Journal of Hydrology 529 (2015) 1690–1700

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Hydrological processes and eco-hydrological effects of farmland–forest–desert transition zone in the middle reaches of Heihe River Basin, Gansu, China

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ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form 31 July 2015
Accepted 3 August 2015
Available online 18 August 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Juan V. Giraldez, Associate Editor

Keywords:
Transition zone
Soil water content
Groundwater level
Hydrological links
Eco-hydrological effect

SUMMARY

The study of the hydrological processes in the transition zone is important, but more complex compared with the homogenous land use units. A typical farmland–forest–desert transition zone in the Heihe River Basin was selected to study the hydrological processes and eco-hydrological effects among these land use units by monitoring the soil water content (SWC), groundwater level (GWL), and vegetation dynamics. Results showed that the sharp fluctuations of daily SWC and GWL in the farmland and the forest were primarily attributed to the irrigation events (7 and 6 times for the farmland and forest, respectively). The hydrological links among the three land use units were exhibited in three patterns. First, the soil water of the upper soil layer near the interface of two land use units moved from the irrigated land use unit to the non-irrigated one under soil water potential gradients through physical diffusion (the lateral water flow rate was less than 1 cm d^{-1}). Second, the water flowed from the irrigated land use unit to the non-irrigated one under GWL gradients through groundwater flow (the lateral groundwater flow rate was less than 10 cm d^{-1}). Third, a portion of the soil water in the farmland was utilized by the extended root system of the trees. The water exchange between the farmland and the forest resulting from one irrigation event was 5–30 mm, which caused increased GWLs for 1 week. At the forest–farmland boundary, the impacts of the extended tree roots reduced maize growth and extended 10–15 m into the farmland. By contrast, no obvious impacts were observed at the forest–desert boundary. Irrigating the farmland and the forest separately and reducing the width of the forest by 15–20 m would be more beneficial for irrigation water efficiency. These results would be useful for soil water management in terms of water balance impact on ecological construction and implementation of water-saving agriculture, as well as for optimal design of land-use patterns and efficient protection of oasis ecosystems to preserve limited water resources.

1. Introduction

Water resources are often scarce and have become a restricting factor for vegetative growth in arid inland river basins, such that in the middle reaches of Heihe River, Gansu, Northwest China (Feng et al., 2000; Wang and Cheng, 2001). Water shortages in these areas have become an increasingly serious problem in recent years because of overexploitation of water for agricultural irrigation within oases. These shortages have substantially changed the local hydrological cycles and caused degradation to distinctive ecosystems (Shen et al., 2014). Therefore, mitigating the consequences of water deficits, increasing the efficiency of water use, and ensuring oasis ecological security are necessary (Li et al., 2007; Su et al., 2007; Ma et al., 2009).

Soil water content (SWC) is a typical indicator of water limitations in ecosystems in arid areas because soil water is a critical component of the hydrological processes connecting the atmosphere, vegetation, and groundwater (Mahmood and Hubbard, 2007). Relevant studies in this area have mainly focused on soil water dynamics in a single land use unit, e.g., farmland (Ji et al., 2007, 2009; Zhao and

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http://dx.doi.org/10.1016/j.jhydrol.2015.08.017

Zhao, 2014a), grassland (Coronato and Bertiller, 1996), forest (Knight et al., 2002), or desert (Li et al., 2008). Compared with the hydrological processes of a single land use unit, the oasis–desert transition zones are naturally more complex because of the lateral water flow and extended root system (Ong et al., 2002; Zhao et al., 2012). The oasis–desert ecotone of arid inland river basin have several representative land use patterns (transition zones), such as farmland–forest, forest–desert, and farmland–forest–desert (Shen et al., 2014). Among these patterns, the study of farmland–forest land use pattern is essential in terms of scarcity of land and water resources and water use efficiency enhancement in agriculture (Wildy et al., 2004; Campi et al., 2009).

Previous studies have concentrated on comparing water use in adjacent land use units and the hydrological interactions among units, especially in typical land use types in arid areas, such as treebelts and pastures (Knight et al., 2002; White et al., 2002; Crosbie et al., 2008) and treebelts and croplands (Smith et al., 1997; Wildy et al., 2004; Karray et al., 2008). Irrigation efficiency may be enhanced because the root systems of forests decrease soil water content from the deep layers of the nearby farmland, thereby decreasing deep water percolation (Wildy et al., 2004; Wang et al., 2011). In addition, forest soil may be recharged under soil water potential gradients when farmlands are irrigated, and such recharge is beneficial to tree growth (Karray et al., 2008). However, quantification of water recharge among land use units is lacking. Furthermore, few studies have been conducted on hydrological processes and ecological effects among the farmland–forest–desert transition zones, particularly under irrigated conditions.

The Heihe River Basin (HRB) is the second largest inland river basin in China and historically one of the primary areas for grain production. With limited precipitation in this region, the water from Heihe River is the principal water source for economic development and for the maintenance of a sustainable environmental balance (Chang et al., 2006). The water from Heihe River is overconsumed in the middle reaches of the basin, and such consumption comprises 86% of total available water resources of Heihe River, 96% of which is used for irrigation (Chen et al., 2003). Recently, preservation of the land in the middle portions of the basin has been difficult in terms of the vegetation-carrying capacity of water and commonly occurring water deficits (Lu et al., 2003; Chang et al., 2006). The oases in the middle reaches are distributed along the Heihe River and artificial channels, with typical farmland–shelter forest–desert transition zones at its boundaries (Li et al., 2001). These transition zones are ideal areas for studying vadose zone hydrology of different land use types and hydrological links among different land use units under arid climate conditions. Although several studies have been conducted to address soil hydrology within a single land use unit (Ji et al., 2009; Liu et al., 2011; Li et al., 2012), studies on the issues of transition zone continuum are limited (Shen et al., 2014). An understanding of the hydrological processes in farmland–forest–desert transition zone is essential, considering that soil water in one land use unit may be used by an adjacent unit, thereby resulting in changes in water budgets within the coupled systems. Optimal design of land use patterns is an important tool for desertification control. Studies on these areas may provide favorable evidence for adoption of water-saving irrigation techniques in the oasis.

In the current study, the farmland–forest–desert transition zone with shallow groundwater level (GWL) in the middle reaches of the Heihe River Basin were selected to investigate the differences in the hydrological processes within these land use units. This study aims to (1) characterize the SWC dynamics and GWL fluctuations affected by land use types, (2) quantify the water exchange among the transition zone, and (3) identify the eco-hydrological effects of the transition zone.

2. Materials and methods

2.1. Study area

The experimental sites are located at the Linze Inland River Basin Comprehensive Research Station of the Chinese Ecosystem Research Network (CERN) in Gansu, Northwest China (Fig. 1; 39°21′N, 100°07′E, altitude 1374 m). These sites are typical representative piedmont valley plain oases in the middle reaches of HRB. The area has a continental arid temperate climate, with an average annual precipitation of 117 mm from 1965 to 2000, 60% of which occurs between July and September. The mean annual temperature is 7.5 °C, with a maximum monthly average value of 39 °C in July and minimum average value of −27 °C in January. The annual pan evaporation is 2390 mm, and humidity changes dramatically throughout the year in the range of 7.3–80.9%. The soil is sand or sandy loam, with low organic matter content (Su et al., 2007). The primary land use units are farmland (e.g., maize, wheat, and cotton), forest (e.g., shelter belt, shrub belt, and riparian forest belt), unused land (e.g., Gobi desert, bare land, and desert), areas associated with water (e.g., wetland and reservoir), and residential areas (Liu et al., 2010; Shen et al., 2014).

