Bringing Ancient Loess Critical Zones into A New Era of Sustainable Development Goals

Xiaoxu Jia[1,2,3], Ping Zhu[1,2], Xiaorong Wei[3*], Yuanjun Zhu[3], Mingbin Huang[3], Wei Hu[4], Yunqiang Wang[5], Tuvia Turkeltaub[6], Andrew Binley[7], Robert Horton[8], Ming'an Shao[1,2,3*]

[1]Key Laboratory of Ecosystems Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100190, China

[3]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi 712100, China

[4]New Zealand Inst Plant & Food Res Ltd, Private Bag 4704, Christchurch 8140, New Zealand

[5]State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, Shaanxi 710061, China

[6]Zuckerberg Institute for Water Research, Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus 8499000, Israel

[7]Lancaster Environment Centre, Lancaster University, Bailrigg, Lancaster, LA1 4YQ, UK

[8]Iowa State University, Ames, Iowa 50011, USA

*Correspondences: Xiaorong Wei (xrwei78@163.com), State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi 712100, China; Ming'an Shao (shaoma@igsnrr.ac.cn), Key Laboratory of Ecosystems Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

Abstract: Critical Zone Observatories (CZOs) have been established initially in natural environments to monitor CZ processes. A new generation of CZOs has been extended to human-modified landscapes to address the impacts of climate change and human-caused actions such as erosion, droughts, floods, and water resource pollution. This review focuses on numerous plot, field, and regional scale studies conducted in the CZO facilities distributed across the China Loess Plateau (CLP). The CLP CZO features the world's largest and deepest loess deposits, highly disturbed by human activities, and consists of a longitudinal series of monitoring sites. This observation system consists of plot, slope, watershed, and regional observatories and is promoted by large-scale comprehensive experiments to achieve multiscale observations. Deep soil boreholes, hydro-geophysical tools, multiple tracers-based techniques, proximal and remote sensing techniques, and automatic monitoring equipment are implemented to monitor CZ processes. Observation and modeling of critical hydrological and biogeochemical processes (e.g., water, nutrients, carbon, and microbial activities) in land surface and deep loess deposits across CLP CZOs have unveiled crucial insights into human-environment interactions and sustainability challenges. Large-scale ecological efforts such as revegetation and engineering such as check dam construction have effectively mitigated flood and soil erosion while enhancing deep soil carbon sequestration. However, these interventions can yield both benefits and drawbacks, impacting deep soil water, groundwater recharge, and agricultural production. Converting arable cropland to orchards for increased income has raised nitrate accumulation in the deep vadose zone, posing a risk of groundwater pollution. These findings, combined with the CZ data, have identified knowledge exchange opportunities to unravel diverse factors within the relations of agriculture, ecosystem, and environment. These could directly improve local livelihoods and eco-environmental conditions by optimizing land use and management practices, increasing water use efficiency, and reducing fertilizer application. These efforts contribute toward Sustainable Development Goals (SDGs) and environmental policies. Overall, studies within the CLP have provided significant scientific advancements and guidance on managing CZ processes and services with regional SDGs, that may be transferable to other highly disturbed regions of the world.

Keywords: Loess critical zone (CZ); Ecohydrological processes; Biogeochemical processes; CZ services; Human activities

1. Introduction

The Critical Zone (CZ) is the thin outer layer of our planet, extending from the top of the vegetation canopy to the bottom of groundwater aquifers in terrestrial environments and encompasses the atmosphere, biosphere, pedosphere, hydrosphere, and lithosphere (National Research Council, 2001). CZ science explores how landscapes evolve from below the Earth's surface to the top of vegetation, supporting all terrestrial life on Earth (Naylor et al., 2023). CZ science is driving a new understanding of the links that connect geomorphology, hydrology, climate, ecosystems, and geology. Critical Zone Observatories (CZOs) have been established initially in "natural" environments to monitor CZ processes (Chorover et al., 2007). However, a transition has occurred where the legacy of natural processes has been affected to various extents by land use and other direct human interactions with ecosystems (Guo and Lin, 2016). The equilibrium of the natural environment is increasingly disrupted. Thus, monitoring CZ processes at CZOs has been extended to human-modified landscapes that dominant our world (Minor et al., 2020; Naylor et al., 2023), showing an evolution from an initial to a new generation of CZOs. The new generation CZO programmes aim to develop a deeper understanding of the impacts of human modification on landscapes.

Loess deposits are CZs that host over 321 million people and are characterized by high disturbances, productive and dynamic ecosystems, ongoing environmental change, and significant values to society. Loess deposits are widely distributed in the mid-latitude arid to semi-arid regions of both the northern and southern hemispheres (Fig. 1a), at altitudes ranging from several meters near the coasts (such as in Argentina and New Zealand) to 5300 m north of the Kunlun Mountains of China (Li et al., 2020). Loess deposits are of variable thickness, from a few meters to >300 m worldwide. The thickest (generally between 10 and 300 m thick with a maximum thickness of 500 m) and most continuous loess deposits worldwide are located on the Chinese Loess Plateau

(CLP; Zhu et al., 2018). The thicknesses of loess in Siberia and Central Asia are usually <200 m. The thicknesses of loess in Europe and North America typically do not exceed 20 m. Still, they can be close to 100 m in the Lower Danube River, the Palouse Region of NW USA, Nebraska, and Alaskan regions (Li et al., 2020). Thick loess deposits preserve a record of a wide variety of recent and past environments, such as paleoclimatic and paleomagnetic variations at various time scales (Kemp, 2001; Liu et al., 2015; Sun et al., 2021). The areas covered by thick loess and similar deposits constitute important and unique CZs on Earth, which are quite different from CZs developed on other lithologies (e.g., karst regions, arctic regions or coastal margins) regarding hydrological and biogeochemical processes. Because of the extensive distribution of loess deposits and typically intensive anthropogenic disturbances, loess regions should be considered an important geographic focus for CZ science. Loess-based observations are also critical for understanding systems influenced by eolian, pedogenic or drought, agricultural practices, and vegetation restoration. Over the past two centuries, there have been two main themes of loess study in the world, i.e., the origin of the loess deposit and the linkage between climate and loess (Smalley et al., 2001).

Loess CZs are known to have supported prehistorical agricultural civilizations. Generally, loess has a homogenous and porous structure and consists primarily of quartz and felspar particles. Loess soils are among the most fertile in the world, principally because the abundance of silt particles ensures a good supply of plant-available water, good soil aeration, extensive penetration by plant roots, and easy cultivation and seedbed preparation (Catt, 2001). The inherent physical and chemical fertility of loess soils had an important prehistorical role in developing early civilizations, such as those of China and Europe. The fertile top-soils of loess landscapes have been extensively utilized in agricultural practices since the Neolithic period, starting 7000 years ago (Whittle and Whittle, 1996; Bellwood, 2005). The agricultural use of the loess lowlands has generally been highly specialized from the past to the present. For example, Chinese culture originated on the CLP and adjacent areas of the North China Plain approximately 7000 years ago (Liu, 2004; Rosen, 2008). Therefore, thousands of years of agricultural practices may have significantly impacted on the landscapes and environments in the loess CZs.

Although loess is fertile, it is also extremely susceptible to both wind and water erosion since loess from aeolian deposits generally has very high porosity, loose particle packing, and consequently low bulk density (Feng et al., 2021). Furthermore, these deposits often contain little clay, leading to organic matter loss under arable cultivation. Water shortage and low vegetation cover are also common problems in loess areas in arid and semi-arid climatic regions, which increase the difficulty of ecological environment protection and restoration in these areas. Water resources in water-stressed loess areas are primarily provided by precipitation, and excessive use of soil water by vegetation, particularly establishing anthropogenic vegetation, can potentially lead to a severe imbalance between water supply and demand due to limited rainwater resources (Zhang et al., 2018a; Li et al., 2023a, b). Reduction in local water availability can, in turn, threaten the health and services of restored ecosystems, as well as human agricultural and industrial activities, particularly in densely populated and water-limited arid and semi-arid regions. All these problems widely exist in loess areas around the world, such as England (Boardman and Hazelden, 1986), Belgium (Evrard et al., 2008), USA (Hanson and Simon, 2001; Bettis et al., 2003), Iran (Doulabian et al., 2021; Sadeghi et al., 2021), France (Delmas et al., 2012; Kervroëdan et al., 2019) and China (Fu et al., 2017; Shao et al., 2018). Nevertheless, loess areas are eco-environmentally vulnerable in the world due to serious soil erosion, water shortage, low vegetation cover, and frequent and intensive human disturbances (Dotterweich, 2013; Fu et al., 2017). Research is needed urgently to address these problems and avoid permanently degrading CZ function.

Soil and water are the most vital natural resources in the CZ, as they directly impact food security, human health, and CZ function (Lin, 2010; Vereecken et al., 2015; Banwart et al., 2019). Soil and water processes within the CZ, such as soil formation, hydrologic partitioning, runoff generation, carbon (C) sequestration, nutrient and biogeochemical cycling, support and/or control of the supplies and benefits that the CZ produces through these processes for humans and the surrounding environment (Zhu et al., 2015a; Zhang et al., 2019) (Fig. 2a). Previous reports on loess CZs emphasize that soil and water are critical to numerous CZ services, such as *provisioning services* (e.g., water, food, and other resources supply), *regulating services* (e.g., water quality, flood regulation, and climate regulation), and *supporting services* (e.g., soil conservation, soil formation, C sequestration, and nutrient cycle). These CZ services, in turn, directly contribute to various Sustainable Development Goals (SDGs) (Field et al., 2015; Richardson and Kumar, 2017; Lal et al., 2021) (Fig. 2b). The CLP CZ has the thickest and most continuous loess deposits in the world. Long-term intensive anthropogenic disturbances (e.g., farming and large-scale ecological restoration) have greatly altered surface landscape properties and critical soil and water processes in the deeper subsurface of the CLP and, consequently, the CZ functions. The depth of measurements is thus important for loess CZ research, which is quite different from other CZs covered by thin soils. Exploring the impacts of anthropogenic activities at the land surface on deeper subsurface hydrological properties and biogeochemical processes with multidisciplinary collaborations and multiple analytical techniques can advance a comprehensive understanding of human-environment interactions.

Historically, the increasing demand for cultivated land and grain production has led to the destruction of natural vegetation and subsequent worsening of soil erosion on the CLP, which in turn, has led to an increase in floods in the Yellow River (YR) Basin (Chen et al., 2012; Wang et al., 2021a). However, various positive measures, such as slope cropland abandonment, afforestation, and cropland-to-orchard transition, have been implemented to improve the eco-environment and farmers income via increasing vegetation cover, reducing soil erosion, decreasing flood disasters, and enhancing C sequestration in the CLP in recent decades. Nonetheless, emerging problems such as food insecurity, water shortage, and severe residual nitrate pollution, hinder the sustainable development of the eco-environment in the CLP. These problems are closely associated with surface and subsurface processes interacting under different human activities, and economic-environmental trade-offs that occur in the loess CZ (Gao et al., 2021a; Wang et al., 2021a). Thus, the key issue to be addressed within loess CZOs is understanding critical soil and water processes in both surface and deeper subsurface and how these processes respond to natural and anthropogenic changes (Fig. 2a). Addressing these issues will have great significance on the judicious management of soil and water resources within CZs, and is important for supporting regional SDGs. Specific scientific questions for loess CZs are:

- Can surface soil erosion be controlled or alleviated?
- Does a large-scale ecological program affect local food security?
- Does large-scale vegetation restoration exacerbate water scarcity?
- Can desiccated deep soils be hydrologically recharged and restored?
- Does precipitation recharge groundwater in thick loess CZs?
- What are the ecohydrological functions of weathered bedrock?
- Do agricultural practices impact groundwater quality?
- Does deep loess soil sequester C from the atmosphere?

In this paper, we first examine the CLP as a typical example to describe a loess CZ's basic hydrogeomorphic features and provide a framework for watershed observatories and best-available datasets. We then discuss critical soil and water process responses to natural and anthropogenic changes occurring on a loess CZ. Finally, we summarize new insights that can benefit the sustainable development of loess CZ's eco-environmental and social needs. This study provides a roadmap to advancing CZ science and inform stakeholders.

2. Loess CZ Observatories and Basic Observations

The development of CZ science has aroused global interest resulting in more than 100 CZOs located in 29 countries being established since 2007 to form a global network of observatories (Lin et al., 2011; Niu et al., 2014; Giardino and Houser, 2015; Guo and Lin, 2016) (Fig. 1a). However, there are only a few CZOs in the loess regions. The lack of knowledge on critical soil and water processes in response to high disturbances inhibits the achievement of regional SDGs in loess-covered regions of the world. In China, scientists, engineers, and managers attach great importance to the loess CZs. There are several observation stations for soil, water, and vegetation processes on the CLP, which constitute the loess CZO's network (Fig. 1b). Within the loess CZO's network, several representative watersheds are chosen as the core sites for soil-water-ecosystem research (Fig. 1b and Table S1), as they cover distinct gradients in the geomorphologic landscape, climate, and human activities across the CLP. Thus, compared to other CZOs around the world, the uniqueness of the setup of the CLP CZO is that it consists of a longitudinal series of monitoring sites rather than a single observatory sub-watershed (Jia et al., 2020).

