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RESEARCH ARTICLE

Hydraulic redistribution in the Inner Mongolia Huangfuchuan basins under different climate scenarios

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Abstract This paper describes the scaling up to a day scale of the Ryel hour scale model incorporating the process of hydraulic redistribution (HR). The Ryel model was applied to the Inner Mongolia Huangfuchuan basins to analyze transpiration, evaporation and stomatal conductance of *Artemisia tridentate*, and to indicate the added value of the feedback by comparing simulations with and without incorporating HR. Five climate scenarios were designed based on 40-y continuous climate data from the study area and the response of HR to the different climate scenarios was modeled. Under 1991 climate conditions, cumulative transpiration and evaporation with HR during the growing season were 161.7 mm and 206.14 mm, respectively, compared with transpiration of 140.7 mm and evaporation of 174.2 mm without HR. Under the five different climate change scenarios, HR influenced evaporation more than transpiration. The effect of HR on transpiration, evaporation and stomatal conductance was very different among the scenarios. Inclusion of HR gave rise to the largest increase in transpiration and evaporation under the T2P0 scenario and the smallest under the T2P2 scenario, but transpiration and evaporation decreased under the T0P-2 scenario. Stomatal conductance significantly increased with the inclusion of HR. The model used in this study has potential benefits for incorporating HR into soil processes, such as water movement and mass transfer.

Keywords climate change, hydraulic redistribution (HR), transpiration, evaporation, stomatal conductance

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1 Introduction

Climate change, as an important part of global change, has been of great concern to scientific researchers in recent years. Global warming is considered to have reached its greatest extent ever and global rainfall patterns have changed synchronously (Deng et al., 2002). The response of terrestrial ecosystems to global climate change and the coupling effect between ecosystems and global change has become a focus (Steffen, 1997; Ni and Zhang, 1998). Each subsystem has also been directly or indirectly influenced by such change. The complex interaction of processes in one important sub-system, the soil-root interface, has been widely studied. Water is a fundamental resource that defines life on this planet, but is often scarce on land. Particularly, soil water has a high degree of spatial and temporal heterogeneity in dry environments (Bauerle et al., 2008; Schenk, 2006).

Studies on water transmission in the soil-plant-atmosphere continuum (SPAC) have received particular attention in recent years. Water movement within the soil column through plant roots has been documented as a widespread phenomenon (Caldwell et al., 1998; Jackson et al., 2000). The upward movement of soil water through roots from wetter deeper layers to drier upper layers was described as “hydraulic lift.” Since then, the reverse movement of soil water downward to drier layers has also been identified, wich can rapidly redistribute rainwater. A growing body of evidence has demonstrated that hydraulic redistribution (HR), the transfer of soil water via plant roots, is common in many ecosystems (Caldwell et al., 1998; Ryel et al., 2002; Ryel et al., 2003). HR through plant roots is a potentially important ecosystem process that can not only increase net primary productivity, but also change the water balance and nutrient cycling in ecosystems (Horton and Hart., 1998; Oliveira et al., 2005). HR has been confirmed as being widespread in plants (Brooks et al., 2002; Hultine et al., 2003; Hultine et al., 2004; Brooks et al., 2006). Experimental investigations with *Artemisia tridentata* have demonstrated that HR appears to increase transpiration rates at least over a period of a few days (Caldwell and Richards, 1989).

Recently, simulation models have been developed to describe vertical movement of soil water, which includes HR by roots. These include a one-dimensional model to simulate the soil water potential (Ryel et al., 2002). Wang et al. (2006) scaled the Ryel model in time and space and then applied the scaled model in the Huangfuchuan Watershed. HR increased water use efficiency of the plant over long time periods (Amenu et al., 2005). Many studies have focused on the ecological consequences of hydraulic lift. Hydraulic lift might enhance transpiration and plant growth during rainless periods by storing water in the otherwise dry rhizosphere that can be accessed by lateral roots during the day (Caldwell and Richards, 1989; Emerman and Dawson, 1996; Caldwell et al., 1998; Lee et al., 2005). HR might also promote plant water conservation by redistributing water deeper in the soil column when it is abundant in near surface soil layers, where it might otherwise evaporate from the soil surface (Ryel et al., 2004; Gao et al., 2006; Xu et al., 2006; Liste and White, 2008; Scott et al., 2008). The behavior of stomata, which regulates transpiration, might also be affected by HR, especially after a certain amount of rainfall, even in drought periods. Stomatal conductance with HR could remain at a higher value than without HR.

