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Simulation of terrestrial carbon equilibrium state by using a detachable carbon cycle scheme

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ABSTRACT

Determining the equilibrium state of terrestrial carbon is a prerequisite for scientific analysis on the carbon cycle. However, the mechanism through which the carbon cycle reaches the equilibrium state remains unclear. Moreover, the carbon cycle in most of the short–term field experiments rarely reaches the equilibrium state. In this study, a detachable carbon cycle (DCC) model was proposed to simulate the equilibrium state of each carbon pool. The model was established based on a pool–and–flux scheme and contained 14 carbon pools, or carbon flow processes, each process could be detached from the main model and evaluated as an independent component. The environmental scalar algorithms of the Integrated Terrestrial Ecosystem Carbon budget model (InTEC) and Community Atmosphere Biosphere Land Exchange (CABLE) were incorporated in the DCC model. Four situations were compared using the two environmental scalar algorithms and model structure (9 *vs.* 14 carbon pools). Furthermore, the size and turnover time of each carbon pool were analyzed at the equilibrium state. A sensitivity analysis was then conducted to investigate the responses of carbon density and equilibrium time to 12 key parameters of the model. Results indicated that the combination of the CABLE environmental scalar algorithm and 14 pools exhibited improved performance on carbon storage simulation than that of the other combinations, and the effect of the environmental scalar algorithm was considerably larger than that of the carbon pool number. Sensitivity analysis indicated that the carbon density of grassland and cropland was more vulnerable and sensitive to key parameters of the model than that of the other biomes. This study elucidates influencing factors and underlying control mechanisms in the carbon accumulation, and provides a framework for quantitative analysis of each component of the carbon cycle.

1. Introduction

Terrestrial ecosystems play a crucial role in the global carbon cycle. The amount of carbon stored in plant biomass and soil is twice higher than that in the atmosphere. The carbon fluxes in the vegetation–soil–atmosphere system are 10 fold higher than CO_2 emissions from fossil fuel (Cao and Woodward, 1998). Soil is the largest carbon storage in the terrestrial ecosystem, such that even slight changes in soil carbon may induce significant fluctuations in atmospheric CO_2 concentration (Chen et al., 2015). Approximately 30% of carbon is released by anthropogenic activities, such as land cover change or fossil fuel combustion (Ise and Moorcroft, 2006). High atmospheric CO_2 concentration results in a strong feedback effect on climate (Friedlingstein et al., 2006). The increase in atmospheric CO_2 concentrations significantly related to temperature (Braswell et al., 1997; IPCC, 2013). A report from the IPCC revealed that the global average near–surface temperatures have increased at an annual rate of 0.89 °C from 1901 to 2012 (IPCC, 2013), resulting in release of carbon stocked in permafrost as CO_2 or methane and creating a positive feedback to amplify global warming.

Determination of carbon equilibrium is a major challenge in studies on the carbon cycle, this process requires setting up the initial values of all state variables in any biogeochemical models prior to analysis (Xia et al., 2012). Moreover, CO_2 released from plant litter and soil microbial heterotrophic respiration is strongly affected

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by carbon pools size at equilibrium state. However, simulation of the carbon equilibrium state hinders carbon cycle research because of the complexity of the ecosystem model and the limitation of field experiments, which are impractical to reach the equilibrium state. Efforts have been exerted to understand the complexity of ecosystem models for model evaluation and intercomparison. Fisher et al. (2014) provided an incomplete overview of terrestrial biosphere models (TBMs) and reported that more than 70 models have been used in research on the terrestrial carbon cycle. For example, Potter et al. (1993) established the Carnegie–Ames–Stanford approach (CASA) biosphere model to predict global terrestrial net primary production and edaphic control in soil microbial respiration. Wang et al. (2010) further developed the CASA–CNP model to investigate the carbon, nitrogen, and phosphorus cycles of terrestrial ecosystems. The Lund–Potsdam–Jena (LPJ) dynamic global vegetation model combines process–based, large–scale representations of terrestrial vegetation dynamics and land–atmosphere carbon exchanges to evaluate the carbon cycle in terrestrial ecosystems (Sitch et al., 2003). Furthermore, the pool–and–flux framework of the CENTURY model remarkably affects the development of the carbon cycle model (Parton et al., 1993; Parton et al., 1987). However, existing models do not provide detailed descriptions on how a carbon pool reaches the equilibrium state. In this regard, Luo and Weng (2011) developed a conceptual framework that recognizes internal ecosystem processes that drive the carbon cycle toward the equilibrium. Xia et al. (2012) introduced a semi–analytical solution to the spin–up of the Australian community atmosphere biosphere land exchange model, which significantly accelerates the equilibrium state of carbon. Thornton and Rosenbloom (2005) tested various methods to identify which can reduce the computational cost of model spin–up. Nonetheless, the source of the error or the extent of the impact of uncertainty in the carbon cycle model is difficult to confirm. Thus far, data remain limited with regard to the detailed description to guide recapitulation and the effect of each parameter on carbon storage.