Notably, there are several other CZOs located in the loess-covered regions, such as the Intensively Managed Landscapes CZO (IML-CZO) in the US Midwest (Fig. 1a). The IML-CZO's network is composed of three highly characterized, well instrumented, and representative watersheds (i.e., Clear Creek, Iowa; Upper Sangamon River, Illinois; and Minnesota River, Minnesota). In the Clear Creek watershed, the loess deposit is about 15 m thick and covers till and clayey paleosols. In comparison, the Upper Sangamon and Minnesota River basins are mantled with thin loess deposits that transition vertically to unweathered fine-grained glacial till within 5 m of the land surface (Bettis et al., 2003; Wilson et al., 2018). The IML-CZO focuses on the US Midwest, one of the world's most intensively managed landscapes. It provides an understanding of how land-use changes affect the long-term resilience of the CZ, similar to the loess CZOs in China.

Generally, the soil and water processes of the Chinese loess CZOs are characterized by multiscale monitoring approaches (Fig. 3). At the plot or slope scale, techniques such as single automatic sensors, neutron probes, borehole drilling, and laboratory analyses are employed. Borehole drilling from the surface down to bedrock or groundwater is a unique and important approach for measuring soil or sediment thickness, hydraulic properties, C storage, and microbiological compositions in the CLP CZ (Zhu et al., 2018; Jia et al., 2018, 2020; Kong et al., 2022; Wang et al., 2024). At the pixel grid or sub-watershed scale, methods such as cosmic-ray soil moisture observing system (COSMOS), neutron probe networks, meteorological stations, and unmanned aerial vehicle (UAV), amongst others, have been utilized. In addition to neutron probe networks and UAV remote sensing, meteorological station networks and hydrological observation stations are also employed at the watershed scale. At the regional scale, apart from the neutron probe and meteorological station network, a hydrological observation network, field sampling, and satellite remote sensing methods are also used to investigate soil and water processes over the entire CLP.

Specifically, in each watershed CZO, multiple observation approaches have been applied to support monitoring needs (Fig. 4). Permanent instrumentation includes automatic meteorological stations, eddy covariance systems (for CO_2, water vapor, and heat exchange fluxes), water balance observation fields, and lysimeter clusters containing typical vegetation types for the measurement of biosphere-atmosphere-hydrosphere exchange processes. The meteorological systems record key parameters, including precipitation, air temperature, relative humidity, air pressure, net radiation, wind speed, and direction. Field observation experiments have been performed in various land use types in each watershed to monitor critical water processes components such as soil water content, evapotranspiration (ET), and runoff. Various runoff plots with different land use types monitor slope runoff and sediment yield. Neutron probes and COSMOS have been installed in each watershed to evaluate the spatiotemporal dynamics of soil moisture (Jia et al., 2013, 2015; Wang et al., 2019a; Liu et al., 2023a). Groundwater level monitoring wells have been installed in each watershed, and soil hydraulic properties, such as soil saturated hydraulic conductivity and porosity, in addition to root distributions have been surveyed (Cheng et al., 2009; Gao et al., 2012; Jian et al., 2014). Precipitation reduction and fertilization experiments are performed to study the responses of ecohydrological and biogeochemical processes to climate change (Jia et al., 2012, 2014; Wei et al., 2016b). Forest hydrological processes, including throughfall, forest interception, stem flow, tree transpiration, and soil water evaporation, have been observed in the forest ecosystem mainly by rain gauges, interception gauges, sap flow monitors (thermal dissipation probes, TDPs), and evaporation dishes installed according to established canopy gap fractions (Wang et al., 2019b). Geophysical methods, such as electrical resistivity tomography (ERT) (Liu et al., 2023b) and electromagnetic induction (EMI) (Turkeltaub et al., 2022), have been used to characterize soil physical properties (soil water content and structure) and infer salt accumulation in soils. Borehole drilling and soil pit methods are used to evaluate deep soil processes and the variability of loess properties in the vertical dimension (Jia et al., 2018, 2020; Qiao et al., 2018), allowing for the collection of disturbed and intact soil samples. Crop/plant (canopy) properties are measured manually or by UAV remote sensing. A 3-D laser scanner is used to monitor and retrieve gravitational erosion parameters.

3. The CLP as an Ideal Loess CZ

3.1. Location of the CLP

The CLP is situated in the upper and middle reaches of the YR Basin, bordered by the eastern Taihang Mountain, western Riyue-Helan Mountain, northern Yinshan Mountain, and southern Qinling Mountain (33°43′–41°16′N and 100°54′–114°33′E). The region covers an area of 64×10^4 km^2 with an elevation of 200 to 3000 m above sea level (Fig. 1b). It is significant for the ecological security of the whole of China, and it has an abundance of natural resources (e.g., coal, oil, and gas) (Zhao et al., 2013). Notably, the plateau is not entirely covered by loess due to the effects of soil genesis and landform (Zhu et al., 2018). The north-western region of the plateau is predominantly covered by aeolian sandy soil, such as the Mu Us Desert, due to its proximity to the source zone of dust and limited precipitation. The westernmost part of the plateau mainly consists of desert soil. The deep and continuous loess deposits are mainly distributed in the middle reaches of the YR, which is considered to be the core region of the plateau (Liu, 1985).

3.2. Regional Geomorphology

Intense soil erosion over thousands of years has transformed over 70% of the once-flat plateau into a region dominated by hills and gullies (Zhao et al., 2013). The unique morphology of the plateau is largely due to paleogeomorphology and erosion intensity. The typical landforms in this area include Yuan, Liang, Mao, as well as various hills and gullies of varying degrees of erosion (Fig. 5). Yuan refers to a high, flat, loess tableland that is not affected by river incisions. In contrast, Liang (a long range of ridges) and Mao (an oval or round loessial hill) are the result of fluvial and hill-slope erosion, respectively (Yang et al., 2009). As most of the Mao loess evolved from Liang loess under further erosion, Liang and Mao formations coexist in many areas and are the most common landscapes on the plateau. In addition, a large number of check dams and terraces have been constructed on the CLP as effective soil and water conservation practices (Fig. 5). These hydraulic engineering structures alter the microtopography of the land surface and offer several attractive advantages, including biodiversity conservation (Jia et al., 2011), water cleaning (Meninno et al., 2020), enhanced groundwater recharge (Luo et al., 2020; Zhao and Wang, 2021), flood damage mitigation (Wei et al., 2016a), C sequestration (Yao et al., 2022), and reduction in nutrient export loads by runoff to local water bodies (Meninno et al., 2020). Furthermore, check dam sediments form fertile flat agricultural areas with abundant nutrients and water to promote vegetation growth and to support livestock (Wen and Zhen, 2020; Yao et al., 2022).

3.3. Climate Change

A temperate, arid, and semiarid continental monsoon climate dominates the LPC region. The mean annual temperature in the region ranges from 3.6 to 14.3 °C, while the mean annual precipitation ranges from 150 to 800 mm. Most precipitation (55–80%) falls between June and September and decreases along a southeast-to-northwest transect (Wang et al., 2012). Over the last 60 years, the region-averaged annual mean temperature has significantly increased from 1960 to 2020 (1.74 °C, $p < 0.05$), with an increasing rate of 0.29 ± 0.1 °C per 10 years (Fig. S1). This warming trend is over two times greater than the northern hemisphere average (0.85 °C) and the global average (0.72 °C) during 1961–2010 (Wang et al., 2012). The annual precipitation was quite steady between 1960 and 2000, but it increased at a rate of 36 mm per 10 years between 2000 and 2020 ($p < 0.05$) (Fig. S1).

3.4. Loess Thickness

Soil or sediment thickness is a fundamental parameter in CZ science studies, but its accurate estimation is challenging, especially in areas with deep soil or sediment.

Determining soil or sediment thickness can be used to confirm the boundary of soil-water processes, which is crucial for investigating and modeling hydrological-biogeochemical processes in the CZ, together with estimations of water, C, and N reservoirs. Combining borehole drilling from the land surface down to bedrock (56–205 m) at five sites from south to north of the CLP and analyzing the elevation difference between the position of bedrock downstream and the adjacent flat loess hills of 162 sites across the CLP, Zhu et al. (2018) found that the loess thickness over the plateau mostly ranges from 0 to 350 m, with a mean value of 92.2 m. The mean thickness of the unsaturated and saturated zone across the CLP is approximately 54.8 and 37.4 m, respectively (Fig. 6).

3.5. Large Variations in Soil Hydraulic Property Values Exist within the VZs

Soil hydraulic properties, including saturated hydraulic conductivity (K_s), saturated soil water content (θ_s), and soil water retention curve $\theta(h)$, are critical for modeling hydrological-biogeochemical processes (Vereecken et al., 2022). Despite receiving increasing attention in recent years, data on high-quality soil hydraulic properties in the deep subsurface remains scarce due to challenges associated with sampling. Therefore, measured hydraulic properties from the surface layer often represent those of the deep unsaturated soil to simulate water flow and solute transport (Turkeltaub et al., 2018; Hu et al., 2019). If the hydraulic properties exhibit small variability throughout the soil profile, using uniform representative profiles in a model may be justified. Additionally, pedotransfer functions (PTFs) can be used to estimate soil hydraulic parameters in equations related to soil heat flow and biogeochemical parameters from readily available soil properties, such as particle size distribution (*PSD*), bulk density (*BD*), and organic C content (Vereecken et al., 2022). While PTFs are widely used, most have only been developed for specific regions and may not be applicable to pedoclimatic conditions for which they are not validated (Paschalis et al., 2022). Since loess deposits are thick and direct measurements of hydraulic properties are often rare, determining hydraulic property values based on soil hydraulic functions estimated by PTFs combined with borehole drilling has been a common approach used by loess CZ hydrologists.

To develop effective PTFs to estimate soil hydraulic properties of the CLP CZ, intensive sampling sites over the CLP were selected to collect both undisturbed and disturbed soil samples from the 0.2–8 m soil layer (Zhao et al., 2020; Niu et al., 2021; Bai et al., 2022). Soil physical properties [e.g., *PSD*, *BD*, porosity, K_s, θ_s, and $\theta(h)$] and organic C content were determined. The van Genuchten (VG) model was used to describe $\theta(h)$ relationships, and VG parameters, including α, n, and residual water content θ_r, were determined by fitting the model to the measured retention curve data. Based on *PSD*, *BD*, and other environmental variables, various PTFs were established to estimate K_s, *BD*, θ_s, θ_r, α, and n of the loess CZ. Compared with other PTFs, including the widely used Rosetta PTF (Schaap et al., 2001), the estimation accuracy of the new PTFs increased by 25–67% (Bai et al., 2022). Notably, compared with others, the new PTFs have better performances for deep soil layers. To create a regional distribution map of various soil hydraulic properties, disturbed soil samples from 0–5 m soil layer at another 243 sampling sites were collected across the CLP (Cao et al., 2018; Zhao et al., 2019). The new PTFs were then used to estimate soil hydraulic properties at the 243 sampling sites for the 0–5 m soil layer. Spatial distribution maps (1 km × 1 km) of soil hydraulic properties within different soil layers across the plateau were generated using geostatistical spatial interpolation via ordinary-kriging (Fig. 7).

3.6. On the Importance of Water Stored in the Loess CZ

Water stored in the VZ, as the primary source of plant available water, is critical to hydrologic processes on the land surface (Vereecken et al., 2015, 2022). It also impacts the transport of solutes and other substances in the soil. Understanding the magnitude and distribution of water storage in the root zone and in the deep VZ is essential for managing water resources and ecosystems. In this context, a VZ water observation network was established in 2012 on the CLP (Fig. 8a).

Based on *in situ* water observations and simulations, the magnitude and distribution of VZ water on the CLP have been quantified. For the loess region covering an area of 37×10^4 km^2, the total water storage capacity in the VZ (with a region-averaged VZ thickness of 54.8 m) was estimated to be approximately 3.1 × 10^{12} m^3, equivalent to a 9.6-m thick layer of water covering the land surface of the region (Zhu et al., 2019). The total water storage capacity is equal to an accumulation of 20 years of mean annual precipitation (1963–2012) across the CLP. The central parts of the region have the highest VZ water storage. In contrast, the northwest and southeast parts have relatively low VZ water storage (Fig. 8b), mainly depending on VZ thickness and precipitation. In addition, the total water storage in the 0–5 m soil layer (the root zone) of the plateau was approximately 2.7 × 10^{11} m^3, of which 42% is available for plants (total water storage minus water storage at the wilting point) (Cao et al., 2018; Zhao et al., 2021). Plant-available soil water storage in the 0–5 m soil layer (ranging between 0 and 1110 mm, with a mean of 306 mm) generally decreases from the southeast to the northwest of the region (Fig. 8c), and it is mainly influenced by soil texture and precipitation (Zhao et al., 2021). Moreover, we deduced the water resource composition across the CLP from the estimates of the VZ and saturated zones water and the runoff discharge data. The water resources composition of the CLP comprises precipitation, river water, VZ water, and saturated zone water (shallow groundwater), accounting for 2.1, 0.1, 42.1, and 55.7%, respectively, suggesting an overwhelming fraction (97.8%) of water resources in the thick loess profiles of the CLP CZ (Zhu et al., 2019).

3.7. Importance and Uniqueness of CLP in CZ Research

The CLP holds the distinction of being both the largest and deepest loess deposit in the world, which today supports a population of 117 million people, accounting for about 36.4% of the total population residing in the loess regions of the world. It covers about 6.7% of China's land area and supports over 8.5% of China's population. The CLP has experienced long-term intensive agricultural disturbances (spanning more than 2000 years), extensive vegetation restoration, and engineering practices, such as check-dam construction and terracing. These activities have significantly altered the land-cover and geomorphic features of the plateau and, consequently, the CZ processes, functions, and services. Additionally, the CLP is one of the most impoverished regions in rural China and requires urgent action to improve environmental sustainability and promote economic growth and welfare in the face of natural resource limitations (Sjögersten et al., 2013). Thus, the CLP is one of the ideal regions in the world to study CZ science under highly managed or disturbed conditions. The CLP CZO consists of a longitudinal series of monitoring sites rather than a single observatory sub-catchment (Fig. 1b). This larger scale, multi-catchment approach facilitates a regional comprehensive understanding of CZ processes and services that encompass spatial variations in landscape properties, land management, and social-economic conditions (Naylor et al., 2023).