In this study, we scaled a soil water dynamic simulation model (the Ryel model) in time and space and applied the model to a *Caragana intermedia* woodland (Ryel et al., 2002; Ryel et al., 2003). We monitored the seasonal patterns of temperature and precipitation for 40 y, designed the five climate change scenarios based on seasonal patterns, and then compared the evaporation, transpiration and stomatal conductance with and without HR under five climate change scenarios. We used the soil water dynamic simulation model to quantify the water movement through *Caragana intermedia* root systems in relation to seasonal patterns of hydraulic redistribution.

2 Material and methods

2.1 Model description

Our model was based on that of Ryel et al. (2002) which simulates vertical movement of soil moisture. Detailed description of the model formulation, parameterization, and validation were described in Ryel et al. (2002, 2003). Changes in water content in the different soil layers were assumed to be due to vertical unsaturated flow, redistribution via roots and transpiration.

2.2 Sensitivity analysis of parameters

Our model included a large number of soil physical and plant parameters. Ryel et al. (2002) analyzed the relationship between root distribution and HR. Root hydraulic conductivity is mainly affected by soil resistance, root-soil interface resistance and root resistance. Any factor affecting soil pore size and shape will affect the soil saturated hydraulic conductivity. We carried out sensitivity analysis of the soil saturated hydraulic conductivity and root hydraulic conductance by setting up gradients. The soil saturated hydraulic conductivity gradients were 0.097, 0.2, 0.5, 0.8, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 5.0 cm/h, and the root hydraulic conductivity gradients were 0.247, 0.5, 1.0, 2.0, 4.0, 6.0, 8.0, and 10.0 cm/(MPa·h). Using each value of root hydraulic conductivity and soil saturated hydraulic conductivity in the model, we calculated the total transpiration over 100 d, as well as the ratio of the redistribution of water to the total transpiration.

2.3 Scale transformation

The major parameters and processes at a given scale tend to become unimportant or uncertain at another, so the parameters obtained at a particular scale were applied to different scales in the same issue, if necessary, we scaled up the model parameters, according to their significance. The main parameters are shown in Table 1. Wang et al. (2006) had verified the result of the model after scaling.

Table 1 Parameter changes of the model when scaling

parameters	Ryel model	scaling model
soil hydraulic conductivity	0.247 cm/h	0.247 × 24 cm/h
root conductivity for water for all roots	0.097 cm/(MPa·h)	0.097 × 24 cm/(MPa·h)
maximum transpiration rate	$\frac{1}{24}$ cm/d	1 cm/d
multiplier for day (1) or night (0)	1 (10 h) – 0 (14 h)	10/24

3 Application

3.1 Data preparation and parameterization of the model

The study was conducted in the Huangfuchuan Watershed of Inner Mongolia (39.46°N, 1171.7°E, 1100 m above sea level). The annual average temperature is 6.2°C, average annual precipitation 368.7 mm, and evaporation 1946.6 mm. There were three main categories of soil: chestnut soils formed from soft rock, and soils formed from Aeolian sand, and loess.

Daily weather records, including precipitation, mean temperature, minimum temperature, maximum temperature, average wind speed and relative humidity, were collected from Shagedu weather station for the period from 1960 to 2000. Rainfall was mainly concentrated in summer in the study area with 61 percent of the annual total rainfall falling from June to August. Rainfall and temperature in 1991 are shown in Fig. 1. Soil data were obtained from nine profiles at a depth of 1m. A LiCor-6400 instrument was used to measure plant-related physiologic data including plant photosynthesis, transpiration and stomatal conductance. The gravimetric soil water content was measured on sub-samples from the soil profile by measuring the weight loss after heating at 105°C for 24 h. These parameters are given in Table 1.

