Simulating the evolution of potential natural vegetation due to long-term climate change and its effect on the water balance of the Hanjiang River basin, China

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Abstract The dynamics of potential natural vegetation in the 21st century and its possible impact on the water budget of the Hanjiang River basin were assessed in this study. Based on the predictions of the IPCC-SRES climate scenarios from the PRECIS regional climate model, changes in plant functional types (PFTs) and leaf area index (LAI) were simulated via the Lund-Potsdam-Jena dynamic global vegetation model. Subsequently, the predicted PFTs and LAI were used in the Xinanjiang vegetation–hydrology model for the rainfall–runoff simulations. The results show that in the 21st century the forest PFTs will be gradually degraded and replaced by the grass PFT, and overall the basin-averaged LAI will decrease. Accordingly vegetation transpiration and evaporative loss of the intercepted canopy water will tend to drop, while soil evaporation may rise sharply. As a result, total evapotranspiration will increase moderately, with a slight increase in annual runoff depth. These both result from higher annual precipitation.

Key words vegetation; climate change; LPJ-DGVM; Xinanjiang hydrologic model

INTRODUCTION

Terrestrial vegetation plays a pivotal role in regional energy and water cycles. While natural vegetation is an indicator of local climate and long-term climate change may lead to corresponding changes in vegetation. Therefore, understanding long-term hydrological predictions under various climate change scenarios must include and analyse future changes in vegetation cover. Various studies have been carried out to predict the possible hydrological responses to future climate change in river basins in China (Su *et al*., 2003; Yuan *et al*., 2005). These studies mainly focus on the use of general circulation models (GCMs) or regional climate models (RCMs) combined with hydrological models to evaluate the direct impacts of climate change on hydrology. However, changes in vegetation cover associated with climate change and the subsequent impacts on regional water balances have not been investigated in detail.

This study develops a method to evaluate how long-term climate change leads to possible changes in potential natural vegetation and further influences future hydrological cycles. Transitions in natural vegetation were simulated using the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model, and the simulated plant functional types (PFTs) and leaf are index (LAI) were used as the input for the Xinanjiang vegetation–hydrology model for the rainfall–runoff simulations.

MODELS

The Lund-Postdam-Jena dynamic global vegetation model (LPJ)

LPJ is a coupled biogeography–biogeochemistry model that has process-based representations of large-scale terrestrial vegetation dynamics and land–atmosphere carbon and water exchanges (Sitch *et al*., 2003). Key ecosystem processes described in the model are seasonal vegetation growth, primary production, plant water productivity, mortality, carbon allocation, and resource competition. To account for variations in structure and function among potential natural plants, 10 PFTs are determined by physiological, morphological, phenological, bioclimatic and fire-response attributes. Seasonal phenology of natural vegetation is dynamically simulated according to the variation of temperature and soil moisture (Sitch *et al.*, 2003). Biomass production is calculated through a coupled photosynthesis–water balance scheme that explicitly considers the mutual dependence of transpiration and carbon uptake (Gerten *et al.*, 2005).

The Xinanjiang vegetation–hydrology model

The Xinanjiang vegetation–hydrology model (Yuan & Ren, 2009) is a modified version of the conceptual Xinanjiang rainfall–runoff model developed by Zhao (1992), which has been successfully applied and widely used for flood forecasting, water resources estimation, design flood and field drainage, and water quality accounting. This spatially-distributed conceptual hydrological model is characterized by the concept of saturation runoff formation on the repletion of soil moisture storage. It uses a runoff parameterisation scheme similar to the original Xinanjiang model to calculate overland flow, interflow and base flow on each grid cell. It employs the Muskingum-Cunge method to route the runoff from each grid cell to the watershed outlet. To consider the effects of land–surface characteristics on hydrological processes, the Xinanjiang vegetation–hydrology model uses the two-source evapotranspiration scheme (Mo *et al.* 2004; Yuan *et al.*, 2008) to calculate the canopy transpiration on the dry vegetation canopy, evaporation of the intercepted water on the wet vegetation canopy, and soil evaporation for various vegetation types. The kinematic wave method is adopted to describe the effect of vegetation on overland flow movement, in which the Manning roughness coefficients are assigned according to various vegetation types.