4. Answers to the Scientific Questions based on Results from Loess CZs

4.1. Can Soil Erosion be Controlled or Alleviated?

Soil conservation is one of the most important loess CZ *supporting services*, directly affecting food production and eco-environmental security of the CZs. Over the past 2,000 years of agricultural reclamation, most forests were cleared for farmland to feed the growing human population on most of the loess CZs, particularly on the CLP. Historical records show that forest coverage on the CLP steadily declined as the population increased, with forest cover dropping from approximately 40% during the time of the North-South dynasties (420–589 CE) to 33% during the Tang and Song dynasties (618–1279 CE). By the time of the Ming and Qing dynasties (1368–1911 CE) and the formation of the People's Republic of China (in 1949), only between 15% and 6% of the forests remained (Xu, 2001). Changes in land use resulted in annual sediment delivery to the YR increasing from about 0.2 billion tons in the 11th century CE to 0.6 billion tons in the 14th century CE. Population growth and reclamation activities continued to increase until 1950 CE, when annual sediment discharge peaked at about 1.6 billion tons, which made the YR the world's largest contributor of fluvial sediment load. Muddy floods due to agricultural runoff were also a widespread and frequent phenomenon in the European loess belt (Boardman et al., 1994), especially in Northern France (Souchère et al., 2003), UK (Boardman et al., 2003) and central Belgium (Evrard et al., 2008). These floods were triggered when high runoff was generated on agricultural land causing severe erosion.

Various government conservation and restoration strategies have been implemented during the past decades to control soil erosion and rehabilitate the degraded ecosystems on the CLP, including the "Grain-for-Green Program" (GfGP, 1999–2020). As a result, vegetation coverage on the CLP has increased from 32% in 1999 to 63% in 2018 (Hu and Zhang, 2020). The combination of increased vegetation coverage and engineering measures such as check-dams, terraces, level furrows, and fish-scale pits has effectively reduced soil erosion on the CLP, with the annual sediment discharge into the YR decreasing from 1.6 billion tons in the 1950s to about 0.2 billion tons in 2015 – similar to historic levels (Chen et al., 2015; Wang et al., 2016a). About 80% of the decline in annual runoff for the YR has been attributed to human activities, including the GfGP, river dam projects, terracing, agricultural irrigation, and other water conservation projects (Liu et al., 2020a). In addition to re-establishing a closed vegetation cover, a high plant functional diversity also played an important role in reducing soil erosion in degraded ecosystems. Runoff experimentations performed in the European loess belt (Kervroëdan et al., 2019) and the CLP (Zhu et al., 2015b) showed that multi-specific communities could be used to mitigate soil erosion, and plant species and functional diversity also offered other ecosystem processes and services.

To protect agricultural soils from erosion, practices such as intercropping and straw mulching are widely used in cultivated loess regions. For instance, intercropping a pecan agroforestry practice with a perennial legume such as kura clover on deep loess soils of the Missouri River hills landscape offers an effective alternative management system to optimize alley crop production while promoting soil conservation (Kremer and Kussman, 2011). Ridge-tillage is more effective than conventional (moldboard plowing or disking) tillage in reducing sediment loss from watersheds through the physical retention of runoff and increasing the baseflow in the loess hills of southwest Iowa (Kramer et al., 1999; Moorman et al., 2004), while Triplett et al. (1996) suggested that no-tillage production systems can be developed for highly erosive loess soils in the U.S. Mid-South. Furthermore, various natural and organic mulches (e.g., crop residues, leaf litter, woodchips, bark chips, biological geotextiles, gravel, crushed stones, biochar, and polyacrylamide) have also been used to protect the loess land surface against the erosive forces of rain and runoff (Guo et al., 2010; Sadeghi et al., 2021). Using stone and gravel mulches in the semi-arid loess region of northwestern China has been an indigenous farming technique for crop production for over 300 years (Li, 2000).

In summary, soil erosion in cultivated loess areas around the world has been mitigated through the implementation of various restoration programs and conservation management practices. Despite this success, soil erosion remains one of the most pressing environmental issues in loess regions, and the regional ecosystem remains fragile. Soil erosion under extreme precipitation events must receive additional attention in the future (Ciampalini et al., 2020; Doulabian et al., 2021).

4.2. Does a Large-Scale Ecological Program Affect Local Food Security?

Food supply is closely related to a region's economy and people's livelihoods (Enenkel et al., 2015; Folberth et al., 2020), and is a major CZ *provisioning service*. The cultivated land area is one of the most important factors for total grain production. Due to the growing human population living on loess soil or other CZs, forests are often converted into farmland to ensure food supply. Interestingly, with the large-scale conversion of farmland to natural land (i.e., grassland and woodland) to protect the degraded ecosystem in some loess CZs, particularly in the CLP, new problems such as food insecurity and water shortage have emerged due to the occupation of farmland and the depletion of soil water by the large-scale revegetation programs (Chen et al., 2015). Such problems may hinder a region's sustainable development of the eco-environment and social-economy. To date, the revegetation programs have converted more than 30,000 km^2 of rain-fed cropland to forest or grassland on the CLP (Feng et al., 2016; Shi et al., 2020). Consequently, the total grain output of the CLP decreased from 23.8 million tons in 1998 to 16.7 million tons in 2001. The corresponding grain self-sufficiency index (GSSI, an index to assess a region's ability to generate enough grain to support its population) of the CLP also dropped sharply from 0.88 in 1998 to 0.60 in 2001 (Zeng et al., 2022). When the GSSI value is less than 0.90, the risks for regional grain shortages increase (Mukhopadhyay et al., 2018). Shi et al. (2020) report mounting pressures on CLP croplands from 1999–2010, with the annual grain yield loss by the GfGP increasing from 0.40 million tons in 1999 to 3.47 million tons in 2010. Although the GSSI has shown a significant upward trend in the region with the continuous adjustment of policies in recent years, the 2015 GSSI value (0.83) in the region was less than 0.90 (Zeng et al., 2022). The reduction in grain production caused by excessive vegetation restoration will inevitably threaten the survival and development of farmers, particularly in the loess mountainous areas (Chen et al., 2015; NFGA, 2020). Therefore, it is possible that too much grain has been traded for green, and land use on the CLP must be re-balanced to avoid exacerbating food shortages in local communities (Chen et al., 2015; Wang et al., 2021a).

Increasing grain production per unit area through promoting intensive agriculture, creating new farmland (e.g., terraces, check dam fields), improving the quality of cultivated land, and increasing water and fertilizer use efficiencies can help increase grain production (Liu et al., 2013; Zheng et al., 2020). The construction of terraces and check dams significantly contribute to grain production on the CLP. From 1999 to 2007, the terraced and check dam field area increased from 1,477 and 181 km^2 to 7,644 and 690 km^2, respectively (Gao et al., 2016). The contribution of terraces and check dam fields to grain yield increased from 0.34 million tons in 1999 to 1.69 million tons in 2007 (Shi et al., 2020). By 2018, the terraced field area increased to 3.7×10^4 km^2. More than 55,000 check dams were constructed on the CLP between 1960 and 2010, and these dams captured approximately 21 billion m^3 of sediments (Jin et al., 2012; Fu et al., 2017). The Chinese government plans to build 15,000 more check dams on the CLP between 2020 and 2035. Terraces and check dams not only help to conserve soil and water but also lead to increased grain production, resulting in an increase in grain self-sufficiency.

In summary, extensive vegetation restoration on CLP farmlands can threaten local food security. Appropriate vegetation restoration strategies and multiple policies (e.g., construction of terraces and check dams and improvements to the agricultural production conditions) should be implemented to increase grain production in order to achieve a win-win situation for Grain and Green areas.

4.3. Does Large-Scale Vegetation Restoration Exacerbate Water Scarcity?

Agricultural production and ecological construction on the loess CZs rely heavily on water resources. As a result, water supply is a major CZ *provisioning service* that is constantly impacted by changes in land use and land cover. In the CLP, the significant increase in vegetation coverage has increased ET but reduced runoff and soil moisture (Feng et al., 2016; Jia et al., 2017a, b; Luan et al., 2022). Such contrasting effects aggravate water resource shortages in arid and semi-arid loessial regions. In the CLP, the regional ET increased at a rate of 4.3 ± 1.7 mm yr^{-1} from 2000 to 2010, while soil moisture and runoff decreased at a rate of 2.4 ± 0.9 mm yr^{-1} and 0.5 ± 0.3 mm yr^{-1}, respectively (Feng et al., 2016). Although recent observations report that runoff increased at a rate of 2.4 mm yr^{-1} from 2011 to 2020 due to a significant increase in precipitation, ET also exhibited an upward trend in most areas of the CLP, with an increasing rate of 5.7 mm yr^{-1} (Cao et al., 2023; Lu et al., 2024). Overall, the recharge amount was generally less than the discharge amount in the CLP from 2001 to 2020, mainly due to large-scale revegetation, and the difference between recharge and discharge was gradually expanding, with a change rate of –0.58 mm yr^{-1} (Lu et al., 2024).

Soil water is the primary limiting factor and driving force behind vegetation growth and ecosystem functioning in the loess CZ (Jia et al., 2017a, b). Unreasonable revegetation practices, which include the extensive introduction of exotic deep-rooted high-water-demanding plant species or over-planting, can result in excessive consumption of deep soil water (Wang et al., 2010, 2011, 2015a; Jia et al., 2017a; Ge et al., 2020). A recent integrative study has shown that land use conversion from arable cropland to forest/grassland caused an 18% decrease in soil water in the 0–18 m profile across the CLP over the past 37 years (1985–2021), with a greater declining rate in the semi-arid region (21%) than in the semi-humid region (15%) (Wang et al., 2024), inducing deep soil desiccation and dry soil layers (DSLs) formation. The formation of a DSL can interfere with the water cycle in the groundwater-soil-plant-atmosphere continuum by preventing water flow between shallow and deep soil layers and may decrease groundwater recharge (Li et al., 2018a, 2019a; Huang et al., 2021). For instance, in the southern CLP region, the conversion of cropland (shallow-rooted) to apple orchards (deep-rooted) decreased soil water storage in the 0–18 m profile by 776, 1106, and 1117 mm, corresponding to 19, 20, and 26-year-old apple orchard, respectively (Li et al., 2018a). Similar results were reported by Wang et al. (2015a) that soil moisture in the 0–18 m profile decreased with increasing ages of apple orchards at Wangdonggou watershed CZO. There was a significant decline in potential groundwater recharge following the land-use change (Zhang et al., 2018b).

Prolonged soil desiccation can reduce drought resistance of plants and limit vegetation growth and natural succession, and may even result in tree mortality (Wang et al., 2010, 2011; Gao et al., 2021a; Shao et al., 2023; He et al., 2023). For instance, during the 2012–2015 drought in California, particularly in the southern Sierra Nevada area, forest die-off was found to be closely tied to multi-year deep-rooting-zone (5–15-m depth) drying (Goulden and Bales, 2019). It has been widely observed that the aboveground growth of planted trees is greatly constrained by deep soil desiccation on the CLP, resulting in so-called "small old trees", where some 30-year-old forest trees only grow to about 20% of their normal height (Fang et al., 2016; Jia et al., 2017a). Recent studies in the CLP have shown that when the soil below a depth of 2 m is dry, the canopy transpiration and the net photosynthetic rate of apple trees are reduced, respectively, by around 40% and 20% relative to that without deep soil desiccation (Li et al., 2021; Yang et al., 2022). Additionally, embolism resistance increases with a decrease in soil water availability, leading to a reduction in xylem hydraulic conductivity and even hydraulic failure of the plantation (Liu et al., 2020b; Fuchs et al., 2021). Furthermore, soil desiccation significantly and negatively affects microbial community structure and functionality in deep soils, with substantially decreased bacterial beta diversity and decreased network robustness in deep soils (120–500 cm) where a DSL occurs (Kong et al., 2022).

Achieving optimal plant coverage, which refers to the maximum leaf area index that can be achieved without causing soil water to dry to the wilting, requires a critical balance of water consumption and eco-environmental service performances for a revegetation program (Fu et al., 2012). Scientists and resource managers who are concerned about the optimization of plant coverage often invoke the concept of *soil water carrying capacity for vegetation* (SWCCV), which has been defined as "the maximum biomass of a given vegetation type, under specific climatic conditions, soil texture, and management regime that a given arid or semiarid area can sustain without diminishing soil water capacity to support future generations" (Xia and Shao, 2009). Several studies have been done on SWCCV of different plant species using field-observations and model simulations at various scales (Xia and Shao, 2008; Zhang et al., 2015, 2018a, 2024; Jia et al., 2019). At the watershed scale, Xia and Shao (2008) developed a physically-based model that builds on the concept of an equilibrium adjustment of plant growth to soil water dynamics. At the regional scale, Jia et al. (2019) determined the optimal plant coverage for non-native plants mainly used in the CLP revegetation program using a modified Biome-BGC model. Eagleson's ecohydrological optimality method (Eagleson, 2002) and the Shuttleworth-Wallace model (Ortega-Farias et al., 2010) were also used to determine the maximum plant coverage over the CLP (Zhang et al., 2018a; Li et al., 2023b). They found that the current vegetation cover has already exceeded the climate-defined equilibrium vegetation cover in many parts of the plateau. This suggests that there was extensive over-planting in those areas where the local limited precipitation did not effectively support revegetated plants, and additional vegetation plantation will cause a water supply shortfall for human activities (i.e., an unsustainable situation).