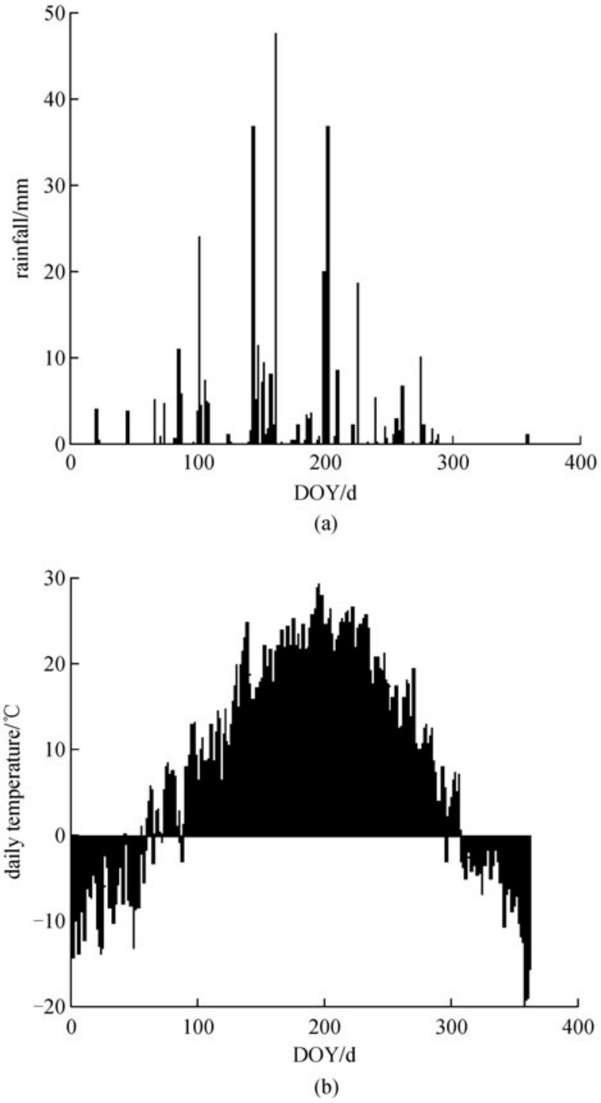

Fig. 1 Daily temperature and rainfall in 1991

3.2 Scenarios and simulation

HR can rapidly redistribute rainfall according to its intensity and root distribution (Horton and Hart, 1998). Climate scenarios are often used in climate change sensitivity analysis. Popular climate scenario methods include analog analysis of historical data, the reconstruction and analysis of paleoclimate data, comprehensive scenario setting, GCMs outputs and weather generator systems (Xu et al., 2006). This paper used comprehensive scenario setting, which is suitable for small-scale research, to reflect the possibility of climate change in the future, and then analyzed the response of hydraulic redistribution to climate change. A total of five climate change scenarios were used in this study, with the different scenarios being shown in Table 2. The model was initialized with a set of typical state variable values (Jia et al., 2005). Transpiration and evaporation with HR and without HR were simulated under each of the five scenarios and the model output statistically analyzed.

Table 2 Design of different climate scenarios

climate scenarios	climate change schemes
T0P0	the current climate scenario specified by the climatic condition of 1991
T0P2	daily precipitation increased 20% with temperature invariant
T0P-2	daily precipitation decreased 20% with temperature invariant
T2P0	daily temperature increased 20% with precipitation invariant
T2P2	daily temperature increased 20% and daily precipitation increased 20%

4 Results

4.1 Sensitivity analysis of parameters

The results of sensitivity analysis are shown in Figs. 2 and 3. Over 100 d, when the root hydraulic conductivity was less than 1 cm/(MPa·h), total transpiration with HR increased with the increasing root hydraulic conductivity. However, when the root hydraulic conductivity was bigger than 1 cm/(MPa·h), total transpiration with HR decreased. At a lower root hydraulic conductivity, HR could make up for the rate of absorption and transmission of water. At larger hydraulic conductivities, water absorption and transmission would be very fast, and the distribution of soil water uniform and HR limited. At the same time, the soil water was used relatively rapidly, but the soil water content was limited, plant transpiration limited, and the total amount of transpiration decreased over a period of time. With increasing root hydraulic conductivity, the ratio of redistributed water to the total transpiration gradually increased, because both transpiration and HR had soil water limitations at the same time. However, once the root hydraulic conductivity increased above about 1 cm /(MPa·h), the ratio tended to remain relatively constant at about 0.8.

