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Integrate carbon dynamic models in analyzing carbon sequestration impact of forest biomass harvest

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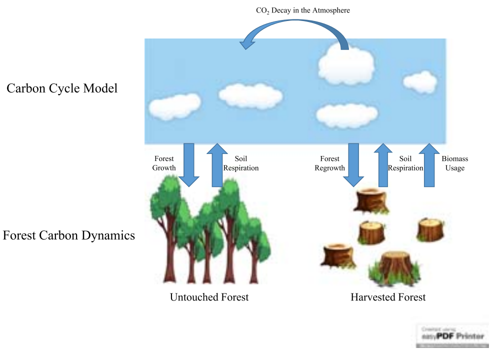
HIGHLIGHTS

- Assess biomass harvest on carbon sequestration by integrating carbon dynamics models.
- Conduct assessment by a Chapman-Richards function and FVS with carbon cycle model.
- Reduce C sequestration impact by increasing growth and reducing harvest intensity.

GRAPHICAL ABSTRACT



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ABSTRACT

Biomass is an attractive natural energy resource for mitigating climate change. However, the loss of carbon sequestration as an ecosystem service due to biomass harvest has not been considered in previous studies. To assess the impact of biomass harvest on carbon sequestration, carbon dynamics in the forests and the atmosphere were integrated. The impact of forest biomass harvests on carbon sequestration was assessed based on the difference between carbon sequestration after harvest and carbon sequestration without harvest. A Chapman-Richards function and the forest vegetation simulator (FVS) were used to simulate the growth of a forest stand. The carbon dynamics in the atmosphere were simulated by the Bern2.5CC carbon cycle model. Characterization factors of the impact were calculated in three time horizons: 20-, 100- and 500-year. According to the simulations, postponement of harvest and low harvest intensity could prolong the compensation period. The annual impact on carbon sequestration was mostly negative over a short time and became positive in the end of compensation period. The highest characteristic factors of the impact on carbon sequestration were found in rotation length of 100 years with the time horizon of 500-year in the Chapman-Richards simulation and in the lowest harvest intensity with the time horizon of 500-year in the FVS simulation. Based on the results, increasing growth rate, postponing harvest, reducing harvest intensity and increasing length of time horizon could reduce the impact of forest harvest on carbon sequestration. The method proposed in this study is more proper to assess the impact on carbon sequestration, and it has much wider applications in forest management practice.

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1. Background

Under the requirement of mitigating climate change, biomass solicits mounting interest and is considered an attractive energy resource because of the promise of low carbon emissions (Ragauskas et al., 2006;

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Zeman and Keith, 2008). Biomass can be used to produce many bioproducts, such as ethanol, pellet fuel, electricity and diesel fuel (Paul, 2009; Snowden-Swan and Male, 2012; Hsu, 2012; Liu, 2015). As one of the largest underexploited resources of cellulosic biomass, forest biomass is identified as a potentially important feedstock for bioproducts (Perlack et al., 2005; Liu, 2015). Therefore, the utilization of forest biomass is encouraged by a number of investigators (Viana et al., 2010; UCS, 2012).

Biomass is generally presumed carbon neutral, given that emissions from biomass combustion are compensated by plant regrowth (Ragauskas et al., 2006; Zeman and Keith, 2008). Recently, researchers have become aware that the climate change impact of biomass utilization should not be ignored. Emissions from land use change (Johnson, 2009; Searchinger et al., 2009) and biomass supply chain (Ulgiati, 2001; Hill et al., 2006) are a significant portion of emissions in the life cycle of biomass utilization. Currently, researchers also noticed that CO_2 emission from biomass combustion, especially from forest biomass, could also have positive global warming potential (Cherubini et al., 2011; Liu et al., 2017). The values of GWP_{bio} (global warming potential of biogenic CO_2 emission) obtained in these studies were 0.13–0.62 and obviously not neutral (Cherubini et al., 2011; Guest et al., 2013; Liu et al., 2017).

Beyond the standpoints mentioned above, the biomass harvest could have more global warming impacts. If a forest was reserved, it will keep growing and have a positive carbon sequestration capacity. When harvest activity is postponed, significant benefits of carbon sequestration can be expected (Cherubini et al., 2011). Carbon sequestration is one of the important ecosystem services, which is defined as net annual rate of atmospheric carbon absorbed by an ecosystem. Therefore, the impact of forest biomass harvests on carbon sequestration (i.e., carbon loss) should not be ignored. However, this portion of carbon loss is excluded in traditional life cycle assessment (Zhang et al., 2010). Zhang et al. (2010) developed an “Ecologically-based LCA” to account this portion of carbon loss. Another approach was developed based on the difference between current land use and an optimal land use (Koellner et al., 2013). However, all these approaches ignored the complexity and dynamics of carbon sequestration in an ecosystem. Recently, researchers started to incorporate carbon dynamics models into the assessment of carbon loss (Levasseur et al., 2010; Arbault et al., 2014).

