WATER BALANCE OF AFFORESTATION ON FORMER AGRICULTURAL ARABLE LAND IN THREE GORGES RESERVOIR AREA OF CHINA

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中国三峡库区退耕造林地水量平衡研究

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Abstract: *A SVAT model (CoupModel) was used to simulate water balance from two forest stands and one arable stand throughout growing season (from May to October) in 2008 and 2009. Measurements included soil moisture and the collection of precipitation, canopy throughfall and stem flow. Simulated soil moisture agreed well with daily FDR-measurements and the R^2 was 0.73–0.91, namely CoupModel had good validation in this region. Results showed that the total evapotranspiration from May to the end of October was estimated to be 824 mm, 815 mm and 790 mm for oak (Lithocarpus glaber), Chinese fir (Cunninghamia lanceolata) and maize (Zea mays), respectively. Deep percolation (or water recharge) declined from approximately 352 mm in maize arable land to 271 mm for oak and 297 mm for Chinese fir forest, mainly due to differences in the interception loss. Compared with the arable land, simulated interception was increased by 87% for oak and 70% for Chinese fir (88 mm to 114 mm) forest. The simulations indicated that tree species also influenced the magnitude of water balance components in SVAT system, calling for further attention on the selection of tree species in future afforestation, particularly when such projects aiming to keep water infiltrating to the groundwater zone.*

Keywords: *Afforestation; the Three Gorges Reservoir area (TGRA); oak; Chinese fir; maize; evapotranspiration; deep percolation*

摘要: *应用SVAT模型（CoupModel）模拟了 2008年和2009年生长季（5–10月）2 个林地和1个农地样 地的水量 平衡。测量变量包括土壤水分、降雨、穿透降雨和树干茎流。土壤水分模拟值与FDR实测值拟合效果较好，决定系数（R^2）为 0.73–0.91， 该模型在本地区得到良好验证。模拟结果表明，石栎阔叶林（Lithocarpus glaber）、 杉木针叶林 （Cunninghamia lanceolata） 和玉米农田（Zea mays）5–10 月总蒸散量分别为 824 mm、815 mm 和 790 mm。 造林后深层渗透量（或地下水补给量）由农地的 352 mm减小到石栎林 271 mm 和杉木林 297 mm， 这主要是由于林冠对降雨截留量的增加作用。与农田相比，石栎林和杉木林冠层截留量分别增加87%和 70%（88 mm到 114 mm）. 模拟结果表明树种对水量平衡亦有影响， 在以提高地下水补给为目标的造林地区应注意树种的选择*

关键词: *造林；三峡库区(TGRA)；石栎；杉木；玉米；蒸发散；深层渗透*

INTRODUCTION

The Three Gorges Dam is one of the largest hydroelectric scheme in the world. With the construction of this huge project, human's interference and destruction inevitably impacted the natural ecosystem of the Three Gorges Reservoir area (TGRA) [1]. Influenced by the climatic change, the expansion of inundated area, as well as the migration project, vegetation degradation and floods and droughts in this region were becoming more and more serious. TGRA was a typical case in terms of the complexity of the natural environment and the fragility of ecosystems in China [1]. Since 1989, the Chinese Central Government enacted a series of policies, such as the Natural Forest Protection Project and the Shelter–Forest Construction Project in the Upstream and Midstream of the Yangtze River, and much effort was made on vegetation restoration to reduce soil and water loss, protect the water source and withstand natural disasters. Benefit from these policies, much of the inefficiently cultivated land (especially slope lands) was converted to forest in this region. By 2000, afforested areas had reached 6.74 million hm^2, forest coverage rate had changed to 25% from 19.9%, and the soil erosion area had been reduced by 42% [2]. Most studies are limited to the effect of afforestation on runoff or sediment, nevertheless, quantitative analyses on water balance and water consumption after afforestation also can provide important information on vegetation restoration or forests managements in TGRA.

引言

作为举世瞩目的巨大工程，三峡工程建设中人类的干扰和破坏将不可避免地加载到三峡库区陆地生态系统上[1]。气候变化的影响、库区淹没面积的不断扩大、移民工作的不断深入，导致该地区植被生态退化严重、水旱灾害频发，三峡库区也成为中国生态环境最为脆弱的区域之一[1]。自1989年，中国政府实施了一系列植被恢复政策以保护水源地、减少水土流失、抵御水旱灾害，如天然林保护工程、长江中上游防护林工程等。得益于这些措施，部分效率低下的农田（尤其是坡耕地）实施了森林恢复措施。截至2000年，该地区造林674万hm^2，森林覆盖率由80年代末的19.9%提高到25%，土壤侵蚀总面积减小42%[2]。但是，大多数文献仅集中于造林对径流和泥沙等分部过程的影响进行研究，而定量分析造林对土壤–植被–大气系统水量平衡的变化以及植被耗水特征的研究，对于指导三峡库区植被恢复与建设具有重要意义。

Traditionally, the components of water balance, especially soil evaporation and transpiration, are technically complicated and associated with uncertainty in measurement procedure under field conditions. One way to quantify the constituents of water balance in forest ecosystems is to use water transfer models based on soil, vegetation, and atmosphere characteristics (SVAT models). The CoupModel is a process–based SVAT model for simulating thermal and hydrological processes and the corresponding biological processes that regulate carbon and nitrogen transfer in the soil–plant–atmosphere system [3]. Recently, Ladekarl et al. [4], Christiansen et al. [5], Schmidt–Walter and Lamersdorf [6] all used CoupModel to calculate water balance among different ecosystems. In China, applications of CoupModel have mainly concentrated in the northern area. For example, Zhang et al. [7] used CoupModel to assess the effects of wheat straw mulch and fallow crops on water balance and water use efficiency in the Loess Plateau. Wang et al. [8] investigated two types of planted vegetation (Liaodong oak and black locust forest), modelled water transfer with CoupModel, and studied the importance of vegetation type and slope in relation to water balance in the hill and gully region of the Loess Plateau. Wu et al. [9] and Zhou et al [10] explored the hydrological processes of frozen soil in the northeast China and Tibetan Plateau through CoupModel. However, CoupModel has rarely been applied in TGRA.

As a part of vegetation restoration projects, we conducted this research to determine the difference in water balance components among three vegetation patterns, namely, oak (Lithocarpus glaber) forest, Chinese fir (Cunninghamia lanceolata) forest, and maize (Zea mays) farmland, and to assess changes in water balance and water consumption after the afforestation of arable land from May to October in 2008 and 2009.

对于水量平衡各分量的测量，传统田间实验花费巨大，尤其植物蒸腾和土壤蒸发等分量的测量难度较高，不确定性较大。借助SVAT模型可以定量化分析土壤–植物–大气系统中水分迁移转化过程。CoupModel是一个基于过程的一维模型，可以模拟SVAT系统土壤热量和水分过程、植物水分过程、大气和积雪过程及碳、氮过程 [3]。 最近，Ladekarl等 [4]，Christiansen 等 [5]，Schmidt–Walter 和 Lamersdorf [6] 利用 CoupModel 分析了不同生态系统的水量平衡。在中国，CoupModel 的应用主要集中于中国北方地区。例如，Zhang等 [7] 利用CoupModel评价了秸秆覆盖和休耕期绿肥作物对黄土高原冬小麦水量平衡和水分利用效率的影响。Wang等[8] 也利用CoupModel模拟了辽东栎和油松2种植被类型的水分运移规律，研究了植被和坡向对黄土丘陵沟壑区水量平衡的影响。Wu等 [9] 和 Zhou 等 [10] 则利用该模型探讨了中国东北和青藏高原冻土区土壤水文过程。但目前未见CoupModel应用于三峡库区的报道。

依托于植被恢复项目，本文利用CoupModel模拟了3种植被类型，即石栎（阔叶）林、杉木（针叶）林和玉米农田2008和2009年5–10月水量平衡差异， 评价了造林对水量平衡及植物耗水的影响。

MATERIAL AND METHOD

Study site

The study site is located in Simian Mountain in southwestern China (N 28°31'–28°46', E 106°17'–106° 30'), upstream of the Yangtze River. This region is also at the upper end of TGRA, a typical case in terms of the complexity of the natural environment and the fragility of ecosystems in China [1]. Simian Mountain is located in a subtropical area and has a continental monsoon climate, with plenty of rainfalls. The elevation ranges from 900 m to 1500 m above sea level. The mean annual air temperature was 18.4 ℃, varying seasonally from approximately 5.5 ℃ in January to more than 37.5 ℃ in August [2]. The mean annual precipitation was 1096.7 mm (1951–2008) and was normally concentrated from May to September. The experiment was carried out from May to October in 2008 and 2009.