SIMULATION DESIGN

The Hanjiang River basin in central China was selected to test the LPJ model. This river is the longest tributary of the middle reaches of the Yangtze River and has a drainage area of 1.59×10^5 km^2. The basin has a subtropical monsoon climate and is rich in water resources. The upper reaches of the Hanjiang River are to become the source area for the middle route in the South-to-North Water Diversion Project, which attempts to alleviate water shortages in northern China.

Climate predictions from the regional climate model PRECIS (providing regional climates for impacts studies) were used to drive the LPJ model for simulating potential natural vegetation dynamics on the 0.5-degree grid cells in the Hanjiang River basin. Five climate scenarios were adopted: baseline (1961–1990), and future scenarios A1, A2, B1 and B2 (1991–2100) that are future emission storylines in the Intergovernmental Panel on Climate Change (IPCC) special report on emission scenarios. These PRECIS outputs contain daily precipitation, daily maximum

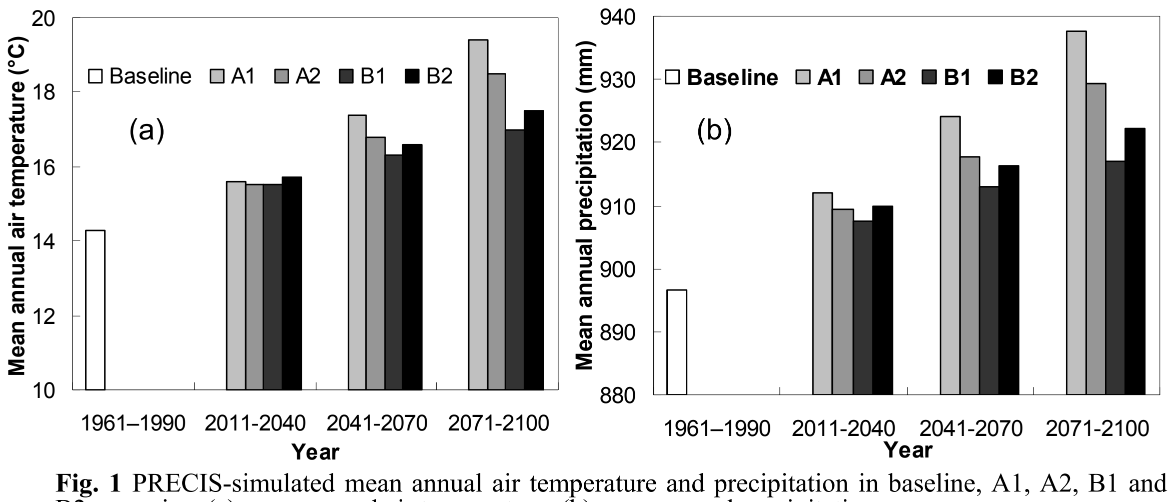

Fig. 1 PRECIS-simulated mean annual air temperature and precipitation in baseline, A1, A2, B1 and B2 scenarios: (a) mean annual air temperature, (b) mean annual precipitation.

and minimum air temperature, and daily cloud cover. Compared with the baseline years (1961–1990), PRECIS predicts an increase of 2.7–5.1°C in the basin-averaged annual air temperature in all future scenarios by the end of the 21st century (Fig. 1). In addition, basin-averaged annual precipitation also tends to rise in all future scenarios (Fig. 1). However, the Mann-Kendall trend test (Kendall, 1975) was conducted on the monthly precipitation time series in 1991–2100 in the A1, A2, B1 and B2 scenarios. It shows that precipitation increases remarkably in the period of January to May, while it tends to drop from July to October (Yuan, 2006).

The CO_2 fertilization effect was not considered in this study. We kept the atmospheric CO_2 concentration at 1960s levels (317.2 ppm) for the whole simulation period (1961–2100). The simulated PFTs and their leaf area indices (LAIs) in the five climate scenarios were computed by the LPJ model. Subsequently, the LPJ-simulated PFTs and LAIs were used in the Xinanjiang vegetation–hydrology model for the rainfall–runoff simulations in the A1 scenario. Two hydrological simulation schemes were adopted: (1) *simulation with vegetation change* and (2) *simulation without vegetation change*. Scheme 1 assumes that vegetation dynamically changes in the long-term climate change and uses the annually-updated PFT cover percentage and monthly LAIs from LPJ for the hydrological simulation in the A1 scenario; while Scheme 2 neglects the possible change in natural vegetation due to long-term climate change and assumes that the spatial distribution of vegetation covers in A1 is time-invariant and is the same as that in the baseline years for the rainfall–runoff computation. Water budgets in these two simulation schemes were analysed and compared with each other.

