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Land use change impacts on the amount and quality of recharge water in the loess tablelands of China

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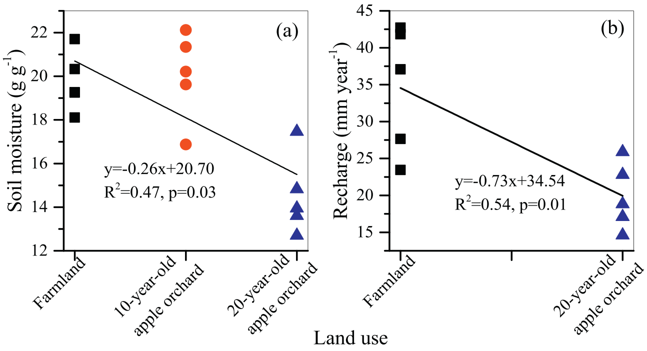
HIGHLIGHTS

- Relationship between land use and groundwater was investigated for depositional environment.
- Conversion from farmland to apple orchard decreases groundwater recharge.
- Recharge rate rather than pollutant concentration controls groundwater quality.
- Impacts of land use change have not reached groundwater.

GRAPHICAL ABSTRACT



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ABSTRACT

Exploring how land use change (LUC) influences the amount and quality of recharge water is important for groundwater sustainability and land use planning. With loess of up to 200 m in thickness and unsaturated zones up to 100 m below the surface, the loess tablelands in China can store abundant groundwater resources. However, groundwater depletion and substantial LUC have been simultaneously observed. It is thus necessary to investigate the relationship between LUC and groundwater. We sampled 10-m soil profiles for three land use types (farmlands, apple orchards of 10 and 20 years old). After measuring the chloride and nitrate concentration in soil pore water, the LUC effects on the amount and quality of recharge water quality were quantified based on the mass balance method. Results showed that soil moisture in aged (20-year-old) apple orchards was significantly reduced relative to that measured in farmlands and younger (10-year-old) orchards, where measured soil moistures were roughly equal. The accumulated nitrate nitrogen and the depth below which nitrate is stable was smallest in farmlands, intermediate in 10-year-old apple orchards, and largest under 20-year-old apple orchards. The diffuse recharge was 33.0 ± 17.9 mm year^{-1}, accounting for $7.3 \pm 1.8\%$ of mean annual precipitation under farmlands; however, the conversion from farmlands to 20-year-old apple orchards reduced recharge by 42%. The nitrate infiltrating to groundwater annually was 4.9 ± 2.9 kg hm^{-2} and 4.1 ± 3.1 kg hm^{-2} under farmlands and 20-year-old apple orchards, respectively. The impacts of LUC over the past decades have not yet reached groundwater because of low recharge rates; further, the primary factor influencing groundwater quality is recharge rate rather than pollutant concentration. As such, the LUC from farmland to apple orchard has little impact on short-term groundwater recharge and quality; long term impact, however, may be significant.

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1. Introduction

Groundwater is an essential and irreplaceable resource for most regions in the world, especially for those regions subject to limited water resources (Scanlon et al., 2005; Gleeson et al., 2016). However, in many regions across the globe, the water table is declining and water quality is deteriorating (Jasechko et al., 2017). Groundwater depletion has been increasing at global scales (Villholth, 2006; Wada et al., 2010), especially in major agricultural areas because of unsustainable groundwater usage in applications such as irrigation (Scanlon et al., 2012; Wada et al., 2012). Meanwhile, groundwater pollution is becoming more prominent. Even the fossil groundwater, dominating the total aquifer storage globally, is vulnerable to modern contamination (Jasechko et al., 2017). Given these factors, it is vital to study the factors controlling groundwater quantity and quality to provide fundamental information for sustainable utilization of groundwater resources.

Climate change, anthropogenic extraction and land use change (LUC) are the main factors controlling the groundwater system (Wada et al., 2010; Taylor et al., 2013). Anthropogenic extraction can directly result in groundwater depletion, while climate change and LUC indirectly influence groundwater by perturbing recharge rates and/or quality. Although anthropogenic extractions and LUC are both human activities, the former has been paid more attention in recent years. However, the impacts of LUC are very important for groundwater since it occurs globally and influences both water quantity and quality (Scanlon et al., 2005). As such, the mechanisms controlling how LUC influences groundwater recharge and quality should be investigated.

LUC influences groundwater recharge by altering the vertical infiltration of rainfall (Liu et al., 2013), as well as the occurrence of preferential flow because of perturbation of the macroporous characteristics of soils (Beven and Germann, 1982). As such, LUC can lead to drastic changes in groundwater systems, especially in arid to subhumid regions. In Argentina, for example, the transformation from grasslands to forests resulted in a water table decline of 38 cm (Jobbágy and Jackson, 2004); however, deforestation increased the recharge and deep drainage by 1–2 times (Santoni et al., 2010). In southwest Niger, with a semiarid to arid climate, 80% of the forests have been converted to farmlands over the past decades, which subsequently increased recharge from 2 to 25 ± 7 mm year^{-1} (Favreau et al., 2009). Investigating the relationships between LUC and groundwater change is of utmost importance for regions such as these, where water is a limiting factor for sustainable development.