Two forest plots and one farmland plot were investigated in the Shuangqiaoxi watersheds. The first forest stand comprised oak (*Lithocarpus glaber*) with an average tree height of 12 m and a mean stem diameter at breast height of 14 cm (in 2008). The second forest stand comprised Chinese fir (*Cunninghamia. lanceolata*), with an average tree height of 14 m and a mean stem diameter at breast height of 10.2 cm (in 2008). The two stands were planted in the 1980s to form shelter woods to control soil and water loss and stand density was approximately 1000 trees/ha. The third plot, located on conventionally managed farmland, was planted with maize (*Zea mays*) from May to September. The two forest stands were converted from arable land many years before the experiments. During the experimental period, all plots received no fertilization or irrigation, and no natural

材料与方法

试验区概况

试验区选择在位于中国西南地区，长江上游重庆市四面山，该地区所在的三峡库区也是中国生态环境最脆弱的区域之一[1]。四面山地理坐标为东经106°17′–106°31′ 北纬28°31′–28°46′，属于中亚热带湿润性季风气候区， 海拔900–1500m，年平均温度18.4℃， 最低温度出现在一月，为5.5℃，最高温度为37.5℃， 出现在八月。多年平均降雨量1096.7 mm (1951–2008年)，主要集中于 5月至 9月。实验时间为 2008 和 2009 年 5–10 月。

2个林地样地和1个农地样地地处双桥溪流域。第1个林地的建群种为石栎（*Lithocarpus glaber*），平均树高12 m，平均胸径为14cm。第2个林地选取杉木（*Cunninghamia. lanceolata*）样地，平均树高14 m，平均胸径为10.2 cm，测定时间为2008年。2个林地为水土保持防护林，造林时间为80年代末，造林密度约为1000株/公顷。第3个样地选取传统耕作方式的玉米 （*Zea mays*） 地作为对照。 林地样地均由农耕地退耕而来。 试验期间所有样地均没有灌溉、施肥等农业管理措施，且地下水位较深，模拟中不考虑地下水的补给

compensation of groundwater resources was observed because of the deep water table. According to the international texture classification system, the three plots displayed similar soil textural characteristics (i.e., sandy loam). Basic information on the experimental plots is presented in Figure 1 and Table 1.

输入。根据国际制土壤质地分类，3个样地土壤质地相同，均为砂壤土。样地基本情况见图1和表1。

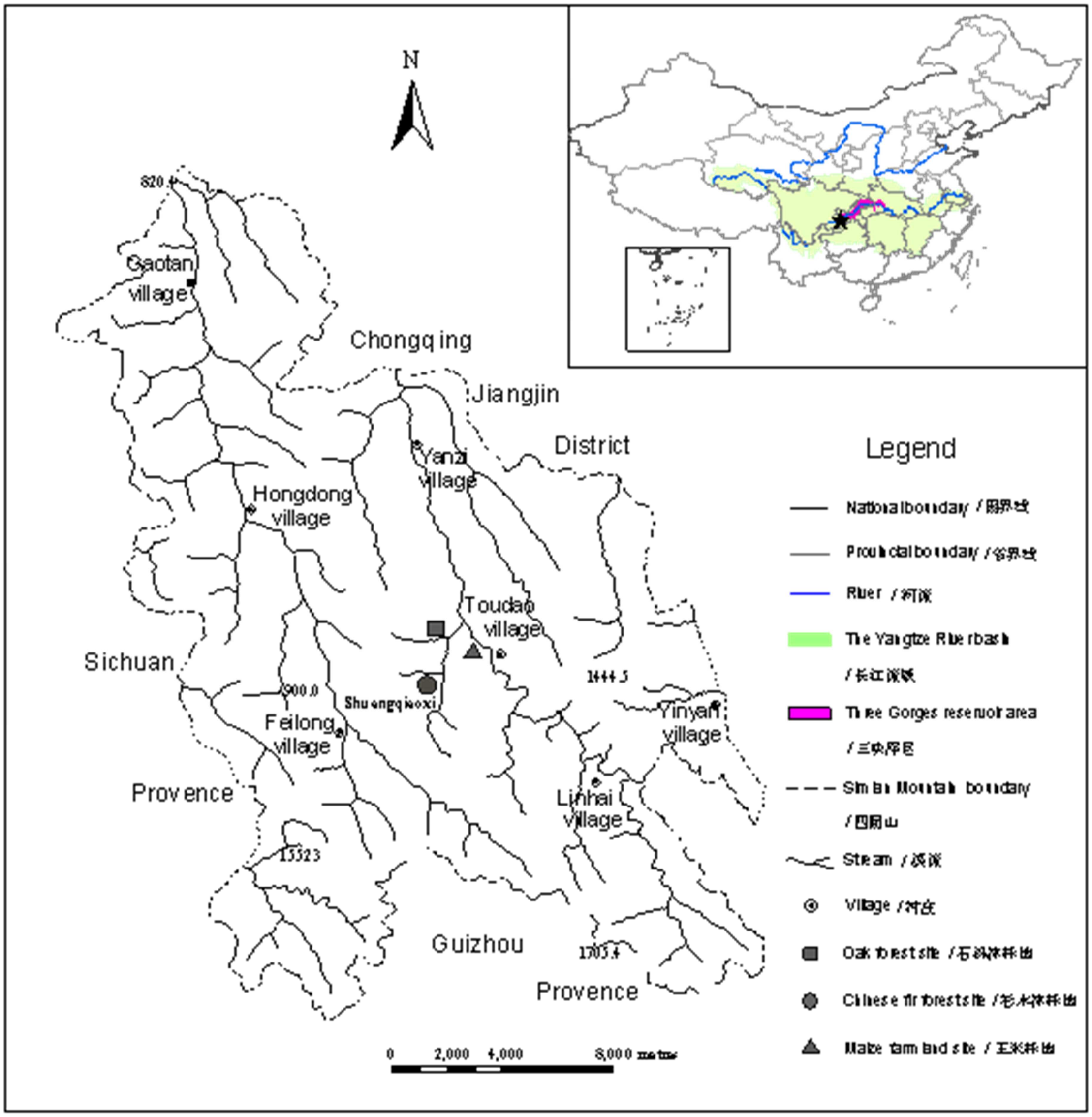

Fig. 1 - Location of the study site

Table1 / *表1*

Basic information of standard land of experimental plots

Vegetation type	***Elevation* [m]**	***Gradient* [°]**	***Aspect***	***Age of trees***	***Canopy height* [m]**	***Tree DBH* [cm]**	***Density* [Plant·ha^{-1}]**	***Coverage* [%]**	***Main vegetation***
Oak	1167	5	SW	20	12.0	14	1000	90	*Lithocarpus glaber* *Schima superba gardn champ* *Hicriopteris chinensis* *Pteridium aquilinum*
Chinese fir	1178	6	SW	20	14.0	10.2	1000	75	*Cunninghamia lanceolata* *Pinus massoniana* *Lespedeza bicolor* *Aster ageratoides*
Maize	1165	3	SW	-	1.2	-	-	85	*Zea mays*

Field data

(1) Meteorological variable

Hourly meteorological data, including precipitation, global radiation, air temperature, wind speed, and relative humidity, were recorded by an automatic weather station Vantage PRO2 (Davis Instruments Corp., USA) positioned at a clear-cut area 600 m from the farmland experimental field. Measurements were taken at a height of 2 m. Sensors were factory-calibrated before installation.

