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Original Articles

Integrate carbon dynamics models for assessing the impact of land use intervention on carbon sequestration ecosystem service

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ABSTRACT

The land use intervention caused a noticeable impact on carbon sequestration as an ecosystem service. To comprehensively project land use change impact on carbon sequestration, the carbon dynamics models in the ecosystem and the atmosphere were integrated, and characterization factors were calculated for different scenarios. In this study, to illustrate the proposed method, the CENTURY model was used to simulate the carbon dynamics for seven land use change scenarios under two climate change scenarios. Carbon dynamics in the atmosphere was simulated by the Bern2.5CC carbon cycle model. The impact on carbon sequestration was calculated based on the difference of carbon sequestration between the land use change scenario and the corresponding baseline and the decay of CO_2 in the atmosphere. According to the simulations, we found that carbon storages and differences of the annual carbon sequestration rate were varied among land use change scenarios and between the two climate change scenarios. After land use conversion, an equilibrium status would be obtained after 100 to 200 years of growth. By integrating the carbon dynamics model with the atmosphere, the characterization factors (CF) were calculated for life cycle assessment. The values of CFs were significantly changed in different land use change scenarios, climate change scenarios and time horizons. The comparison to the previous assessment method indicated that the previous method was too conservative. The results suggested that the method in this study could provide a more reasonable assessment of the impact of land use intervention on carbon sequestration.

1. Introduction

Ecosystem service was first used by Ehrlich and Ehrlich (1981) and became flourish in the last few decades (Fisher et al., 2009). It is defined as human benefits obtained from ecosystems. In particular, the Millennium Ecosystem Assessment (MA) did a monumental work and classified ecosystem services into four categories (MA, 2005): provisioning, regulating, cultural and supporting services. Carbon sequestration is an important ecosystem service and defined as the net annual rate of atmospheric carbon absorbed by an ecosystem. Under the requirement of mitigating climate change, carbon sequestration as a regulating service brings more interest and was intensively studied. The United Nations Framework Convention on Climate Change (UNFCCC) also advocates cooperation of all countries to enhance carbon absorption by terrestrial ecosystems (1992).

The land use intervention could significantly change carbon sequestration of an ecosystem (Searchinger et al., 2008; Lawler et al., 2014; Schulp et al., 2008). However, the estimation of carbon sequestration is complex as it is affected by many different factors, such as ecosystem type, tree stand age, soil type, elevation, initial and final land use, and the duration of land use change (Adamus et al., 2000). With the development of sophisticated model and technology, researchers can simulate carbon sequestration of an ecosystem more accurately and efficiently. Naidoo et al. (2008) mapped the global carbon sequestration using the Terrestrial Ecosystem Model (TEM). They found high carbon sequestration rate in eastern U.S., northern South American, middle Africa, southeastern China and eastern Australia. By incorporating satellite-derived NDVI, climate data and the terrestrial Carnegie-Ames-Stanford Approach (CASA) ecosystem model, the analysis of carbon sequestration efficiency in the Loess Plateau indicated a shift from a carbon source in 2000 to a carbon sink in 2008 by China's Grain to Green Project (Feng et al., 2013). Petrie et al. (2015) studied carbon dynamics in arid ecosystems using statistical regression with field observations, and found a significant increase of carbon sequestration from grassland to shrubland. Moreover, many simulation tools have been developed and available to model carbon dynamics for

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different ecosystems, such as CENTURY (Parton et al., 2001), FVS (Forest Vegetation Simulator, Dixon, 2002), CBM-CFS3 (Carbon Budget Model of the Canadian Forest Sector, Kurz et al., 2009), CO2FIX (Schelhaas et al., 2004) and ForCSv2 (Forest Carbon Succession v2.0) extension for the LANDIS-II model (Dymond et al., 2002).

Although the difficulty in carbon sequestration estimation for an ecosystem, the quantification of carbon sequestration as an ecosystem service is critical for decision making (Nelson et al., 2009). Due to the importance of carbon sequestration, the impact of a product/service on carbon sequestration of an ecosystem should be analyzed in life cycle assessment (LCA). LCA is a widely used tool to assess the environmental impact of a product/service in its life cycle. However, the analysis of carbon sequestration is usually excluded in the traditional LCA (Zhang et al., 2010b). Therefore, the development of new systematic approaches for this analysis is in demand. Zhang et al. (2010b) developed an "Ecologically-based LCA" and illustrated this method by applying to drinking cup (2010a). However, this approach is an independent method more than an extension of LCA (Othoniel et al., 2016). Impact of carbon sequestration can be also assessed by the method developed for land use impact assessment on ecosystem service (Koellner et al., 2013). In this method, the characterization factor (CF) is calculated based on the difference between current land use situation and a suitable reference. However, all those approaches were developed for static systems. In fact, the analysis of carbon sequestration impact in an ecosystem is complex and dynamic. Recently, researchers also tried to consider time-dependent dynamics when conducting LCA. Levasseur et al. (2010) developed a dynamic CF by the sum of remaining emissions in the atmosphere at different years. This method has a potential to be used as a global metric approach if incorporating with carbon dynamics model. Arbault et al. (2014) implemented dynamic model GUMBO (Global Unified Meta-model of the Biosphere) to assess the impact on ecosystem services. All these efforts significantly advance the dynamic characterization of impacts on carbon sequestration. However, more time-dependent carbon dynamics in ecosystems and in the atmosphere need to be integrated into the analysis (Yan, 2018). In this study, our objectives are 1) to integrate carbon dynamic models and develop an approach to account the impact of land use change on carbon sequestration as an ecosystem service, and 2) to use case studies to illustrate the implementation of this approach.