NUMERICAL SIMULATIONS

Present-day natural vegetation

LPJ simulates that in the baseline years (1961–1990) the temperate needle-leaved evergreen PFT, temperate broad-leaved evergreen PFT, temperate broad-leaved summergreen PFT and temperate herbaceous PFT are the four major natural vegetation types in the Hanjiang River basin. These vegetation types occupy 12.9, 3.4, 69.7 and 14% of the total basin area, respectively. To validate the LPJ model, the LPJ-simulated present-day natural vegetation data were converted to the same format as that of the global potential vegetation data set developed by Ramankutty & Foley (1999). The spatial distribution of the LPJ-simulated dominant natural vegetation types in the baseline years, basically agrees with that of the global potential vegetation data set, although a large discrepancy exists in the spatial pattern of the mixed forest type (Fig. 2).

Natural vegetation changes in the 21st century

The rise in annual air temperature and the drop in summer–autumn precipitation are the main driving force of PFT change in the Hanjiang River basin in the 21st century. As described above, although annual precipitation in the whole basin is predicted to rise in all future climate scenarios,

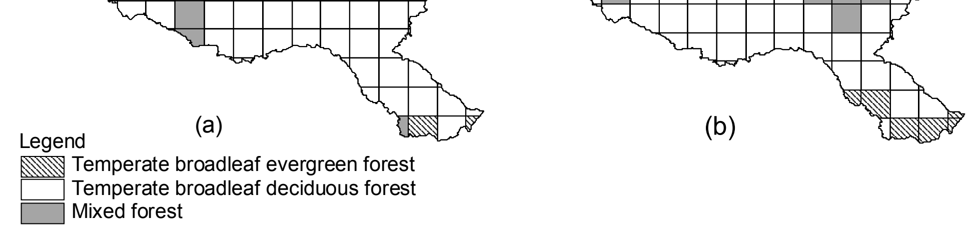

Fig. 2 Spatial distribution of the LPJ-simulated dominant vegetation types: (a) and the global potential vegetation data set (Ramankutty & Foley, 1999), (b) in the baseline years (1961–1990).

precipitation is predicted to decrease during the months of July to October, and this is the main growing season for most natural vegetation in the Hanjiang River basin. In general, during the growing season plants tend to consume more soil water to maintain growth and physiological demand. The reduction in summer–autumn precipitation in the future climate scenarios would therefore lead to a deficit of soil moisture in the growing season. Meanwhile, as air temperature increases, the atmospheric demand for evapotranspiration is also enhanced, which will further deteriorate the soil moisture deficit and further threaten the survival of the forest PFTs. As a result, the percentage of forest cover in the Hanjiang River basin is predicted to decrease gradually in all four future climate scenarios compared to the baseline years (Fig. 3). For example, 2071 is predicted to be much drier and warmer, with an annual air temperature of 20.1°C and annual precipitation of 771.1 mm and an associated forest cover expected to be 48.6% in the A1 scenario. This is the lowest predicted forest cover in the 21st century. With the reduction of the forest PFTs, the herbaceous PFT tends to increase in the Hanjiang River basin (Figs 4 and 5(d)). The model outputs indicate that the rise in annual air temperature and the reduction in summer–autumn precipitation would result in the degradation of the forest PFTs, leading to the establishment and succession of the herbaceous PFT in the Hanjiang River basin.

