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Deep rooted apple trees decrease groundwater recharge in the highland region of the Loess Plateau, China

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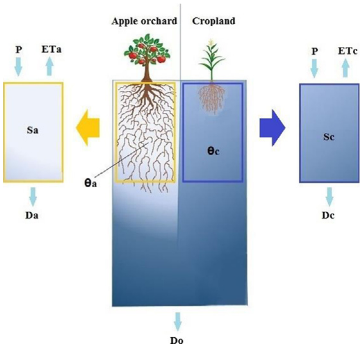
HIGHLIGHTS

- Deep-rooted vegetation is ubiquitous in arid and semi-arid zones.
- Groundwater recharge beneath deep-rooted vegetation is poorly understood.
- New method is built to estimate groundwater recharge below deep-rooted vegetation.
- Conversion of cropland to apple orchards decreased groundwater recharge.

GRAPHICAL ABSTRACT



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ABSTRACT

Unlike recharge in shallow rooted ecosystems, estimating the groundwater recharge beneath deep rooted plants that absorb water from deep soil remains difficult. The purpose of this research is to develop an approach to estimate the groundwater recharge beneath deep-rooted vegetation by combining water mass balance and chloride mass balance (CMB) and to quantify how the conversion of shallow-rooted cropland to deep-rooted apple orchards changes groundwater recharge. The proposed groundwater recharge rate under deep-rooted vegetation in this study is the difference between the groundwater recharge rate in a cropland (obtained using CMB) and the mean annual soil water storage deficit beneath an adjacent deep-rooted vegetation. The results show that the conversion from cropland (shallow-rooted) to apple orchard (deep-rooted) decreased soil water storage by 776, 1106, and 1117 mm, corresponding to 19, 20, and 26-year-old apple orchards, respectively. Groundwater recharge beneath cropland, on average, was 58 mm yr^{-1}, which amounts to 10% of the average annual precipitation. Groundwater recharge beneath the apple orchards were variable, but all being <3% of the average annual precipitation. The conversion of cropland to apple orchards lead to a substantial decrease in groundwater recharge, potentially threatening the sustainability of the land use change.

1. Introduction

Groundwater recharge is one of the most important fluxes in the hydrological cycle for evaluating, managing and developing groundwater resources (Wood and Sanford, 1995; Scanlon et al., 2006). It is also the

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primary mechanism by which contaminants enter the groundwater system. Evaluation of groundwater renewal and potential to contamination requires knowledge of recharge fluxes and the residence time for water between the land surface and the water tables. Therefore, the determination of groundwater recharge is important for the groundwater quality and quantity in arid and semiarid regions.

Many researchers investigated groundwater recharge in semiarid and arid environments (Scanlon et al., 2006), and most of their results are based on the Chloride Mass Balance (CMB) methods. CMB methods assume the atmospheric input of chloride in wet (precipitation) and dry deposition is concentrated in the soil water through evapotranspiration (ET) (Guan et al., 2013). By measuring chloride concentrations in soil water beneath the root zone, or the resulting groundwater, one can estimate the recharge rate, by assuming the surface chloride mass flux is equal to the chloride mass flux below the root zone. CMB methods provide a direct and time-integrated estimate of groundwater recharge and are frequently used because of their low cost. The basic assumptions of CMB methods are: (1) chloride in soil originates only from precipitation (Wood and Sanford, 1995); (2) chloride mass flux has not changed over time or is in equilibrium with the surface vegetation and climate conditions; and (3) chloride is conservative in soil. However, the steady state condition can be disturbed by land use changes, climate change, and changes in soil management (Scanlon et al., 2006; Guan et al., 2013). In addition, to reestablish steady-state conditions requires a long time after land use changes, especially in semiarid and arid zones and when the unsaturated zone is deep, because the flow beneath soil can be very slow.

Land use change can affect groundwater recharge substantially. A few studies showed that the same rainfall produces more infiltration and thus larger groundwater recharge in forests than in cropland or grassland (Bruijnzeel, 2004; Ilstedt et al., 2007), because there is usually less soil compaction in forests and, depending on soil type, soil structure may improve. On the contrary, numerous studies showed that replacing forest by cropland (forest clearance) progressively increases total water storage in the vadose zone and ground water recharge (Allison and Hughes, 1983; Allison and Hughes, 1978; Colville and Holmes, 1972; Scanlon et al., 2005; Sharma et al., 1986), elevating both “green” and “blue” water, thus enhancing resilience of the environment to increased variability in climate (Taylor et al., 2012). However, recharge process may also increase groundwater salinity in the long term, by flushing the solute content stored at depth through the deep vadose zone (Massuel et al., 2006), as it was shown at a global scale in semiarid regions (Scanlon et al., 2006).