Our field monitoring activities were conducted in a farmland–forest–desert transition zone (Fig. 1b), which is a typical land use pattern at the edge of the oases in this region. The farmland was developed from the wetland areas by covering the soil with sand (40–70 cm thick) in the 1980s and planting with maize (*Zea mays*) since 2004. Management actions (e.g., sowing, irrigation, fertilization, and tillage) are applied mainly based on the experiences of local farmers and government guidance for farmland and forest operations. Maize is usually sown in mid-April and harvested in mid-September. The forest land was developed in 2006 by removing sand (20–70 cm thick) from the soil surface and planting the areas with poplar trees at a density of 1200 trees (*Populus alba*) per hectare. The removed sand was accumulated near the forest–desert interface, which consequently caused altitudinal differences. Small elevation differences exist among the three land use units (Fig. 1c), with relatively flat surfaces in the farmland and forest, but irregular surfaces in the desert. The trees usually sprout in late April and begin to shed leaves in late September. The desert areas were undisturbed. The primary types of vegetation in the desert consist of bulrush (*Phragmites australis*), sacsaoul (*Haloxylon ammodendron*), reaumuria (*Reaumuria soongorica*), and halogeton (*Halogeton glomeratus*). The vegetation growth period in the desert is from early May to middle October.

2.2. Measurements

A total of 15 TRIME-TDR (Imko, Germany) access tubes (0.04 m diameter, 1.5–3 m length) and 17 monitoring wells for GWL were installed along the farmland–forest–desert transition zone (Fig. 1c) for in suit monitoring of SWC and GWL, respectively. The monitoring sites were distributed densely at the interfaces between the farmland–forest and the forest–desert transition zones. Measurements were performed from April to October in 2012. The SWC and GWL were measured with the TRIME-TDR and the Million Water Level Measurement Device (Yamayo, Japan, accuracy: ±1 mm), respectively. The SWC was measured every 5 d, whereas GWL was measured daily. Additional measurements were taken before and after irrigation or when significant rainfall events occurred. TDR calibration was performed in the field by measuring the gravimetric water content ranging from dry to wet conditions and converting to volumetric water content using bulk density

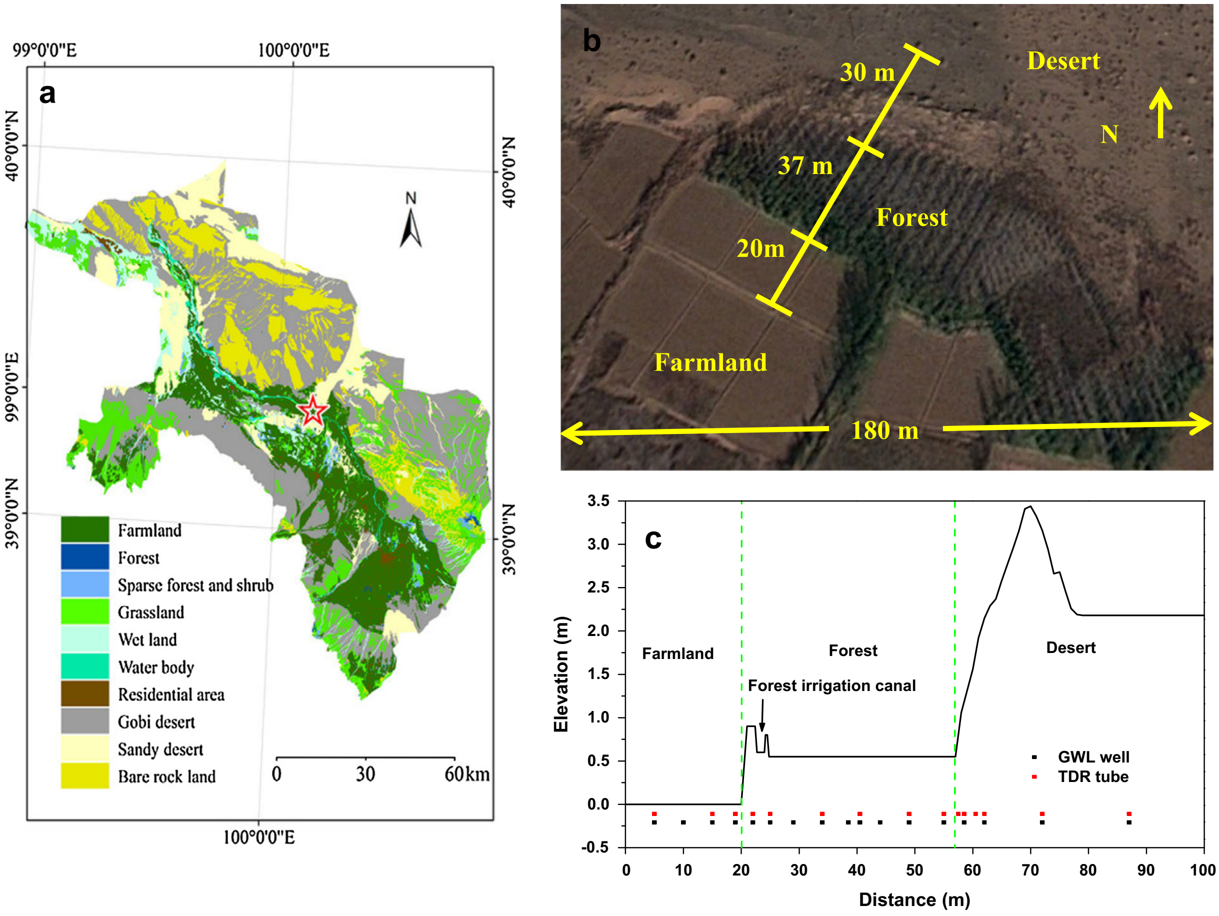

Fig. 1. Location map of study area, with (a) the location of the Heihe River Basin (HRB) and land-cover types in this region (referenced from Zhao and Zhao (2014a)); (b) location of the farmland–forest–desert transition zone and the monitoring transact; and (c) the elevations of the transition zone, the locations of the groundwater wells, and the locations of the time domain reflectometry (TDR) tubes.

data (Yi et al., 2014). GWL measurements were calibrated to a common horizontal reference elevation for all measurement sites.

Root distribution was surveyed by carefully removing plant roots from soil samples. These soil samples were obtained at 10 cm intervals within the soil pits excavated at different locations in parallel with the TDR access tubes in early September. The poplar and maize roots were separated by color and aroma differences, dried at 70 °C for 24 h, and then weighed (Sudmeyer et al., 2004). Samples were obtained from 6 rows of maize (80 maize per row) from the farmland–forest interface to 20 m away to measure the biomass of the maize grain and straw when the crop was harvested in mid-September. The leaf area index (LAI) of the maize and poplar was measured by LAI-2200 canopy analysis instrument (LI-COR, USA) from April to October for 10 times. In addition, the height of the poplar trees was measured with an ultra-sonic measuring system (Vertex IV, Haglof, Germany), and the diameter at breast height (DBH) was measured with a tape measure in late September. Meteorological data were obtained from a weather station located 1 km away from the study area. At the beginning of the experiment, soil samples were collected on the soil profile at the center of each land use unit to determine soil texture (pipette method), bulk density, saturated water content (oven drying method), and saturated hydraulic conductivity (constant head method). The soil physical properties in the three land use sites are shown in Table 1, and certain data were cited from Yi et al. (2014).