Although there are ongoing efforts to understand the vegetation productivity threshold, equilibrium vegetation coverage, and SWCCV, the consistency of revegetation thresholds obtained by different methods remains uncertain. A serious challenge exists to address the contradiction between water shortages and eco-sustainability due to climate change and human activities. Future research should focus on comparative studies of different methods to determine the upper limit of vegetation restoration under the influence of climate change and human activities (e.g., agricultural and industrial water use).

In summary, excessive large-scale anthropogenic revegetation enhances water consumption and exacerbates water scarcity in loess CZs. The continued decline in available water resources will further exacerbate the limitation of water on the CZ service, jeopardizing its current stability and future ecological and socioeconomic sustainability. It is essential to determine critical revegetation thresholds to control soil erosion without negatively impacting water availability, thereby ensuring a sustainable ecohydrological environment in the loess CZs.

4.4. Can Desiccated Deep Soils be Hydrologically Recharged and Restored?

Given the significant negative effects of deep soil desiccation on ecological and hydrological processes (see section 4.3), immediate action to remediate DSLs is required. Field experiments and numerical model simulations have been performed to evaluate water recovery in desiccated deep soils. It has been acknowledged that negative ecohydrological impacts of soil desiccation can be partly alleviated through rational management measures, such as thinning, pruning, or changing vegetation type and structure. These measures not only significantly decrease water loss by reducing ET but also improve deep soil water recharge, thus ensuring water supply for plants under drought conditions (Ma et al., 2019; Wang et al., 2020, 2023a). For example, a 2-year field experiment situated in a semi-arid loess hilly area of the CLP showed that thinning the stand density by 67% or pruning 25% of the branches significantly promoted plant rejuvenation and improved soil water use efficiency for a degraded *C. korshinskii* plantation resulting from overplanting (Wang et al., 2023a).

The replacement of exotic trees and shrubs by native grasses or crops also benefits water recovery in desiccated deep soils. Huang and Gallichand (2006) showed that soil water levels in the 0–10 m soil layer were recovered in 6.5–19.5 years after replacing a 30-year-old apple orchard with winter wheat in the southern CLP. A 5-year field experiment in the northern CLP showed that water content in the 0–8 m soil profile increased drastically after alfalfa was replaced by soybean, especially after consecutive wet years when the soil water content of the 0–8 m profile was recharged up to 0.16 $cm^3\ cm^{-3}$ (Ge et al., 2022). Simulation results for the semi-arid grass zone of the CLP showed that a 5 m thick DSL could recover 2–13 years after replacing artificial forests/shrubs with natural grasses, while the time of soil water recovery depended on the degree of soil desiccation, soil hydraulic properties, and slope within a specific climatic zone (Bai et al., 2021).

Moreover, slope engineering measures such as infiltration holes (Wang et al., 2020; Zhang et al., 2023), fish scale pits (Wang et al., 2021b), and rainwater collection and infiltration systems (Song et al., 2020) can contribute to intercepting runoff and increasing deep soil water replenishment, which helps to mitigate soil desiccation induced by overplanting. For example, Yang et al. (2023) found that integrating various slope engineering measures significantly increased soil water storage, organic C, and total nitrogen (N), and promoted plant growth in a degraded *Prunus davidiana* plantation. Heavy rainfall events (>50 mm) are also conducive to water infiltration into desiccated deep soils, indicating the possibility of DSL recovery under natural conditions (Shi et al., 2021; He et al., 2022).

In summary, desiccated deep soils caused by excessive plant water uptake can be recharged and restored through rational management measures, including vegetation management and slope engineering measures. In this way, the vegetation does not only decrease surface runoff, but also increases infiltration rate, ultimately conserving soil and water and improving the microclimatic environment.

4.5. Does Precipitation Recharge Groundwater in Thick Loess CZs?

Groundwater is the primary drinking water source in many loess CZs. Groundwater recharge (GR) indicates the existence of renewable groundwater resources and is an important component of the sustainability of CZ services (Moeck et al., 2023). However, GR largely varies in space and time and is difficult to measure directly. Furthermore, the spatial parameterization of hydrological modeling to estimate GR in loess CZs is challenging and is subject to high uncertainty (Turkeltaub et al., 2018).

Loessial soils are regarded by many as transmissive and rechargeable (Lin and Wei, 2006; Seiler and Gat, 2007). Assessment of recharge rates under loessial soils for various climates and vegetation has been investigated through infiltration experiments and numerical modeling (Baran et al., 2007; Gvirtzman et al., 2008; Dafny and Šimůnek, 2016; Turkeltaub et al., 2018). On the CLP, modeling results indicate significant spatial variations in GR fluxes, with relatively high GR in the south area of the plateau, characterized by concentrated irrigated agricultural fields, more moderate GR in the north parts of the plateau, and low GR in the center of the region (Turkeltaub et al., 2018; Hu et al., 2019). Additionally, the transition from cropped fields to forest and grassland has caused a reduction of 6.1% in the total annual recharge between 1975 and 2008. However, changes in GR do not always occur simultaneously with land-use conversions, and delays may be influenced by the VZ thickness, soil texture, climate, and water input frequency and quantity. In areas with thin VZs, recharge generally decreases with a cropland-to-forestland conversion, consistent with findings reported by Dafny and Šimůnek (2016) that recharge rates decrease with an increase in the vegetation cover under sandy loess deposits (~20 m) south of the Gaza Strip. Additionally, the time lag between specific rainy seasons and corresponding recharge events increases with increasing vegetation cover. However, at many CLP sites, the VZ is relatively thick, and precipitation takes a relatively long time to recharge groundwater. Nevertheless, to examine the potential effects of climate change and land-use change on GR, a long-term climate and land use database is required, or alternatively, stochastic methods can be used to construct long climate records (Turkeltaub and Bel, 2023).

Precipitation can recharge shallow groundwater by a dual process consisting of infiltration via various preferential flow pathways (e.g., macropore, crack, burrow, finger, and lateral flows) in response to heavy precipitation, followed by a piston-like (or uniform) flow (Manna et al., 2017). The behavior of preferential flow and piston flow co-evolving within a CZ has been labeled as one of the 23 unsolved problems in hydrology (Blöschl et al., 2019). Over the past decades, numerous methods, including infiltration experiments, chloride mass balance, water isotopes (e.g., ^{3}H, ^{2}H and ^{18}O), and numerical modeling have been used to quantify dual recharge mechanisms in the deep VZ of the loess CZs (Baran et al., 2007; Gvirtzman et al., 2008; Huang and Pang, 2011; Huang et al., 2017, 2020; Hu et al., 2019; Li et al., 2017, 2019a; Lu et al., 2020; Xiang et al., 2019, 2020; Shi et al., 2021; Gao et al., 2023). Despite extensive research, precise identification of the recharge mechanisms remains elusive. Some studies have identified piston flow as the dominant GR mechanism after investigating signatures of multiple tracers from a thick VZ and underlying saturated zone (Baran et al., 2007; Huang and Pang, 2011; Huang et al., 2017, 2020; Xiang et al., 2019; Shi et al., 2021). In numerical simulations, piston flow is generally assumed to be the dominant water transfer mechanism in layered loess deposits (Dafny and Šimůnek, 2016; Turkeltaub et al., 2018). Conversely, preferential flow was identified as a dominant mechanism in the Luochuan and Changwu highland areas (with a VZ thickness of 40–80 m) (Wang, 1982; Yan, 1986; Xu and Chen, 2010) and Heihe watershed (with a VZ thickness of 30–100 m) (Li et al., 2017) on the CLP. Similar results were also observed in the western CLP (Tan et al., 2016), likely due to sinkholes and slip surfaces or landslide surfaces. However, results from Huang et al. (2019) indicated a combination of GR mechanisms in deep loess deposits. Tracers in the VZ suggested piston flow, while detectable tritium in the VZ implied preferential flow. Some other GR mechanisms in loess CZs have also been reported. Gao et al. (2023) employed a coupled liquid–vapor–heat–airflow STEMMUS (simultaneous transfer of energy, mass, and momentum in unsaturated soil) model to investigate the impact of extreme precipitation on loess CZ hydrological processes. They found that thermal-gradient-driven vapor transfer is an important mechanism for deep-layer recharge in the loess CZ. Hou et al. (2018) considered the ground-atmosphere interactions and found that water percolation in a thick loess VZ was in liquid and vapor phases. Furthermore, heterogeneous and layered loess deposits (e.g., loess-paleosol sequences, alternating silty-sand and sandy-clay loess layers) may influence deep recharge (Gvirtzman et al., 2008). The above methods are commonly used to study the GR process in the loess CZs. Considering the complexity and uncertainty of GR mechanisms, it is necessary to apply multiple methods simultaneously, rather than a single method, to obtain reliable conclusions.

In summary, compared to results from similar loess CZ sites, the primary GR mechanism differed among sites and may depend on spatial scales, geomorphology, and landscape (Xiang et al., 2019; Chen et al., 2023). Not enough information has been collected to fully understand *how* and *when* groundwater is recharged at the regional scale, resulting in this topic emerging as a key research priority. The mechanisms of GR are highly complex in loess CZs due to the dry climate, thick VZ, complex geomorphic landscapes, and large vegetation change from shallow- to deep-rooted plants, requiring further long-term monitoring and investigation. In addition, the mechanisms controlling water transport (exchange processes, fluxes, and travel times) from root zone to groundwater and interactions within the groundwater-soil-plant-atmosphere continuum remain unclear (Fig. 9).

4.6. What Are the Ecohydrological Functions of Weathered Bedrock?

Weathered bedrock is crucial in the Earth's CZ. It connects soil moisture dynamics and shallow groundwater recharge, and therefore plays an essential role in the ecohydrological and biogeochemical cycling on the Earth's land surface (Salve et al., 2012; Rempe and Dietrich., 2018). Rock moisture is a critical component of terrestrial water and C cycling (McCormick et al., 2021). Weathered bedrock redefines the hydrological distribution in shallow soils (Hasenmueller et al., 2017; Rempe and Dietrich., 2018), which directly affects surface infiltration and ET processes (Rathay et al., 2018; Hahm et al., 2022; Jiménez-Rodríguez et al., 2022). Moreover, bedrock is the source of most mineral nutrients (e.g., Fe, Ca, P, and other elements), shaping vegetation growth and community composition (Morford et al., 2011; Jiang et al., 2020).

Early studies and field investigations indicate that the vegetation type and distribution may be related to the upper loess thickness and the underlying bedrock geological structure on the CLP (Zhang and An, 1994; Zhang et al., 1998). They report that shallow soil hillsides with coarse-textured weathered bedrock underneath are suitable for woody vegetation growth. This might be associated with the relatively humid environment deriving from deep rainwater infiltration and low evaporation consumption. Similar results are reported for the Elder Creek Watershed CZO in northern California that up to 27% of the annual rainfall is seasonally stored as rock moisture, which exceeds soil moisture and is a critical and stable source of plant-available water in drought years (Rempe and Dietrich, 2018). The thick VZ and weathered, fractured bedrock (30 m thick at ridgetops) in the CZ at Elder Creek thus allow ample water storage and support for a dense evergreen forest canopy. However, because of the inaccessibility of the weathered bedrock underlying thick loess deposits and few direct observations of rock moisture, its hydrologic properties and dynamics are poorly understood.

The emergence of research on the CZ, which extends from the vegetation canopy through the soil and weathered bedrock has further identified knowledge gaps. Recently, *in-situ* observations and simulation experiments were performed to investigate rock core sample characteristics and ecohydrological functions of weathered bedrock at the Liudaogou Watershed CZO in northern CLP (Luo et al., 2023, 2024). Borehole investigations showed that weathered bedrock layers had a thickness of more than 5.0 m, and the weathering intensity gradually decreased with depth. The underlying weathered bedrock is mostly limestone with soft lithology, which provided pathway for roots to penetrate and extend into bedrock cracks to absorb water and nutrients (Zhang et al., 1998). Simulation experiments showed that stable infiltration rates increase linearly with weathered bedrock thickness, which accelerates by 0.5–5.7 times more than bulk soil layers, whereas cumulative evaporation presents a significant decrease of 7.4–32.8%. Overall, water conditions in profiles with weathered bedrock are better than those in thicker soil layers, with an average rock moisture twice that of soil moisture. Moreover, field investigations using UAV orthophotos clearly showed that the vegetation growth in Wuqi County was better than that in Dingbian County of the northern CLP (Luo et al., 2023). The main differences were that upper soil layers were thinner, and underlying weathered bedrock layers were thicker in Wuqi than in Dingbian. In addition, a field survey found that there was water seepage through the exposed weathered bedrock layers (Fig. 9), suggesting that the composition of streamflow (runoff) was influenced by the transit of infiltrating rainfall through meters of weathered bedrock (Banks et al., 2009; Kim et al., 2017).

In summary, weathered bedrock substantially suppresses surface infiltration and evaporation and plays an important role in mediating vegetation growth and composition (especially for deep-rooted trees and shrubs) in water-limited loess CZs.

Although the loess CZ is a representative landform with a thick layer of loess deposits, the ecohydrological functions of weathered bedrock should be a focus of CZ science, particularly integrating moisture storage in weathered bedrock with vegetation, hydrological, and climate models (Jiang et al., 2020; Lapides et al., 2024).