(2) Measurement of soil moisture content (SMC)

Soil volumetric water content (θ) was measured by frequency domain reflectometry (FDR; Diviner 2000, Australia). Before the experiment, nine PVC probes (three samples in each plot) were vertically installed in mineral soil after the removal of the O-horizon (if present). Daily readings of soil moisture content (SMC) were recorded at 20 cm depth intervals from the surface down to 80 cm from May to October in 2008 and 2009. The FDR sensors were calibrated in the field by the comparison of measured soil water gravimetric content in all replicate plots during the experimental period.

(3) Throughfall and stemflow measurement

Throughfall (TF) was collected in three plastic buckets beneath three standard trees in forest stands with an area of 314 cm^2, and water was gathered in measuring cylinders after rainfall. Filters were placed over the top of the containers to avoid contamination of the sample by leaves and animals [5]. Stemflow (SF) was collected through a longitudinally split PVC tube around the trunks of three separate trees at a 1.5 m height in each stand and sealed with silicone along the trunk to avoid water running beneath the tube. The tube bottom was connected to a closed bucket on the ground [5,8] After the rainfall, canopy interception capacity was calculated by precipitation (P) minus TF and SF.

(4) Vegetation properties

Vegetation characteristics, such as leaf area index (LAI), canopy height, and vertical root distributions, were surveyed for use as model input. LAI was measured with a LAI–2000 Plant Canopy Analyzer (LICOR, Lincoln, USA) once a month in the growing seasons of 2008 and 2009 with at least 10 adjacent plants on each occasion. In the three plots, 10 plants were chosen as standards, and their heights were surveyed with a measuring rod once a month during growing season. Root depth was investigated by excavating the soil profile, and this procedure was repeated once a month in growing seasons.

(5) Collection of soil samples and laboratory analyses

Volume-intact soil samples were taken through steel cylinders (100 cm^3) [5] at 20 cm depth intervals to a depth of 80 cm in May 2008. Within each horizon, three replicates were taken to eliminate soil heterogeneity. The soil samples were kept cold and dark until analyzed. Soil physical characteristics were determined in the laboratory. The particle size of the soil samples was analyzed by the hydrometer method, and saturated hydraulic conductivity (mm/d) was measured by the constant hydraulic head method [8]. In addition, parameters in the Brooks–Corey equation [11] were estimated according to measured points of pF curves by a pressure membrane apparatus (1500F1, Soil Moisture Corp., USA). Soil parameter values in CoupModel were mainly derived from measurements in laboratory, but they also required calibration during simulation.

(6) Surface runoff

Runoff plots were established to measure surface runoff beside every stand. The size of each runoff plot was 5 m × 20 m. At the bottom of the runoff plots, iron runoff buckets were installed to collect runoff. The size of the runoff buckets, 80 cm in diameter and 100 cm in

试验数据

（1）气象参数

在距离农地样地600m处布置有一台Vantage PRO 2 小型气象站（Davis公司，美国），以小时为间隔连续观测降雨、总辐射、气温、风速、相对湿度，观测高度为2m。气象站在出厂前已经和标准气象站观测数据进行了校正。

（2）土壤水分（SMC）的测量

试验开始前，每个样地除去腐殖质层后垂直埋设3根长80 cm的 FDR 探管，采用 Diviner2000 FDR （澳大利亚产）频域反射仪定位观测，每天1次，测定深度为80cm，土层间隔20cm.测量时间为2008和2009 年5-10月。 FDR传感器需根据重量含水量校正后方可使用

（3）林冠截留与树干茎流

分别选取样林地样地内3株标准木，布设简易雨量筒收集穿透降雨。雨量筒面积为314cm^2，其表层需安置滤布以防止落叶或动物的破坏而影响水量[5]。树干径流量测定采用收集槽法，在标准木1.5m高处环状刻出小沟，将聚乙烯塑料管纵向剖开后，沿树干周围呈螺旋状固定，用硅胶将接触处密封，塑料管下端接容器承接树干径流[5,8]。雨后由降雨量(P)、穿透雨量(TF)及树干径流量(SF)订算出林冠截留量。

（4）植被特征

模型需要输入的植被参数为叶面积指数、冠层高度、根系深度。叶面积指数采用LAI－2000（Lincoln公司，美国）冠层影像分析系统，生长季内每月测定1次。冠层高度采用测杆测量，根系深度采用人工挖土壤剖面的方法测量。以上参数取样地内不低于10株植物进行测量。

（5）土壤样品的收集与测定

通过 100 cm^3 体积的取样器采集土壤样品 [5]， 每个样地 3 个重复，取样深度为 80cm，间隔 20cm，测定时间为2008年5月。土壤样品分析前需密封保存。实验室内测定土壤物理性质，比重计法测定土壤颗粒组成、恒定水头法测定土壤饱和导水率[8]。采用1500F1型压力膜仪 （Soil Moisture 公司， 美国） 测定土壤水分特征曲线，由不同土壤含水率对应的土壤基质吸力，拟合Brooks–Corey方程 [11] 中的参数。 根据室内土壤物理性质的测量初步确定参数值，并在模拟过程中进一步确定。

（6）地表径流

在每个样地旁各布设一个径流小区（5 m × 20 m），小区下方安放直径为 80 cm， 高度为100 cm 的二级径

height, was designed according to the hydrological data derived from the Jiangjin meteorological station. After each runoff event, the water level in the runoff buckets was measured to calculate runoff volume [8]. Since the topography was flat, no surface runoff was found during the experimental period.

流桶（径流桶的大小根据江津气象站气象水文资料计算而来），降雨后定时收集径流量 [8]。本实验中所有样地地形平坦，试验期间未观测到地表径流。

Model description

Two coupled differential equations for water and heat flow represent the core of the CoupModel. These equations are solved using an explicit numerical method. The basic assumptions behind these equations are that the law of mass and energy conservation is observed and that flows occur as a result of water potential (Darcy's Law) or temperature gradients (Fourier's Law) [3]. Soil texture and water retention curves are used as model inputs, while the Brooks–Corey equation [11] is applied to describe soil water retention, in combination with the Mualem equation [12] to estimate unsaturated hydraulic conductivity. A detailed technical description of the model was given by literature[3] and software can be found at http://www.lwr.kth.se/Vara%20Datorprogram/CoupModel. The important plant and soil water modules used in this study are described below.

(1) *Water balance*

Water balance over a period of time can be expressed as follows:

模型简介

CoupModel的核心是两个耦合的水热流偏微分方程，具有明确数值解。方程遵循质量和能量守恒定律，假定流动是由水势梯度(Darcy′s Law) 和温度梯度 (Fourier′s Law) 产生的，使用有限差分法求解方程 [3]。 土壤质地和水分特征曲线作为模型输入项，依据 Brooks –Corey 方程 [11] 来计算， 非饱和导水率采用 Mualem公式[12] 计算。模型技术说明详见专著[3]，软件下载地址为 http://www.lwr.kth.se/Vara%20Datorprogram/ CoupModel 模型植物和水分模块主要控制方程如下。

(1) 水量平衡

每日的水量平衡方程可以用下式来表示：

$$P = I + E_{ta} + E_s + D + \Delta S + q_{surf} \tag{1}$$

where:
P is precipitation [mm], I is interception [mm], E_{ta} is plant transpiration [mm], E_s is soil evaporation [mm], D is deep percolation [mm], ΔS is the change in soil water storage [mm], and q_{surf} is surface runoff [mm].

