rainfall gradients (Zhang *et al.* 2016, 2017).

4. Modelling of soil moisture distribution patterns

The soil moisture conditions are important for regional vegetation restoration and sustainability. However, it is relatively difficult to accurately predict the spatial distribution of soil moisture. Different methods for soil moisture prediction have been developed by researchers in the last several decades (e.g., Robinson *et al.* 2008; Vereecken *et al.* 2008; Baroni *et al.* 2013; Table 2).

These studies include interpolation based on field measure data at the plot, field and catchment scales (Zehe *et al.* 2010), as well as the prediction of soil moisture patterns based on soil moisture data obtained using remote sensing technologies at large scales (Zreda *et al.* 2008; Gao *et al.* 2013). Each method has advantages and disadvantages. Manual soil moisture sampling using a time-domain reflectometer, a soil auger, a neutron detector or a capacitance detector and automatic monitoring are frequently used (Su *et al.* 2014). However, the independent use of these conventional point measurement methods is costly and difficult to employ over a large area (Qiu *et al.* 2001b). In addition, good prediction and mapping using spatial interpolation, which relies on field measurement data, can only be achieved when the sampling density is high, the differences between variables are insignificant and the variables are continuous.

The Loess Plateau has thousands of gullies and fragmented terrain, and its soil moisture has significant temporal and spatial variability. Soil moisture sampling in the Loess Plateau is difficult and costly. Consequently, the use of an interpolation method to predict soil moisture in the Loess Plateau is limited (Qiu *et al.* 2010; Gao *et al.* 2013). During recent years, remote sensing technologies have developed rapidly, which provides a quick and effective method for estimating soil moisture on large scales. However, remote sensing technologies also have certain limitations for predicting soil moisture. For example, remote sensing images generally have relatively low

Table 2 Soil moisture modelling methods.

Modelling methods	Required tools or data	Characteristics	References
Manual sampling	A soil auger, a neutron detector or a capacitance detector, etc.	Accurate but costly and not widely used	Qiu *et al.* (2001b), Brocca *et al.* (2007), Su *et al.* (2014)
Spatial interpolation	Soil moisture data at different scales	Relatively accurate but the assumed variables are insignificant, continuous and require a high sampling density	Kuilenburg *et al.* (1982), Kim & Barros (2002), Perry & Niemann (2008), Yao *et al.* (2013), Ford & Quiring (2014), Yuan & Quiring (2017)
Remote sensing retrieval	Field measurement data and remote sensing images	Quick, effective and suitable at large scales, but with a lower accuracy and no predictive ability in deep layers	Choi *et al.* (2007), Zreda *et al.* (2008), Zhang *et al.* (2011), Gao *et al.* (2013), Kolassa *et al.* (2016), Kolassa *et al.* (2017)
Multivariate regression method	Field measurement data and influencing factors	Relatively accurate and generally applicable	Wu *et al.* (2007), Yin *et al.* (2008), Qiu *et al.* (2010)

spatial resolution. Therefore, it is very difficult to accurately predict soil moisture on small scales using remote sensing. On the other hand, even if the sensor signals have relatively high accuracy, image interpretation is also affected by terrain roughness and vegetation. In addition, current remote sensing technologies can only retrieve soil moisture data in relatively shallow layers and cannot effectively predict soil moisture content at different depths (Choi *et al.* 2007).

These comments highlight the need to develop the soil moisture content prediction methods at depth. New methods should be able to predict deep soil moisture using existing data or auxiliary information that is easily obtainable. Because the methods for predicting soil moisture at depth require development, it is difficult to accurately predict deep soil moisture using conceptual or physical models (Qiu *et al.* 2003; Venkatesh *et al.* 2011). Therefore, the development of multivariate regression models for each influencing factor is recommended (i.e., the mathematical relationships between soil moisture content at various depths and each influencing factor). Once established, the model application may not be limited to the region and scale on which the model is based; instead, the model may be generally applicable with validation. Qiu *et al.* (2010) verified the feasibility of using multivariate regression analysis combined with relevant environmental factors to predict the soil moisture content of shallow soil layers (Qiu *et al.* 2010). However, further studies are needed to determine (i) how to consider ecosystem factors when developing statistical models, (ii) how to consider soil moisture at different depths and (iii) how to map soil moisture at different depths.

5. Research perspectives on soil moisture

There has recently been marked progress on soil moisture research and ecosystem sustainability on the Loess Plateau. Soil moisture research is gradually moving from static to dynamic, from qualitative description to quantification and from empirical to mechanism-based approaches. Future research on soil moisture may focus on:

(1) Mechanisms and models of deep soil moisture.

Current research on soil moisture primarily focuses on the relatively shallow zone in the variable layers (Hébrard *et al.* 2006). Studies of the mechanisms that affect deep soil moisture in the stable layers are often based on statistical analysis (Wang *et al.* 2012; Yang *et al.* 2012a; Jia & Shao 2014). Research on the internal hydrodynamic mechanisms that operate in the stable soil layers is still lacking. Therefore, it is difficult to develop mechanism-based models for predicting deep soil moisture patterns. This limits the development of research on deep soil moisture. For future research, it will be necessary to focus on the heterogeneity of deep soil moisture, including the mechanism-based models for predicting deep soil moisture.

(2) Research on soil moisture should be conducted on multiple scales.

Currently, most soil moisture studies are conducted at the plot (Jia & Shao 2014) and slope (Wang *et al.* 2008) scales, and relatively few studies are conducted at the medium-scale level (e.g., catchments) (Yang *et al.* 2012a, 2014a, 2014b; Fang *et al.* 2016). Even fewer are large-scale studies, and they only focus on dry soil layers (Wang *et al.* 2011a, 2011b; Liu *et al.* 2016). Although medium-scale studies are often the ideal scale (i.e., highly relevant when formulating policies for vegetation sustainability), different study areas may require different spatial scales. In addition, careful comparisons are required for research results conducted at various scales and when referencing such research (Qiu *et al.* 2001a; Cantón *et al.* 2004; Zhu & Lin 2011; Zhang *et al.* 2016).

(3) Soil moisture research should be used to formulate strategies for sustainable vegetation restoration.

Future soil moisture research should incorporate vegetation restoration and its sustainability. The following are key challenges that need to be addressed in the Loess Plateau: (1) vegetation restoration should be performed at appropriate times (e.g., the rainy season) and locations with deep soil moisture conditions; (2) the sustainability of restored ecosystems should be evaluated based on the soil moisture carrying capacity; and (3) landscape management measures that promote sustainable vegetation should be formulated based on temporal and spatial soil moisture variability patterns and the mechanisms by which soil moisture is affected.

(4) Some possible approaches to soil moisture research.

New research paradigms are emerging for soil moisture. Soil moisture research is a 'pattern–process–service–sustainability' paradigm (Zhao & Wang 2016) with environmental factors used for the landscape pattern (elements and their spatial distribution) and soil moisture dynamics for the ecological processes. In addition to the natural driving factors, the focus should be on human influences and the relationships between landscapes and hydrology. Any ecosystem degradation in terms of structure and functionality will eventually result in a loss of human well-being (Lü *et al.* 2015b). We need to analyse the relationships between the biotic (human and vegetation) and abiotic factors (environment) on soil moisture and assess their potential effects on ecosystem services and sustainability.

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