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Hanqin Tian
Auburn University

Chi Zhang
Chinese Academy of Sciences

Jiyuan Liu
Chinese Academy of Sciences

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EFFECTS OF LAND-USE AND LAND-COVER CHANGE ON EVAPOTRANSPIRATION AND WATER YIELD IN CHINA DURING 1900-2000[1]

Mingliang Liu, Hanqin Tian, Guangsheng Chen, Wei Ren, Chi Zhang, and Jiyuan Liu[2]

ABSTRACT: China has experienced a rapid land-use/cover change (LUCC) during the 20th Century, and this process is expected to continue in the future. How LUCC has affected water resources across China, however, remains uncertain due to the complexity of LUCC-water interactions. In this study, we used an integrated Dynamic Land Ecosystem Model (DLEM) in conjunction with spatial data of LUCC to estimate the LUCC effects on the magnitude, spatial and temporal variations of evapotranspiration (ET), runoff, and water yield across China. Through comparisons of DLEM results with other model simulations, field observations, and river discharge data, we found that DLEM model can adequately catch the spatial and seasonal patterns of hydrological processes. Our simulation results demonstrate that LUCC led to substantial changes in ET, runoff, and water yield in most of the China's river basins during the 20th Century. The temporal and spatial patterns varied significantly across China. The largest change occurred during the second half century when almost all of the river basins had a decreasing trend in ET and an increasing trend in water yield and runoff, in contrast to the inclinations of ET and declinations of water yield in major river basins, such as Pearl river basin, Yangtze river basin, and Yellow river basin during the first half century. The increased water yield and runoff indicated alleviated water deficiency in China in the late 20th Century, but the increased peak flow might make the runoff difficult to be held by reservoirs. The continuously increasing ET and decreasing water yield in Continental river basin, Southwest river basin, and Songhua and Liaohe river basin implied regional water deficiency. Our study in China indicates that deforestation averagely increased ET by 138 mm/year but decreased water yield by the same amount and that reforestation averagely decreased ET by 422 mm/year since most of deforested land was converted to paddy land or irrigated cropland. In China, cropland-related land transformation is the dominant anthropogenic force affecting water resources during the 20th Century. On national average, cropland expansion was estimated to increase ET by 182 mm/year while cropland abandonment decreased ET by 379 mm/year. Our simulation results indicate that urban sprawl generally decreased ET and increased water yield. Cropland managements (fertilization and irrigation) significantly increased ET by 98 mm/year. To better understand LUCC effects on China's water resources, it is needed to take into account the interactions of LUCC with other environmental changes such as climate and atmospheric composition.

(KEY TERMS: China; Dynamic Land Ecosystem Model; evapotranspiration; land-use and land-cover change; water yield.)

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[2]Respectively, Postdoctoral Fellow (M. Liu), Professor (Tian), Graduate Research Assistant (Chen, Ren, and Zhang), Ecosystem Science and Regional Analysis Lab, School of Forestry and Wildlife Sciences, Auburn University, Alabama 36849; and Professor (J. Liu), Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China (E-Mail/Tian: tianhan@auburn.edu).

INTRODUCTION

Severe water deficiency, frequent floods, and droughts have been the most serious environmental problems that have threatened China's ecosystem sustainability and human health since the beginning of the 20th Century (Brown and Halweil, 1998; Xia and Chen, 2001; Liu and Diamond, 2005). The water deficiency has become more evident with increasingly intensive land use and water use, environmental pollution, and climate change in recent years. Watershed level studies indicated that rapid land-use and land-cover changes (LUCC) in some regions of China during the 20th Century could have significant impacts on its water resources (Yu, 1991; Wei *et al.*, 2005; Liu *et al.*, 2007). However, little is known about how LUCC has affected water resources nationwide due to the complexity of LUCC-water interactions over a long-term period and at finer spatial resolutions.

The effects of LUCC on water resources have been studied through paired-watershed experiments and empirical models in the past decades (Bosch and Hewlett, 1982; Andréassian, 2004). LUCC was suggested to be an important factor that controlled water resources in both local and global scales during the last century (Hutjes *et al.*, 1998; Vörösmarty *et al.*, 2000; Costa *et al.*, 2003; Foley *et al.*, 2005; Mu *et al.*, 2007). Results from climate models indicated that LUCC could affect the regional climate through biogeochemical and biogeophysical processes (Dale, 1997; Feddema *et al.*, 2005; Gordon *et al.*, 2005; Pielke *et al.*, 2007). Colman (1953) produced a major synthesis of the effects of vegetation management on hydrologic processes and water yield. Paired-watershed experiments showed that deforestation increased annual water flow, while reforestation decreased it (Bosch and Hewlett, 1982; Andréassian, 2004). Several river basin level studies also showed that deforestation increased water yield (Costa *et al.*, 2003). Reverse conclusions, however, have been drawn by the studies in tropical forests in northeastern Thailand (Wilk *et al.*, 2001) and southeastern Asia (Bruijinzeel, 2004). In addition, much uncertainty exists in estimating the LUCC effects on flood frequency and intensity (Andréassian, 2004).

Paired-watershed experiments are generally expensive and time-consuming. They generally focus on short-term hydrological consequences induced by reforestation/afforestation, deforestation, and cropland abandonment in specific watersheds. Therefore, the limited knowledge gained from paired-watershed experiments is not enough for us to estimate the effect of LUCC on water resources at large spatial and long-term scale (e.g., decades to centuries). Bruijinzeel (2004) pointed out the importance by linking process-based distributed hydrological model with the paired-watershed experiments to predict the onsite and off-site effects along streams, and the long-term and short-term effects of LUCC on the water yield in large basins. Until now, however, few spatially explicit studies have been carried out at a continental scale, due to the difficulties in acquiring and compiling high resolution regional datasets, especially the historical land use.

Chinese scientists have studied the relationship between forest and hydrology for over 400 years (Yu, 1991), but it was not until the 1980s that science-based investigation on the forest-water relationship began to emerge in China (Wei *et al.*, 2005; Sun *et al.*, 2006). Sun *et al.* (2006) stated that even recently the majority of studies in forest hydrology in China did not follow rigorous paired-watershed approaches in determining LUCC impacts. Several studies have estimated regional effects of historical or potential human activities on water resources in China based on empirical models (Ren *et al.*, 2002; Sun *et al.*, 2006). Although 85% of freshwater withdrawal in China is used for irrigation (Brown and Halweil, 1998), which can directly affect the hydrological cycles and water resources (Foley *et al.*, 2005), few studies discussed its contributions to the variations of evapotranspiration (ET) and water yield at a national scale.

China experienced unprecedented changes in land use and land cover during the 20th Century, and this process is expected to continue in the future. Remotely sensed data showed that China's urban area increased by 25% from 1990 to 2000 (Liu *et al.*, 2005a). Its cropland area, according to historical records, increased by about 35% between 1661 and 1999 (Ge *et al.*, 2004). More recently, the total forest coverage has recovered from 11% in the 1980s to 16.7% (or 163.5 million ha) in 2000 due to the implementation of several national conservation programs (FAO, 2001). It is important to understand how these land-use changes have affected the water resources of China during the 20th Century.