(2) *Soil water flux*

Soil water flow is the sum of matrix, vapour, and bypass flow which is assumed to obey Darcy's law as generalized for unsaturated flow by Richards (Richards, 1931) [13]:

式中：
P为降雨量[mm]；I为冠层截留量[mm]；E_{ta}为植被蒸腾量[mm]；E_s为土壤蒸发量[mm]；D为深层渗透量[mm]；ΔS为土壤储水增量[mm]；q_{surf} 为地表径流量[mm]。

（2）土壤水分过程

土壤水流通量为基质流、蒸汽流和大孔隙流的加和，土壤水分运动过程主要基于Darcy定律和Richards方程 [13]：

$$q_w = -k_w\left(\frac{\partial \psi}{\partial z} - 1\right) - D_v\frac{\partial C_v}{\partial z} + q_{bypass} \tag{2}$$

Where:
q_w is water flux, k_w is the unsaturated hydraulic conductivity, ψ is the water tension, Z is depth [m], C_v is the concentration of vapour in soil air [g·m^{-3}], D_v is the diffusion coefficient for vapour in the soil (dimensionless), and q_{bypss} is a bypass flow of water in the macro-pores [mm].

(3) *Interception*

Interception rate (I) is calculated by a threshold function:

式中:
q_w 是水流通量 [mm]，k_w 为非饱和导水率 [mm·day^{-1}]， ψ为水势[kPa]，Z为土层深度 [m]， C_v 为土壤空气中的水汽浓度[g·m^{-3}]，D_v 为土壤的水汽扩散系数 (无量纲)， q_{bypss} 为大孔隙绕流 [mm]。

（3）冠层截留

截留量(I)由简单的阈值函数计算：

$$I = \min\left(P(1 - f_{th,d}), \frac{(S_{i\max} - S_i(t-1))}{\Delta t}\right) \tag{3}$$

where: P is precipitation [mm], $f_{th,d}$ is the fraction of precipitation that reaches the soil surface directly without being affected by vegetation (dimensionless), S_{imax} is interception capacity [mm], and S_i (t-1) is interception storage remaining from the previous time step [mm].

式中，P为降雨量[mm]，$f_{th,d}$ 为穿透降雨占总降水量的分数(无量纲)，S_{imax} 为截留容量[mm]，S_i (t-1) 为前期截留剩余储水量[mm]。

(4) *Soil evaporation*

In CoupModel, the actual evapotranspiration can be divided into three parts: evaporation of intercepted water in the canopy, evaporation from the soil surface and transpiration from plants. Soil evaporation (E_s) is based on the Penman combination equation [14]:

（4）土壤蒸发

模型中实际蒸散为3部分的和：冠层截留蒸发、地表土壤蒸发和植被蒸腾。土壤蒸发(E_s)采用修正的Ponteith–Monteith公式[14]进行计算：

$$L_v E_s = \frac{\Delta(R_{nc} - q_h) + \rho_a c_p (e_s - e_a)/r_{as}}{\Delta + \gamma\left(1 + r_{ss}/r_{as}\right)} \qquad (4)$$

where:
L_vE_s is latent heat from the soil surface, R_{nc} is net radiation at the soil surface [J·m^{-2}·day^{-1}], q_h is heat flux to the soil [J·m^{-2}·day^{-1}]; ρ_a is air density [kg·m^{-3}], c_p is the heat capacity of air [J·kg^{-1}·℃$^{-1}$], e_a is the actual vapour pressure in the air [Pa], e_s is the vapour pressure at the soil surface [Pa], r_{as} is the aerodynamic resistance [s·m^{-1}], r_{ss} is the surface resistance at the soil surface [s·m^{-1}], Δ is the slope of the curve of saturated vapour pressure against temperature [Pa·℃$^{-1}$], and γ is the psychrometer constant [Pa·℃$^{-1}$].

(5) *Actual transpiration*

The potential transpiration, E_{tp}, is also calculated from Penman combination equation [14], and the water uptake is assumed to be equal to transpiration and is partitioned between the soil layers on the basis of root distribution. Actual transpiration, E_{ta}, which accounts for drought, oversaturation, and temperature effects, is calculated according to:

式中，
L_vE_s为地表潜热通量 [J·m^{-2}·day^{-1}]，R_{nc} 为地表净辐射 [J·m^{-2}·day^{-1}]，q_h 为土壤热通量 [J·m^{-2}·day^{-1}]， ρ_a为空气密度 [kg·m^{-3}]，c_p 为空气定压比热容 [J·kg^{-1}·℃$^{-1}$]， e_a 为实际饱和水汽压 [Pa]， e_s 为饱和水汽压 [Pa]， r_{as}为地表空气动力学阻力 [s·m^{-1}]，r_{ss} 为土壤表面阻力 [s/m]， Δ为饱和水汽压曲线斜率 [Pa·℃$^{-1}$]， γ为干湿表常数 [Pa·℃$^{-1}$]。

（5）实际蒸腾

植被潜在蒸腾E_{tp}也采用修正的Penman–Monteith公式[14]进行计算。假定植物根系对水分的吸收即为植被蒸腾，实际蒸腾E_{ta}受到干旱、过饱和或温度等的影响，由下式计算：

$$E_{ta} = E_{ta}^* + f_{umov}(E_{tp}^* - E_{ta}^*) \qquad (5)$$

$$E_{ta}^* = E_{tp}^* \int_{z_r}^{0} \min(f(\psi(z)), f(\pi(z))\, f(T(z))\, r(z)\, dz \qquad (6)$$

$$E_{tp}^* = \max(0, E_{tp} - E_{ia}/e_{rat}) \qquad (7)$$

where:
E_{ta} is actual transpiration [mm], E_{ta}^* is transpiration without considering water uptake [mm], f_{umov} is the degree of compensatory water uptake (dimensionless), E_{tp}^* is potential transpiration minus intercepted evaporation [mm], *f(Ψ(z)), f(π(z))* and *f(T(z))* are functions that reduce the water uptake by roots due to unfavourable soil moisture, salt and soil temperature conditions respectively, *r(z)* is the relative root density, E_{ia} is evaporation of intercepted water [mm], and e_{rat} is the ratio between potential evaporation rate from interception storage and potential transpiration (dimensionless).

(6) *Deep percolation*

In this region, the lower boundary of the simulated soil profile is unsaturated since the deep groundwater tables, and the vertical flow (*D*) is calculated by function:

式中，
E_{ta}为实际蒸腾量[mm]，E_{ta}^*为不考虑补偿吸水的蒸腾量[mm]，f_{umov}为根系吸水补偿度(无量纲)，E_{tp}^* 为截留蒸发折减后的潜在蒸腾量[mm]，*f(Ψ(z))*，*f(π(z))*和 *f(T(z))*分别为土壤水势、渗透水势和土壤温度的响应函数，*r(z)* 为相对根系密度分布，E_{ia} 为截留蒸发量[mm]，e_{rat} 为截留蒸发与潜在蒸腾量之比(无量纲)。

（6）深层渗透

因地下水位较低，模型深层为非饱和下边界条件，深层渗透量 (*D*)计算公式为：

$$D = k_{wlow} \qquad (8)$$

where: *D* is deep percolation [mm] and k_{wlow} is hydraulic conductivity in the lowest soil layer [mm].