Over 100 d, the total transpiration increased with increasing soil saturated hydraulic conductivity both with

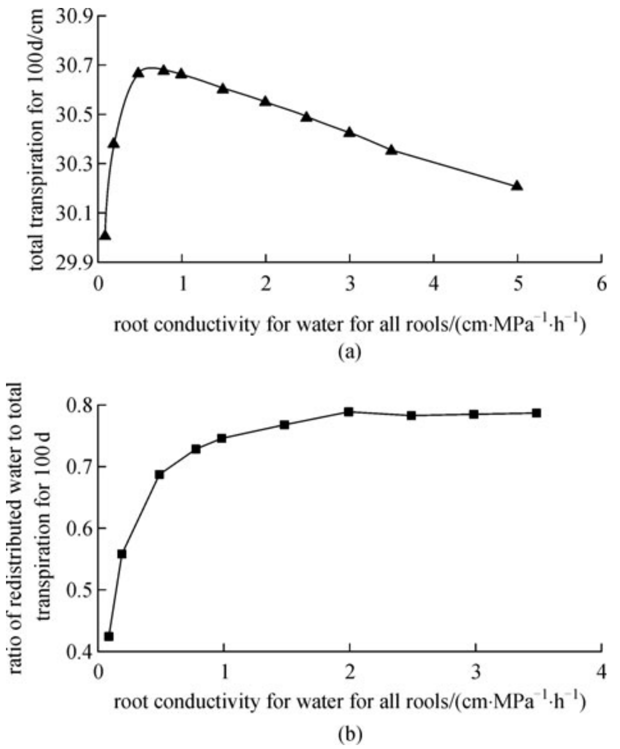

Fig. 2 Total transpiration (a) and ratio of water redistributed by roots (b) to total transpiration for 100 d with root water conductance

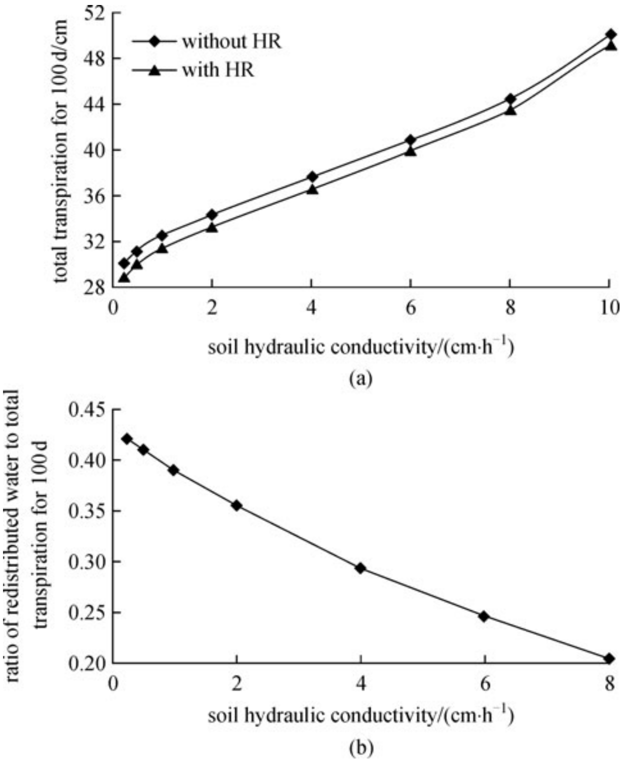

Fig. 3 Total transpiration (a) and ration of water redistributed by roots (b) to total transpiration for 100 d with soil hydraulic conductance

HR and without HR. Both showed very similar rates of change (Fig. 3(a)). This shows that the effect of soil saturated hydraulic conductivity on transpiration was similar regardless of considering HR or not. There was a strong negative correlation between transpiration and the soil saturated hydraulic conductivity. Increased soil saturated hydraulic conductivity led to an increase in the unsaturated water flow, leading to a more even relative distribution of soil water at all levels, thereby reducing the impact of HR.

4.2 Impacts of HR on evaporation and transpiration under five scenarios

Figure 4 and Table 3 show the impacts of HR on evaporation and transpiration under five scenarios. The left-hand side of Fig. 4 showed the change of temperature and rainfall under the five scenarios, while the right-hand side showed evaporation and transpiration with HR and without HR. The general trend of changes in transpiration and evaporation was consistent with precipitation changes under the five scenarios, with transpiration and evaporation reaching a maximum when precipitation decreased. Both transpiration and evaporation with HR remained unchanged for some time compared with those without HR.