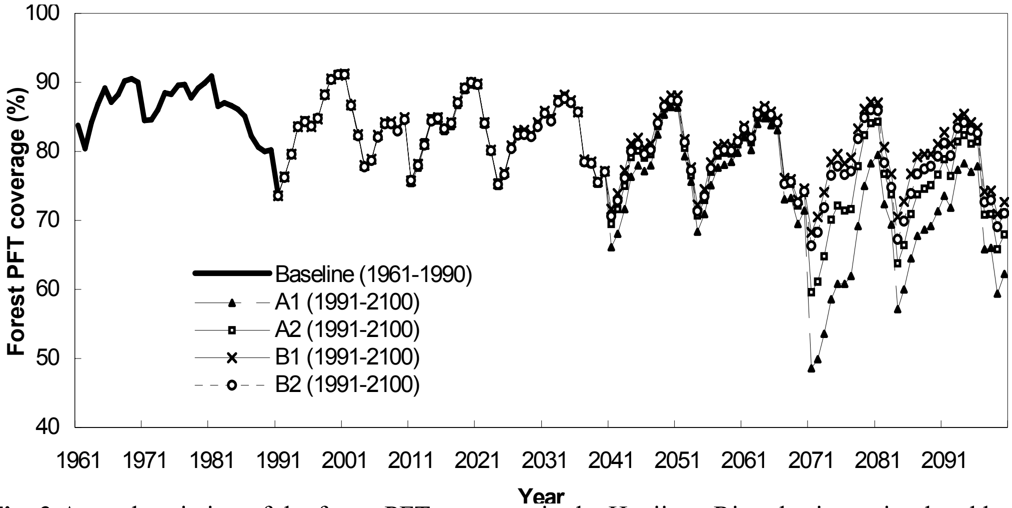

Fig. 3 Annual variation of the forest PFT coverage in the Hanjiang River basin as simulated by the LPJ model.

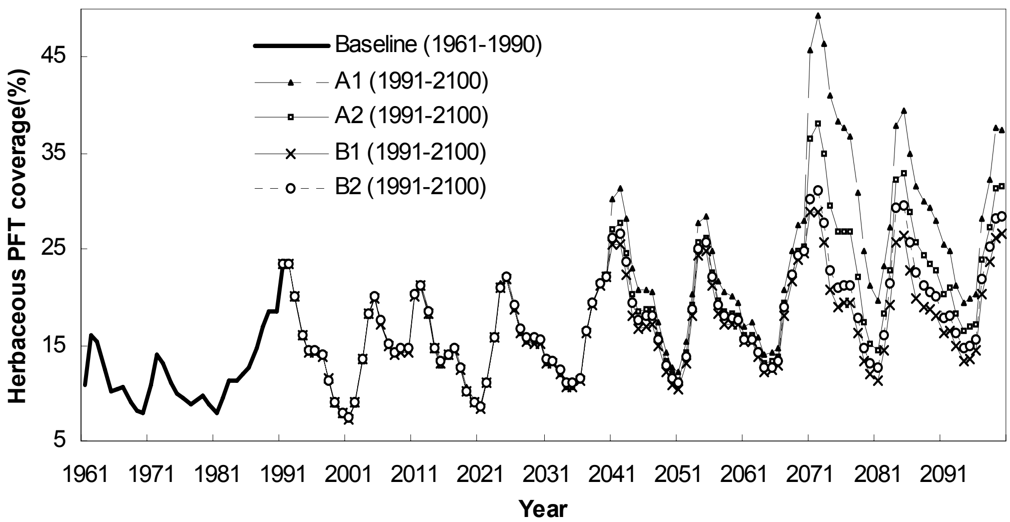

Fig. 4 Annual variation of the herbaceous PFT coverage in the Hanjiang River basin as simulated by the LPJ model.