4.7. Do Agricultural Practices Impact Groundwater Quality?

Nitrate groundwater contamination is an important issue in many parts of the world (World Health Organization, 2007). Recent studies at both national and catchment scales have shown that there can be substantial (and increasing) storage of nitrate in soils, the VZ, and groundwater (Worrall et al., 2015; Ascott et al., 2016; Meter et al., 2016). Globally, VZ nitrate storage per unit area is greatest in North America, China, and Europe, which have thick VZs and extensive historical agriculture activities (Ascott et al., 2017). The loess CZ is known for its deep soil and long-term extensive agriculture, which makes it possible to accumulate large amounts of nitrate or other pollutants, gradually traveling downward and reaching the aquifer. In some cultivated regions of the CLP, such as the Guanzhong Plain, Changwu and Luochuan tablelands, centuries of agricultural activities have resulted in significant nitrate accumulation in deep soils, including contamination of groundwater in some areas (Jia et al., 2018; Huang et al., 2021; Gao et al., 2021a, b, c; Zhu et al., 2021; Lu et al., 2022; Niu et al., 2022; Ren et al., 2023). Analyses from five boreholes, for example, showed that the measured nitrate content in the entire profile at Fuxian, An'sai, and Shenmu is low (Jia et al., 2018). Still, significant accumulations were observed in the 30–50 m layer at Yangling and Changwu (Jia et al., 2018). High nitrate accumulations are attributed to large N-fertilizer applications, long agricultural history, high precipitation coupled with irrigation, and high atmospheric N deposition rates. Significant nitrate accumulation in deep soils (~7 m) was also found in an intensively farmed loess area in Obernai, Alsace (Rhine Valley, France) (Baran et al., 2007).

The Guanzhong Plain (GP) is situated in the southern part of the CLP and is recognized as the birthplace of an ancient Chinese agricultural civilization, where farmers used organic waste to maintain crop production and soil fertility for thousands of years (Niu et al., 2022). Long-term manure applications led to an anthropogenic surface layer over the zonal soil profile termed the Lou soil (or Manurial Loessial soil), the depth of which is 30–100 cm (Zhu, 1964). This may have resulted in nitrate accumulation, causing environmental pollution of groundwater. For over a millennium, numerous ancient county annals recorded nitrate-rich groundwater, also known as nutritive groundwater, in the GP (Gun et al., 2007). The spatial distribution of nitrate-rich groundwater over the region was first reported in the 1970s prior to chemical fertilizer applications (Peng et al., 1979).

Water quality *regulating services* were impacted by land-use change, such as the cropland-to-orchard transition in the middle and south parts of the CLP (Gao et al., 2021a; Lu et al., 2022). Since the 1990s, land-use-pattern changes from cereal croplands to apple or kiwifruit orchards have been promoted in the GP and other tablelands (e.g., Changwu and Luochuan) due to economic benefits. Provincial Yearbook data show that the total area of orchards in Shaanxi Province increased from 0.10 million ha in 1980 to 1.15 million ha in 2020, with approximately 45% of the area in the GP. This increase in orchards has significantly reduced rural poverty and improved farmer income (Gao et al., 2021c). However, compared to croplands, orchards require higher amounts of irrigation water and N-fertilizers, leading to nitrate entering the deep soils due to an accelerated leaching rate (Niu et al., 2022) (Fig. 10). This excess nitrate can migrate vertically towards the groundwater table or horizontally through shallow subsurface flow, resulting in nitrate accumulation and contamination of downstream water bodies. For instance, Chen et al. (2019) noted that land-use change from arable lands to orchards reduced soil erosion but increased nutrient loss in the southern part of the CLP. Gao et al. (2021b) also found that long-term kiwifruit production deteriorated groundwater quality in the Yujiahe catchment within the GP. Furthermore, excessive fertilization has been observed to disturb the acid-base equilibrium in apple orchards, resulting in significantly lower soil pH than in tree plantations and cropland (Gao et al., 2021c). This major environmental issue seriously threatens regional environmental security and the sustainable utilization of water and soil resources in cultivated loess CZ.

Previous studies on N biogeochemical cycling in terrestrial ecosystems have predominantly focused on its storage and transport within the top 1 m of the soil, which is usually defined as the biologically active soil zone (or the root zone) in agricultural ecosystems (Walvoord et al., 2003). In some of the deepest soil boreholes ever taken from the land surface down to bedrock (56–205 m) at five sites from south to north of the CLP, we found that a substantial amount of N in deep soils was overlooked due to the limitation of sampling depth. The stock of mineral N measured by deep sampling (50–200 m) at the CLP CZO amounted to 0.2–1.0 Pg (Jia et al., 2018), which can potentially influence the groundwater quality, especially under agricultural land uses (Turkeltaub et al., 2018). To characterize nitrate accumulation in deep soils and trace the sources of nitrate in soils and groundwater in the highly-disturbed loess CZ, an extensive set of groundwater and soil samples from cropland and orchard areas were collected in the GP. The average amounts of accumulated nitrate in the 0–10 m soil profile of the orchards were observed to be approximately 3.7 times higher than those in the same layers of the croplands, suggesting that the cropland-to-orchard transition aggravated nitrate accumulation in deep soils (Niu et al., 2022). Over 38% of the groundwater samples had nitrate concentrations exceeding the WHO permissible standard for drinking (10 mg N L^{-1}). Analyses of groundwater $\delta^{15}N$ and $\delta^{18}O$ of nitrate indicated that manure and sewage N have been the largest contributors to groundwater nitrate, followed by soil N and chemical N-fertilizer (Niu et al., 2022). However, in some areas with thin VZs, the contribution of manure and chemical fertilizers to groundwater nitrate was comparable (Gao et al., 2021b; Niu et al., 2022).

The time lag or residence time of nitrate in the VZ has been estimated using the chloride mass balance method (Niu et al., 2022) and process-based models (Turkeltaub et al., 2018). Results indicate that the time required for nitrate to enter the water table ranges from decades to centuries over the GP. Results of the residence time and source apportionment suggested that chemical N-fertilizer applied since the 1980s has not become the dominant source of groundwater nitrate in the entire GP due to the low recharge rate and thick VZ. However, in Europe and parts of the US and Canada, some peaks in nitrate in groundwater following intensive post World War II agriculture have been observed (Spalding et al., 1982; Egboka, 1984; Power and Schepers, 1989; Nixon et al., 2003). It appears that in some parts of the world (e.g., CLP) such peaks are yet to be observed due to more recent intensive use of N-fertilizers, deep VZ, and slow transport. Whereas nitrate has already entered the water table in some areas with a shallow groundwater table in the GP. Unlike the south region of the CLP, groundwater nitrate contamination in the central part of the region may not be a problem in the near future due to the thick VZ (>100 m) (Huang et al., 2018; Turkeltaub et al., 2018). However, the degradation of groundwater quality in the long term appears to be inevitable.

In summary, agricultural land-use changes from cropland to orchards can result in a relatively high N surplus in deep soils and increase the risk of groundwater nitrate pollution in the future. The widespread conversion of croplands to orchards on the CLP should thus be cautiously approached, particularly in areas with shallow VZ and coarse soil texture. In the short term, a thick VZ increases the time needed for nitrate to reach the aquifer. However, even with a thick VZ, future generations will suffer from nitrate in groundwater due to management practices. Thus, it is important to understand both short-term and long-term consequences and mitigation procedures. Therefore, it is necessary to modify agricultural production methods (e.g., optimizing fertilization and irrigation strategies and developing smart water-saving technologies) to achieve a compromise between the ecological environment and economic development in cultivated areas with a high risk of groundwater pollution.

4.8. Does Deep Loess Soil Sequester C from the Atmosphere?

Investigating organic C in the Earth's CZ and its response to land-use change is crucial for understanding the biogeochemical cycling of C and its interaction with the environment (Marin-Spiotta et al., 2014; Jia et al., 2020). Over the past few decades, various CLP conservation and restoration strategies have reduced soil erosion and flooding and enhanced C sequestration and habitat *supporting services* (Jia et al., 2011; Fu et al., 2017). A regional-scale investigation of vegetation productivity changes from 2000 to 2010 revealed an annual vegetation C sequestration rate of 9.3 ± 1.3 g C m^{-2} yr^{-}

^{1} on the CLP (Feng et al., 2016). This increase in primary production *supporting services* contributes to the CZ's bioenergy production or other forms of production to support life (Field et al., 2015).

Organic C in deep soils greatly contributes to the total C stock and is thus a vital part of terrestrial C cycles (Rumpel and Kögel-Knabner, 2011; Harper and Tibbett, 2013). Several studies have explored soil organic C stock at various depths in the loess CZs, such as 2 m (Liu et al., 2011), 5 m (Wang et al., 2016b; Jia et al., 2017c), 18 m (Gao et al., 2017), 21 m (Wang et al., 2015b), 25.2 m (Li et al., 2019b), and 56–205 m (Jia et al., 2020). Previous studies limited to shallow soils showed that total organic C in the 0–2 m loess layer was 5.85 Pg across the entire CLP (Liu et al., 2011). Calculations from the deepest soil boreholes demonstrated that organic C stored in the 0–100 m loess profile, the mean loess thickness on CLP, amounted to 10.06 Pg for the entire CLP region (Jia et al., 2020). These studies indicate the high soil organic C sequestration capacity of deep soil layers. Furthermore, paleosol (generally developed in a period of warmth and wetness), which is buried at various depths below the loess, may have high levels of organic C. Marin-Spiotta et al. (2014) found that the Brady soil (one paleosol), which is buried under 6 meters of loess in southwestern Nebraska, USA, stores large amounts of organic C. The enrichment of organic C in a buried paleosol could be explained by an abrupt change in climate, fire, and the loss of vegetative cover during its exposure and pedogenesis (Marin-Spiotta et al., 2014). The accumulation of buried organic C in loess-paleosol sequences thus proves the importance of feedback between climate and the land C sink at geologic and contemporary timescales (Arbogast, 1996; Zech, 2012).

Intensive vegetation-restoration activities could significantly influence the magnitude and distribution of organic C content and stock in deep soil profiles. Net soil C sequestration in both shallow and deep soil layers has been observed after farmland conversion in the loess CZ (Wang et al., 2015b). Deng et al. (2014) showed that soil C sequestration potentials in the 0–20 cm soil layer across the CLP could reach 0.59 Tg yr^{-1} following farmland conversion. Lan et al. (2021) demonstrated that soil organic C storage in artificial forests increased by 0.9–6.33 kg m^{-2} compared to farmland in the

20 m soil profile of the semi-arid loess hilly area. Li et al., (2019b) note that while afforestation of long-term farmland with apple orchards (roots deeper than 20 m) did not appear to significantly alter soil organic C of the deep soil, it still contributed 0.44 ± 0.15 Mg C ha^{-1} yr^{-1} to the deep soil via root biomass. Notably, vegetation type, soil depth, and precipitation significantly affect the soil organic C sequestration effect. Wang et al. (2023b) indicate that woodland had the highest organic C sequestration in deep soils, while grassland had the lowest on the semi-arid CLP. Soil organic C sequestration primarily occurred from 2 to 10 m under woodland, 2–6 m under shrubland, and 2–4 m under grassland. In addition, deep soil organic C sequestration in woodland significantly decreased as precipitation increased, but no significant relationship occurred for shrubland and grassland.

The vegetation-restoration induced C sequestration in deep soils of the loess CZ is mainly attributed to the roots C inputs. Perennial grass and forest species on the CLP can extend their roots deeper than 10 m (Li et al., 2019c; Wang et al., 2021a). Large amounts of organic C are released into the soil via root exudation, mycorrhizal associations, and fine root mortality (Germon et al., 2020; Panchal et al., 2022). These processes not only significantly altered deep soil microbes' composition, activities, and functionality, but also combined with soil physical and chemical properties changes significantly modifying deep soil C cycling. For instance, the microbial biomass is much lower in deep soil layers than in the topsoil, which, in combination with oxygen limitations, could decrease the mineralization rate and hence enhance organic C sequestration (Rumpel and Kögel-Knabner, 2011; Marin-Spiotta et al., 2014; Kong et al., 2022). Therefore, the interactions among C cycling, land-use change, roots, microbes, and soil environments along the deep soil profile should be a new focus of the loess CZ science and should be included in the framework of the loess CZ observations.

In summary, with large-scale vegetation restoration, deep loess soil can potentially sequester C from the atmosphere via enhancing organic C content or root biomass, of which degree depends on climatic conditions and vegetation type. Soil C, root biomass, and exudates in deep soils should be considered when evaluating terrestrial C cycling and soil C sequestration potentials in the loess CZ and similar regions worldwide in the future.

5. New Insights on How Loess CZs Can Achieve SDGs

Severe soil erosion, water shortage, ecosystem degradation, environmental pollution, and high pressures from human activities are the main socio-ecological problems for the Earth's loess CZs. Conventional field sampling approaches and assessments often fail to account for the subsurface's role in CZs with thick loess deposits. Subsurface influences on loess CZ services (the benefits that loess CZ provide to the biosphere) have often been ignored or oversimplified in regional assessments and local planning studies. Therefore, it is important that optimal management interventions are developed to solve the main socio-ecological problems by considering the CZ framework. Given the critical role of soil and water in achieving SDGs of the loess CZs, it is imperative to strengthen our understanding of the relationships between soil and water processes and agro-ecosystem services, such as grain production, net primary productivity, C sequestration, water retention, and soil erosion control. The current understanding of soil and water processes in loess CZs, particularly in the CLP, can provide some important new insights into achieving SDGs.