(7) *Runoff*

If the precipitation reaching the soil surface exceeds the infiltration capacity, a pool of water is formed on the soil surface. The surface runoff (q_{surf}) is calculated as:

式中，*D* 为深层渗透量[mm]，k_{wlow} 为土壤剖面最下层土壤的非饱和导水率 [mm]。

（7）地表径流

如果降水超过入渗量，土壤表面将产生积水，则地表径流 q_{surf} 由下式计算：

$$q_{surf} = a_{surf}(W_{pool} - w_{pmax}) \quad (9)$$

where:
α_{surf} is an empirical coefficient (0.8, dimensionless), W_{pool} is the total amount of water in the surface pool [mm] and W_{pmax} is the maximum amount of water that can be stored on the soil surface without any surface runoff occurring [mm].

Model settings and parameters calibration

The simulation ran from May to October in 2008 and 2009. Input variables included precipitation, global radiation, air temperature, wind speed, and relative humidity, with daily outputs of soil moisture and water balance components produced.

In CoupModel, upper and lower boundary conditions were defined as flux boundaries, with the upper boundary accounting for precipitation. As a lower boundary condition, unit gradient gravitational water flow was set up, representing groundwater recharge in this study. Capillary rise and lateral runoff were disregarded. Soil physical and hydraulic properties were measured on the basis of observed values in the laboratory, and air entry tension, saturated water content, wilting point, and residual water content (parameters in the Brooks–Corey equation) were calculated by measurements of pF curves.

In this study, the farmland vegetation canopy was represented by a single leaf concept, whereas for the forest plots, two layers, namely, the tree layer and the understory, were used. Thus, the switch of multiple big leaves was chosen. The most important vegetation characteristics used in the simulations were LAI, tree height, and root distribution, which were measured in the field. Water uptake was defined as a pressure head approach, calculated on the basis of response functions for water content and soil temperature [3]. For forest lands, the start of the growing season (and the corresponding water uptake) was defined by a trigging temperature approach; growing season began when the day length exceeded 10 h and the accumulated temperature was above 9.8 ℃, and ended when the da y length became less than 10 h according to meteorological observations [5]. However, for farmland, growing season started in May and ended in September.

We used soil moisture (0–80 cm) and throughfall as validation variables in the simulations. Based on field measurements and relevant literature, several parameters were calibrated to achieve satisfactory agreement between the simulated and measured values. All parameter values used to adjust the CoupModel are presented in Table 2.

式中:
α_{surf} 是经验系数(0.8，无量纲)，W_{pool} 是地表积水总量[mm]，W_{pmax}是不产生地表径流的情况下，地表能够储存积水的最大量[mm]。

模型设置与参数校核

模型模拟时间段为2008和2009年5–10月。 输入数据包括降雨、总辐射、气温、风速和相对湿度， 输出数据为每日的土壤水分和水量平衡各分量。

模型上下边界为流动边界，上边界条件为大气降雨，下边界条件为最下层土壤的单位梯度流，代替研究中的地下水补给或交换。本研究中忽略毛细管上升水流和侧向径流。 土壤物理和水力学性质在实验室实测值的基础上而来。 土壤进气吸力、饱和含水量、凋萎系数和残留含水量（即 Brooks–Corey 方程中的参数） 由水分特征曲线测量值计 算而来。

在本研究中，农田植被层采用单层大叶模型；而林地植被层则采用双层大叶模型，即林冠层和林下灌草层。在植被特征模拟时，最重要的参数包括叶面积指数，树高和根系深度，均由样地实测而来。根据土壤水分和温度的响应函数，水分上升方式定义为压力水头响应[3]。对于林地，生长季的开始时间（即根系吸水时间）定义为触发温度方式 生长季开始于光照时间超过 10 h或日积温高 于9.8 ℃， 结束于光照时间低于10h [5]。 但对于农地，生长季从5月份开始，9月底结束。

使用土壤水分（0–80cm） 和穿透雨量作为模型校验变量。 基于野外测定和相关参考文献，调整对模拟结果较为敏感的参数，使得模型模拟值与实测值达到合适的精度。本次模拟中调整的参数值见表2。

Table 2 / *表2*

Parameters adjusted in the simulations

Parameter	*Symbol*	*Oak*	*Chinese fir*	*Maize*	*Source*
Alt met station [m]	e_{levmet}	1165	1165	1165	*Measurement*
Alt sim position [m]	e_{levsin}	1167	1178	1165	*Measurement*
Slope E-W [m·m^{-1}]	p_x	0.59	0.63	0.67	*Measurement*
Slope N-S [m·m^{-1}]	p_y	-0.12	-0.08	-0.11	*Measurement*
Air temp mean [℃]	T_{amean}	19	19	19	*Measurement*
Max LA [m^2·m^{-2}]	A_1	4.5	4.0	4.0	*Measurement*
Canopy height [m]	H_p	12.0	14.0	1.5	*Measurement*

Parameter	*Symbol*	*Oak*	*Chinese fir*	*Maize*	*Source*
Root depth [m]	z_{etr}	1.2	1.3	0.5	*Measurement*
Latitude [°]	e_{latit}	28.51	28.51	28.51	*Measurement*
Albedo wet [%]	a_{wet}	15	15	15	*Reference [7]*
Albedo dry [%]	a_{dry}	25	25	25	*Reference [3]*
Plant albedo [%]	a_{veg}	10	13	15	*Reference [8]*
Light extinction coefficient	k_{rn}	0.5	0.5	0.5	*Reference [7]*
ThScaleLog 土	x_{hf}	0.4	0.4	0.4	*Reference [7]*
Organic layer thickness [m]	Δz_{humus}	0.08	0.05	0	*Measurement*
Dvap tortuosity	d_{vap}	0.66	0.66	0.66	*Reference [8]*
Water capacity base [mm]	S_{imax}	2.3	2.3	0.5	*Calibrated Reference [15]*
Water capacity per LA [mm·m^{-2}]	i_{LAI}	0.25	0.25	0.15	*Reference [6], Calibrated*
Cond VPD [Pa]	g_{vpd}	450	450	200	*Calibrated*
Cond MAX [m·s^{-1}]	g_{max}	0.005	0.005	0.020	*Reference [16] Calibrated*
Flexibility degree	f_{umov}	0.9	0.6	0.6	*Reference [8]*
Crit threshold dry [cm]	ψ_c	1500	1000	1000	*Calibrated*
Root frac exp tail	r_{frac}	0.1	0.05	0.02	*Calibrated*
PsiRs-1p	r_{ψ}	150	150	100	*Calibrated*
Ra increase with LA [s·m^{-1}]	r_{alai}	60	60	50	*Calibrated*

Statistical analyses

To evaluate the performance of the model, the indices used in this study were R^2, the coefficient of determination of the linear regression between simulated and measured values, the mean error of the model ME, and the root mean square error of the model RMSE [5, 7-9]. These indices were calculated according to the following equation:

数据分析

采用决定系数 （Determination Coefficient, R^2）、 平均误差（Mean Error, ME）、均方根误差 （Root Mean Square Error, RMSE） [5, 7-9] 对模拟结果进行评价， 其计算公式为：

$$ME = \frac{1}{n}\sum_{i=1}^{n}(S_i - M_i) \quad (10)$$

$$RMSE = [\frac{1}{n}\sum_{i=1}^{n}(S_i - M_i)^2]^{1/2} \quad (11)$$

where: S_i and M_i are the values at the ith observation and n is the number of observations.