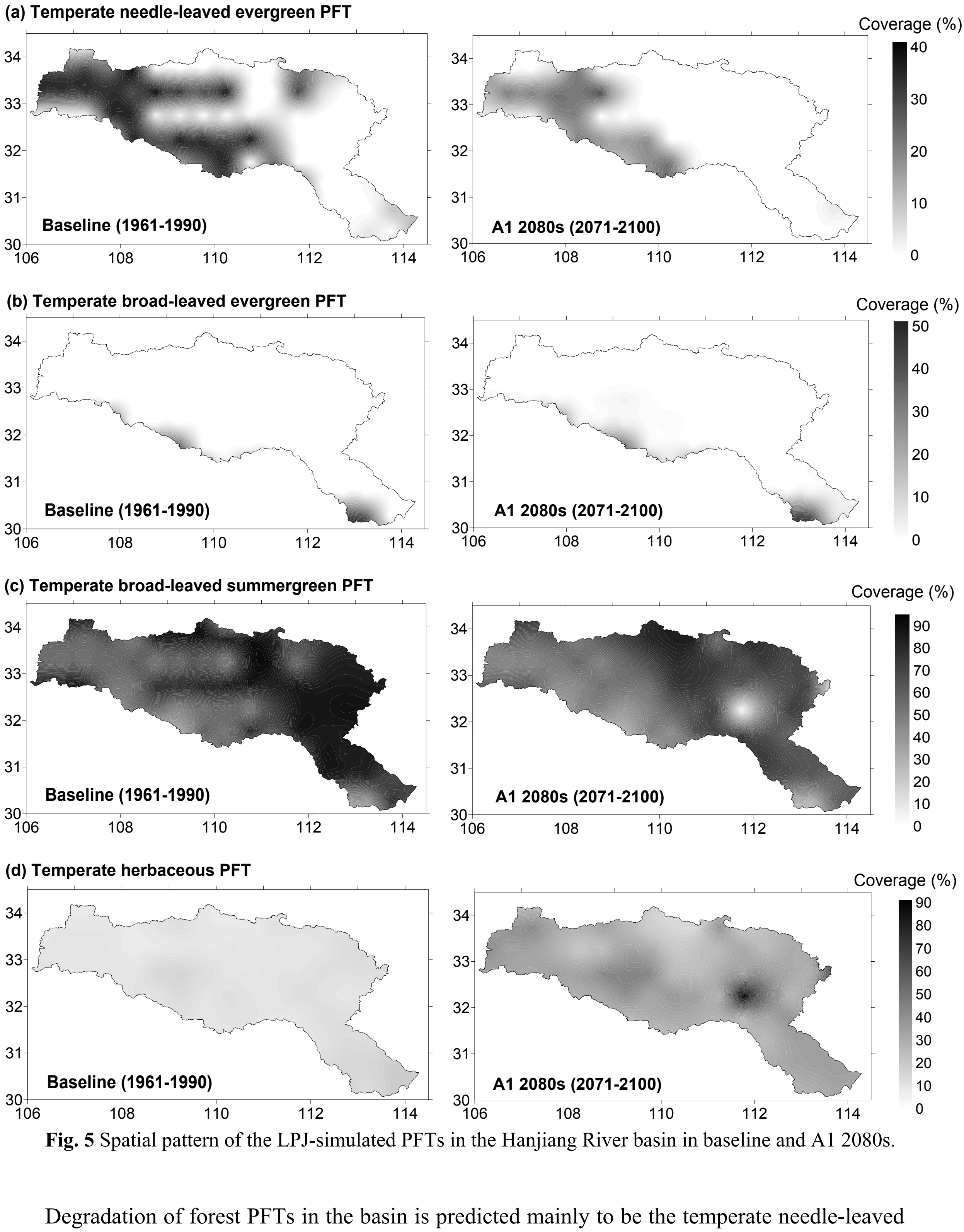

Fig. 5 Spatial pattern of the LPJ-simulated PFTs in the Hanjiang River basin in baseline and A1 2080s.

Degradation of forest PFTs in the basin is predicted mainly to be the temperate needle-leaved evergreen forest and temperate broad-leaved summergreen forest (Fig. 5(a),(c)). The percentage of these two forest PFTs is reduced sharply in the entire watershed in A1 2080s (2071–2100) as compared with that in the baseline years. However, the establishment of the temperate broad-leaved evergreen PFT strongly depends on the air temperature, and the rise of the air temperature may promote the growth of this PFT. Figure 5(b) shows that the temperate broad-leaved evergreen

PFT is mostly distributed in the south of the watershed and the percentage of this PFT cover increases from 3.4% in the baseline years to 4.2% in A1 2080s.

A comparison of the LPJ-simulated basin-averaged monthly LAIs in the baseline years (1961–1990), A1 2020s (2011–2040), A1 2050s (2041–2070) and A1 2080s (2071–2100) is given in Fig. 6. This shows that the forest PFTs, with denser canopies, are gradually succeeded by the herbaceous PFT, with sparser canopies. The basin-averaged monthly LAIs in the A1 scenario also decrease by degrees.

