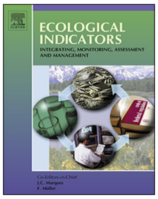
Ecological Indicators 91 (2018) 542–554

Contents lists available at ScienceDirect

Ecological Indicators

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



Original Articles

Spatiotemporal features of the hydro-biogeochemical cycles in a typical loess gully watershed

Fubo Zhao[a], Yiping Wu[a,*], Linjing Qiu[a], Bellie Sivakumar[b,c], Fan Zhang[a], Yuzhu Sun[a], Liqun Sun[d], Qinglan Li[d], Alexey Voinov[e]

[a] Department of Earth and Environmental Science, School of Human Settlements and Civil Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi Province 710049, China
[b] School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[c] Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA
[d] Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, Guangdong Province 518055, China
[e] Faculty of Engineering & IT, University of Technology Sydney, NSW 2007, Australia

ARTICLE INFO

Keywords:
Carbon cycle
Loess Plateau
SWAT-DayCent
Water cycle
Watershed ecosystem

ABSTRACT

Hydrological and biogeochemical processes are essential for material and energy exchange among climate-soil-plant systems and, thus, play an important role in terrestrial ecosystems. In particular, the water-carbon dynamics determine the status and change of ecosystems. Therefore, understanding the spatiotemporal features of the water and carbon cycles is of great importance for watershed ecosystem management. This study employed a newly coupled hydro-biogeochemical model (SWAT-DayCent) to investigate the spatiotemporal characteristics and evolution of the water cycle (evapotranspiration (ET), soil water, and water yield) and carbon cycle (net primary productivity (NPP), soil organic carbon (SOC)) in a typical loess gully watershed (the Jinghe River Basin, JRB) on the Loess Plateau of China during the period of 2000–2010. The satisfactory performance of the coupled model demonstrates that the SWAT-DayCent model is capable of simulating hydro-biogeochemical processes at the watershed scale in the Loess Plateau region. The spatial distributions of hydro-biogeochemical components varied significantly over the JRB—a decreasing gradient from south to north in hydrological variables and NPP, a higher SOC in the western margin than other parts, and a general increasing trend for all the five components in the southeastern part. Temporally, the hydrological variables showed a slightly decreasing trend, the NPP underwent a slight upward trend, but the SOC decreased significantly in the whole basin under the current climate conditions. The correlation analysis between hydrologic components and carbon cycle indicated that the water cycle may have synergies with NPP but may exert little influence on SOC. Overall, our quantitative analyses over time and space can be informative in soil and water conservation practices and ecosystem service enhancement in the JRB specifically and other parts of the Loess Plateau region as well.

1. Introduction

Hydro-biogeochemical cycles not only are the key link in the exchange of material and energy among the climate-vegetation-soil systems, but also play a vital role in the terrestrial ecosystems (Tian et al., 2010; Yu et al., 2006). To some extent, the dynamics of hydro-biogeochemical processes reflect the changes of multiple ecosystem functions (Zhang et al., 2016a). In particular, the hydrological and biogeochemical cycles are closely linked and are interdependent (Xiao et al., 2009; Yu et al., 2008). For example, the hydrological processes are influenced by the vegetation systems, such as canopy interception and water uptake by plant growth. Similarly, many vegetation systems are limited by water, and their structures and functions are driven by the water availability (Loheide and Gorelick, 2007). In addition, hydro-biogeochemical components, such as soil water and carbon storage, are key factors in many ecosystem services related to biodiversity and ecosystem productivity and are important for soil and water conservation (Li et al., 2017; Su and Fu, 2013). Therefore, accurate quantification of water and carbon cycles over regions can improve our understanding of the interactions among climate-vegetation-soil variables and can help in watershed management.

There has been a large amount of research interest on the water and carbon cycles in the terrestrial ecosystem during the past few decades, especially in the context of climate change (Voinov et al., 2004; Wang et al., 2014; Yang et al., 2011; Zhang et al., 2017). With the development of observational techniques, such as the eddy covariance technique, which

---

* Corresponding author.
E-mail addresses: yipingwu@xjtu.edu.cn, rocky.ypwu@gmail.com (Y. Wu).

https://doi.org/10.1016/j.ecolind.2018.04.027
Received 1 February 2018; Received in revised form 11 April 2018; Accepted 12 April 2018

is a direct approach for understanding the water-carbon-heat fluxes, scientists have gained a relatively good understanding of carbon and water cycles and their interactions in local or regional scales (Wang et al., 2013; Xiao et al., 2012). However, the traditional site-scale observations cannot meet the requirements of large-area investigation on water and carbon dynamics, considering the heterogeneity of the hydrological and biogeochemical cycles (Niu et al., 2011; Voinov and Cerco, 2010). Therefore, a number of fundamental models have been developed to investigate the hydrological and biogeochemical processes and their responses to human activities and environmental factors. On the one hand, the hydrological model such as Soil and Water Assessment Tool (SWAT) and Hydrologic Simulation Program-Fortran (HSPF) (Johnson et al., 2003), have been widely used to assess the impacts of climate and land use and land cover (LULC) changes on the water cycle and nutrient cycle and loadings (Yang et al., 2011; Zhang et al., 2013). On the other hand, the biogeochemical models, such as DayCent (Parton et al., 1998), Erosion-Deposition Carbon Model (EDCM) (Liu et al., 2003), and BioGeoChemical Cycle (BGC) model (Running and Gower, 1991) have been extensively used to evaluate the plant production, carbon dynamics and greenhouse gas emissions (Cheng et al., 2014; Peng et al., 2013; Zhou et al., 2012). However, most of the existing studies only focused on either hydrological or biogeochemical process. Few studies have investigated the hydro-biogeochemical cycles together using a coupled hydro-biogeochemical model at regional scale. Wu et al. (2016) developed an SWAT-DayCent Coupled model which is promising in investigating the hydro-biogeochemical cycle but its capability in simulating the water-carbon cycles in a certain watershed has not been tested yet. Our motivation for the present study is use SWAT-DayCent to investigate the hydro-biogeochemical dynamics in the Jinghe River Basin (JRB) on the Loess Plateau, China.