In this study, we used a process-based Dynamic Land Ecosystem Model (DLEM) in conjunction with spatial data of LUCC and other environmental factors to examine the impacts of LUCC on hydrological processes in terrestrial ecosystems of China during the 20th Century. LUCC in this study includes two aspects: (1) land-use/land-cover conversions between natural vegetation and land use (i.e., cropland and built-up area) and (2) cropland management (irrigation and fertilization). Specifically, we will address the following topics in this analysis: (1) hydrological component of DLEM model; (2) LUCC in the 20th Century; (3) assessment of LUCC impacts on ET, runoff, and water yield; and (4) uncertainty in our current analysis.

METHODOLOGY

The DLEM Model

The DLEM model used in this study is a highly integrated, process-based terrestrial ecosystem model that aims to simulate the structural and functional dynamics of land ecosystems affected by multiple environmental factors including climate, atmospheric compositions (CO_2 and O_3), precipitation (PPT) chemistry (nitrogen deposition), natural disturbances (fire, insect/disease, hurricane, etc), LUCC, and land management (harvest, rotation, fertilization, irrigation, etc.). DLEM couples major biogeochemical cycles, the hydrological cycle, and vegetation dynamics to make daily, spatially explicit estimates of water, carbon (e.g., CO_2 and CH_4), and nitrogen fluxes (e.g., N_2O) in terrestrial ecosystems (Tian *et al.*, 2005; Chen *et al.*, 2006; Ren *et al.*, 2007b; Zhang *et al.*, 2007; Tian *et al.*, 2008).

Dynamic Land Ecosystem Model includes four core interactive components: (1) biophysics, (2) plant physiology, (3) soil physics and biogeochemistry, and (4) vegetation dynamics as shown in Figure 1. In brief, the biophysics component simulates instantaneous fluxes of energy, water, and momentum within the land ecosystem and their exchanges with the surrounding environment. The plant physiology component simulates major physiological processes, such as plant phenology, carbon (C) and nitrogen (N) assimilation, respiration, allocation, and turnover. The soil physics and biogeochemistry component simulates the changing hydraulic prosperities of soil, cycling of nutrients, and dynamics of microbes. Primary biogeochemical processes, including mineralization/immobilization, nitrification/denitrification, decomposition, and methane production/oxidation are simulated by this component. The vegetation dynamics component simulates the dynamics of vegetation caused by disturbances and land use. Three major processes can be simulated: the biogeographical redistribution with climate change, the recovery and succession of vegetation after disturbances, and land management (e.g., fertilization, irrigation, harvest, etc.). Like most other dynamic global vegetation models, DLEM builds on the concept of plant functional types to describe vegetation distributions. The land use and management processes simulated in this component handle the effects of LUCC and land management on the fluxes of water, carbon, nitrogen, and the structure of ecosystem. DLEM emphasizes the modeling and simulation of managed ecosystems including agricultural ecosystems, plantation forests, and pastures. The spatially explicit management datasets, such as irrigation, fertilization, rotation, and harvest are used as model inputs for the LUCC submodel. DLEM also can estimate the impacts of urban impervious surface and urban lawn management on the hydrological processes.

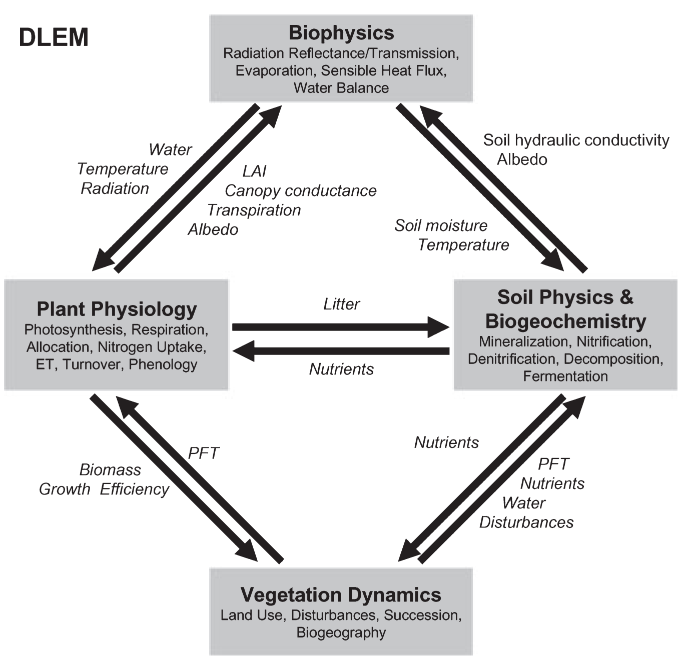

FIGURE 1. Dynamic Land Ecosystem Model (DLEM).

The major hydrological processes of DLEM are shown in Figure 2. The soil is represented by three layers: one litter layer (or above ground-water table) with flexible depth, and two mineral soil layers with fixed depth of 0.5 and 1.0 m, respectively. At the beginning of each simulating step, PPT is separated as snow (Ps) or rain (Pr) according to air temperature. Projected Leaf Area Index is used to estimate the intercepted water at the canopy which is eventually evaporated ($E_{\mathrm{can,evap}}$) or sublimated ($q_{\mathrm{can,sub}}$) to the air. Part of the throughfall water and melted snow is intercepted by the litter layer and the remaining infiltrates into the first mineral soil layer (W_{s1}) instantly. If W_{s1} exceeds the saturated water content (estimated by Saxton and Rawls, 2006), the excess water forms the surface runoff ($q_{\mathrm{surf,runoff}}$). The water that exceeds the field capacity of the mineral soil layers was set to percolate into the lower layers at a rate estimated by Darcy's law. The percolation from the second mineral soil layer forms the subsurface runoff ($q_{\mathrm{sub,runoff}}$). Estimates of water uptake by plants are based on the distribution of roots and soil moisture at the depth of the roots. ET is simulated by using Penman–Monteith combination

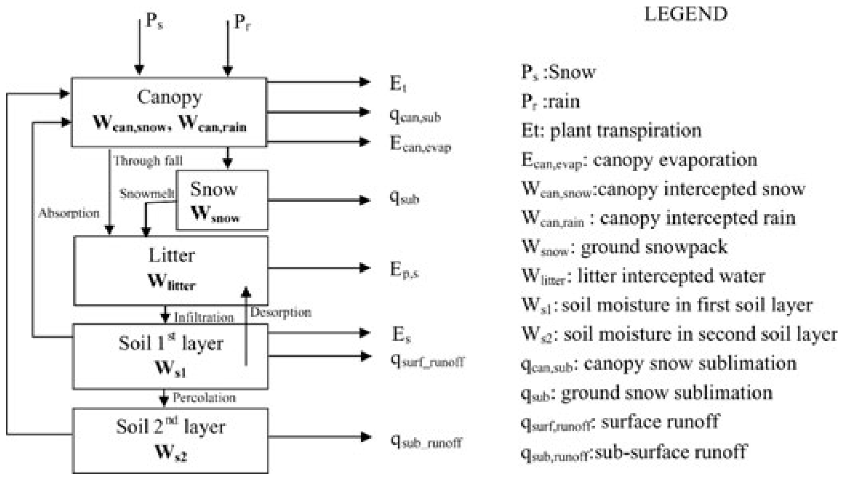

FIGURE 2. The Hydrological Components in Dynamic Land Ecosystem Model.

equation (Monteith, 1981) as Wigmosta *et al.* (1994) and Kimball *et al.* (1997) approaches.