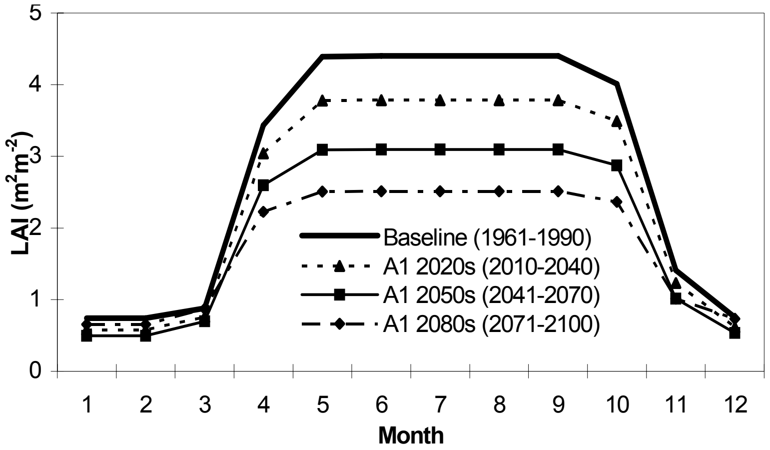

Fig. 6 Monthly variation of the basin-averaged LAIs in baseline, A1 2020s, A1 2050s and A1 2080s as simulated by the LPJ model.

Hydrological changes in the 21st century

The LPJ-calculated hydrological variables, such as the mean annual evapotranspiration, canopy transpiration, evaporation of the canopy intercepted water, soil evaporation and runoff depths in A1 in the two hydrological simulation schemes are compared with each other (Table 1). In the scheme *simulation without vegetation change*, the percentage of forest cover in A1 is at a very high level, 86%, the same as that in the baseline years. Therefore, in A1 2020s, 2050s and 2080s, the evapotranspiration components are in a relatively stable proportion of the total actual evapotranspiration. The canopy transpiration, the interception evaporation and the soil evaporation occupy 27.2–27.5%, 25.1–27.8% and 47.5–53.5% of the total evapotranspiration, respectively. In the scheme *simulation with vegetation change*, the forest PFTs are gradually replaced by the herbaceous PFT. Accordingly, the ratios of the canopy transpiration and the interception evaporation to the total evapotranspiration decrease from 24.7% and 22.8% in A1 2020s to 16.4%

Table 1 Comparison of the calculated hydrological variables in the A1 scenario with vegetation change and those without vegetation change.

Hydrological Variables	Simulation without vegetation change: 2020s	2050s	2080s	Simulation with vegetation change: 2020s	2050s	2080s
P (mm)	912.0	924.1	937.6	912.0	924.1	937.6
AE (mm)	522.1	543.5	565.9	523.2	534.7	544.7
EC (mm)	142.9	143.5	141.8	128.9	109.7	85.6
EI (mm)	131.1	137.7	145.0	119.0	112.8	106.8
ES (mm)	248.1	262.3	279.1	275.3	312.2	352.3
R (mm)	389.9	380.6	371.7	388.8	389.4	392.9

Note: P is the mean annual precipitation (mm), AE is the mean annual actual evapotranspiration, EC is the mean annual canopy transpiration, EI is the mean annual evaporation of the intercepted water on canopy (mm), ES is the mean annual soil evaporation (mm) and R is mean annual runoff depth (mm).

and 20.5% in A1 2080s, respectively; while the soil evaporation increases remarkably by 77 mm in A1 2080s as compared with that in A1 2020s. In terms of the scheme *simulation without vegetation change*, the total evapotranspiration represents a little higher increase than the precipitation does; the runoff depth is in a minor decrease in A1 2050s and 2080s as compared with that in A1 2020s. However, the situation in the scheme *simulation with vegetation change* is different. An increase in the total evapotranspiration is lower than precipitation, but runoff depth tends to gently increase.

CONCLUSIONS AND DISCUSSION

The predicted evolution of potential natural vegetation in the 21st century and its effects on the water budgets of the Hanjiang River basin were assessed via the one-way coupling of the LPJ dynamic global vegetation model and the Xinanjiang vegetation–hydrology model. The simulation results show long-term climate change may generate pronounced changes in natural vegetation in terms of PFTs and LAIs. This vegetation change may further influence the regional water balance. Therefore, for long-term hydrological prediction, change in vegetation cover cannot be neglected since the terrestrial biosphere plays an important role in land surface hydrological responses.

The study area, the Hanjiang River basin, is a very important agricultural region in China. Thus in addition to natural vegetation cover, the dynamic of agricultural croplands should also be considered in evaluating current and future water resources. Furthermore, in the near future, the CO_2 fertilization effect should also be taken into account for assessing the vegetation dynamics and hydrological responses.

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