In the 2012 growing period from April to October, the farmland and the forest were irrigated by conventional flood irrigation for 7 and 6 times, respectively. The irrigation events occurred in the farmland on May 30, June 16, July 6, July 20, August 7, August 25, and September 8, whereas those in the forest occurred on April 29, May 17, June 16, July 6, July 24, and August 16. The amount of irrigation water was measured with the water meter located at the irrigation water outlet.

2.3. Water balance and lateral water flow

The actual evapotranspiration rate (ET_a) was estimated by the following equation (Allen et al., 1998):

$$ET_a = K_c ET_0 \quad (1)$$

where K_c is the crop coefficient, and ET_0 is the reference crop evapotranspiration rate (mm d^{-1}), which was calculated by the FAO Penman–Monteith equation (Allen et al., 1998). The values for K_c for the farmland, forest, and desert were 0.7–1.2 (Zhao et al., 2010), 0.4–1.2 (Xi, 2013), and 0.15–0.25 (Zhao and Zhao, 2014b), respectively, during the water balance calculation period.

The soil water balance equation, based on the soil layer between the soil surface and the deepest GWL (1.5, 2.0, and 2.7 m for the farmland, forest, and desert, respectively) was used to calculate the water exchange at one location. Given that no runoff was observed in the monitoring zone, the water balance after one irrigation event was calculated using the following equation:

$$P + DR - \Delta S - ET_a = 0 \quad (2)$$

Table 1
Physical properties of soils located within the three landscapes.

Land use type	Soil depth (cm)	Soil texture (%)			Bulk density (g cm^{-3})	Saturated conductivity (cm d^{-1})
		Clay	Silt	Sand		
Farmland	0–70	8.5 (1.9)	5.1 (2.6)	86.4 (3.0)	1.57 (0.02)	72.0 (30.5)
	70–80	17.0 (1.4)	27.4 (3.3)	55.6 (4.3)	1.62 (0.05)	16.4 (8.7)
	80–130	5.6 (2.3)	3.5 (1.2)	90.9 (3.5)	1.66 (0.09)	142.8 (68.7)
	130–150	25.1 (7.5)	42.8 (1.3)	24.5 (7.5)	1.56 (0.02)	0.1 (0.1)
Forest	0–20	9.2 (1.9)	7.0 (2.2)	83.8 (2.7)	1.52 (0.09)	124.5 (30.2)
	20–130	7.3 (3.5)	6.4 (5.4)	86.4 (8.8)	1.58 (0.03)	79.1 (32.5)
	130–170	4.2 (1.6)	2.6 (1.1)	93.2 (1.4)	1.56 (0.03)	157.1 (25.1)
	170–200	25.1 (7.5)	42.8 (1.3)	24.5 (7.5)	1.56 (0.02)	0.1 (0.1)
Desert	0–130	3.0 (1.1)	2.7 (0.4)	94.3 (0.7)	1.58 (0.04)	420.9 (207.3)
	130–230	11.1 (0.1)	48.4 (5.3)	40.5 (5.2)	1.69 (0.03)	2.2 (1.4)
	230–280	8.5 (1.9)	35.1 (2.6)	56.4 (3.0)	1.64 (0.04)	8.6 (2.3)

where P is the precipitation and irrigation, DR is the daily water exchange (i.e., a positive value indicates that the soil domain is recharged, whereas a negative value indicates that the water leaves the soil domain). ΔS is the change in soil water storage. The DR consisted of lateral water flow from the adjacent domain (LF, lateral flow under soil water potential and GWL gradient), vertical water flux (VF) at the bottom of the soil domain, and root water uptake (RU) by the extended root system from adjacent land use units.

The LF (or VF) rate can be calculated by the following equation (Darcy's law):

$$\mathrm{LF} = K\frac{\Delta H}{\Delta L} \tag{3}$$

where K is the saturated/unsaturated hydraulic conductivity (cm d^{-1}), ΔH and ΔL are the soil water potential (GWL) gradient and distance of the same soil depths between two monitoring sites, respectively. The K and ΔH in the unsaturated conditions were determined as a function of SWC following van Genuchten (1980), and the relevant hydraulic parameters were referenced from Yi (2015).

3. Results

3.1. Dynamics of soil water content and groundwater level in each land use unit

Fig. 2 shows the spatial and temporal distributions of soil water content (SWC) in the center of each land use unit during the 2012 growing period. The daily SWC fluctuated sharply in the upper soil layers and gently in the deep soil layers for the three land use units. Most variations occurred above the 60, 120, and 60 cm depths for the farmland, forest, and desert, respectively.

The dynamics of the daily SWC varied in the three land use units. The farmland had the highest SWC at all times, followed by the forest, and then the desert. The SWC dynamics responded to irrigation events in the farmland and forest, with 7 and 6 distinct

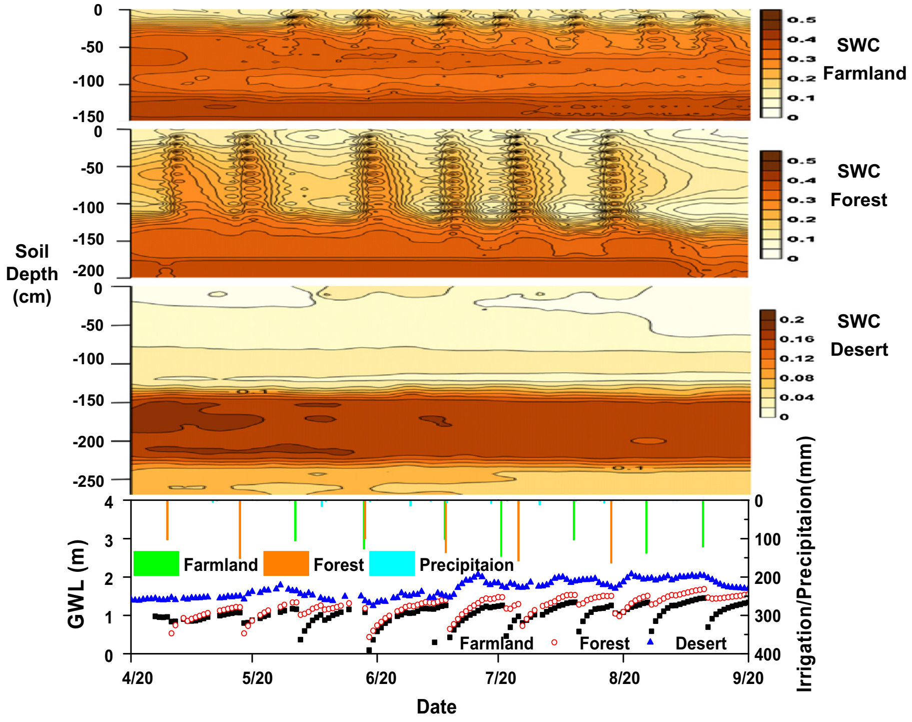

Fig. 2. Dynamics of soil water content (SWC) and groundwater level (GWL) in the center location of each landscape, and relevant irrigation/precipitation information from April 20 to September 20 in 2012. (The GWL were calibrated to a constant horizontal elevation that was referenced to the farmland monitoring site at a 15 m distance from the farmland–forest interface.)

spikes, respectively. Continuously decreasing SWC was observed in the farmland and forest after the last irrigation (i.e., August 17 and September 6 for the farmland and forest, respectively). By contrast, the SWC fluctuations in the desert were more gradual than those observed in the farmland and forest, with large SWC changes only in the upper (0–30 cm) soil layers. Obviously, higher SWC in the upper soil layers in the desert were observed from early June to late August, especially in June, compared with the values in May and after August, because of the substantial rainfall events that occurred in the former period (Fig. 2).