2. Methods

In this section, we described the model to simulate carbon dynamics for land use change in the first subsection. A method to account carbon sequestration impact in life cycle assessment was proposed in the following subsection. In the case studies, seven land use change scenarios were defined to analyze the performance of the integration of carbon dynamic model.

2.1. Simulation of carbon dynamics

The CENTURY4.0 model was used to estimate the carbon sequestration of different vegetation types during land use interventions. The CENTURY model was developed by Natural Resource Ecology Laboratory of Colorado State University and initially used for cropland/grassland simulation (Parton et al., 1987). Current developed CENTURY model was also able to estimate carbon processes of forest land. In this study, we used CENTURY model because this model was extensively validated by field observations around the world (Henderson et al., 2015). The CENTURY model was initiated by a 2000-year spin-up through a serial of management sequence using CRU mean monthly climate data. A 2000-year spin-up ensured a stable state was reached, especially soil organic carbon (SOC) equilibrium. The future climate data were simulated from twenty different Global Climate Models. To estimate the impact of land use interventions on carbon sequestration as an ecosystem service, we also modeled the carbon sequestration of the land uses without any intervention as reference scenarios (baselines).

2.2. Life cycle impact of carbon sequestration

To analyze the impact of land use interventions on carbon sequestration, original land cover before the intervention was used as a baseline. If a land use intervention induces carbon sequestration change at year 0, annual carbon sequestration at year t is $C(t)$ gC/m^2 (tC: metric ton carbon equivalent) in original land cover and $C'(t)$ gC/m^2 after intervention. Therefore, annual carbon sequestration difference $\Delta C(t)$ is $C'(t) - C(t)$.

Because carbon emissions decay in the atmosphere in the interaction of ocean-atmosphere systems (Joos et al., 2013), a discount effect should be included when calculating total impact (T) on carbon sequestration that caused by land use intervention. In this study, we assumed all the carbon emissions are CO_2, and the remaining fraction is $y(t)$ in year t. Thus,

$$T = \int_1^{TH} \frac{\Delta C(t)}{y(t)} \quad (1)$$

$$y(t) = y_0 + \sum_{i=1}^{3} y_i e^{-t/\tau_i} \quad (2)$$

where TH is the chosen time horizon; $y(t)$ is the fraction of the initial CO_2 emission in year t, while y_i and τ_i are estimated parameters. TH is 20-, 100- and 500-year in this study. The CO_2 decay model (Eq. 2) is developed according to the Bern2.5CC carbon cycle model when CO_2 concentration is 378 ppm in the atmosphere (Joos et al., 2013). The parameters are fitted based on a set of climate models: $y_0 = 0.217$, $y_1 = 0.224$, $y_2 = 0.282$, $y_3 = 0.276$, $\tau_1 = 394.4$, $\tau_2 = 36.54$, $\tau_3 = 4.304$ (Joos et al., 2013).

To incorporate the total impact into LCA, the total impact of carbon sequestration is divided by a physical unit (i.e., 1 ha/1 m^2 of land use change). In LCA study, this physical unit is recognized as functional unit (FU). Therefore, characterization factor (CF) is defined as follows:

$$\text{CF} = \frac{T}{FU} \quad (3)$$

2.3. Case study

2.3.1. Site Description

We assumed that the land use interventions occurred near Nineveh, IN, the USA in 2012 (39.3152 N, 86.0512 W). This site is characterized by a humid subtropical climate with hot, humid summers and mild to cool winters. The annual average temperature is 11.6 °C, and the average annual precipitation is 1,074 mm from 1901 to 2012. This site was chosen in this study because all the simulated vegetation types (i.e., mixed forest, grassland and cropland) can be found near this site. Soil data were obtained from USDA (U.S. Department of Agriculture) soil data explorer (https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx). The soil texture was clay 18%, sand 18% and silt 64% in 2012.

2.3.2. Climate data

The historical climate data from 1901 to 2012 was downloaded from the Climate Research Unit (CRU) of the University of East Anglia (Mitchell and Jones, 2005). The climate data include monthly precipitation, average daily maximum and minimum air temperature.

The future climate data were simulations of twenty different Global Climate Models (GCM) in two climate change scenarios (medium and high greenhouse gas concentration) defined by Nakicenovic et al. (2000). The twenty GCMs were BCC-CSM1-1, BCC-CSM1-1-M, BNU-ESM, CanESM2, CCSM4, CNRM-CM5, CRIRO-Mk3-6-0, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-CC365, HadGEM2-ES365, INMCM, IPSL-