In this model, paddy crops and wetland were assumed to produce no runoff (i.e., the excess water stays in the field unless the depth of surface water exceeds the maximum water holding capability which was set as 0.2 m). Irrigation was activated when available water in the first mineral soil layer decreases to 30% of the maximum available water (field capacity minus wilting point) during the growing season. After irrigation, the soil moisture in the first mineral soil layer will reach to the field capacity.

Model Calibration and Validation

Dynamic Land Ecosystem Model has already been carefully calibrated and widely applied to regional studies in both China (e.g., Chen *et al.*, 2006; Ren *et al.*, 2007a; Liu *et al.*, 2007; Tian *et al.*, 2008) and the United States (e.g., Zhang *et al.*, 2007; Tian *et al.*, 2008). Field data from the Chinese Ecological Research Network, U.S. Long-Term Ecological Research Network, and AmeriFlux network have been used to calibrate and validate the model.

In this study, we evaluated the simulation results on water variables against the results from both field data and other models. For validating the spatial patterns of simulated ET from natural vegetation, we compared our model results with estimates from Ahn and Tateishi (1994, monthly data) and from Zhang *et al.* (2001) and Sun *et al.* (2005). The ET estimation from Ahn and Tateishi (1994) was based on the mean climate data during 1920-1980, while the simulation results from Zhang *et al.* methods was based on mean climate during 1961-1990. We found a significant correlation between DLEM simulated ET and these studies, suggesting that the parameterization of ET was fairly accurate across China (Figure 3). For validating the seasonal patterns of ET, we compared simulation results with long-term field observation ET at Qianyanzhou Station (23°10′N, 112°34′E) in southeastern China. The vegetation of this area is typical temperate evergreen needle leaf forest. ET observations have been conducted by an eddy flux tower for four years from 2002 to 2006 (Song *et al.*, 2006; Song, 2007). For this comparison, contemporary climate data was used to drive the simulation model. Figure 4 shows that the simulated results have successfully reflected the variations of dry-wet season at this

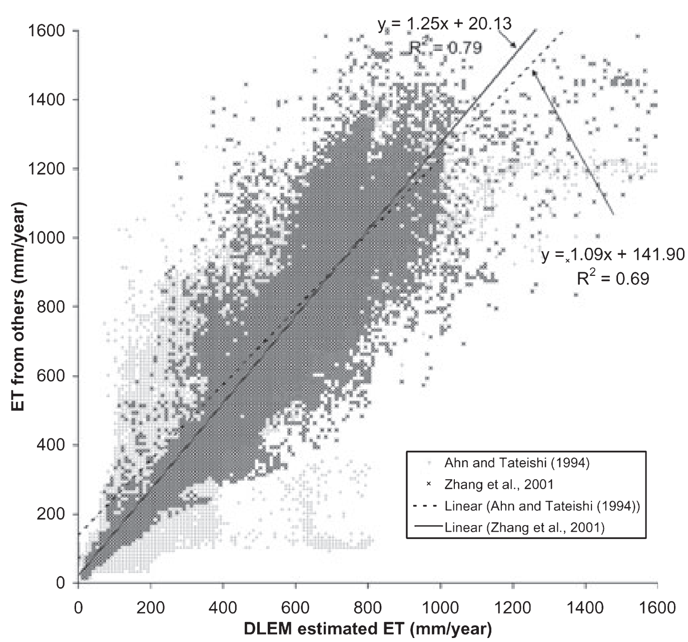

FIGURE 3. Spatial Distribution of Each River Basin and the Weather Stations Used for Generating the Climate Data.

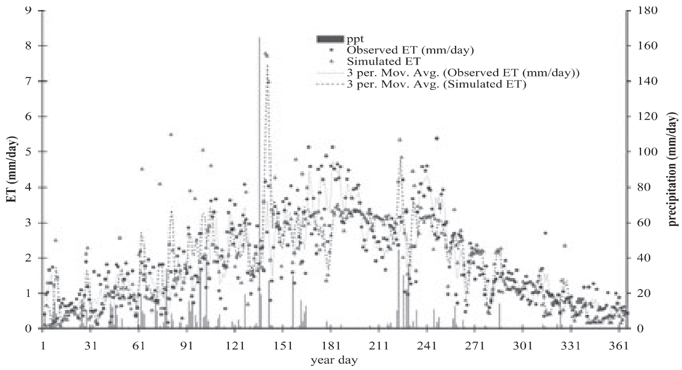

FIGURE 4. The Regression Scatter Plots of Our Simulation *vs*. Other Estimations on Annual Mean Evapotranspiration From Natural Vegetation Types.

station. ET observations from flux-tower on raining days were often unstable and many missing ET data were interpolated from other days' observations or from lookup tables (Song, 2007). Therefore, we can say our simulated ET fits the observational data very well although there are some differences between simulations and the observations on raining days (Figure 4). For validating our simulations on managed crop ecosystems, we selected a double-cropped winter wheat-summer maize system on Luancheng (37°53′N, 114°40′E) Agro-Eco-Experimental Station of Chinese Academy of Sciences. Contemporary climate data during 1997-2005 was used to get the simulation results that matched the observing period in Zhang *et al.* (2006) experiments. Our simulated average annual total ET during 1997-2005 was 797 mm which is within the range of 654 mm under minimum irrigation treatment and 850 mm under full irrigation treatment in Zhang *et al.* (2006) observations.

To validate our simulations at the river basin level, we also compared our model results with river discharge data. Five river gages from Global Terrestrial Network for River Discharge (http://gtn-r.bafg.de/servlet/is/Entry.2492.Display/) and RIVDIS datasets (Vörösmarty *et al.*, 1998; http://www.rivdis.sr.unh.edu/) have been selected to compare with simulations, in which contemporary climate data was used as input (Figure 5). The observed river discharges have been transformed into water yield depth in the contribution area. These comparisons indicate that DLEM can capture both interannual variations and quantity of water yield in these river basins.

Model Input Data

The DLEM uses both spatially explicit datasets and non spatially explicit datasets as model input. The spatially explicit datasets include climate,