Although many advances have been achieved in the previous studies, no method has been proposed to estimate the impact of forest biomass harvest on carbon sequestration of a forest stand with consideration of carbon dynamics in both forest and the atmosphere (Haberl et al., 2012; Arbault et al., 2014). In this study, a new approach was proposed that integrated carbon dynamics models to account for this impact. We also studied the performance of this approach by simulations of two different forest growth models.

2. Methods

2.1. Forest stand modeling

In this study, two forest stand growth models were used to simulate the carbon dynamics of a forest stand. One was a combination of a Chapman-Richards function (Lenthall, 1986) and Yasso07 model (Tuomi et al., 2010). The other was Forest Vegetation Simulator (FVS; Dixon, 2013). The detailed description of the two simulations was in the following two subsections.

2.1.1. Chapman-Richards function and Yasso

The Chapman-Richards function is formulated as $B(a) = b_1(1-e^{-b_2 a})^{b_3}$, where a is stand age, $B(a)$ is biomass accumulation at stand age a and measured in tC/ha (tC: metric ton carbon equivalent), b_1, b_2 and b_3 are empirical parameters based on earlier studies (Lenthall, 1986). This biomass accumulation function provides a reasonable growth estimation of a forest stand. As showed in Table 1, three sets of parameter configurations were used to simulate growth of three different types of forest stands: i.e., a tropical rain forest (fast-growing), a temperate deciduous forest (moderate-growing) and a boreal forest (slow-growing).

The average available biomass is assumed to be a fraction (θ) of live biomass. Thus, the available biomass is calculated as $A(a) = \theta B(a)$, where $A(a)$ is the available biomass at stand age a and measured in tC/ha. In this study, θ was set to 0.5. Three rotation lengths were simulated for each type of forest stand, which were 30, 50 and 100 years, respectively. All the live biomass was reset to zero after the harvest activity, while biomass remaining in the field was considered dead organic matter (DOM). To assess the impact on carbon sequestration, a scenario of no harvest was also simulated for every forest stand.

The decomposition of DOM was simulated by Yasso07. This is a widely used model to simulate biomass decomposition in forest stands (Tuomi et al., 2010). The initial inputs of DOM into soil were 5% of leaf/needle and 45% of branch/stem/root. These initial inputs of DOM were averages of the inventory data by Zhang et al. (2015). Table 2 lists the average chemical composition of different biomass types (Liski et al., 2009). Based on the Yasso07 simulation, the decomposition rates of leaf/needle and branch/stem/root were represented as fractions of initial inputs (Fig. 1). The detailed parameter setting and calculation of Yasso07 simulation can be found in the supporting information.

2.1.2. FVS simulation

The FVS is a highly integrated system of forest growth simulation models (Dixon, 2013). This is a useful analytical tool that provided by U.S. Department of Agriculture. In this study, forest stands in three inventoried sites were randomly selected in the US. The inventory data are available at USDA Forest Service Website (https://apps.fs.usda.gov/fia/datamart/datamart_access.html). They were douglas fir stand in Washington (WA, 47°00′02.4″N 121°29′13.2″W), chestnut oak stand in West Virginia (WV, 39°17′28.3″N 78°36′09.0″W) and loblolly pine stand in Florida (FL, 30°23′32.8″N 83°27′23.8″W), respectively. Different variants of FVS were applied for different sites, East Cascades Variant (EC) for WA, Northeast Variant (NE) for WV and Southern Variant (SN) for FL. The simulations were conducted with Fire and Fuels Extension (FFE) program (Sharma, 2010; Saud et al., 2013). The clear-cut was scheduled under the conditions of at least 30 years after last harvest and 35%, 50% and 65% over normal stocking. Low percentage over normal stocking indicates high harvest intensity. Trees with a diameter larger than 5 cm were clear-cut by leaving 12 legacy trees (DBH > 30 cm) per hectare. The first harvest was assumed to occur in 2017. To assess the impact of carbon sequestration, a scenario of no harvest was also simulated for every forest stand.

2.2. Impact assessment

The impact of forest biomass harvest on carbon sequestration was assessed based on the difference between carbon sequestration after harvest and carbon sequestration without harvest. If a forest stand is not harvested, the annual carbon sequestration at stand age t is $\Delta B(t) = B(t) - B(t-1)$. Once the forest stand is harvested at stand age m, the biomass growth in the first few years should be accounted as compensation of biomass combustion. The compensation period is defined as the length of time required to fully compensate the biomass-derived carbon emissions remaining in the atmosphere. Determination of the compensation period can be found in the end of this section. Afterwards, the annual carbon sequestration by biomass growth is $\Delta B'(n) = B'(n) - B'(n-1)$, where $n = t - m$ and $B'(n)$ is biomass accumulation in the n^{th} year after harvest. Before the end of the compensation period, $\Delta B'(t)$ is set to zero.

At each harvest site, the annual carbon emissions from the DOM decomposition in the n^{th} year after harvest is calculated as $\Delta S(n) = S(n-1) - S(n)$, where $S(n)$ is the sum of carbon emissions

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