式中：S_i为第i个模拟值；M_i为第i个观测值；n为样本总数

RESULTS AND DISCUSSION

Model validation

Soil moisture is a prime environment variable related to land surface climatology, hydrology, and ecology [4]. Variations in soil moisture strongly affect surface energy, water dynamics, and vegetation productivity (actual crop yield). In addition, changes in soil moisture are also directly connected to evapotranspiration (*ET*) because this process is usually related to moisture in the upper 1 m to 2 m of the soil profile, at which depth moisture can easily evaporate or be extracted by plant roots [6]. In short, soil moisture is usually an important validation variable in hydro-ecological simulations.

The time series of measured and simulated soil moisture at depths of 0–20 cm, 20–40 cm, and 40–80 cm for the three plots are shown in Fig. 2. The temporal variation of soil moisture is similar for the three stands, showing a distinct trend with the highest values during

结果与讨论

模型验证结果

作为最重要的环境变量之一，土壤水分受到地表气象、水文与生态的影响[4]，其动态变化与地表能量、径流和植被生产力紧密相关。此外，因植物根系主要分布于1–2m 深度的地表土壤，土壤水分也与蒸散过程直接相关 [6]。 土壤水分通常是水文生态模拟中一个重要的状态变量。

图2为试验期间3种植被类型0–20，20–40和40–80 cm土壤水分的动态变化。由图中看出，3个样地土壤水分表现出相似的季节变化，受降雨量影响，夏季（6–8月） 达

summer (especially from June to August). This trend is consistent with that of precipitation events. Compared with the variability of soil moisture at the 40–80 cm layer, that at the depth of 0–20 cm is significant, with direct and rapid changes as reactions to rainfall. In the entire soil profile (0 cm to 80 cm), the average soil moisture ranged as follows: oak forest (10.22%) < Chinese fir forest (10.88%) < maize farmland (12.36%).

到峰值。相比 40–80 cm 层，表层（0–20 cm）土壤水分对降雨的响应更为直接和迅速。整个土壤剖面上（0–80cm），土壤水分平均值大小依次为阔叶林（10.22%）< 针叶林（10.88%）< 农地（12.36%）。

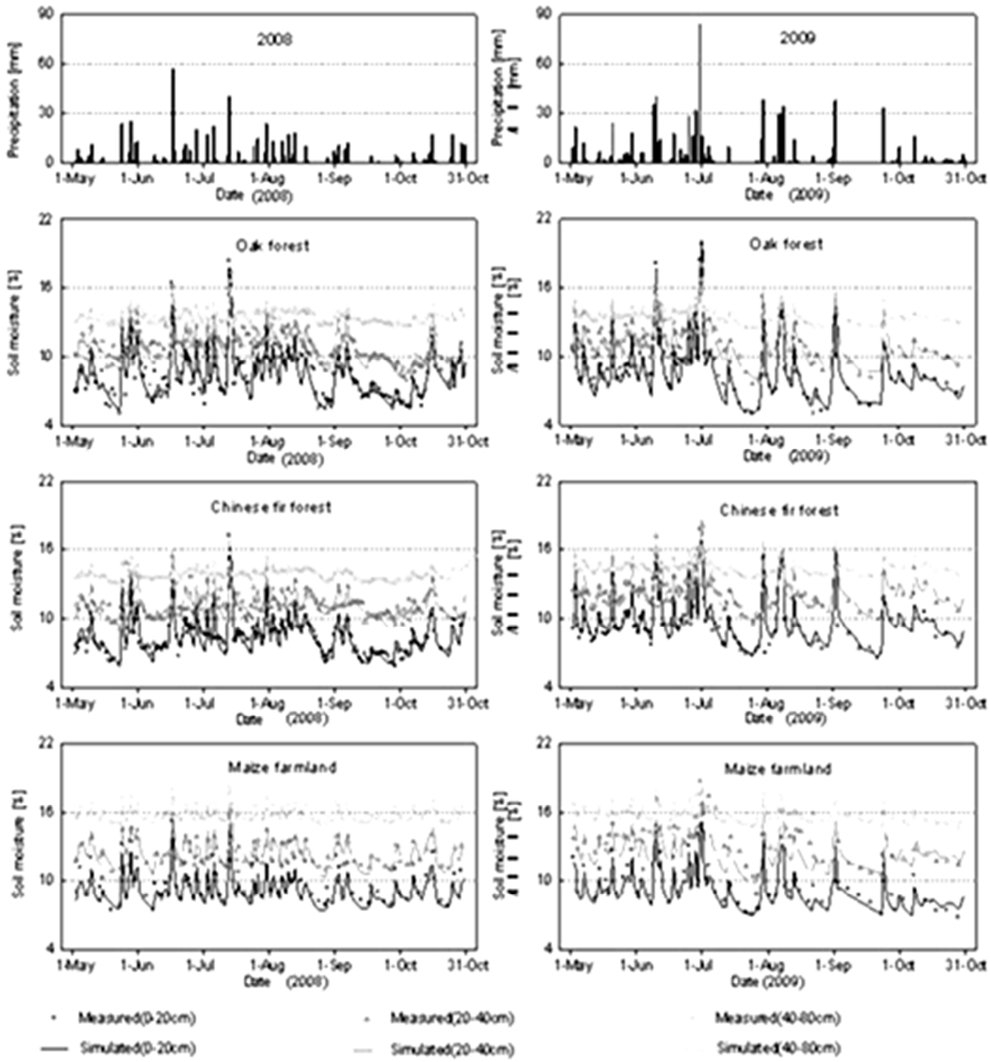

Fig. 2 - Daily simulated and observed soil moisture

As can be seen from Fig. 2, wider margin of variation between simulated and measured values mainly appeared in the following two circumstances: firstly, a few simulated values were lower than measured values after the rainfall, namely they failed to indicate extreme values. Secondly, a few simulations became higher than measured values in the dry season (e.g. late September). This was probably in relation to soil water movement equation that applied in the model, Darcy's law and Richards equation, assumed soil as homogeneous medium [4], thus they cannot exactly reflect and explain dynamic change process of water flow in the heterogeneous soil (e.g. the preferential flow).

Validation results showed the desired conformity between the simulated and measured data (Fig. 2 and Table 3). The coefficient of determination for the linear regression (R^2) between the observed and simulated soil moisture in the entire soil profile (0 cm to 80 cm) was

从图2可以看出，模拟值与实测值偏差较大的时段主要发生于两种情况：第一，降雨过后，模拟值较实测值偏低，未能表示出某些极端值；第二，长时间未降雨情况下，模拟值较实测值则偏高（如9月）。这可能与模型中应用的土壤水分运动方程有关，Darcy定律、Richards方程都假设土壤为均质介质[4]，不能真实反映和准确解释水分在异质性土壤中的动态变化过程（例如优先流）。

由图2和表3可见，模型模拟值与实测值具有较好的一致性。整个剖面上（0–80cm），石栎林的决定系数

0.83–0.91 (p<0.001) for oak forest but slightly lower for Chinese fir forest (0.8–0.85) and farmland (0.73–0.87). Generally, R^2 is useful for describing the difference between the simulated and observed dynamics of variables with cyclic fluctuations. In this study, R^2 is above 0.73 for all plots, indicating that CoupModel well simulates soil moisture. ME and RMSE reflect the deviation between the simulated values and measured values and thus facilitate the depiction of the irregular patterns of variables for soil moisture changes in response to infiltration events and drying processes. For the three plots, ME is -0.83%–1.79%, with RMSE of 0.46%–2.81%. We deduce that the deviation was small between the simulated and measure values, indicating that the model effectively captured the dynamic changes in soil moisture and that the simulation results were reliable. Compared with soil moisture, simulated throughfall had disappointing measurements, with R^2 of only 0.62–0.69, possibly because of the small number of samples.