Table 3 Transpiration and evaporation under five climate scenarios with HR and without HR

climate scenarios	transpiration/cm		evaporation/cm	
	with HR	without HR	with HR	without HR
T0P0	161.7	140.7	206.14	174.2
T0P2	205.5	195.3	200.9	185.5
T0P-2	90.12	102.2	174.4	177.3
T2P0	172.8	139.1	226.4	182
T2P2	104.7	101.5	223.3	215.2

Without HR, transpiration was largest at 195.3 cm under the T0P2 scenario, and smallest at 101.5 cm under the T2P2 scenario. Evaporation was largest at 215.2 cm under the T2P2 scenario, and smallest at 174.2 cm under the T0P0 scenario. With HR, transpiration was largest at 205.5 cm under the T0P2 scenario, and smallest at 90.1 cm under the T0P-2 scenario, while evaporation was largest at 226.4 cm under the T2P0 scenario, and smallest at 174.4 cm under the T0P-2 scenario. Comparing the accumulated transpiration and cumulative evaporation with HR and without HR, we found that HR increased the accumulated transpiration from 3.2% to 14.9%, and the cumulative evaporation from 3.8% to 24.4% under four scenarios (T0P0, T0P2, T2P0, T2P2). Under the T0P-2 scenario, HR decreased the accumulated transpiration by 12.08 cm (13.4%), and the cumulative evaporation by 2.9 cm (1.7%).