Afforestation is the conversion of cropland to forests, and has occurred through massive eco-restoration efforts on the Loess Plateau of China, since 1999. However, high vegetative water consumption of the new vegetation leads to widely-observed soil desiccation (Wang et al., 2010). The depth of soil water depleted by alfalfa, caragana brush, and pine forest reached 15.5, 22.4, and 21.5 m, respectively (Wang et al., 2009). Further, the impact of land use on soil desiccation varied among different climatic regions. For example, land use change had no significant effect on soil water storage in the arid regions, but had significantly decreased soil water storage in deep soil in the semiarid and semihumid regions (Wang et al., 2011; Yan et al., 2015). In contrast, estimates of recharge rates are only available for a few locations on the Loess Plateau. For instance, tritium peak-displacement rates yielded recharge estimates of 47 and 68 mm yr^{-1} (or approximately 12–13% of mean annual precipitation) (Lin and Wei, 2006). The CMB suggested recharge rates of 33 to 55 mm yr^{-1} for two sites beneath winter wheat cultivation (Huang and Pang, 2013; Huang et al., 2013). Therefore, despite the wide distribution of the soil desiccation, there is poor understanding on how land use change and resulting soil desiccation alter ground water recharge.

Assumptions of the CMB for evaluating groundwater recharge are likely met for long-term croplands (Wood, 2005; Huang et al., 2013), but not for land just being converted to deep rooted vegetation. This is because the revegetated deep-rooted plants such as apple trees, with roots as deep as 18 m, may absorb water from the deep soil layers that charged from the previous land use; therefore, the deep soil chloride is from the old land use, but the extraction of water by deep-rooted trees changes the chloride concentration. Consequently, the concentration of deep soil chloride is not only affected by the ET through the root zone of the crops, which violates the assumptions of the CMB. The lack of an appropriate method hampers the understanding of groundwater recharge under deep-rooted vegetation. Therefore, this study pursued the following objectives: (1) to develop and assess a new method to evaluate groundwater recharge beneath deep-rooted apple orchards and (2) to determine the impact that the conversion of cropland to apple orchards has on water storage in deep soil layers.

2. Materials and methods

2.1. Site description

About 70% of the world's loess is located on the Chinese Loess Plateau, deposited by wind in the last 800,000 years. Due to the alternation between wet and dry climate in the Holocene, there are alternation of finer (interglacial and wet) and coarser materials (glacial and dry) with depths. Located on the Loess Plateau, the study sites are in Changwu county (35°12.701′N to 35°16.717′N) and Jingchuan county (107°33.701′E to 107°52.982′E), which are along the border of Shaanxi Province and Gansu Province, China (Fig. 1). Due to severe water erosion, the loess landscape is divided into highland and deep-cut gullies in southeastern part of the Loess Plateau, with elevations ranging from 1170 m to 1310 m above sea level. The climate is semihumid with an average annual precipitation of 571 mm, 50% of which falls in June to September (Chen et al., 2009).

Annual winter wheats or maize were the main crops grown prior to the planting of apple orchards (Zhu, 1989). Large amounts of cropland were converted to apple orchards in the late 1980's. Since then, apple orchards have been the main land use type (Huang et al., 2001). This area was rain-fed agriculture without irrigation, and all the orchards and croplands were managed by local farmers using conventional farming techniques. The orchards have been fertilized each year with N, P, and K fertilizers and usually the K is applied in the form of KCl. Groundwater in the region is larger than 50 m deep and therefore, has little effects on the root zone soil water (Liu et al., 2010).

As each farmer owns a small piece of land, usually only a fraction of a hectare, there is a mosaic distribution of wheat/maize fields and apple orchards. Furthermore, because the conversion of farmland to apple orchards happened at different time, orchards of different stand ages are also randomly distributed in the region. The farmland and orchards of different stand ages provide an excellent opportunity for comparing, through space-time substitution (Blois et al., 2013), the impact of land use change on groundwater recharge.

2.2. Soil sampling

Before the rainy season in May 2014, three representative mature apple orchards were chosen in Gaoping, Xianggong, and Wangdong villages (Fig. 1), respectively (refer to as GP, XG, and WD sites hereafter). Apple trees in the three orchards were planted in 1988, 1994, and 1996 respectively. A cropland at each of the three sites was selected adjacent to each orchard as a control site. The detailed biophysical parameters of three orchards measured in 2015 are shown in Table 1.

At the center of each orchard and cropland, two soil cores were taken from the center point between two rows. The soil samples were collected with a soil auger (0.06 m in diameter) at 0.2 m intervals, with an 18-m-deep soil core. Additional cores with 10-m-deep were collected at XG and WD sites as replicates to double check the spatial variability of soil water contents. As there were no significant