（R^2）为 0.8–0.91 （p<0.001）， 而杉木林和农地稍微低些， 为0.8–0.85和0.73–0.87。 R^2反映了时间动态上模拟值与实测值的线性关系，本研究中模拟结果R^2均在0.73以上，说明该模型对土壤水分总体模拟效果较好。ME和RMSE则反映了模拟值与实测值之间的偏差，能够较好反映出土壤水分入渗或处于干旱状态下不规则（非线性）的动态变化过程。二者的范围分别为-0.83%–1.79%和0.46%–2.81%， 说明模拟值与实测值偏差较小， 模型较好地捕捉到了水分的动态变化，模拟结果是可信的。而相比土壤水分，模型对林内穿透雨量的模拟吻合程度稍低R^2仅为0.69–0.72，模拟结果偏大， 可能与样本数量较少有关。

Table 3 / 表3

Validation of simulated results

Vegetation type		*Oak*					*Chinese fir*					*Maize*				
Variable	*Depth*	R^2	*ME [%]*	*RMSE [%]*	*Average [%]*	*n*	R^2	*ME [%]*	*RMSE [%]*	*Average [%]*	*n*	R^2	*ME [%]*	*RMSE [%]*	*Average [%]*	*n*
Soil moisture	0－20	0.83	1.79%	2.81%	7.79%	320	0.8	1.52%	2.11%	8.56%	320	0.73	0.49%	0.46%	9.27%	229
	20－40	0.84	0.39%	1.41%	10.36%	320	0.85	0.83%	1.48%	11.06%	320	0.85	-0.83%	1.41%	12.11%	229
	40－80	0.91	-0.02%	1.38%	12.51%	320	0.83	0.26%	1.22%	13.03%	320	0.87	-0.12%	1.89%	15.71%	229
Throughfall	-	0.72	1.37mm	2.51mm	-	34	0.69	1.92mm	3.2mm	-	34	-	-	-	-	-

Simulated water balance components

Simulated monthly outputs of interception (I), transpiration (E_{ta}), soil evaporation (E_s), and deep percolation (D) were illustrated in Fig. 3 and Fig. 4. Similar to the seasonal variation in the soil moisture, a clear pattern can be seen in the monthly sums of the water balance components of the study plots. For the whole simulation period, evapotranspiration (ET), the sum of I, E_{ta} , and E_s , gradually increased in May and reached the highest values (118 mm to 128 mm) in June and August. Afterward, it was then reduced by cold weather with low rainfall. In this study, evapotranspiration was main output of water balance with the percentage up to 91%, and it was ranked as follows: oak forest (824 mm) > Chinese fir forest (815 cm) > farmland (790 mm).

Interception and transpiration generally showed the same temporal variation in the two forest stand and the values in oak stand were higher in most cases.

In 2008, interception increased from 34 mm in May, fluctuated between 36 mm and 51 mm through June–September, then declined and reached the minimum (19 mm) in October. For the Chinese fir stand, the maximum and minimum values of interception were 47 mm and 16 mm, which were lower than that from oak. Compared with forest stand, the farmland exhibited the lowest interception loss, accounting for 17% of the precipitation and equaled 121 mm, while it was respectively 232 mm (32%) and 209 mm (29%) for oak and Chinese fir forest. Similar to interception, transpiration from the oak stand was also biggest, equaled 203 mm and constituted 28% of precipitation in 2008. From June to August, the transpiration was at a maximum (36 –57 mm per month), then it reduced to the minimum (20 mm) in October. The difference was not huge between simulated transpiration

水量平衡模拟

图3和图4为截留、蒸腾、土壤蒸发与深层渗透的模拟输出值。与土壤水分动态相似，3种植被类型的水分通量也呈现出明显的季节变化。 实际蒸散 （即截留、 蒸腾与土壤蒸发之和）， 从 5月份开始缓慢增长并于 6 月和8月达到峰值 （118 mm 到 128 mm）， 之后随着天 气的变冷和降雨的减少而下降。 本研究结果表明，蒸散是水量平衡中主要的支出项， 比例高达91%以上，其大小顺序为石栎林 >杉木林>农地， 分别为824 mm，815 cm和790 mm。

2种林地的截留和蒸腾呈现出相同的 变 化， 石 栎 林 在 数值上 比 杉 木林高一些。

2008 年5 月份石栎林截留量为 34mm， 6 月到 9 月期间在 36 和 51 mm之间波动， 到 10 月份下降到最低值 19 mm。 而杉木林稍低于石栎林，截留量的最大值和最小值则为 47 mm 和 16 mm。 对比于 2 种林地，农地的截留量就小很多，仅为 121 mm， 占降雨量的 17%， 而石栎林和杉木林则分别为 232 mm （32%） 和 209 mm （29%）。 植被蒸腾量与截留相似，3 个样地中也是石栎林最大， 2008年为203mm，占降雨的28%，并于6到8月达到峰值（每月 36–57mm）， 10 月份也下降到最小值 20 mm。 与截留量不同，3个样地的蒸腾量之间差距并不

in three plots, in Chinese fir forest and farmland, it was 22 mm and 43 mm lower than oak, while this value was 23 mm and 111 mm for interception (Fig. 2 and Table 4). In contrast to the seasonal fluctuations of I and E_{ta}, soil evaporation (E_s) remained relatively constant (8 mm to 32 mm every month) throughout the growing season and presented a modest rise in October. For farmland, soil evaporation was 144 mm and constituted 20% of precipitation in 2008, which was significantly higher than that of oak (11% of P) and Chinese fir (13% of P) stand.

大，杉木林和农地的蒸腾量仅比石栎林小 22 mm和 43 mm，而截留量之间的差距却达到了 23 mm和 111 mm（图2和表4）。与截留和蒸腾的季节变化不同，整个试验期间土壤蒸发相对恒定，波动范围为每月8 mm到32 mm，并在10月份呈现出轻微的上升。农地2008年土壤蒸发为144mm，占降雨量的20%，显著高于石栎林和杉木林，后者分别占降雨量的11%和13%。

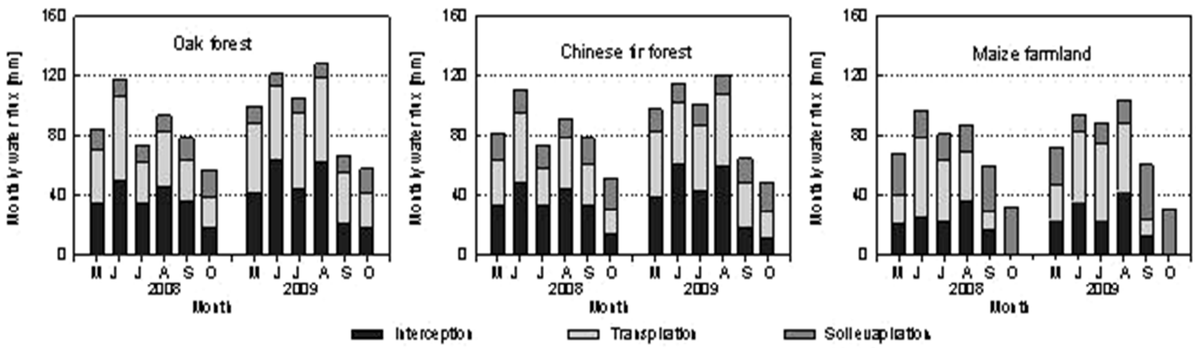

Fig. 3 - Simulated monthly water fluxes for three plots

Unlike the gentle fluctuation of evapotranspiration (ET), deep percolation (D) always abruptly changed (maximum of 200 mm per month) with rainstorm events (mainly in June 2008 and between June and August 2009). In 2009, 438 mm deep percolation /drainage formed in the farmland, more than 45% of the gross precipitation. Corresponding to farmland, the oak and Chinese fir forest plots presented lower deep percolation, accounting for only 36% and 39% of the precipitation. We can deduce that forest significantly reduced the deep percolation.