In this study, we propose a detachable carbon cycle (DCC) model by using a pool–and–flux scheme, and considering 14 carbon pools. Each carbon pool can be regard as independent component. The detachability of the model facilitates the identification of how uncertain parameters affect carbon storage, this feature also enables the correction and improvement of the carbon cycle model, because each carbon flow process can be assessed quantitatively. The carbon storage was compared among the biomes by incorporating external temperature and moisture algorithms of Community Atmosphere Biosphere Land Exchange (CABLE) (Wang et al., 2011) and Integrated Terrestrial Ecosystem Carbon (InTEC) budget model (Ju et al., 2006) to the DCC model. The proposed model was used to determine the effect of temperature, moisture factors and model structure (9 pools vs 14 pools) on global carbon storage. Each carbon pool size and turnover time was analyzed in detail. The effect of crucial parameters of the DCC model on the carbon storage and equilibrium time (the time required by the carbon pool to reach the equilibrium state) of each biome was also specified. The established model framework that can be used to simulate the carbon equilibrium state, elucidate how internal and external factors regulate the carbon cycle in a detachable perspective, and quantitatively analyze each component of the model.

2. Materials and methods

2.1. Biomes distribution

A moderate resolution imaging spectroradiometer land cover product (MOD12Q1) was used to specify biomes (Fig. 1). The dataset (developed by the International Geosphere–Biosphere Program Data and Information System) includes 17 land cover classes for each year since 2001. The data of 2001 was selected to consistent with NPP data. This product provides maps of global land covered at a 1 km spatial resolution. The coordinate and projection system was converted to World Geodetic System 1984, the pixel resolution was resampled to 0.08° by using a nearest neighbor method. At the global and regional scales, the distribution of vegetation and land cover types is qualitatively realistic and the classification algorithm performs well (Friedl et al., 2002).

2.2. Datasets used to drive the model

The global NPP product MOD17A3 (Heinsch et al., 2003) was established by the NASA Earth Observation System program and is the first satellite–driven dataset for monitoring vegetation

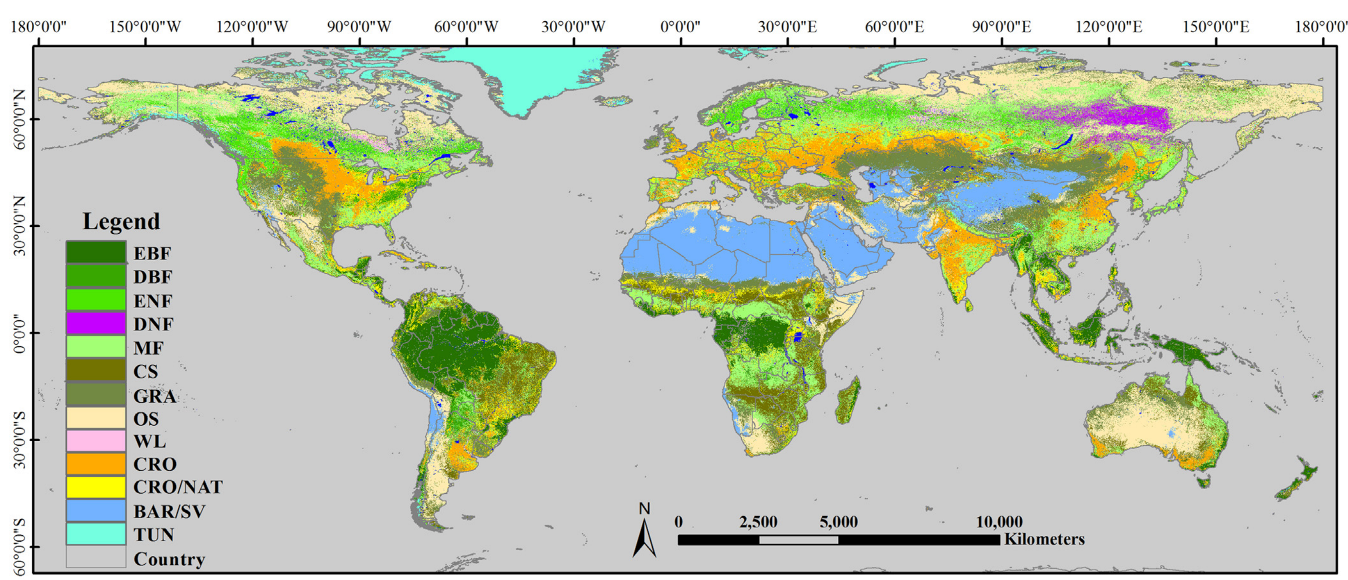

Fig. 1. The global distribution of biomes based on IGBP classification system. EBF: Evergreen Broad–leaf Forest. DBF: Deciduous Broad–leaf Forest. ENF: Evergreen Needle–leaf Forest. DNF: Deciduous Needle–leaf Forest. MF: Mixed Forest. CS: Closed Shrubland. GRA: Grassland. OS: Open Shrubland. WL: Wetland. CRO: Cropland. NAT: Nature land. BAR: Barren land. SV: Sparse Vegetation. TUN: Tundra. The biomes of WL, BAR/SV, and TUN were excluded in this study because of the lack of material or without cover of vegetation.