The fluctuations of daily GWL also varied in the three land use units. The farmland had the shallowest GWL, then the forest. The desert had the deepest GWL. These differences diminished rapidly after the final irrigation for the farmland in early September. The increments of GWL in the farmland and forest were closely associated with the irrigation events, and fluctuated more sharply than the GWL in the desert during the irrigation periods.

3.2. Dynamics of GWL and SWC along the transition zone

As presented in Fig. 3, the increased values of GWL and SWC in the farmland at different locations (1 and 15 m away from the farmland–forest interface) were sensitive to the irrigation events that occurred in the farmland (i.e., 7 times) and the adjacent forest (i.e., 4 times), but less affected by the rainfall events. Seven irrigation events in the farmland led to the sharp increase in GWL, and the additional four staggered irrigation events in the forest also resulted in elevated GWL in the farmland. Consistent with the GWL increment, the SWC of the entire soil profile in the farmland increased when the farmland or the forest was irrigated, but the SWC in the farmland increased more sharply with the farmland irrigation events. By contrast, the rainfall events had minor effects on the GWL fluctuations and only increased the SWC in the upper layers in the farmland.

The dynamics of GWL and SWC at different locations in the farmland responded differently to the irrigation events in the forest. Although the elevation of the GWL affected by the forest irrigation could extend up to 15 m or more from the farmland–forest boundary, substantial increase in GWL occurred in the areas adjacent to the forest. Meanwhile, the increased SWC was more obvious at locations within 1 m of the forest than at locations 15 m away for both the upper or lower soil layers.

Similar to the farmland, the increased GWL and SWC in the forest at the three locations (e.g., 2, 14, and 35 m away from the farmland–forest interface) were sensitive to irrigation events in the forest (i.e., 6 times) and the adjacent farmland (i.e., 5 times), but were less affected by rainfall events. As presented in Fig. 4, a sharp increase in GWL was observed in the forest for all monitoring locations after each forest irrigation event. GWL increase was observed in the forest for the nearby locations (e.g., 2 and 14 m away from the farmland–forest interface) after each of the five staggered irrigation events in the farmland. Consistent with the GWL increments, the SWC of the entire profile in the forest increased after forest irrigation. However, the SWC increment in the forest after farmland irrigation was only observed in the deep soil layers (e.g., 100 and 150 cm), indicating that lateral groundwater flow (LGF) occurred between the forest and farmland. By contrast, rainfall events had minimal effects on the GWL in the forest, and only increased the forest SWC in the upper soil layers (e.g., 10 cm).

The dynamics of GWL and SWC at different locations within the forest responded differently to the farmland irrigation events. More substantial increments were observed for the area located near the farmland (e.g., 2 m) than the area located at a greater distance (e.g., 14 m) from the farmland. By contrast, no obvious increases in GWL or SWC within the forest were observed at locations 35 m away from the farmland when the farmland was irrigated.

The increments of GWL and deep SWC within the desert were primarily attributed to the irrigation events in the forest (i.e., 6 times), rather than the farmland irrigation and rainfall events. As presented in Fig. 5, six irrigation events in the forest increased GWLs in the desert at locations close to the forest. Consistent with

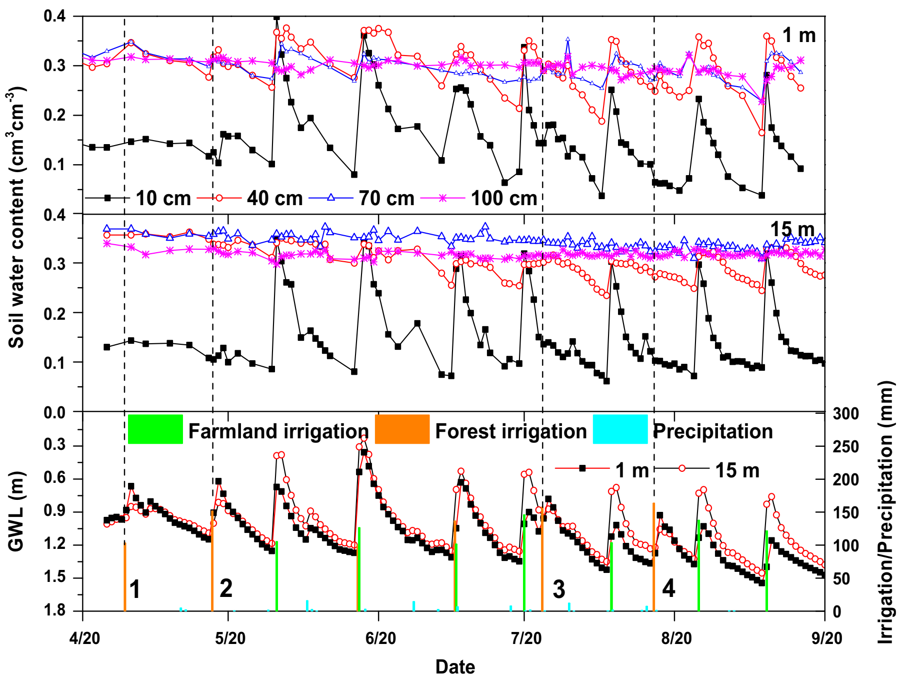

Fig. 3. Dynamics of the groundwater levels (GWLs) and the soil water contents (SWCs) of different locations in the farmland. (The GWL were calibrated to a constant horizontal elevation that was referenced to the site at a 15 m distance from the farmland–forest interface; the Arabic numbers present the water recharged times resulted by the forest irrigation event.)

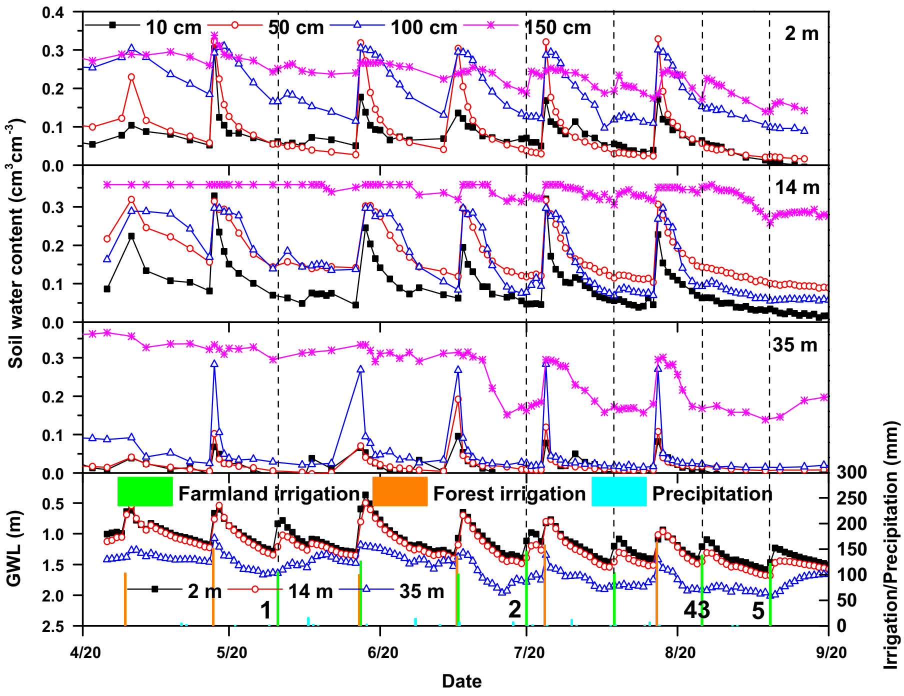

Fig. 4. Dynamics of the groundwater levels (GWLs) and the soil water contents (SWCs) of different locations in the forest. (The GWL were calibrated to a constant horizontal elevation that was referenced to the site at a 14 m distance from the farmland–forest interface; the Arabic numbers present the water recharged times resulted by the farmland irrigation event.)