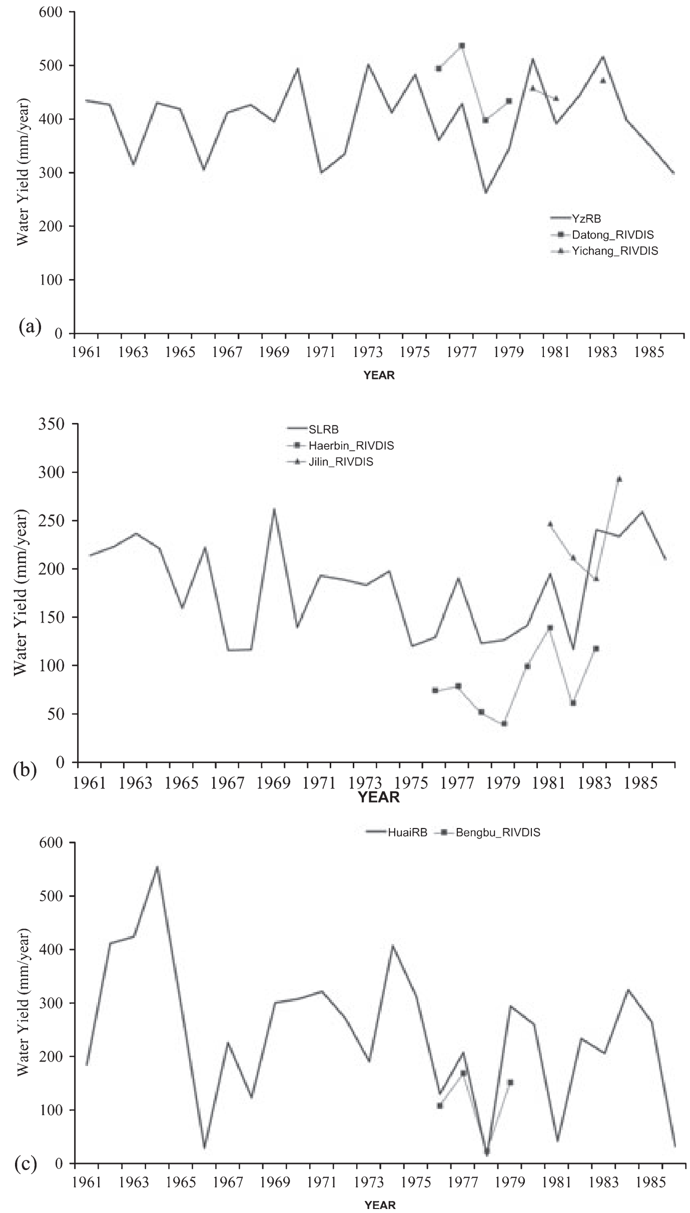

FIGURE 5. Comparison of Simulated Water Yield With Observations in Selected River Basins.

potential and contemporary vegetation, soil properties (e.g., soil texture and pH), land use, land management, PPT chemistry (e.g., nitrogen), and atmospheric compositions (e.g., O_3 and dry nitrogen deposition). The non spatially explicit data include atmospheric CO_2 concentration and calibrated parameters. In this study, all the spatially explicit datasets are generated with 10 km resolution.

The daily climate data, including maximum, minimum, and average temperature, PPT, and relative air humidity, were spatially interpolated based on 740 weather stations from China's mainland, six stations from Taiwan province, and 29 stations from other countries around China by using the

FIGURE 6. Comparison of Simulated Water Yield With Observations.

Thornton *et al.* (1997) method (Figure 6). To distinguish LUCC effect from other factors, such as climate change, we used the 30 years' climate mean data during 1961-1990 instead of the real transient climate data to run the model. Thus, the simulation results in this study represented only LUCC effects on hydrological cycles with mean climate conditions.

A potential vegetation map is needed to get the simulation baseline (Table 1 shows the name of each type). This map was generated by integrating multiple sources, including high resolution national land cover dataset (NLCD) from Landsat TM/ETM in 1999/2000 (Liu *et al.*, 2005a), global potential vegetation map (Ramankutty and Foley, 1998), global C_4 vegetation map (Collatz *et al.*, 1998), Chinese vegetation map at a scale of 1:4,000,000 (Hou, 1982), and Eurasia land cover database (version 2.0) from U.S. Geological Survey (http://edcsns17.cr.usgs.gov/glcc/eadoc2_0.html#vers2). The information of soil pH and texture was extracted from the 1:1 million soil type map (Shi *et al.*, 2004) and the second national soil survey of China (Tian *et al.*, 2006).

The spatially explicit fertilization and irrigation data were developed from the county level agricultural census data for 1990 (CITAS, http://citas.csde.washington.edu/data/chinaA/gswa.htm) and the provincial tabular data for 1950-2005 from NBS (2006).

The land-use history datasets (i.e., cropland and built-up area) were generated from remote sensing-based NLCD (three periods: 1990, 1995, and 2000) (Liu *et al.*, 2003, 2005a), historical census data (i.e., cropland and population), and archives from 1700 to 1990 (Xu, 1983; Ge *et al.*, 2004; NBS, 2006). In this study, we assume that the land transformation only

TABLE 1. Estimated Annual Mean ET, Runoff, Water Yield (PPT-ET) (unit: mm/year), and ET/PPT Ratio of Each Land-Use/Cover Type in China During the 1990s.

Land-Use/Cover Type	ET	PPT-ET	Runoff	ET/PPT
Tundra	390	114	114	0.77
Boreal broadleaf deciduous forest	376	69	69	0.84
Boreal needleleaf deciduous forest	369	80	80	0.82
Temperate broadleaf deciduous forest	529	158	158	0.77
Temperate broadleaf evergreen forest	791	735	735	0.52
Temperate needleleaf evergreen forest	675	620	620	0.52
Temperate needleleaf deciduous forest	398	134	134	0.75
Tropical broadleaf deciduous forest	902	518	518	0.64
Tropical broadleaf evergreen forest	979	691	691	0.59
Deciduous shrub	366	210	210	0.64
Evergreen shrub	664	482	482	0.58
C3 grass	263	99	99	0.73
C4 grass	467	195	194	0.71
Dry farmland	635	3	119	1.00
Paddy land	1,189	−48	61	1.04
Wetland	450	36	36	0.93
Gebi and Desert	86	13	13	0.87
Built-up area	678	161	260	0.81

Notes: ET, evapotranspiration; PPT, precipitation.

occurs between natural vegetation and cropland/built-up area, and between cropland and built-up area. The major procedure for reconstructing the annual historical cropland and urban maps include the following steps: (1) developing the baseline data for 1990, in which the cropland and built-up areas are represented by fraction of each 10×10 km grid cell; (2) reconstructing annual fractional cropland and built-up area maps for period of 1900-2000 based on the census data, baseline data, and NLCD 1995 and NLCD 2000; and (3) identifying the distinct division value of cropland and built-up area for each province. All the grid cells with higher fraction of cropland or built-up area than this division value were assigned one for cropland or built-up area accordingly. Otherwise they were assigned zero. Then we produced annual Boolean distribution maps for cropland and built-up area, which have the same statistical areas as the reconstructed fractional data at the provincial scale.

A national river basin boundary map from the Data Center of Resources and Environmental Sciences, Chinese Academy of Sciences was used to analyze the regional variations of hydrological cycles in this study. The major basins in China are Songhua and Liaohe river basin (SLRB); Haihe river basin

TABLE 2. Land-Use Change in Each River Basin During the 20th Century (units: 1,000 ha).[1]

Land Use	**Cropland**			**Built-Up Area**			**Forest**		
Period	**1900s to 1950s**	**1950s to 1990s**	**1900s to 1990s**	**1900s to 1950s**	**1950s to 1990s**	**1900s to 1990s**	**1900s to 1950s**	**1950s to 1990s**	**1900s to 1990s**
River basins									
SLRB	14,726	4,029	18,755	146	598	744	−4,154	−830	−4,984
HaiRB	−52	−2,312	−2,364	222	1,774	1,996	−21	187	166
HuaiRB	−467	−4,751	−5,217	701	3,984	4,685	−145	474	329
YellowRB	7,248	5	7,253	99	774	873	−663	77	−585
YzRB	7,907	−8,439	−532	118	1,242	1,360	−5,333	5,105	−228
PearlRB	2,464	−377	2,087	103	668	772	−2,278	−51	−2,328
SERB	−1,600	−1,663	−3,264	46	304	350	1,465	1,316	2,780
SWRB	257	623	881	2	8	10	−148	−311	−459
CRB	1,066	5,038	6,104	22	125	147	−28	−61	−89
Total	31,550	−7,848	23,702	1,458	9,477	10,935	−11,304	5,907	−5,398

Notes: CRB, Continental river basin; HaiRB, Haihe river basin; HuaiRB, Huaihe river basin; PearlRB, Pearl river basin; SERB, Southeast river basin; SLRB, Songhua and Liaohe River Basin; SWRB, Southwest river basin; YellowRB, Yellow river basin; YzRB, Yangtze river basin.