When linking CZ services with SDGs, three important parts, i.e., agricultural production, ecological restoration, and environmental protection, should be carefully considered in loess CZs, given their fragile environments and the great pressure to sustain large populations. For example, the promotion of agricultural production by expanding the planting area and intensive use of chemical fertilizers helps to increase farmer income and alleviate rural poverty (SDGs 1, 2, 3); however, agricultural intensification has incurred clear eco-environmental trade-offs in terms of high soil erodibility (SDG 15), severe residual nitrate pollution (SDG 6), and low soil organic C sequestration (SDG 13). As to ecological restoration, revegetation helps to alleviate soil erosion and promote sequestration of more above- and below-ground C, whereas extensive planting of exotic deep-rooted species has led to severe deep soil desiccation and reduced groundwater recharge (SDG 6). Sustainable solutions to these problems are essential to improve the delivery of environmental and human-centered SDGs (Fig. 2). Knowledge from loess CZOs informs us about the critical soil and water processes controlling CZ functions and services. Notably, we focused on the CLP as an example but many (perhaps not all) of the issues we raised are also relevant to other loess CZs. The following are new insights into how critical processes respond to anthropogenic changes and how to sustain regional SDGs:

(1) Large-scale vegetation restoration of farmland has reduced soil erosion, but further revegetation may exacerbate deficits in the local food supply because of diminished farmland. Engineering measures such as building check-dams in channels and constructing terraces on hillslopes have been widely used as powerful ecological restoration tools to enhance soil and water conservation, gully rehabilitation, and hydrological regulation. Terraces and check dam sediments often form fertile agricultural lands, with abundant nutrients and water (Wen and Zhen, 2020; Wei et al., 2021; Liu et al., 2023b), promoting crop production and supporting livestock. Therefore, construction and sustainable management of such engineering measures are effective ways not only to conserve soil and water but also to increase grain production, thus, achieving a win-win situation on Grain and Green on loess CZs.

(2) Intensive vegetation restoration enhances deep soil C sequestration while aggravating water shortages and resulting in deep soil desiccation due to overplanting. The trade-offs between C sequestration and water consumption for various vegetation types are thus critical for the sustainability of loess ecosystems because most loess CZs are limited by water resources (Feng et al., 2017; Li et al., 2018b, 2023a). Future vegetation restoration planning should carefully consider the maximum vegetation productivity capacity (i.e., the revegetation threshold) supported by local water resources. Additionally, vegetation management needs to focus on reducing the uptake of (often) limited soil water by vegetation, including plant removal by thinning in high plant density areas, and substituting water use efficient native species for water depleting species. Furthermore, slope engineering measures (e.g., fish scale pits and infiltration holes) can also be useful for deep desiccated soil restoration. Such management practices can contribute to the protection and sustainable use of limited

water resources in loess CZs.

(3) The fluxes and mechanisms of GR in loess CZs remain highly uncertain due to the thick VZ and complex geomorphic landscapes. However, multiple tracers and model simulations have emphasized the importance of preferential or piston-like flow. In addition, water stores in weathered bedrock plays an essential role in shaping ecohydrological functions, which should not be ignored in the earth system model. New monitoring and measurement methods must be developed in the loess CZs, such as hydro-geophysical tools, tracer-based techniques, groundwater dating techniques, and automatic monitoring equipment. *In situ* observations of water movement and exchange processes should be further deployed within the entire loess profile from the surface to the groundwater or the weathered bedrock. This information is essential to fully understand hydrological processes and evaluate groundwater quantity and quality in the loess CZs, providing a reference for sustainable water resource management in other loess regions of the world.

(4) The risk of groundwater nitrate pollution is increasing due to a high N surplus in deep soils. Although a thick VZ can delay the movement of nitrate to the aquifer, and groundwater nitrate contamination in areas with thick VZs may not be a problem in the near future, this issue must not be neglected because of the large nitrate accumulation in deep soils. Additionally, future agricultural land-use transitions from croplands to orchards are cautioned against in areas with shallow VZs and coarse soil texture. Given that groundwater is the only source of water for the people and industries situated in most loess CZs, farmers in the region should receive guidance to enable them to make informed decisions about adopting optimal agricultural management practices, thereby increasing their income without compromising future eco-environmental quality.

6. Recommendations for Future CZ Study

The above new insights provide useful information for local and central governments to implement large-scale ecological projects and agricultural management practices, achieve harmonious development between society and the environment and sustain SDGs. However, one challenge to realizing regional SDGs is the comprehensive understanding of CZ processes and services, hindered by the lack of long-term observations of subsurface processes and the integration of CZ science outcomes across scales. Another challenge to the application of CZ knowledge is a scarcity of well-trained specialists with a deep knowledge of CZ science. A major concern that some CZ scientists have expressed is the lack of a holistic disciplinary foundation to support those engaged in CZ science or related activities directly relevant to achieving SDGs. Based on our knowledge and experience from the CLP CZOs, we make the following recommendations for future CZ studies.

(1) *Strengthen subsurface process observations and use models to help design future CZ studies*. The findings from the CLP CZOs have demonstrated that subsurface processes are important for delivering CZ services, such as grain production, water supply, water quality, and C sequestration. While significant progress and breakthroughs have been achieved via loess CZ research, quantifying subsurface roles in the CZ remains challenging for several reasons: nonlinear physical and biogeochemical processes dominate behaviour; heterogeneous soils and weathered bedrock cause additional variability; and obtaining high-resolution images or samples of these belowground processes and properties proves difficult (Zhu et al., 2018; Dennedy-Frank, 2019; Vereecken et al., 2022). Observation and modeling of hydro-biogeochemical processes (e.g., water, nutrients, carbon, and microbial activities) in thick soils or sediments from surface to bedrock is recommended for future CZ studies to provide comprehensive valuation of CZ services that benefit the sustainable development of both the eco-environment and social needs. Future studies will require multidisciplinary collaborations and the use of multiple observation and analytical techniques to develop an extensive database that is useful for resolving the bottlenecks in the coupling interactions of CZ surface and subsurface processes and functions.

(2) *Integrate a series of monitoring sites to guide future regional CZ research.* The CLP CZO comprises a series of monitoring sites rather than a single observatory sub-catchment. The network covers a distinct gradient in geomorphologic landscape, climate, human activities, and social context across the CLP. Multi-catchment approaches facilitate a regional understanding of CZ processes and services that

encompass spatial variations in landscape properties, land management, and social-economic conditions (Luo et al., 2019). We recommend integrating multiple monitoring sites and outcomes (including data, knowledge, and evidence-based management measures) to gain a sufficiently comprehensive understanding of CZ processes and responses at scales appropriate to local, regional, and national contexts. Scientists, CZ residents, and land managers should be involved in data gathering, review, and implementation of management change and monitoring to develop strategies to support ecosystem function and regeneration across scales, while providing roadmaps for sustainable economic development (Naylor et al., 2023).

(3) *Translate CZ science into action through innovative options*. Effective communication of the SDGs to societal leaders requires a basic grounding in CZ science to enable the public to understand the importance of the Earth's CZ in human lives. This includes understanding how soil and water in the CZ are sustained, vary across the landscape, and relate to fundamental aspects of the regional economy, such as agriculture, forestry, livestock, ecology, and conservation. To bridge the gap between researchers, policymakers, farmers, and land managers, and to achieve SDGs, there is a strong need to translate CZ science into action through innovative options (Naylor et al., 2023). For instance, farmers in the area should receive guidance, enabling them to make informed decisions to adopt optimal agricultural and water management practices, thus increasing income by maintaining or increasing agricultural production. The loss of the benefits from sloping land farming after vegetation restoration can bring about significant gains in CZ services such as soil conservation and C sequestration that are more valuable on a monetary scale than the crop production, and there will be opportunities for compensation from payment schemes for CZ services (Richardson and Kumar, 2017). The local farmers and the public may be more motivated to engage in environmentally friendly natural resource use activities, which conforms to the national strategy for developing an ecological civilization on the plateau.

(4) *Exchange CZ knowledge across sectors and countries*. Policy recommendations on soil and water conservation, vegetation restoration, and poverty alleviation for CZ services based on scientific evidence from CZ research must be

presented to policymakers in a timely manner. Modern means of communication (e.g., online connectivity and social media) could be explored to reach stakeholders, practitioners, and policy makers (e.g., local environmental protection department and agricultural management department) designing policies to improve decision-making effectiveness on CZ service-related issues. Scientific findings from CZ research should also be transferable regionally, nationally, and internationally to ensure sustainable provision of CZ services in terrestrial CZ environments where soil degradation, water shortage, climate warming, and human perturbation problems are prevalent and where these issues have consequences for rural poverty and the human-environment relationship. We thus call for international collaborations with multidisciplinary efforts to address these issues. These efforts should involve sharing background information about the nature and value of loess CZs, including their cultural and economic importance, geological formation and evolution, soil properties, water features, erosion, degradation, pollution, and restoration and protection efforts and techniques. It is important to identify the key scientific challenges of loess CZs worldwide, including the current state of knowledge, results of past and planned research, and ongoing research needs, with a special emphasis on possible solutions from ecological, social, and economic perspectives.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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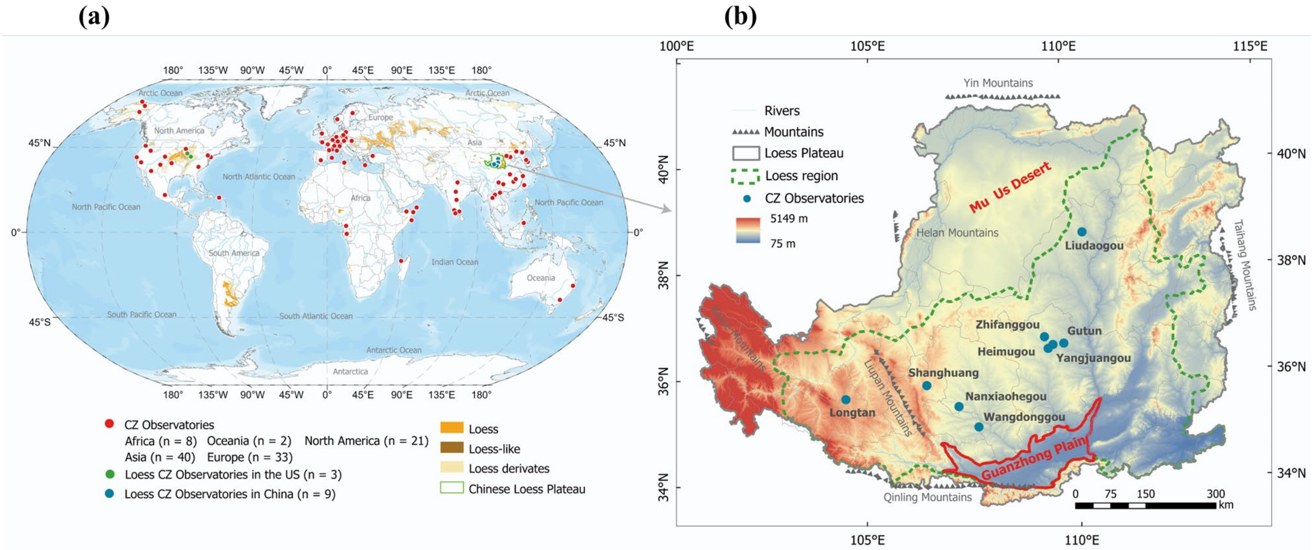

Fig. 1 Worldwide distribution of loess deposits and Critical Zone Observatories (CZOs) (a) and the representative watershed CZOs on the Chinese Loess Plateau (CLP) (b). In the CLP, there are nine monitoring sites, constituting the CLP CZO's network. These monitoring sites focus on critical soil, water, and vegetation processes in both land surface and deeper subsurface layers (down to groundwater or weathered bedrock).

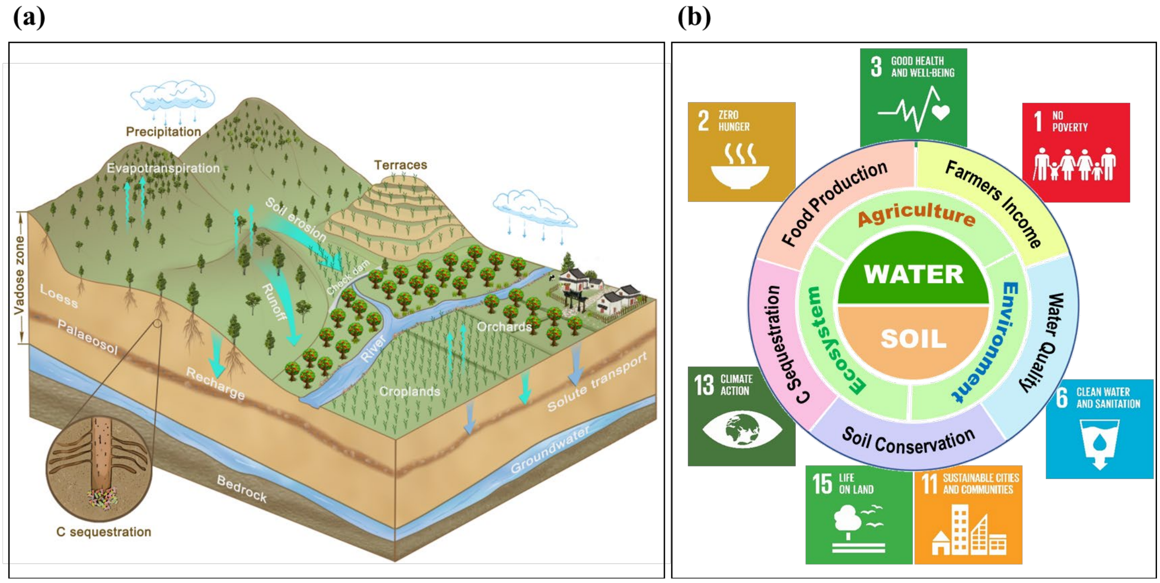

Fig. 2 Critical soil and water processes in the Loess Critical Zone (a) and the relationship of the soil and water processes, the CZ services and seven UN Sustainable Development Goals (b) [SDG 1, No poverty; SDG 2, Zero hunger; SDG 3, Good health and well-being; SDG 6, Clean water and sanitation; SDG 11, Sustainable cities and communities; SDG 13, Climate action; SDG 15, Life on land].