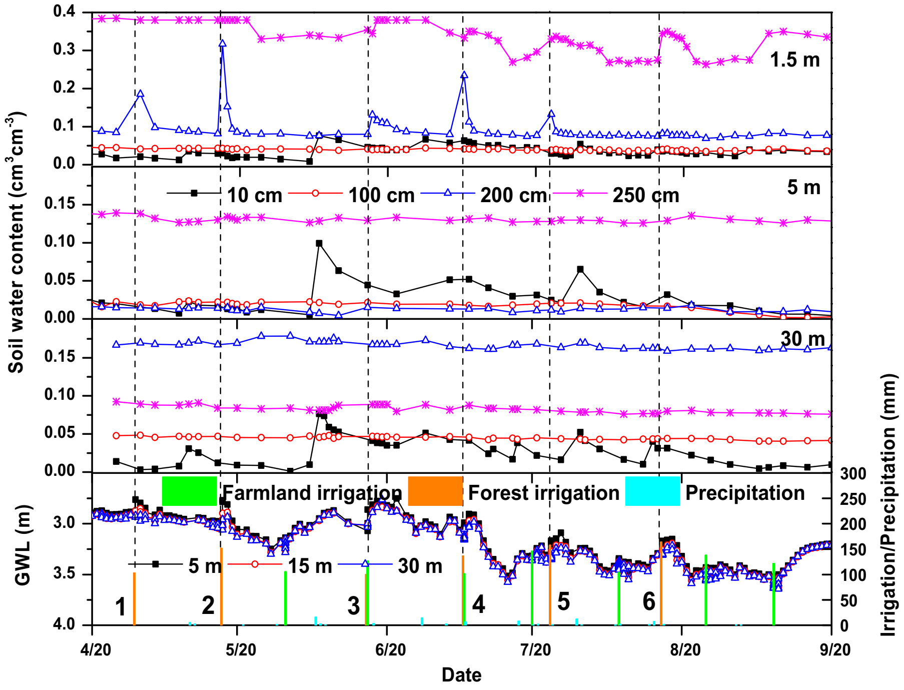

Fig. 5. Dynamics of the groundwater levels (GWLs) and the soil water contents (SWCs) of different locations in the desert. (The GWL were calibrated to a constant horizontal elevation that was referenced to the site at a 5 m distance from the farmland–forest interface; the Arabic numbers present the water recharged times resulted by the forest irrigation event.)

the increased GWLs after the forest irrigation event, the SWC in the desert at the deep soil layers (e.g., 200 and 250 cm) of the area located near the forest–desert interface increased when the forest was irrigated. By contrast, minimal changes in GWL were observed in the desert after the farmland irrigation and rainfall events. The SWCs in the desert increased in the upper soil layers after rainfall events, rather than after farmland irrigation events.

Distance from the forest directly affected GWL and SWC dynamics in the desert. The largest increment in GWL was observed at locations closest to the forest. Accordingly, the increase in SWC in the desert was more obvious at the area 1.5 m away from the forest than the sampling location at a 5 m distance. At sampling locations at distances of 30 m or greater, no obvious increments in SWC were observed after the forest was irrigated.

3.3. Groundwater flow and water exchange of single irrigation event

Obvious differences in GWL and LGF rates were observed for different locations within the farmland and the desert (Fig. 6). The GWL was shallower in the early stages of the growing period and decreased with vegetation growth period extension. Except for the periods when irrigation events occurred in the forest instead of in the farmland, the shallowest GWL was observed in the farmland, followed by the forest. The deepest levels were observed in the desert. Consistent with the GWL gradients, the groundwater always moved from the farmland toward the forest, and abrupt LGF appeared when the farmland or the forest was irrigated (Fig. 6b), thereby leading to water exchange among different land use units.

Lateral groundwater exchange was observed among different land use units when irrigation events occurred. The GWLs in the farmland and desert increased when the forest was irrigated and increased in the forest when the farmland was irrigated, but did not increase in the desert in response to the farmland irrigation event. More obvious GWL increments and LGF in the desert were observed when larger quantities of water were used for irrigation in the forest on August 16 compared with that on July 6. The distance of obvious GWL increases for the farmland and desert following the forest irrigation event was at least 15 and 5 m, respectively. The increased GWL in the forest following the farmland irrigation event occurred at 20–25 m from the farmland–forest interface.

The GWL in the farmland increased in response to the forest irrigation in August 16 to August 24 when about 140 mm of irrigation water was applied. As presented in Fig. 7, the GWL of the three monitoring locations in the farmland rose quickly after the forest was irrigated, reached the shallowest GWL after approximately 24 h, and then started to decrease at the closer sites. The increases in GWL were maintained for more than 1 week for all monitoring sites. Higher GWL increments and longer times of maintenance were observed at all times for the areas closer to the forest (i.e., 0.47, 0.38, and 0.21 m GWL increment for 1, 5, and 15 m sites, respectively).

Consistent with the increased GWL observed within the farmland, the soil in different areas within the farmland was recharged in response to the irrigation events. The daily water exchange (DR)

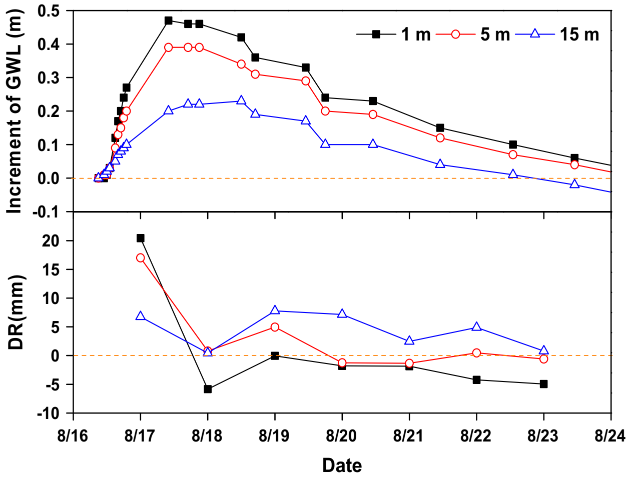

Fig. 7. Dynamics of the groundwater level (GWL) increments and daily water exchange (DR) of the soil domains for different locations in the farmland with different distances from the farmland–forest interface in a forest irrigation event that occurred in August 16–24.