[1]1900s: the average area during 1901-1920; 1950s: the average area during 1946-1955; 1990s: the average area during 1991-2000.

(HaiRB); Huaihe river basin (HuaiRB); Yellow river basin (YellowRB); Yangtze river basin (YzRB); Pearl river basin (PearlRB); Southeast river basin (SERB); Southwest river basin; and Continental river basin (CRB) (Figure 6).

According to the reconstructed historical datasets, China experienced significant land-use change during the 20th Century (Table 2). Its cropland area increased 23.4 million ha or 18%, built-up area increased 11.0 million ha, and forest area decreased 5.4 million ha or 2.5%. The dominant land-use change in this period was the land transformation from grassland and shrub to cropland and the urbanization from cropland (Ge *et al.*, 2000; Liu *et al.*, 2005a,b). The land-use change in China shows substantial spatial and temporal variations. For forest land, two significant changing periods can be identified. In the first period, from 1900 to 1946, China lost 15 million ha of forest land. Its forest then recovered slowly during the second period (1947-2000). Significant changes of forest area were found in YzRB, SLRB, PearlRB, SERB, and HuaiRB (Table 2; Figure 7). YzRB lost 5.3 million ha or 8% of forest in the first half of the 20th Century, but gained 5.1 million ha of forest in the second half of the century. In SLRB and PearlRB, forest area decreased 5.0 and 2.3 million ha, respectively, during the 20th Century. The forest area in SERB and HuaiRB, however, increased about 2.8 and 0.3 million ha, respectively, in the same time period. During the study period, the cropland of SLRB and YellowRB has increased significantly, while that of HuaiRB and SERB has decreased (Table 2). Built-up area increased in all river basins, especially significant in HuaiRB, HaiRB, and YzRB (Table 2).

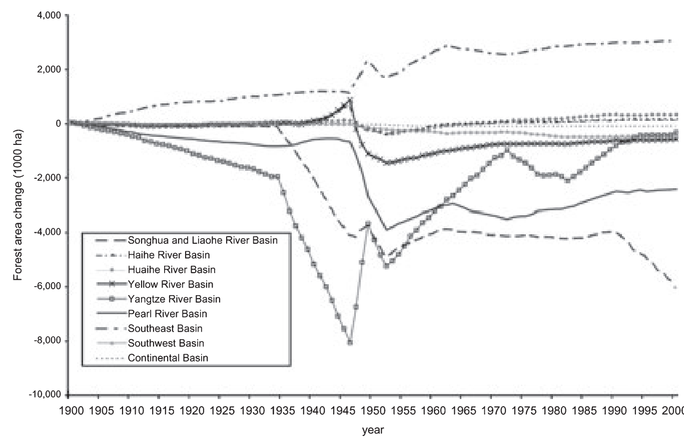

FIGURE 7. Changes in Forest Area for Each River Basin During 1900-2000 Based on Reconstructed Historical Land-Use Data (unit: 1,000 ha).

Simulation Experiments

To estimate effects of LUCC and land management on ET, runoff, and water yield we designed the following two simulations experiments. The first one used transient land-use data (i.e., annual Boolean cropland and built-up area data) with contemporary fertilization and irrigation data as driving forces. The second one also used the transient land-use data as model input but without fertilization and irrigation for cropland. Before these transient simulations, different baselines for these two simulations were generated with two steps: (1) the Equilibrium run, which is to run the model by using the potential vegetation and mean climate data to reach ecosystems' equilibrium state, that is, the annual net flux of carbon, nitrogen, and water flux from each grid is less than

0.01 (gram carbon/m^2 for carbon, gram nitrogen/m^2 for nitrogen, and mm water/m^2 for water); (2) and the Spin-up run, which is to run the model separately for these two experiments for 600 years with the same contemporary land-use map in 1900 but with different management treatments. For the first experiment (i.e., with land management), the spin-up run considers fertilization and irrigation on cropland; while for the second experiment, this procedure does not. After the spin-up run, transient runs for the two different simulation experiments were conducted by using transient land-use data and different management practices as model input.

RESULTS AND DISCUSSIONS

Spatial and Temporal Patterns of ET

Our simulation results indicated that the average ET in the 1990s was 432 mm/year and the ratio of ET to PPT was 0.73. ET correlates significantly with PPT except for some major agricultural regions such as northwestern China. ET varied from 86 mm/year for Gebi to 1,190 mm/year for Paddy rice (Table 1; Figure 8). Grassland and built-up areas had moderate ET with 263 and 678 mm/year, respectively. The built-up area in our simulation actually consists of two kinds of land covers: the impervious surface and the remnant land cover that has not been converted. The percentage of the impervious surface was calculated from the Landsat TM/ETM datasets (Liu *et al.*, 2005a). Our estimation of urban ET is very close to the results from Grimmond and Oke (1999). The ET/PPT ratio ranges from 0.52 for temperate evergreen forest to 1.04 for paddy cropland (Table 1). We found that the ratio of ET/PPT decreased with decreasing latitude, which was consistent with field observation data (e.g., Wei *et al.*, 2005).

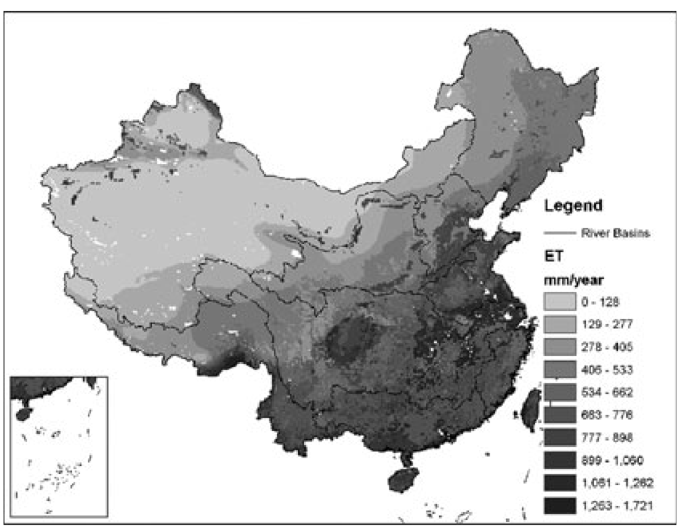

FIGURE 8. Spatial Distribution of Estimated Mean Annual Evapotranspiration (mm/year) Over China During the 1990s With Mean Climate Condition.

We found LUCC has led to large ET variations in more than half of the river basins during the 20th Century (Figure 9). The patterns and intensity of these changes, however, are quite different among river basins. For example, ET in CRB increased by 10% (12 mm), on the contrary, it decreased by 8% (67 mm) in SERB (Figure 9). Similar to CRB, ET in SLRB, PearlRB, and YellowRB shows an increasing trend in the 20th Century. Historically, the biggest changes in ET occur during the second half of the century. Figure 10 shows the spatial distribution of changes in ET between the 1950s and the 1990s in response to the LUCC, revealing that ET decreased mostly in humid and semi-humid regions (East China) and increased mostly in arid and semi-arid regions (West China). Because ET represents the total water losses out of the land system, the spatial variations in ET indicates that the imbalance of water resources in China was exacerbated by LUCC during the 20th Century.