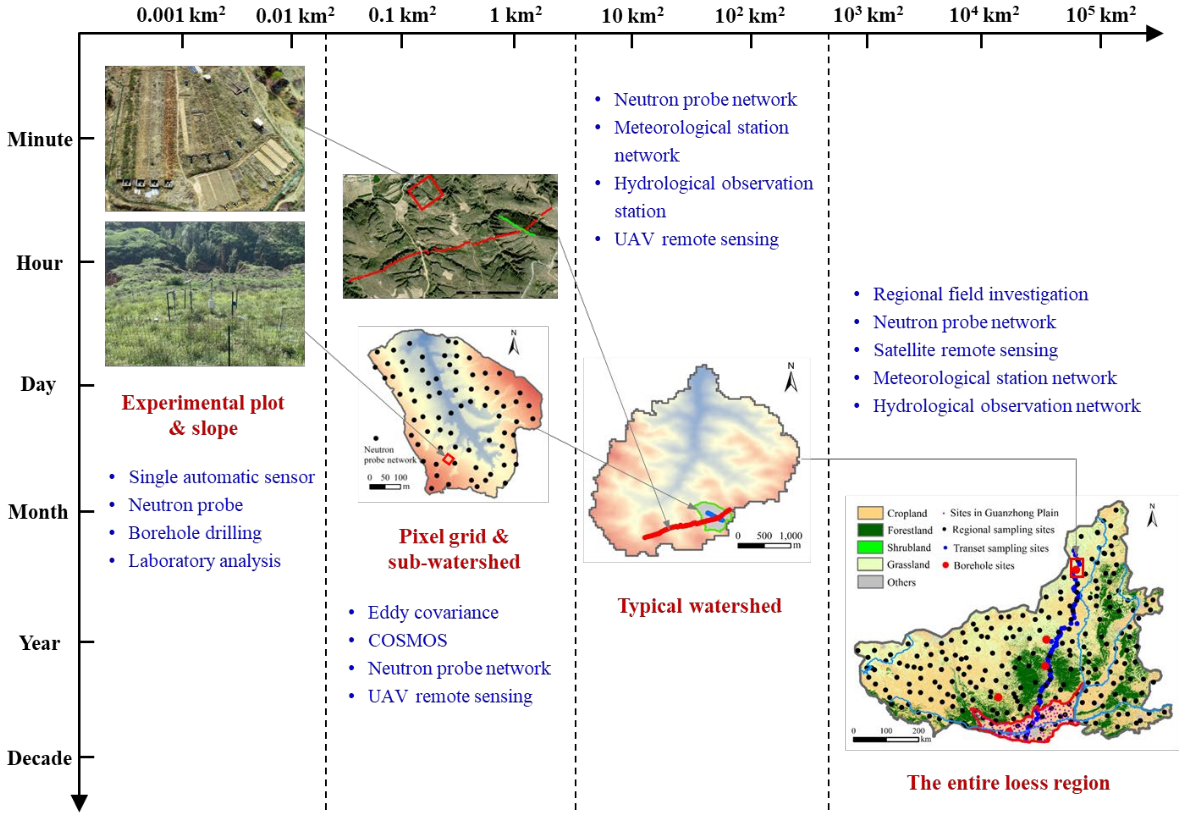

Fig. 3 Schematic diagram of the multiscale observation system on the CLP. UAV: unmanned aerial vehicle; COSMOS: cosmic-ray soil moisture observation system.

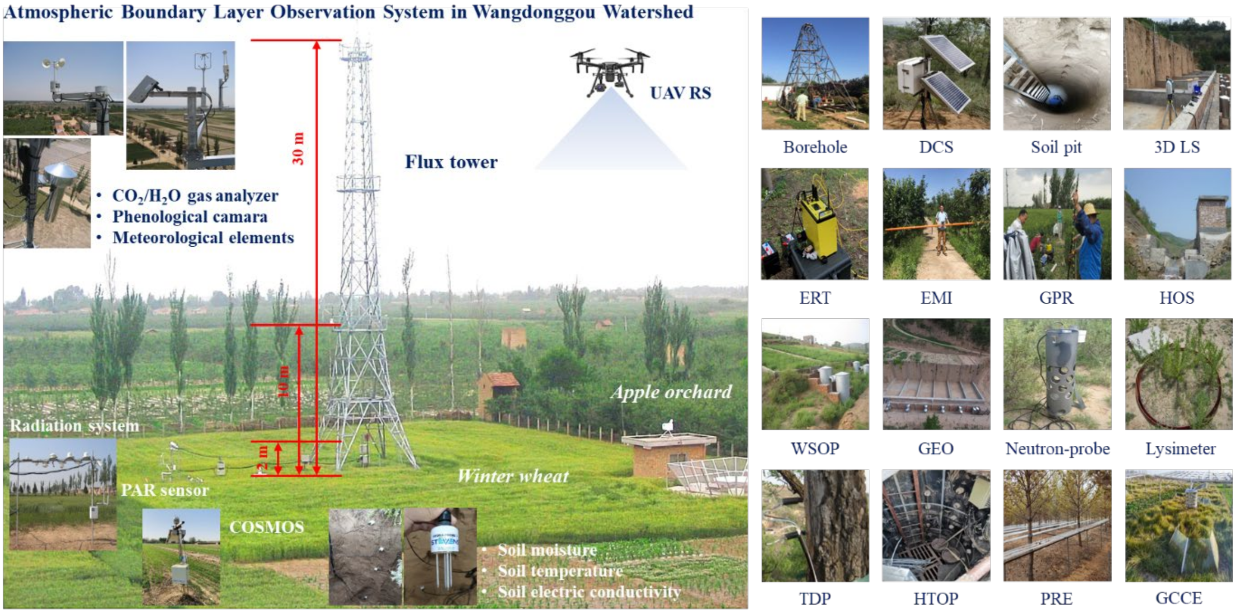

Fig. 4 Instrumentation configuration of the grid- and plot-scale observation system at the Wangdonggou Watershed Critical Zone Observatory. UAV RS: unmanned aerial vehicle remote sensing; COSMOS: cosmic-ray soil moisture observation system; DCS: data collection system; 3D LS: 3-D laser scanner; ERT: electrical resistivity tomography; EMI: electromagnetic induction; GPR: ground penetrating radar; HOS: hydrological observation station; WSOP: water balance and sediment observation plot; GEO: gravitational erosion observation system; TDP: thermal dissipation probes; HTOP: hydrothermal observation profile; PRE: precipitation reduction experiment; GCCE: global climate change experiment.

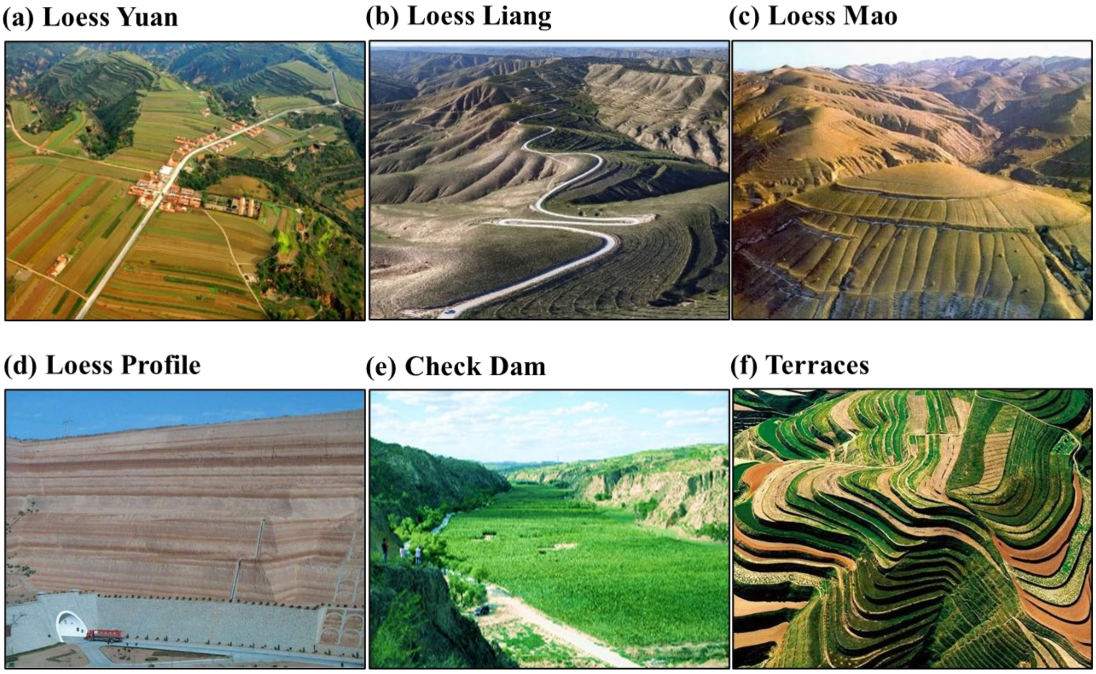

Fig. 5 Typical loess landforms are (a) Loess Yuan, (b) Loess Liang, and (c) Loess Mao. (d) A loess profile, (e) check dams and (f) terraces on the Chinese Loess Plateau. Figure modified from the Institute of Soil and Water Conservation, CAS.

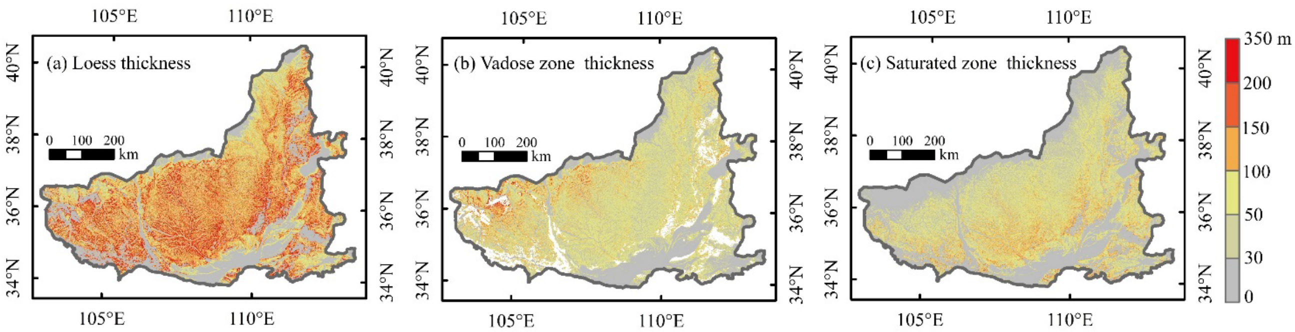

Fig. 6 Maps of loess thickness (a), vadose zone thickness (b), and saturated zone thickness (c) across the CLP. Figures are adapted from Zhu et al., (2018).

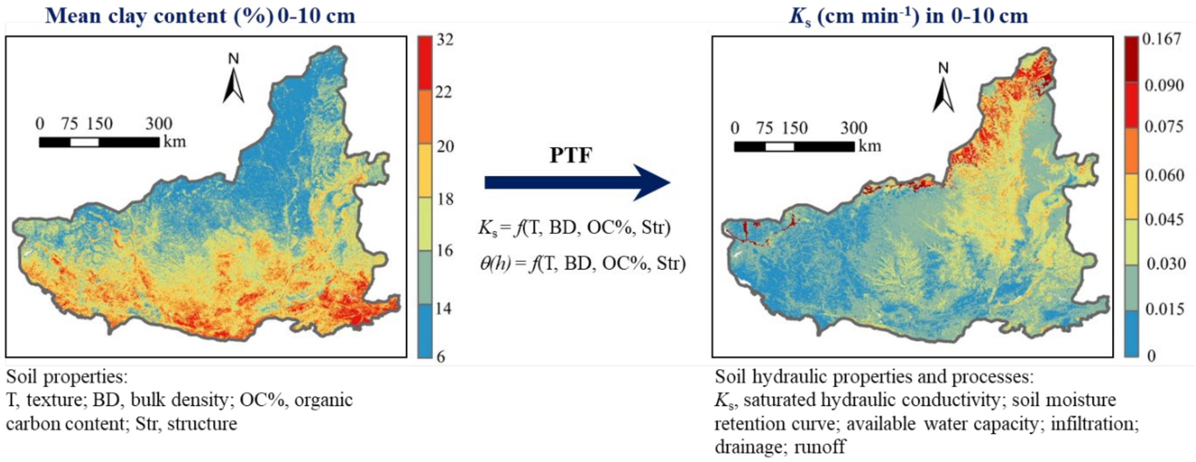

Fig. 7 Pedotransfer functions (PTF) were developed to estimate soil hydraulic property values from selected soil property values. Estimated hydraulic property values can then serve as a basis to estimate large-scale soil hydrological processes, such as available water capacity, infiltration, drainage, and runoff. Figures are adapted from Bai et al., (2022).