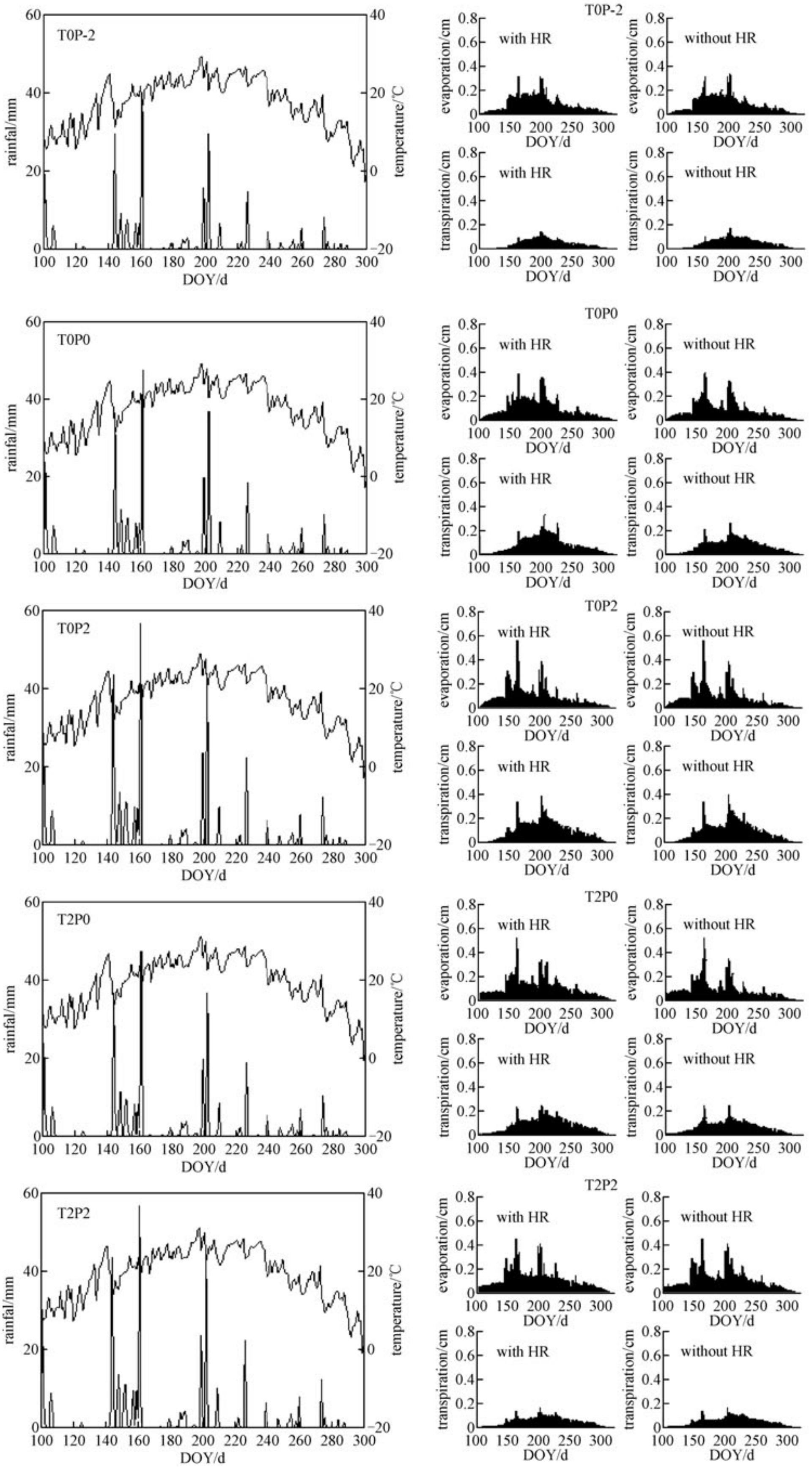

Fig. 4 Evaporation and transpiration in 1991's growing seasons under different climate scenarios (left: climate scenarios, meaning as Table 1; right: corresponding Ev and Tr)

Inclusion of HR increased transpiration and evaporation under four of the five different climate change scenarios in the order: T2P0 > T0P0 > T0P2 > T2P2. However, inclusion of HR decreased transpiration and evaporation under the T0P-2 scenario.

4.3 Impacts of HR on stomatal conductance under five scenarios

Figure 5 shows the impacts of HR on the stomatal conductance under the five climate scenarios. Under the T0P0 scenario (the 1991 climate conditions), the difference in stomatal conductance fluctuated after the bigger rainfall incidents. Differences in stomatal conductance with HR were significantly higher than those without HR under three scenarios (T0P0, T2P0, and T0P2) with the differences being larger in the latter part of the growing season. Under the T0P-2 scenario, the difference in stomatal conductance was generally less than zero, especially in the latter part of the growing season. Stomatal conductance without HR was much greater than that with HR at the same time, with a larger decline in the difference after day 200, which might be related to high transpiration during the mid-growing season. Under scenario T2P2, the difference in stomatal conductance remained steady after a larger difference in stomatal conductance in the early growing season when stomatal conductance with HR was far greater than that without HR. Subsequently, differences in stomatal conductance reduced and remained flat through the rest of the growing season. As a whole, the effect of HR and climate change on stomatal conductance was complex, but significant changes were present in the mid and latter parts of the growing season. Different rainfall intensities greatly influenced the effect of HR, because high-intensity rainfall will influence HR for a longer time than a low-intensity event and cause bigger differences between the simulations with HR and without HR.

5 Discussion

This paper scales the Ryel model and applies it to a *Caragana intermedia* woodland under five climate scenarios. Comparing simulations of the *Caragana intermedia* woodland with HR and without HR demonstrates that *Caragana intermedia* can rapidly redistribute rainfall downwards in rainy periods and lift water from deeper soil layers to topsoil horizons in dry seasons (Jackson et al., 2000; Ryel et al., 2002; Ryel et al., 2003; Liste and White, 2008). HR can affect the transpiration, evaporation and stomatal conductance but, at the same time, HR had different responses to different climate change scenarios.