Spatial and Temporal Patterns of Runoff

According to our simulation, the average annual runoff depth from China's land was 179 mm (Table 1). PPT, ET, soil physical properties, and land cover types were major factors controlling the runoff processes. Among all the land use/cover types, the temperate evergreen forest and the tropical forest

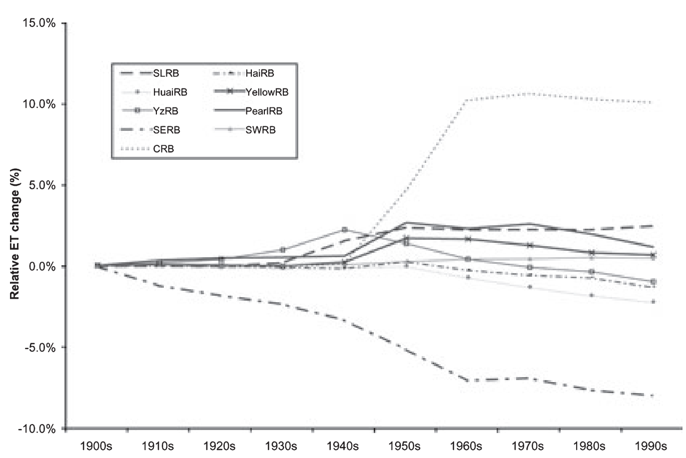

FIGURE 9. Relative Changes in ET for Each River Basin Caused by LUCC (simulated by DLEM).

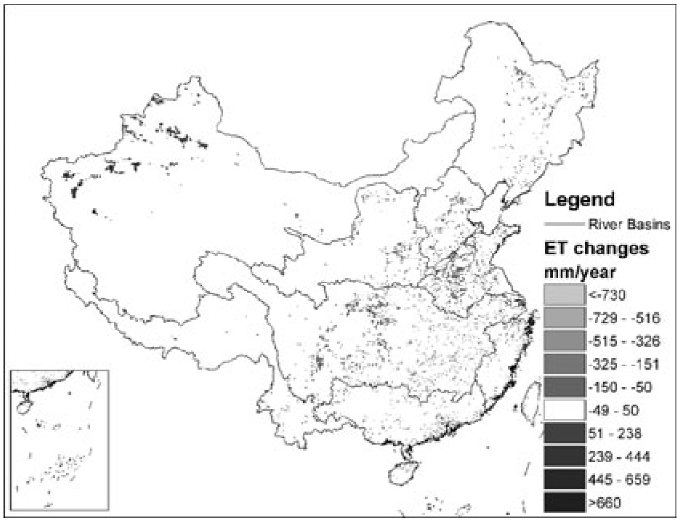

FIGURE 10. Spatial Distribution of Changes in ET Over China Between the 1990s and the 1950s Caused by LUCC (unit: mm/year).

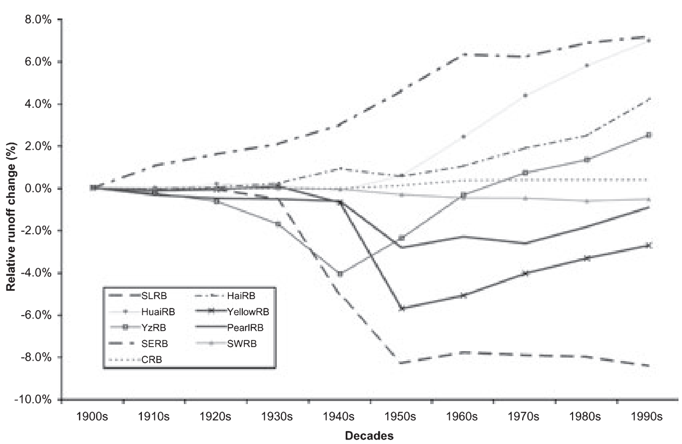

FIGURE 11. Relative Changes in Runoff for Each River Basin Caused by LUCC (simulated by DLEM).

had the highest runoff (Table 1), while cropland and grassland had relatively lower runoff than forests and shrubs. Due to large variations in climate and land cover types, the estimated runoff for all the river basins showed obvious differences that range from 20 mm/year in CRB to 670 mm/year in SERB. LUCC in China affected the runoff process significantly in most of the river basins (Figure 11). Similar to ET, large changes in runoff in all the investigated river basins occurred in the second half century except for SLRB where runoff dropped down during the 1940s and 1950s and then leveled off. In the second half century, LUCC led to increased runoff in most river basins (Figure 11). For example, runoff in HuaiRB increased by 6.3% (10 mm/year) during 1950-2000, and the runoff in YzRB increased by 5.0% (15 mm/year). Runoff in HaiRB and YellowRB increases by 3.6 and 3.2%, respectively. Higher runoff could likely result in intensive soil erosion, flood risks, and water source losses.

As DLEM did not track sources of the irrigation water, the estimated annual runoff ($q_{\text{surf,runoff}} + q_{\text{sub,runoff}}$) from cropland was different from the estimated water yield, i.e., annual PPT minus annual ET (Sun *et al.*, 2005; Table 1).

Spatial and Temporal Patterns of Water Yield

Water yield from river basins is also referred to as total discharge (runoff), but "yield" is used more in the sense of "harvest" (Lee, 1980). Water yield is the total water budget of an ecosystem and river basin, and it can be used as an index representing the overall water availability for use by human and others. In this article, the annual water yield refers to the remaining precipitated water after loss through ET, so we use "PPT minus ET" to represent water yield.

A regional significant imbalance of water resources in China can be found from Figure 12. Most of the cropland areas have low or negative water yield, which indicated that less water resources were available for other services except for crop production. The negative water yield also indicated requirements of additional water resource for cropland irrigation. SERB had the highest (993 mm/year in 1990s), and PearlRB has the second highest water yield (667 mm/year in 1990s). The average water yield in YzRB during the 1990s was 307 mm/year. HaiRB had a negative water yield of −44 mm/year during the 1990s. This negative water yield was consistent

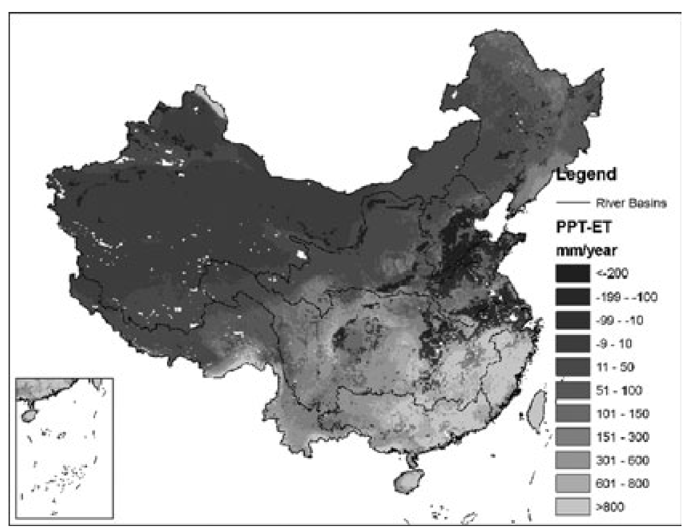

FIGURE 12. Spatial Distribution of Estimated Annual Mean Water Yield During the 1990s With Mean Climate Condition.

with the observed declination of ground-water table in HaiRB (TWRCHR, 1998; Liu *et al.*, 2007).