The Loess Plateau, located in the middle stream of the Yellow River in North China, is known for its severe soil erosion and water loss. Although the Chinese government has implemented many efforts to restore the deteriorated environments since the end of the 20th century, such as “Grain for Green” and “Natural Forest Protection”, the fragile ecological environment, increasing severity of water shortages, and land degradation are still threats to the livelihoods of local communities (Feng et al., 2012; Fu et al., 2011; Luo et al., 2015). In addition, the climate in the Loess Plateau is becoming warmer and drier (Wang et al., 2012; Xin et al., 2010), and this tendency not only can exert an influence for the water cycle, but may also affect the plant growth and the carbon cycle among climate-plant-soil systems. Therefore, it is of great importance to investigate the hydro-biogeochemical processes under such critical environments in the Loess Plateau region.

The overall goal of this study was to investigate the water and carbon cycles in the JRB — using the SWAT-DayCent Coupled model. The specific objectives of the study were to 1) validate the suitability and performance of the SWAT-DayCent for the specific conditions in the JRB, 2) investigate the spatiotemporal distribution patterns of key hydrological (e.g., soil water, evapotranspiration (ET), and water yield) and biogeochemical components (e.g., net primary productivity (NPP), soil organic carbon (SOC)), 3) analyze the temporal changes of the hydro-biogeochemical variables in different ecosystems of the JRB, and 4) explore the relationship between the water and carbon cycles at the Hydrological Response Unit (HRU) level.

2. Materials and methods

2.1. SWAT

The SWAT model, developed by the United States Department of Agriculture – Agricultural Research Service (USDA — ARS), is a continuous, distributed hydrological model for predicting the impacts of land use and climate change on water, sediment, and chemical components at the watershed scale (Arnold et al., 1998). As a physically-based model, the SWAT model has been increasingly applied to address numerous watershed issues especially under climate shifts and human activities at the watershed scale (Arnold et al., 2000; Luo et al., 2018; Panagopoulos et al., 2015). The main outputs of SWAT are surface runoff, lateral flow, baseflow, ET, soil water, water yield, sediment load, and nutrient loads. Further details about SWAT are available in its theoretical documentation (Neitsch et al., 2011). We selected SWAT in this study because it is physically-based and is open-source. It was essential that we could modify and enhance the model if needed. Besides, it is probably the best tested and documented model in the field.

2.2. DayCent

The DayCent model, a daily time-step version of CENTURY biogeochemical model, is a widely-used terrestrial biogeochemical process-based model of intermediate complexity (Del Grosso et al., 2009). DayCent comprises several key sub-models related to biogeochemical cycle and has been widely applied to simulate ecosystem responses to changes in climate and management practices in crop, grassland, forest, and savanna ecosystems (Álvaro-Fuentes et al., 2017; Field et al., 2016). DayCent has a strong ability in simulating carbon cycle and tracking carbon stocks. Numerous applications of the model have shown that DayCent is able to simulate the carbon stocks and dynamics with a high accuracy (Del Grosso et al., 2010). The major model outputs are NPP, Biomass, grain yield, SOC, soil respiration, and soil nitrate content. Further details about DayCent can be found in Parton et al. (2001) and Parton et al. (1998). Again, we selected DayCent in the study because it is open-source, well documented and well recognized for simulating the carbon cycle.

2.3. SWAT-DayCent

To achieve the integrated implementation of SWAT and DayCent for a comprehensive evaluation of eco-environmental issues, Wu et al. (2016) developed a modeling coupler, SWAT-DayCent, that can allow a customized SWAT project to simultaneously run the SWAT and DayCent models. In the operation of SWAT-DayCent, the SWAT was set as a basic framework and the DayCent was embedded into SWAT with some new functions, aiming to take each HRU as a single site and write the input files required by DayCent (that is, unify the calculating unit (HRU) in both SWAT and DayCent). The HRU is generated in the SWAT running process and its configuration is required for the DayCent simulation. Each HRU has the unique soil and land cover type, and can be used as a specific site in DayCent. DayCent then obtains the specific variables in HRU to simulate the carbon cycle across all HRUs through a loop. In fact, in the coupling procedure, the SWAT and DayCent runs separately using the same input data based on the HRU (Wu et al., 2016). Finally, DayCent merges the simulated spatial and temporal variables at the HRU level, such as NPP, SOC, biomass, greenhouse emissions, soil respiration, etc. Further details about the development and implementation of SWAT-DayCent can be found in Wu et al. (2016).

2.4. Study area

The JRB (106°E–108°E, 34°N–37°N), a typical watershed located on southern part of the Chinese Loess Plateau (Fig. 1), is characterized by typical loess hills and gullies. The Jinghe River originates from the eastern part of the Liupan Mountains with a total length of approximately 455 km, and flows through Gansu, Ningxia, and Shaanxi provinces (Ning et al., 2016). The basin lies in the semi-humid and semi-arid transitional zone and is controlled by a typical continental climate, with a hot and humid summer and dry and cool winter. The mean annual precipitation is about 514 mm and temperature is 8 °C. About 80% of precipitation occurs in summer and autumn. The LULC of the basin is dominated by three major vegetation types—grassland, cropland, and forest, accounting for 90% of area. The crop growing season is between April and October (Peng et al., 2013).