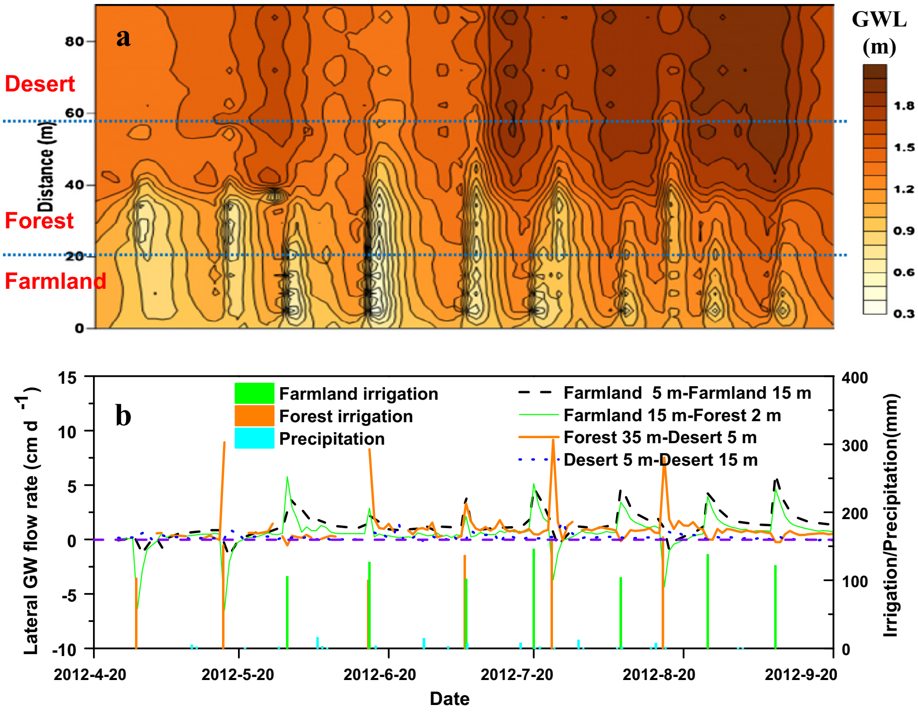

Fig. 6. The groundwater levels (GWLs) along the farmland–forest–desert transition zone (a, the GWL were calibrated to a constant horizontal elevation that was referenced to the farmland monitoring site at a 15 m distance from the farmland–forest interface) and calculated lateral groundwater flow rate of different areas in the monitoring zone (b, the positive value means the groundwater move from the farmland to the desert direction, the negative value means the groundwater move from the desert to the farmland direction).

increased simultaneously after the forest was irrigated. The highest DR occurred during the first day after the forest was irrigated for all monitoring sites in the farmland, with about 20 mm for the area closest to the forest and lower values for the area far from the forest. The maintained time of positive water exchange was the longest for the area furthest away from the farmland–forest interface, followed by the middle area, and was shortest for the area closest to the interface (i.e., 7, 3, and 1 d for the 15, 5, and 1 m sites, respectively).

The GWL in the forest was sensitive to farmland irrigation event for the area closer to the farmland that occurred in August 25 to September 3 when 140 mm of irrigation was applied. As shown in Fig. 8, the GWL in the forest located 2 and 14 m from the farmland–forest interface increased rapidly after the farmland was irrigated, but decreased in the forest located 35 m from the farmland–forest interface, suggesting limited water recharge from the farmland irrigation events and evapotranspiration reduced the GWL at the location because the GWL was shallow. The area closer to the interface reached the shallowest GWL at about 24 h after the farmland was irrigated, and maintained for more than 1 week with a slightly decreasing trend. Therefore, higher GWL increments that persisted for longer periods were observed in the forest for the area closer to the farmland, compared with the area further away.

Consistent with the increased GWL in the forest, the forested soil located 2 and 14 m from the farmland–forest interface was recharged by the farmland irrigation events, but the soil located greater than or equal to 35 m from the farmland–forest interface was not recharged. The DR increased simultaneously with the increase in GWL after the farmland was irrigated, and then decreased rapidly. The highest DR occurred during the first day after the farmland was irrigated, with values of about 25 mm for the locations at 2 and 14 m. The DR was consistent for the locations 35 m from the farmland–forest interface.

The dynamics of the GWL at different locations in the desert responded differently to the forest irrigation events that occurred in July 24 to August 2 when 135 mm of irrigation was applied. The GWL in the desert located 1.5, 3.5, and 5 m from the interface increased rapidly after the forest was irrigated. The desert GWL reached the shallowest value after the forest had been under irrigation for about 4 h, but the GWL decreased at locations 15 m or further from the interface (Fig. 9). The shallow GWLs at the locations with shorter distances from the interface within the desert were maintained for about 4 d. The GWL increments in the desert were greater for the areas located near the forest, and characterized by maintaining the GWL increments for longer periods. Consistent with the GWL increment in the desert, the desert soil located 0.5, 1.5, and 3.5 m from the interface was recharged by the irrigation events. The DR of the closer locations increased simultaneously with the SWC increase after the forest was irrigated, and then decreased rapidly. Delayed increment of DR was observed for the location 3.5 m away from the interface. The largest DR in the desert occurred during the first day after the forest was irrigated, with values of about 200 mm for the monitoring location closest to the forest.

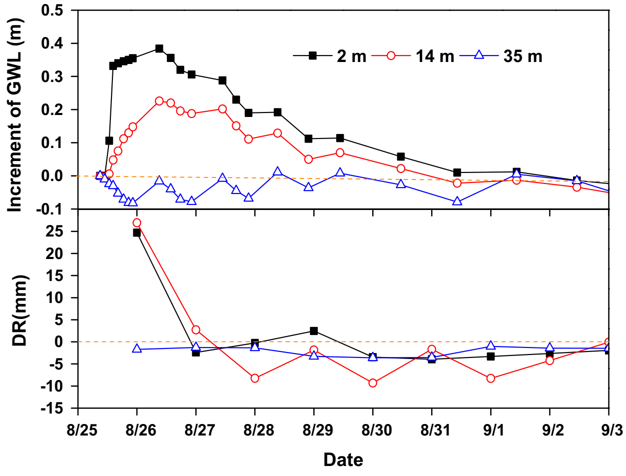

Fig. 8. Dynamics of the groundwater level (GWL) increments and daily water exchange (DR) of the soil domains for different locations in the forest located at different distances from the farmland–forest interface during a farmland irrigation event that occurred in August 25 to September 3.

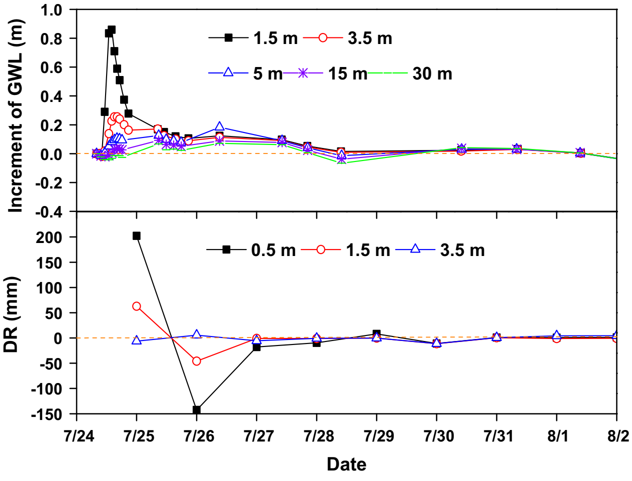

Fig. 9. Dynamics of the groundwater level (GWL) increments and daily water exchange (DR) of the soil domains within the desert at different locations that were located at different distances from forest–desert interface for a forest irrigation event that occurred in July 24 to August 2.