LUC directly affects soil biogeochemical cycles, through changes in factors such as fertilizer application and altered surface roughness (McCracken et al., 1994; Vörösmarty et al., 2000). Nitrogen fertilizer is widely over-applied (Alkaisi and Yin, 2003); subsequently, the excess nitrogen accumulates in the soil profile and infiltrates into the groundwater, an effect which is more prominent in semiarid to arid regions (Liu et al., 2011). The potential pollution from nitrogen fertilizer varies with vegetation. High-yield crops, nitrophile and deep-root plants can reduce the risk of residual nitrate nitrogen (NO_3–N) accumulation and leaching (Scherer-Lorenzen et al., 2003); for example, with the same nitrogen fertilizer application levels, bromegrass exhibited almost no accumulation or leaching phenomenon, while corn had a cumulative depth of up to 2 m (Lv et al., 1999). LUC from woody savanna to crops indirectly increased 75% of measured $\delta^{15}N$ values in groundwater by 4–8‰, indicating a risk of groundwater pollution (Favreau et al., 2009). Similar phenomena have been reported in Chihuahuan Desert of Mexico (Jackson et al., 2004), in Europe (Strebel et al., 1989; Costa et al., 2007; Beaudoin et al., 2005), and in the San Joaquin Valley of USA (Schoups et al., 2005). Analysis of the LUC effects on groundwater quality provides information for the improvement of water security.

To analyze the effects of LUC on groundwater recharge and quality, two main methods have been widely employed, i.e. modeling and tracer methods (Allison and Hughes, 1978; Flint et al., 2002; Dyck et al., 2003; Lin and Wei, 2006). However, the strength of these methods varies with their application. Modeling methods can replicate the effects of LUC on both recharge rates and water quality at large scales, but its accuracy is still subject to model structure and calibration from observation at point or regional scales (Andraski and Jacobson, 2000; Simmons and Meyer, 2000; Li et al., 2014). Nitrate isotopes and chloride are popular tracers, of which nitrate isotopes can be used qualitatively to interpret the LUC effects on water quality, while chloride mass balance methods (CMB) quantify the LUC effects on recharge rates (Sharma and Hughes, 1985; Radford et al., 2009). Accordingly, tracer methods are very important since they provide basic inputs for modeling. However, further quantification of the relationship between LUC and water quality is necessary.

China's Loess Plateau is one of the regions with the most severe soil erosion in the world due to low vegetation coverage, erodible loess, intensive rainfall, and steep slopes (Li et al., 2009). To control soil loss, China's government launched the Grain for Green project in 1999 to improve vegetation through the return of farmland to forests and grasslands. Subsequently, the land use has been substantially changed (Li et al., 2016; J. Li et al., 2017). The LUC further altered hydrological processes, such as reducing soil water contents and surface runoff (Zavaleta et al., 2003; Wang et al., 2011; Maria et al., 2015; Li et al., 2017b). However, investigations of the effects of LUC on groundwater have been minimal. The main reason for this is that the thickness of the loess (of up to 200 m), and of the unsaturated zone (30 m to 100 m), hinders the application of conventional methods, such as soil moisture and water table monitoring. Further, as the groundwater recharge is far less than rainfall and evaporation in arid regions, the estimation errors from conventional water balance methods are very large (Gee and Hillel, 1988; Allison et al., 1994; Liu et al., 2010). As such, CMB methods are more appropriate for this region, and have been employed by several studies to estimate the LUC effects on recharge rates (Liu et al., 2009; Gates et al., 2011). Further analysis relating groundwater quality to LUC can provide important information for the management of water security.

How does LUC affect groundwater recharge under the deep unsaturated loess? How much nitrate enters the groundwater? To answer these questions, we first measured the soil moisture, chloride, and NO_3–N concentrations under farmlands and apple orchards of different ages on a loess tableland. We then qualitatively analyzed the LUC effects on soil moisture and nitrate nitrogen migration, and further quantified the LUC impacts on groundwater recharge and pollution from nitrate. The results provide valuable information for groundwater management and land use planning in regions with thick depositional cover.

2. Materials and methods

2.1. Study area

The sampling sites are located in a loess tableland in the southern part of the Loess Plateau (Fig. 1a). The mean annual precipitation is 576.7 mm and mean annual temperature is 9.4 °C (1957–2013). The soil is predominantly silt loam, with silt contents >50%. The land use types are farmland and apple orchard, among which the apple orchards are converted from farmlands in the past 30 years. The tableland is flat with negligible runoff, and the agriculture is rain-fed, without additional irrigation. Further, the tableland is isolated from neighboring regions, with surrounding gullies cut deeply into the bedrock, which is described in the hydrogeological profile (Fig. 1b). Above the mudstone and sandstone beds, there are three layers of loess, i.e. Wucheng Loess, Lishi Loess and Malan Loess, among which the Wucheng Loess is the aquitard. The depth to water table ranges from 30 to 100 m. Without water inputs from river or from horizontally connected regions, the groundwater in the tableland only originates from precipitation (Li et al., 2017a).Some previous studies have indicated that dual recharge modes can coexist, i.e. piston and preferential flow. However, preferential flow only occurs in specific areas where features such as vertical fissures, macropores