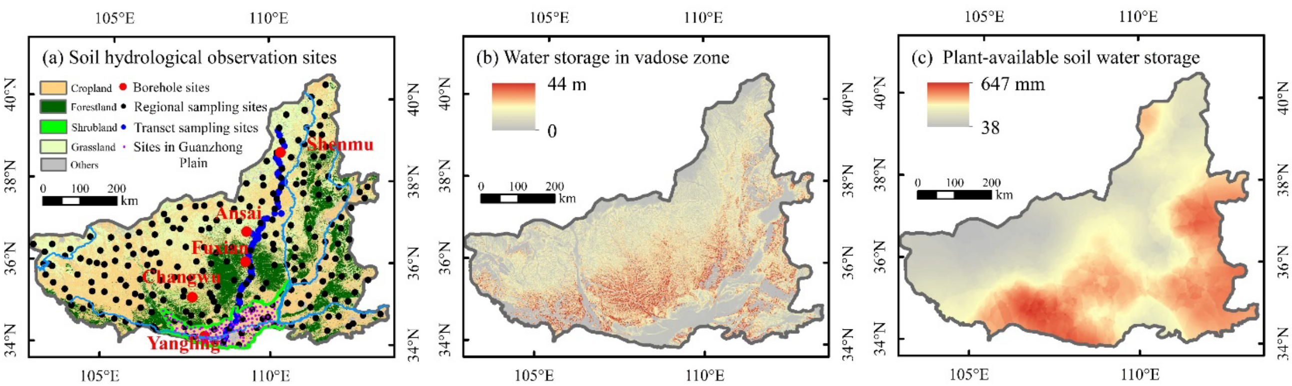

Fig. 8 Maps of soil hydrological observation sites (a), water storage in vadose zone (b), and plant-available soil water storage (PASWS) in the 0-5 m soil layer (c) across the CLP. The PASWS was calculated as the difference between the measured SWS (SWS_m) and the SWS at the wilting point (SWS_{wp}). The PASWS was equal to zero when SWS_m was less than SWS_{wp}. Figures are adapted from Cao et al., (2018), Zhu et al., (2019) and Zhao et al., (2021).

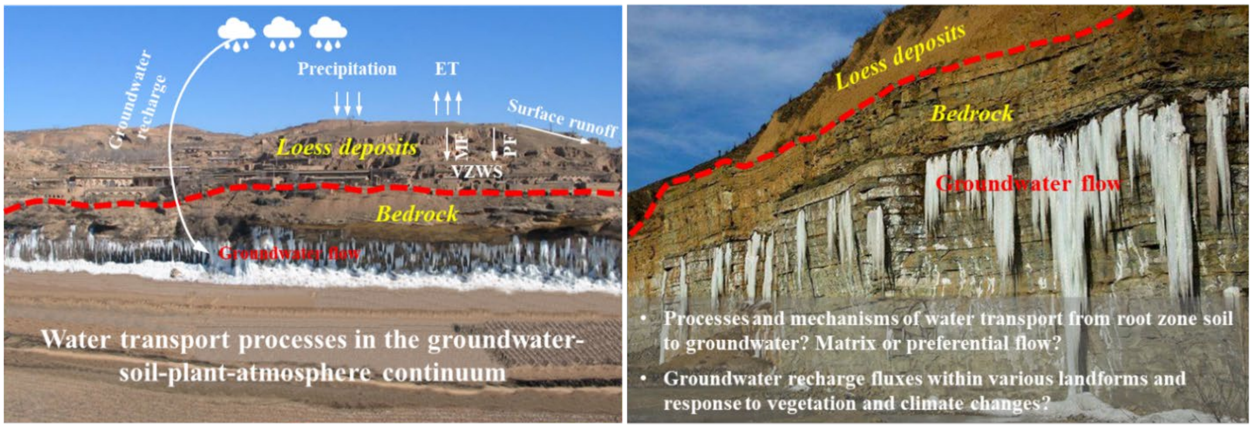

Fig. 9 A schematic diagram of hydrological processes in the Loess Critical Zone, including evapotranspiration (ET), surface runoff, vadose zone water storage (VZWS), groundwater recharge, and water seepage through weathered bedrock. Typically, water flows either through the matrix flow (MF) or through preferential flow (PF) paths.

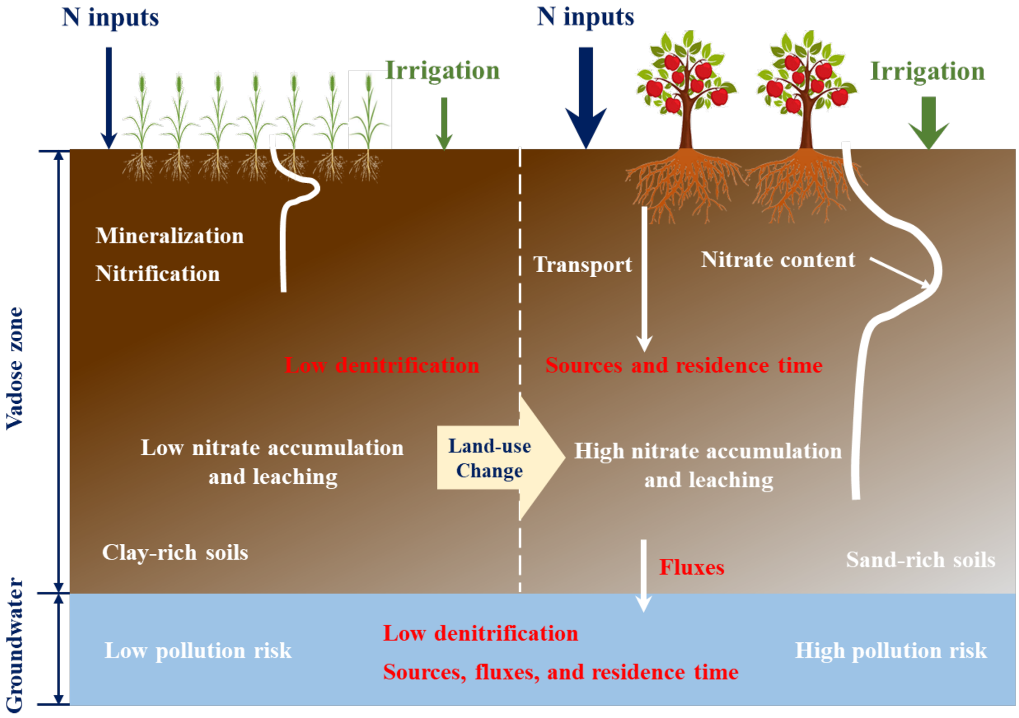

Fig. 10 Sketch illustrating the effect of agricultural land-use change from cropland to orchard on nitrate accumulation and transport in the vadose zone-groundwater system.

Bringing Ancient Loess Critical Zones into A New Era of Sustainable Development Goals

Xiaoxu Jia[1,2,3], Ping Zhu[1,2], Xiaorong Wei[3*], Yuanjun Zhu[3], Mingbin Huang[3], Wei Hu[4], Yunqiang Wang[5], Tuvia Turkeltaub[6], Andrew Binley[7], Robert Horton[8], Ming'an Shao[1,2,3*]

[1]Key Laboratory of Ecosystems Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2]College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100190, China

[3]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Northwest A&F University, Yangling, Shaanxi 712100, China

[4]New Zealand Inst Plant & Food Res Ltd, Private Bag 4704, Christchurch 8140, New Zealand

[5]State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, Shaanxi 710061, China

[6]Zuckerberg Institute for Water Research, Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus 8499000, Israel

[7]Lancaster Environment Centre, Lancaster University, Bailrigg, Lancaster, LA1 4YQ, UK

[8]Iowa State University, Ames, Iowa 50011, USA

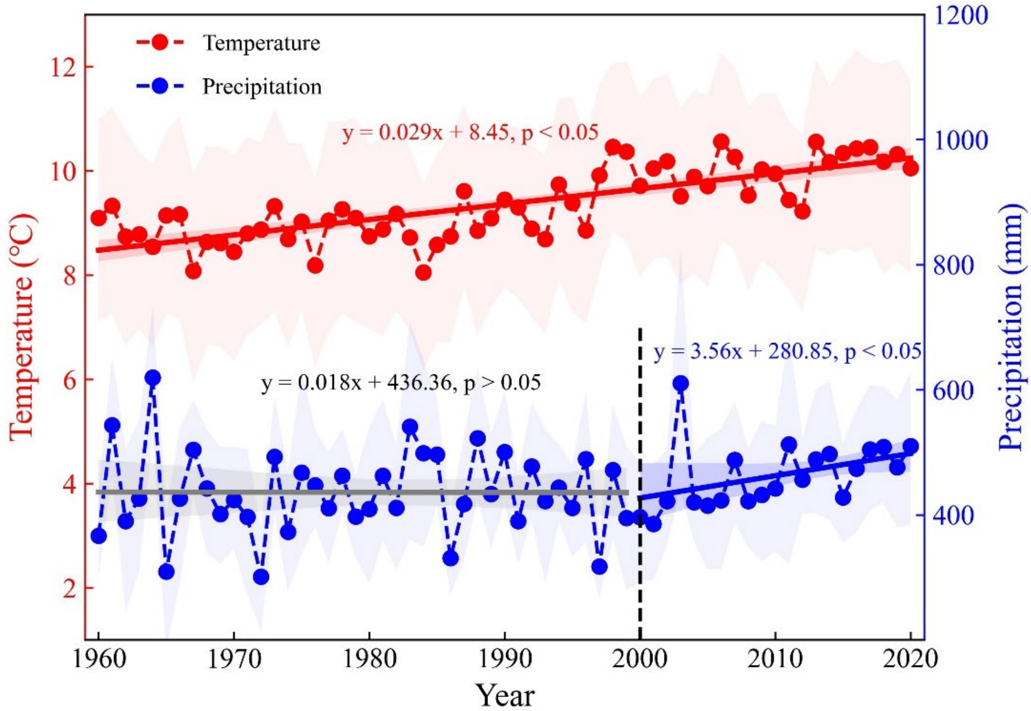

Figure S1. Interannual variation and monotonic trends in the annual temperature (*red*) and the amount of precipitation (*blue*) on China's Loess Plateau during 1960-2020. The lines denote the linear fits.

Table S1 Basic information for the representative Loess CZ Observatories on China's Loess Plateau.

Watershed	Longitude	Latitude	Area (km^2)	MAP (mm)	MAT (°C)	Elevation (m)	Water table (m)	Land use	Soil type	Landform
Wangdonggou	107.67	35.20	8	592	9.5	1100-1300	80	Cropland (winter wheat and maize), apple orchards, grassland (e.g., *S. bungeana*), shrubland (e.g., *C. korshinskii*), and forestland (e.g., *R. pseudoacacia*)	Heilutu silt loam	Tableland-gully region
Zhifanggou	109.32	36.86	8	512	9.2	1010-1430	66	Cropland (millet and maize), grassland (e.g., *A. gmelinii*, *A. giraldii*, *L. davurica*, and *S. bungeana*), shrubland (e.g., *C. korshinskii*, *H. rhamnoides*, and *S. viciifolia*), and forestland (e.g., *R. pseudoacacia*)	Loessial soil	Hilly-gully region
Liudaogou	110.37	38.80	7	425	9.1	1080-1270	35	Cropland (millet and maize), grassland (e.g., *S. bungeana* and *M. sativa*), shrubland (e.g., *C. korshinskii*, *S. psammophila*, and *A. desertorum*), orchard (e.g., *A. vulgaris*) and forestland (e.g., *P. Simonii* and *P. tabuliformis*)	Loessial Mein soil and aeolian sand soil	Hilly-gully region
Shanghuang	106.43	36.00	8	422	7.0	1500-2000	56	Cropland (millet and maize), grassland (e.g., *S. grandis* and *M. sativa*), shrubland (e.g., *C. korshinskii*) and orchard (e.g., *P. armeniaca*)	Heilutu silt loam and Loessial Mein soil	Hilly region
Heimugou	109.40	36.64	8	600	10.0	1000-1200	65	Cropland (millet and maize), grassland (e.g., *S. bungeana* and *B. ischaemum*), shrubland (e.g., *S. viciifolia*, *E. pungens*, and *R. xanthina*), orchard (e.g., *P. persica*) and forestland (e.g., *P. orientalis, R. pseudoacacia* and *P. tabuliformis*)	Heilutu silt loam	Tableland region
Gutun	109.79	36.72	42	500	9.1	900-1280	63	Cropland (millet and *S. italica*), grassland (e.g., *S. bungeana*), shrubland (e.g., *H. rhamnoides*, and *A. fruticosa*), orchard (e.g., *M. pumila*) and forestland (e.g., *R. pseudoacacia*)	Heilutu silt loam and Loessial Mein soil	Hilly-gully region
Longtan	104.48	35.74	16	386	6.8	1850-2200	66	Cropland (millet and maize), grassland (e.g., *S. bungeana, L. secalinus, S. grandis* and *M. sativa*), shrubland (e.g., *C. korshinskii*), apple orchards and forestland (e.g., *P. tabuliformis*)	Loessial Mein soil	Hilly-gully region
Nanxiaohegou	107.20	35.59	27	523	9.3	1050-1420	71	Cropland (millet and *S. italica*), grassland (e.g., *M. sativa*), shrubland (e.g., *S. davidii* and *H. rhamnoides*), orchard (e.g., *P. armeniaca* and *M. pumila*) and forestland (e.g., *P. orientalis, P. tabuliformis* and *R. pseudoacacia*)	Loessial Mein soil	Hilly-gully region
Yangjuangou	109.52	36.71	2	535	8.5	1000-1500	65	Cropland (millet and maize), grassland (e.g., *S. bungeana*), shrubland (e.g., *H. rhamnoides*), orchard (e.g., *P. armeniaca* and *M. pumila*) and forestland (e.g., *R. pseudoacacia* and *P. spp*)	Loessial Mein soil	Hilly-gully region

MAP: mean annual precipitation (1961–2020); MAT: mean annual temperature (1961–2020).