与蒸散（ET）的温和变化不同，受暴雨事件的影响（主要发生2008年6月、2009年6–8月）， 深层渗透（D） 常具有突发性，且数量变化巨大，极端值甚至达到200 mm/月。以2009年为例，农地土壤深层渗透量为438 mm，达到了同期降雨的45%。相对应地，石栎林和杉木林地具有较小的深层渗透量，分别为36%和39%，林地对渗透量的降低作用明显。

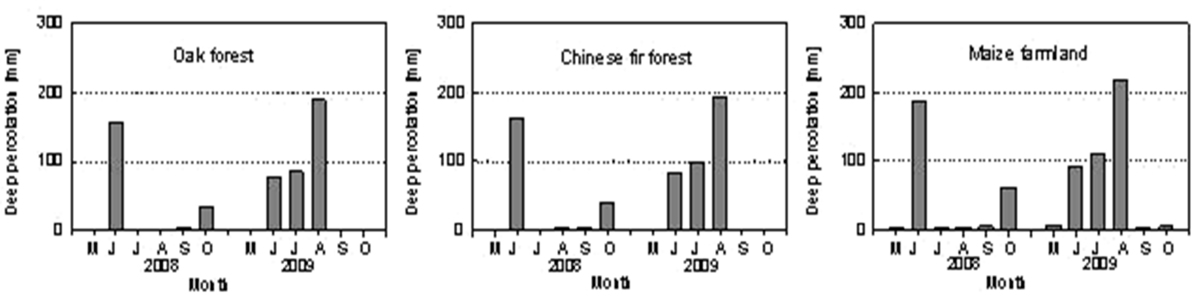

Fig. 4 - Simulated monthly deep percolation for three plots

Effect of afforestation on water balance

Table 4 showed simulated water balance among three plots from May to October in 2008 and 2009. It indicated that a shift from cropland to forest would lead to an increase in canopy interception (I) while a reduction in deep percolation (D) (or groundwater recharge). First, annual interception increased (88 mm to 114 mm, 67%–92% of P) after afforestation (Table 4). Compared with crops, trees had a large leaf area in our study sites, implying high canopy capacity for interception storage and a low amount of precipitation directly reaching the ground [6]. Moreover, forests support great biomass with long growing periods as undergrowth, and thus facilitate canopy interception [8]. Second, a 51 mm to 85 mm

造林对水量平衡的影响

表 4为 2008 和 2009 年 5-10 月期间 3 个样地水量 平衡模拟结果。 结果表明， 在耕地上造林后， 冠层截留增加 的同时深层渗透量 （或地下水补给量） 会减少。 第一，由表4可见，造林后截留量会增加 88–114 mm （占降雨量的 67%–92%）。 与农作物相比， 树木具有较大的叶面积，即具有更大的冠层容水量，则直接到达地面的穿透降雨较少[6]。另外，森林更大的生物量和林下灌草层也对

(14%–25% of *P*) reduction in annual deep percolation was estimated after afforestation. The probable reason was that most precipitation in forestlands was absorbed by the soil surface and rapidly diffused by evaporation or transpiration after afforestation, thereby decreasing infiltration depth and soil water content below the infiltration depth [5]. Therefore, on sites with low plant available soil water capacity and with roots that have no access to the water table, a change in land use from cropland to forest may negatively affect groundwater recharge. The simulations also indicated that tree species influenced the magnitude of water balance components in SVAT system. Compared with Chinese fir of the same age, oak had the highest interception and lowest deep percolation, that mainly because of the higher water consumption of oak.

截留量的增加具有促进作用[8]。第二，本研究模拟得出，造林后深层渗透量比耕地减少51–85 mm（占降雨量的14%–25%）。 其原因可能与林地内大部分降雨被地表土壤所吸收并迅速通过蒸发或蒸腾以气态形式散失，深层土壤湿度和入渗深度减小有关[5]。因此，在植物可利用的水分含量较低、且根系无法触及地下水的地区，耕地向林地的转变将不利于地下水的补给。模拟结果进一步显示了树种对水量平衡亦有影响。与同林龄杉木相比，石栎具有最大的截留量和最小的深层渗透量，主要与石栎耗水较大有关。

Table 4 / 表4

Simulated water balance from May to October

Year	*Plot*	*P* [mm]	*ET* [mm] *(% of P)*	*I* [mm] *(% of P)*	E_{ta} [mm] *(% of P)*	E_s [mm] *(% of P)*	*D* [mm] *(% of P)*	*ΔS/±* [mm] *(% of P)*
2008	*Oak*	729	715 (98%)	232 (32%)	203 (28%)	82 (11%)	188 (26%)	23 (3%)
	Chinese fir	729	702 (96%)	209 (29%)	181 (25%)	98 (13%)	214 (29%)	27 (4%)
	Farmland	729	691 (95%)	121 (17%)	160 (22%)	144 (20%)	265 (36%)	38 (5%)
2009	*Oak*	978	933 (95%)	253 (26%)	261 (27%)	66 (7%)	353 (36%)	44 (5%)
	Chinese fir	978	928 (95%)	232 (24%)	228 (23%)	89 (9%)	379 (39%)	50 (5%)
	Farmland	978	888 (91%)	139 (14%)	179 (18%)	132 (14%)	438 (45%)	89 (9%)

CONCLUSIONS

Based on field measurements from May to October in 2008 and 2009, a physical process-based model (CoupModel) was applied to evaluating the effect of afforestation on water balance in Simian Mountain in the terminal section of the Three Gorges area (TGRA) of China. Afforestation was performed using oak and Chinese fir on former arable land of maize. The simulated values of soil moisture were fairly consistent with the measured ones, with a determination coefficient (R^2) of 0.73–0.91. This result indicated that CoupModel can successfully demonstrate the complex interactions between hydrological processes in soil–vegetation–atmosphere (SVAT) system. Evapotranspiration was the main output of water balance from May to the end of October, with a percentage of up to 91%, and it was estimated to be 824 mm, 815 mm and 790 mm for oak, Chinese fir and maize, respectively. Deep percolation (or water recharge) declined from approximately 352 mm in arable land to 271 mm in the oak stand and 297 mm in the Chinese fir stands, mainly due to differences in the interception loss. Compared with the arable land, simulated interception of different tree species was increased by 87% for oak and 70% for Chinese fir (88 mm to 114 mm). The simulations indicated that tree species also influenced the magnitude of water balance components in SVAT system, calling for further attention to the selection of regrown tree species in the planning for afforestation projects, particularly when such projects aim to keep water infiltrating to the groundwater zone.

结论

根据2008年和2009年5–10月试验资料， 应用一个基于过程的物理模型（CoupModel），评价了位于长江三峡库区（TGRA）库尾的四面山地区造林对水量平衡的影响。本研究中林地样地造林树种为石栎和杉木，均由玉米农田退耕造林而来。结果表明土壤水分模拟结果与实测值具有很好的一致性，决定系数（R^2）为0.73–0.91，说明CoupModel可以很好地描述本地区土壤–植物–大气系统之间的水分交换过程。蒸散是5–10 月水量平衡中主要的支出项，比例高达91%，石栎、杉木和玉米样地总蒸散量分别为824 mm、815 mm和790 mm。造林后深层渗透量（或地下水补给量）由农地352 mm减小到石栎林 271 mm 和杉木林297 mm， 主要是由于林冠对降雨截持量的增加。与农田相比，石栎林和杉木林冠层截留量分别增加87%和 70%（88–114 mm）。 模拟结果进一步显示了树种对水量平衡亦有影响，在今后的退耕恢复造林过程中，特别是以提高地下水补给为目标的地区， 应注意树种的选择。

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