3.4. Root distribution and plant growth

The growth of maize was affected by the hydrological links between the farmland and forest, especially for the locations that were near the forest (Fig. 10). The roots of poplar trees in the farmland were primarily distributed within the nearest 6 m from the farmland–forest interface, and could extend to over 10 m in the farmland, indicating that the soil water within the farmland may be absorbed by the extended roots of the trees. However,

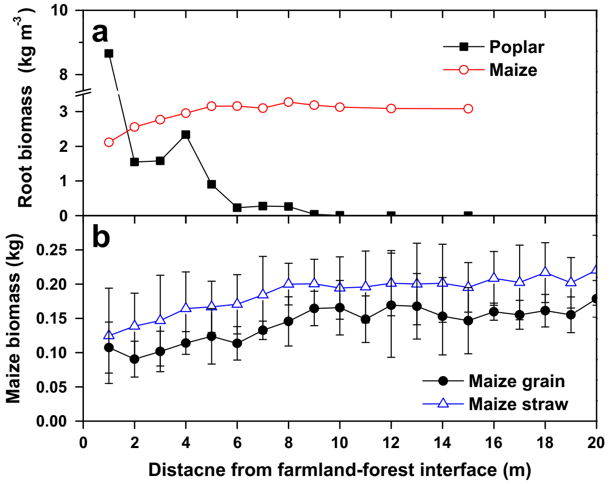

Fig. 10. Root (a) and maize biomass (b) distributions at different locations with different distances from the farmland–forest interface.

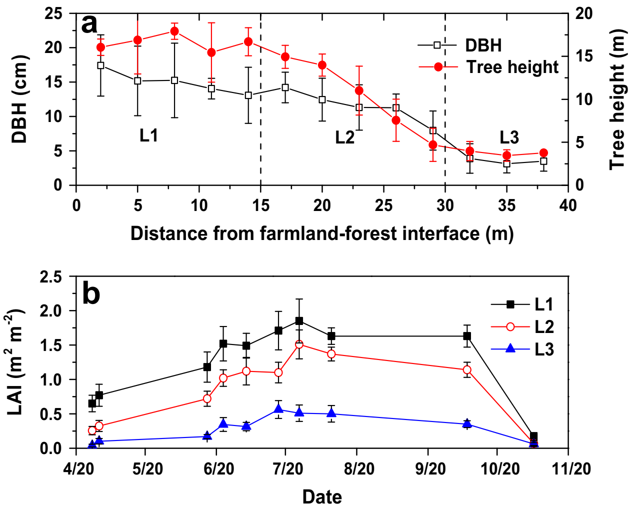

Fig. 11. The diameter at breast height (DBH), the poplar tree height, and the leaf area index of poplar trees (LAI) at different locations within the forest with different distances from farmland–forest interface.

Table 2
Water balance of different locations after one irrigation event in the adjacent land use unit in 2012.

Land use unit (date)	Monitoring site (m)	P (mm)	ET_a (mm)	ΔS (mm)	DR (mm)
Farmland (8.16–8.22)	1	1.2	24.9	−13.2	10.5
	5	1.2	35.5	−14.3	20.0
	15	1.2	42.7	−11.2	30.3
Forest (8.25–9.2)	2	0.8	47.7	−37.7	9.2
	14	0.8	39.0	−42.2	−4.0
	35	0.8	17.3	−28.9	−12.4
Desert (7.24–7.31)	0.5	12.8	12.6	29.4	29.2
	1.5	12.8	10.1	2.4	−0.3
	3.5	12.8	7.6	−6.5	−11.7

P is precipitation and irrigation, ET_a is actual evapotranspiration, ΔS is change in soil water storage, and DR is the water exchange.

the tree roots extended to only about 0.5 m in the desert and mainly distributed within 0–70 cm depths of the soil. By contrast, the roots of maize and desert vegetation were not found within the forest soil. The root, grain, and straw biomass of maize were smaller for the area closer to the farmland–forest interface, with 12%, 33%, and 30% less for the locations at 0–5 m from the interface compared with that at 15–20 m from the interface.

The poplar tree growth was mainly affected by the hydrological links among the transition zone, and partially affected by the position of the forest irrigation channel (Fig. 11). The DBH and height of the poplar trees continuously deceased from the farmland–forest interface to the forest–desert interface. The growth distribution of poplar trees could be divided into three groups: (1) poplar trees with large height and large DBH that decreased slightly within the 0–15 m area, (2) poplar trees that displayed decreased height and DBH within the 15–30 m area, and (3) poplar trees that displayed the lowest values of height and DBH slightly decreased within the 30–37 m area. Compared with the first group, the height, DBH, and LAI of the poplar trees were 37%, 24%, and 32% smaller for the second group and 78%, 79%, and 66% smaller for the third group, respectively.

4. Discussion

4.1. SWC and GWL in different land use units

The increments of SWC and GWL within the different land use units are largely attributed to the irrigation and rainfall events, whereas the decrements of SWC the GWL are mainly attributed to ET_a (i.e., transpiration and evaporation). Irrigation is the primary driving factor for the sharp increases in SWC and GWL in the farmland and forest, indicating that irrigation water is the most important water source for the growth of maize and trees within the study area, as indicated in other studies (Chang et al., 2006; Zhao and Zhao, 2014a). The quick decrements of SWC and GWL observed in the farmland and forest after the irrigation events are attributed to the large ET_a under the well-grown vegetation (Table 2). By contrast, the weak increments of SWC in the desert that occurred in the soil surface are attributed to the rainfall events, whereas the dynamics of SWC in the deep soil layers are caused by GWL fluctuations. This result was not unexpected because it has been previously shown that GWL plays a significant role in the growth of desert vegetation (Sheng et al., 2004; Wang et al., 2007a,b).

The highest SWC in the farmland resulted from the irrigation events and the presence of the relatively shallow GWL that can replenish soil water by the capillarity of the sandy soil with about 40 cm height in our case (Aghajani et al., 2011). The low SWCs in the upper soil layers in the desert during May and after August are attributed to plant water use and lack of rainfall during those periods. The slightly decreased SWC in the 230–270 cm soil layers in the desert is attributed to the decreased GWL and the root water uptake. The roots of sacsaoul may extend up to the 4 m soil depths, as documented in a previous study (Sheng et al., 2004).

4.2. Hydrological links among the transition zone

Our data seem to support the hydrological links among the three land use units in three ways. First, soil water moved from the irrigated land use unit to the non-irrigated one between the two land use unit interfaces under a soil water potential gradient through physical diffusion (Karray et al., 2008). The SWC at the same elevation depth (e.g., 0–10 cm for the farmland and 50–60 cm for the forest) for two closest sites showed large differences (e.g., 0.14 and 0.32 cm^3 cm^{-3} in the farmland and forest when the forest was irrigated on July 24, corresponding to the soil water potential of −243 and −22 cm, respectively), which would lead to soil water movement from the forest to the farmland because of the existence of a soil potential gradient. This lateral soil water flow is also supported by the obviously increased SWC for the 10 cm soil depth in the farmland at 1 m distance to the forest after forest irrigation (e.g., July 24), but minor SWC increase was observed for the 15 m area. The distance affected by the soil potential-driven water exchange (physical diffusion) is normally limited to a few meters because of the relatively low unsaturated hydraulic conductivity when the SWC is low (e.g., 4.72, 0.116, and 0.02 cm d^{-1} when the forest SWCs are 0.20, 0.10, and 0.05 cm^3 cm^{-3}, respectively), consistent with the findings of Karray et al. (2008). Second, the groundwater flowed from the irrigated land use unit to others under the GWL gradient observed among the three land use units, and then moved upward to recharge the soil water following the GWL rise. This groundwater movement resulted in earlier increase in SWC in the lower soil layers than in the upper layers. Some researchers have postulated that this type of recharge for SWC occurs as a preferential subsurface flow pattern (Lin and Zhou, 2008). Third, the soil water in the farmland may have been used by the trees roots that extended into the farmland. Notably, this type of water usage in transition zone has been widely reported by previous researchers (Radersma and Ong, 2004; Sudmeyer et al., 2004; Zhao et al., 2012; Shen et al., 2014).