Based on its definition, the changes of water yield in the 20th Century is the same as ET in quantity but the opposite in direction. Figure 13 shows the relative decadal change in water yield in all basins from 1900 to 2000. SERB has the biggest increase in water yield during the 20th Century (about 70 mm/year). The biggest relative change, however, occurred in HuaiRB that increased by 53%, and in CRB that decreased by 53%, respectively. The same as runoff, water yield in most of river basins had an increasing trend in the second half of the 20th Century. For example, water yield in SERB increased 24 mm/year, HuaiRB 17 mm/year, YzRB 16 mm/year, and HaiRB 9 mm/year during 1950-2000 (Figure 12). YellowRB also had a slightly elevated water yield (4 mm/year) during 1950-2000. Water yield in YzRB had declined in the 1940s and the 1950s and rose up slowly afterward. Generally speaking, increased water yield in most basins during late half century implied mitigation or at least no further worsening of national water deficiency, especially for North China.

Impacts of Different LUCC Types on ET, Runoff, and Water Yield

Deforestation/Reforestation Impacts. Our simulation showed that ET from forests was generally higher than that from grasslands. The conversion from forest to grassland would decrease ET and increase water yield. Studies based on paired-watershed experiments indicated that deforestation increases annual streamflow, while reforestation decreases it (Bosch and Hewlett, 1982; Sahin and Hall, 1996; Andréassian, 2004). But these studies were extremely scattered and even contradicted each other (Hibbert, 1967; Ingwersen, 1985; Cao *et al.*, 1991; Andréassian, 2004; Wei *et al.*, 2005). Although the water yield change can be partly explained by the changes of land cover (Bosch and Hewlett, 1982; Sahin and Hall, 1996), such an explanation is not sufficient without considering the development stage of forest (Bosch and Hewlett, 1982; Andréassian, 2004). The hydrological consequences of deforestation/reforestation also depend on the corresponding land-use/cover types. For example, the reforestation from paddy land abandonment would generally decrease ET and increase water yield (Farley *et al.*, 2005). Reforestation from grassland, on the contrary, would generally increase ET and decrease water yield. To estimate the hydrological consequences of LUCC, we need to consider both the environmental factors and land-use history. By considering the forest dynamics after cropland abandonment, DLEM is able to simulate both the short-term and long-term LUCC consequences on the hydrological processes.

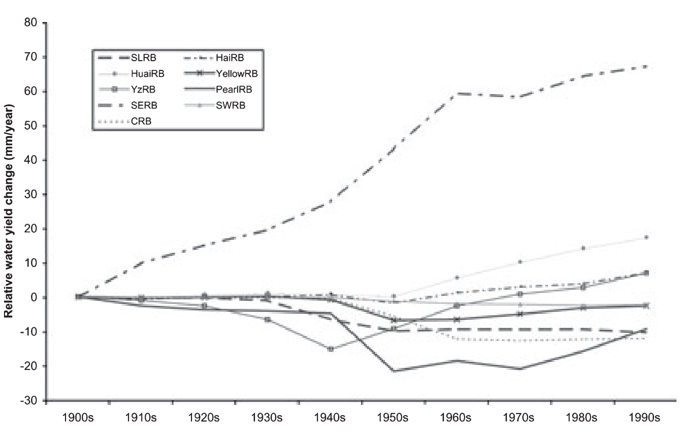

FIGURE 13. Relative Changes in Water Yield for Each River Basin Caused by LUCC (simulated by DLEM).

According to our simulation, during the 20th Century, deforestation resulted in an annual ET change from −546 mm (decrease) to +834 mm (increase) with an average of +138 mm, while reforestation induced an annual ET change from −1,070 mm to +89 mm with an average of −422 mm (Figure 14). Extreme values appeared in areas with specific environmental condition and land-use history, for example, the young forest which is newly established on abandoned cropland usually has low ET. Our results implied that in China deforestation may have increased ET and decreased water yield, while reforestation may have decreased ET and increased water yield. Our results are different from the study of Sun *et al.* (2005), probably because their estimations only focus on the land-cover conversion among natural vegetation types without considering the effect of cropland management on hydrological processes. According to our analysis on forest changes in China, deforestation and reforestation are always associated with cropland or built-up area. Most areas of deforestation have been converted into paddy land or irrigated dry farming land which normally has higher ET than the non-irrigated forest. Therefore, the deforestation in China normally increased ET, and vice versa for reforestation. We found that the large scale changes of forest area in SERB, SLRB, YzRB, HuaiRB, and HaiRB might have significant influences on water resources (Table 2; Figure 14). Although large-scale deforestation that occurred in the first half of the 20th Century increased ET and decreased the water yield significantly, the increasing trend in forest area in YzRB, SERB, HuaiRB, and HaiRB during the second half century will undoubtedly increase water yield in the long run (Table 2).

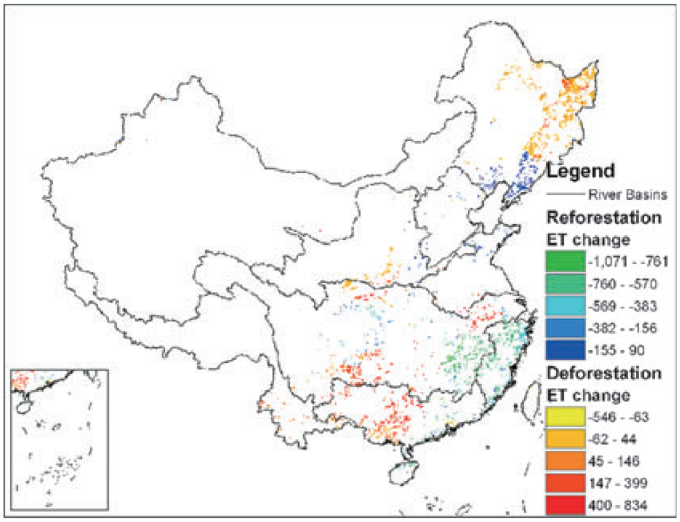

FIGURE 14. Spatial Distribution of Deforestation/Reforestation Effects on ET Over China During 1900-2000.

Urbanization Impacts. The rapid urban sprawl in China has resulted in more and more arable land conversion to built-up areas (Heilig, 1997; Liu *et al.*, 2005a). The water cycle in urban areas is different from that in other vegetation covers as most of the trees and lawns in urban areas are irrigated. ET in urban areas is often neglected because it is considered to be considerably lower than that from the surrounding areas (Grimmond and Oke, 1999). However, in many urban areas, there is a large area of urban vegetation and scattered trees and these areas have higher ET than the same vegetation covers in non-urban regions due to managements (Grimmond and Oke, 1999). Grimmond and Oke (1999) pointed out that ET from urban areas should be included in water balance modeling.

Our model simulation showed that on average, urbanization decreased ET by 98 mm/year and increased water yield during the 20th Century due to the increased imperious surface area. Another possible reason for decreased ET is that most of the new built-up areas were converted from irrigated cropland (especially from paddy land in the East and Southeast of China), which has a much higher ET than any other vegetation types.

Although we estimated that ET decreases due to urbanization in most river basins, it does not necessarily mean improved water resources. On the contrary, urbanization is usually accompanied by degradation of water quality, especially where wastewater treatment is absent (Wear *et al.*, 1998; Foley *et al.*, 2005). In addition, higher water supply would be required to support urban residents than rural residents because of different industry intensity, population density, living standard, and food structure (Brown and Halweil, 1998; Gleick, 2003). Furthermore, the increasing peak flow due to impervious surfaces and urban pipelines can result in higher flood risk and less water discharge to the underground reservoir. According to our simulations, the hydrological cycles in HuaiRB, HaiRB, YzRB, YellowRB, and SLRB have already been significantly changed by urbanization. With a prospect of accelerated urbanization in China in the future (Cohen, 2004), the consideration of not only gross urban water balance but also urban water quality should be included in any assessments of national water resources.