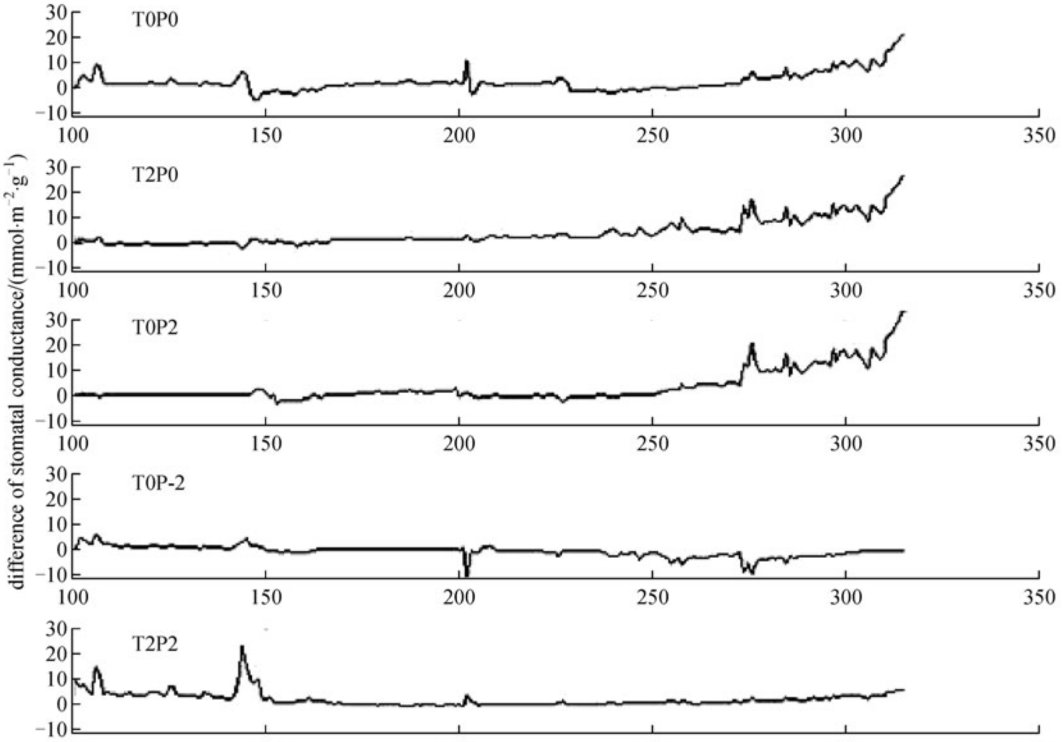

Fig. 5 Response of stomata conductance to HR under different climate in 1991’s growing season

This result has also been drawn in previous studies (Ryel et al., 2002; 2003; Bauerle et al., 2008). Comparison of simulations with and without HR using the 1991 climate scenario (T0P0) indicated that transpiration and evaporation increased when HR was included, implying that HR affects the water cycle in the soil-plant-atmosphere continuum (SPAC). Simulations which do not take into account the impacts of HR are therefore not reasonable.

Both simulated transpiration and evaporation for the *Caragana intermedia* woodland under the T0P0 scenario are comparable to those obtained by Jia et al. (2005) and are also similar to those calculated by Ryel et al. (2002). The simulated transpiration and evaporation values with HR were much higher than those without HR, implying that HR has a considerable impact on the hydrological cycle in terrestrial ecosystems. However, there is still a long way to go to clarify the patterns of use and redistribution of soil water by plant species.

The 1991 climate scenario (T0P0) produced model values for transpiration and evaporation with HR, which were 161.7 cm and 206.14 cm, respectively. These values were 14.9% and 18.3% greater than those calculated for the cases without HR during a simulated summer growing season. Under the five climate scenarios, the increase in transpiration and evaporation was largest under the T2P0 scenario and smallest under the T2P2 scenario while the values decreased under the T0P-2 scenario. The results show that the effect of HR on water movement is controlled by rainfall or soil water content.

Stomatal conductance with HR was significantly higher than that without HR after high-intensity rainfall, with particular differences apparent in the latter half of the growing season. The intensity of rainfall had a bigger influence when HR was included in the simulations because of the impact of a longer time and greater rainfall intensity on stomatal conductance.

HR, as a water movement process, can alter the water balance of entire ecosystems and regions, and hence can directly or indirectly influence ecosystem processes and patterns (Espeleta et al., 2004). Variation in rainfall and rising temperature are hot spots of climate change. This study provides quantitative changes in transpiration, evaporation and stomatal conductance with HR and without HR simulations under five climate scenarios. The results show that HR responds differently under different climate scenarios. While climate change has a strong effect on HR, HR may modify the seasonal climate in a particular area (Lee et al., 2005). Therefore, along with the next steps toward the application of HR, the response and effects of climate on HR could be further explored and assessed with including the effects of HR on material transportation and energy transmission.

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