Researchers (Sudmeyer et al., 2004; Zhao et al., 2012; Shen et al., 2014) have also reported that the extended tree root system in the adjacent land use unit is the primary factor for the hydrological links in an agroforestry system. In another study, quantitative calculations determined that over 50% of the water transpired by the olive trees came from the cropland in a tree-annual crop intercropping system (Karray et al., 2008). In our study, LGF may be the most important pattern of water recharge. As shown in Fig. 6, GWL was maintained at a continuously decreased tendency from the farmland to the desert, with a 0.5 m GWL difference, thereby indicating that the groundwater continuously moved from the farmland to forest and even to the desert. In addition, an obvious LGF rate was identified (Fig. 6b), especially for the movement from the farmland to the desert. By contrast, the lateral physical diffusion rate between the farmland and the forest ranged from $-0.5\ \mathrm{cm\ d^{-1}}$ to $0.5\ \mathrm{cm\ d^{-1}}$, which was obviously smaller than the LGF rate. Compared with other studies (Wildy et al., 2004; Karray et al., 2008; Shen et al., 2014), the hydrological links in our study are particularly attributed to the frequent irrigation and shallow GWL (e.g., about 1.1 m in the farmland), which resulted in a sharp GWL rise when moving across the transition zone between the farmland and the desert and a large GWL gradient observed among the transition zone after irrigation (Fig. 6a). Moreover, the coarse-textured soils characterized by the high hydraulic conductivity in this study greatly facilitated the groundwater flow.

The water exchange between the farmland and the forest was different from that between the forest and the desert (Figs. 7–9 and Table 2). The exchange between the forest and the desert was significant during the first day after the irrigation events in the forest, but subsequently diminished rapidly (Fig. 9). The exchange between the forest and the farmland showed a larger extended distance of groundwater gradient and longer time the GWL increment was maintained at a given level. By contrast, although the amount of water exchange in the desert for the areas adjacent to the forest–desert interface was huge in the first days after the forest was irrigated, the increased GWL and positive DR were maintained for a short period (Fig. 9b). These features are attributed to the high hydraulic conductivity of the sandy soil in the desert combined with disturbed soil from forest surface, which consequently facilitated more rapid water movement (Fig. 6b), resulting in lower SWC values and restricting vegetative growth and water use in the desert.

4.3. Eco-hydrological effects and implications

The water exchange between the farmland and forest by extended tree root system and lateral water flow had negative effects on maize growth. The effects of reduced water (and/or nutrient) availability for maize growth can be observed at about 7 m into the farmland field. Although the effects on growth were clearly apparent, the effects at 7 m distance was less than that observed in other studies (Woodall and Ward, 2002; Sudmeyer et al., 2004). This reduced distance may be attributed to the relatively young age of the trees (i.e., 6 years old) and the frequent irrigation in the farmland and the forest, which resulted in higher SWC at the monitoring locations in the farmland and the forest compared with the SWCs reported previously by other researchers. Higher SWC would help maintain the maize growth and reduce the water uptake by trees from the farmland. The 7 m distance would have been greater if less water was supplied through irrigation within the farmland or the forest.

The water recharge from farmland to the forest or forest to the desert also had an impact on the growth of poplar trees. The growth gradient of the trees in the farmland–treebelt–desert transition zone was identified in our study area. Shen et al. (2014) reported 37-cm DBH values near the farmland and 21-cm DBH values at some distance away from the farmland, which was consistent with our study. For the forest areas closer to the farmland, the trees were evidently able to obtain more water and nutrient through their extended root system into farmland soils. Water exchange also affected the vegetation growth in the desert. However, previous researchers have reported that the hydrological links between the treebelt and the desert were not strictly observed (Shen et al., 2014). This difference may be attributed to the increased number of irrigation events in the forest in this study, which resulted in the soil water near the forest–desert interface within the desert being frequently recharged that is beneficial to the survival and growth of vegetation. More herbaceous plants were observed near the forest–desert interface, and the vegetation quantity decreased with the increase in distance from the forest–desert interface. The increased vegetation was characterized by the increased appearance of plants, such as bulrush and halogeton, which were beneficial for sand fixation in the desert to help prevent desertification.

The lateral water flow among the transition zone is important because the water can be used by the vegetation in the adjacent land use units and result in enhanced irrigation efficiency. An understanding of the hydrological links among the transition zone would provide information to help develop improved water use management techniques for these oasis areas. For instance, the farmland and the forest can be irrigated separately, which will provide reciprocal water recharge between the adjacent land use units and consequently result in improved irrigation efficiency for the whole transition zone. In addition, the separate irrigation scheme in the farmland and the forest leads to smaller GWL gradient between the farmland/forest and desert, which would minimize the potential of water movement to the desert where the ratio of recharged water use from forest irrigation was low. In addition, the width of the forest could be reduced by 15–20 m from the current about 40 m because the effective distance of groundwater recharge in the forest from the farmland irrigation event was limited to 20–25 m (Fig. 6a). Moreover, the trees in the 15–20 m area grew as well as those near the farmland–forest interface, whereas obviously decreased values of DBH and tree height for the poplar trees were observed at distances farther than 20 m. Utilizing an appropriate forest width for the most effective irrigation efficiency can help maintain the healthy growth of trees and reduce irrigation amount within the forest. These apparently simple changes for irrigation efficiency enhancement may result in substantial water resource savings within oasis areas.

5. Conclusions

Based on the SWC, GWL, and vegetative monitoring in a growing period within the farmland–forest–desert transition zone, the hydrological processes among these three land use types were characterized. The associated eco-hydrological effects were identified. Irrigation was the primary factor that influenced the different hydrological processes within the three land use units and resulted in water exchanges among the transition zone. Hydrological links among the three land use types were identified by the lateral water flow caused by the differences in soil water potential and GWL gradients, as well as the extended root system of the poplar tree that was mainly observed in the farmland. The LGF was assumed to be the most important aspect for maintaining the hydrological links. The water exchange between the farmland and the forest (obvious SWC and GWL increment maintained for 1 week could be observed for the area further than 15 m) caused by one irrigation event was more tight than that between the forest and desert (obvious SWC and GWL increment maintained for 1–4 d for the area within 5 m). The weakest water exchange was observed between the farmland and desert because the SWC and GWL in the desert were not sensitive to farmland irrigation events. Obvious eco-hydrological effects were observed among the transition zones, as proven by the growth gradients of maize and poplar trees in the farmland–forest–desert transition zone direction.

This study indicated that irrigating the farmland and the forest separately and reducing the forest width by 15–20 m would be most beneficial for improving irrigation efficiency. These results are helpful to soil water management in terms of water balance effect on ecological construction and the implementation of water-saving agriculture. The results could be also very useful for the optimal design of land-use patterns and the efficient protection of oasis ecosystem to preserve limited water resources. Further studies are needed to distinguish the vertical and lateral water flow (i.e., VF, LF), as well as the extended root water uptake of the forest (i.e., RU), through the use of e.g., isotope tracing and model simulation.

Acknowledgements

This study was financially supported by National Natural Science Foundation of China (91025018, 41371234, 41371233, 41201279), the Chinese State Key Laboratory Fund (K318009902-1427), and the Northwest A&F University Fund (Z111021308, Z111021309). We thank our colleagues for the joined field work and data analysis. Special thanks go to the staff of the Linze CERN station. Drs. Y. Iwata and W. Hu are thanked for their constructive comments that helped to improve the manuscript.

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