Cropland Reclamation and Abandonment Impacts. Our simulation showed that the land-use conversion from natural vegetation to cropland increased annual ET by an average of 182 mm/year (Figure 15). Cropland abandonment decreased ET by an average of 379 mm/year. These findings implied that newly cultivated cropland could increase local water demands, while cropland abandonment could decrease the water loss and eventually increase the water availability. Such consequences were most obvious after the conversion of irrigated cropland into natural vegetation in dry and semi-dry regions (Figure 15).

During the 20th Century, cropland expansion in SLRB, YellowRB, and CRB had led to an increase in ET and a reduction in the overall water resources for other uses. The cropland abandonment during 1950-2000 in YzRB, HuaiRB, HaiRB, and SERB, on the contrary, could increase water yield and decrease water loss through reducing ET. From this perspective, the reforestation program in arid dry and semi-arid areas that return irrigated cropland to forest or grassland could increase water storage in reservoir

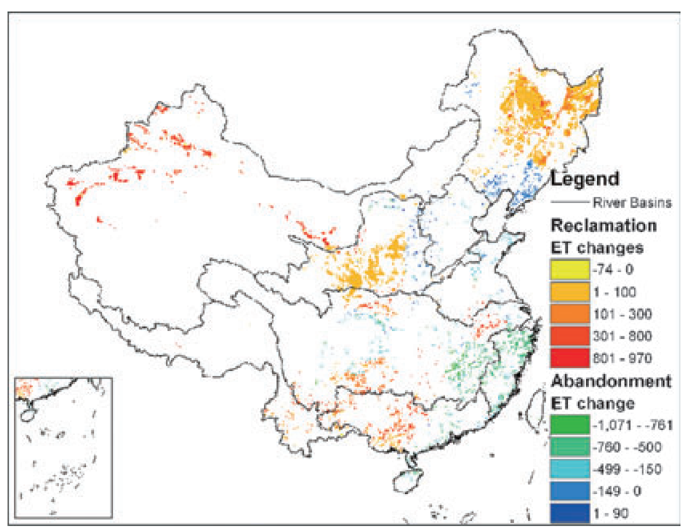

FIGURE 15. Spatial Distribution of Cropland Reclamation/Abandonment Effects on ET Over China During 1900-2000.

and protect the water resources for wildlife and ecosystem functions.

Management Impacts. In China, 85% of freshwater withdrawal has been used for irrigation (Brown and Halweil, 1998). Agricultural activities such as fertilization and irrigation potentially have large influences on water resources. Our comparisons between two simulations with/without cropland management indicated that cropland management could increase ET by 98 mm/year (Figure 16). The biggest impact of management on ET was found in the arid and semi-arid regions where croplands normally need to be irrigated. The HuaiRB and YzRB also revealed significant management effect on ET. These simulation results are close to field observations of Zhang *et al.* (2006). They reported that full irrigation treatment on double-cropping system of winter wheat and maize increased ET by about 250 mm/year comparing with minimum irrigation treatment in North China Plain. Matson *et al.* (1997) also pointed out that increasing agricultural production by better management requires more water for irrigation. Therefore, the increasing demand for food requires intensive cropland management, which would add more pressure on the already stressed water resources in China, unless break-through technology will be developed to dramatically increase the cropland's water use efficiency.

Uncertainties and Future Considerations

In simulations of hydrological systems at the regional scale, many factors, such as model structure, parameters, and meteorological input, can lead to large uncertainty due to the "inherent multi-scale space-time heterogeneity" (Sivapalan *et al.*, 2003). Our studies focus on the impact of LUCC, which involves the changes in cropland and built-up area, on hydrological cycles in China. The natural vegetation dynamics caused by national engineering projects, such as South-North Water Transfer Scheme and "Three North" protection forest project, may also have significant effects on regional hydrological cycles (Liu, 1998). In addition, climate change, combined with human-caused environmental degradation and pollution, such as increasing atmospheric CO_2, surface O_3, desertification, and soil erosion, could change the distribution of forest and grassland and hence influence hydrological processes (Vörösmarty and Sahagian, 2000; Tian *et al.*, 2003; Gedney *et al.*, 2006; McLaughlin *et al.*, 2007). Thus to improve the current study, we need to address the processes of vegetation dynamics induced by climate change, air pollution, and soil degradation in the future. The effect of land-use change on runoff and soil erosions also depends on the rainfall regimes (Wei *et al.*, 2007). Therefore, to accurately estimate the effect of LUCC on water cycles, we should take into account other factors and processes including intensive forest and crop management, water use structure and climate change (Jackson *et al.*, 2001).

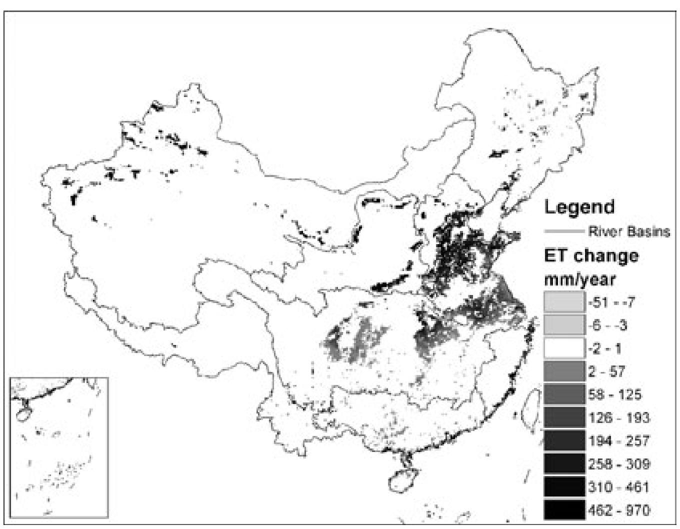

FIGURE 16. Spatial Distribution of Crop Management Effects on ET Over China (unit: mm/year).

CONCLUSIONS

Through comparisons of DLEM results with other model simulations, field observations, and river discharge data, we found that DLEM can adequately catch the spatial and temporal patterns of hydrological processes. Our simulation results demonstrated that LUCC led to significant changes in ET, runoff, and water yield in most of China's river basins during the 20th Century. We found that deforestation/reforestation, urbanization, cropland expansion/abandonment, and management had important effects on the regional ET, runoff, and water yield in China during the 20th Century. Reforestation (from abandoned cropland) in China normally decreased ET and increased water yield because irrigation on cropland can significantly change the hydrological cycle. Urbanization influences hydrological cycles by decreasing ET and increasing water yield in most of the economically developed river basins.

Substantial spatial and temporal variability in LUCC effects on water cycles revealed by this study suggested that higher spatial resolution environmental information, continuous historical land-use data, and processes-based ecosystem model are critical for improving our assessment of LUCC effects on the hydrological cycle at large scales.

To better understand LUCC effects on China's water resources, we should also take into account the complex interactions among LUCC and other environmental changes such as climate and atmospheric chemistry in future research. To sustain water resources in China, clearly, it is of critical importance to improve land-use planning and watershed management.

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