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Analysis

Carbon, climate, and economic breakeven times for biofuel from woody biomass from managed forests

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ABSTRACT

Woody biomass harvested from old-growth forests results in a significant "carbon debt" when used as a feedstock for transportation fuel. This is because previously stored forest carbon is released to the atmosphere as CO_2. The debt is eventually repaid provided that the life cycle CO_2 emissions of the biofuel are lower than the conventional fuel that is displaced. Managed forests are an alternative to old-growth forests with the potential to reduce the carbon debt associated with woody biomass-derived fuels. This work is the first to quantify the carbon debt incurred by transportation biofuels derived from woody biomass from managed forests. The breakeven time of this carbon debt is computed along with breakeven times for radiative forcing, temperature change, and economic damages. In the case of biofuel production for 30 years, we find that breakeven times for carbon, radiative forcing, and temperature change are 59, 42, and 48 years, respectively. If cumulative economic damages are computed for discount rates of 1–2%, the breakeven time is greater than 100 years, while damages never break even at discount rates above 2%. Breakeven times decrease if the prevailing harvest cycle is left unchanged, but increase if biofuel production is sustained indefinitely.

1. Introduction

Greenhouse gas (GHG) emissions from transportation are expected to cause 10–20% of the global mean temperature rise over the next century (Skeie et al., 2009). Alternative transportation fuels produced from biomass feedstocks have recently received attention as a means of mitigating this climate impact (Favero and Mendelsohn, 2014; Korobeinikov et al., 2010; Timilsina and Mevel, 2013). Current biofuel supply in the United States predominately comes from corn ethanol (U.S. Environmental Protection Agency, 2014); however, the Renewable Fuel Standard (RFS 2) mandates increased use of cellulosic biofuels, such as those from forestry biomass. According to the RFS 2, 16 billion gallons of cellulosic transportation fuels need to be produced in 2022 (U.S. Environmental Protection Agency, 2008), which is ~20% higher than the 2013 U.S. corn-ethanol production.

Fuels derived from biomass have the potential to reduce (life cycle) GHG emissions compared to their conventional counterparts since the carbon released during combustion was initially removed from the atmosphere during biomass growth. Fuels derived from slow-growing biomass may not provide immediate climate benefits because carbon is emitted quickly during fuel combustion but reabsorbed over a long regrowth period (Edwards and Trancik, 2014). Land management practices can also substantially reduce the amount of carbon stored in growing biomass, litter pools, and soil organic matter. However, the use of land for bioenergy purposes does not necessarily incur a short-term carbon debt. Stratton et al. (2011), for example, show that using perennial grasses such as *Panicum virgatum* (switchgrass) can help to restore soil carbon if planted on land whose carbon stock has been depleted by intense farming. Since biofuel production is motivated by environmental policy (Khanna and Chen, 2013), it is important to consider the transient impacts of GHG emissions and land use change when evaluating the societal benefits of alternative fuels (Cherubini et al., 2013; Levasseur et al., 2010).

Woody biomass is a readily available feedstock that can be converted to transportation fuel. In the near term, using fuels from woody biomass harvested from old-growth or natural forests is more greenhouse gas intensive than fossil fuels, because old-growth forests store large amounts of carbon and, if left undisturbed, can be net carbon sinks (Luyssaert et al., 2008; McKechnie et al., 2011). Cutting down old-growth forests for fuel production releases the stored carbon and eliminates the carbon sink. If the forest is replanted, this "carbon debt" can be repaid, but over a long time dictated by the rate of regrowth and maturity. Therefore, it is generally accepted that clearing natural forests for biofuels is environmentally counterproductive. However, millions of acres of managed forest are regularly harvested for the production of

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Abbreviations: BAU, business as usual; LCA, life cycle analysis; GHG, greenhouse gas; APMT, Aviation Environmental Portfolio Management Tool.

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lumber and pulp and paper feedstocks. Given that some biogenic carbon is temporarily sequestered in forestry products, it is not immediately obvious whether biomass feedstocks from these managed forests could provide climate benefits. Managed forests are expected to have lower carbon debts when harvested for bioenergy because they store less carbon and are cut down and replanted periodically (Havlík et al., 2011). The tradeoffs between a forest managed for bioenergy and a forest managed for timber are not easily quantified, because the magnitude of the carbon debt and the potential for near term climate benefits depend on management practices before and after conversion to biofuel production (Davis et al., 2013).

The time required to “pay back” this carbon debt is a useful metric for evaluating the potential of alternative fuels to provide near-term climate benefits in general (Fargione et al., 2008; Timilsina and Mevel, 2013), and for the importance of different types of forest and forest management practices for realizing these benefits (Eriksson et al., 2007; Fahey et al., 2009) in particular. We define the metric as the CO_2 breakeven time, or the point in time when the cumulative CO_2 emissions from an alternative fuel become equal to the cumulative CO_2 emissions from the displaced fossil fuel. Before the breakeven time is reached, alternative fuels increase total atmospheric CO_2; only after the carbon debt is repaid do benefits begin to accrue. Given that climate change is expected to have severe socioeconomic impacts over the next 100 years (Field et al., 2014), it is important to identify the timescales of expected climate benefits when making policy decisions. The carbon debt breakeven time has been used in several studies to illustrate the consequences of using woody biomass from old-growth forests for alternative energy (Colnes et al., 2012; Bright et al., 2012; Holtsmark, 2012; Walker et al., 2010). Breakeven time is not strictly a climate metric but a comparative value, since it measures the emissions of one scenario relative to another. The breakeven time for a given biofuel depends on the transient behavior of emissions as well as the type of fossil energy displaced. This is similar to other life cycle analysis (LCA) methods which attempt to eliminate the need for a specific time horizon (Dyckhoff and Kasah, 2015). The carbon debt breakeven time by itself helps to define a relevant time horizon for environmental policy.

Greenhouse gas emissions are comparably easy to quantify and regulate, but are less useful for motivating policy decisions than the earth's physical response and its effect on human welfare. Economic damage is a particularly meaningful metric for policy comparisons, since it represents the monetized cost of climate change borne by society. The CO_2 breakeven time indicates the parity point for cumulative emissions, but it does not give any indication of the breakeven time in terms of climate response and associated economic impacts. The breakeven times for radiative forcing, temperature change, and economic damages are distinct as will be shown. Each of these metrics is ultimately a function of CO_2 emissions, but each represents a different means of quantifying the impact of those emissions.

Although the concentration of CO_2 in the atmosphere increases immediately following an emission event, a fraction of the emitted carbon is slowly removed from the atmosphere by terrestrial and oceanic carbon sinks. Hence, the net perturbation to atmospheric CO_2 attributable to the emission event decreases over time. This means that ceteris paribus the cumulative CO_2 emissions from a process are greater (at any given time) than the net change in CO_2 perceived by the atmosphere. Since radiative forcing is proportional to the atmospheric CO_2 concentration, it follows that radiative forcing breaks even before cumulative CO_2 emissions. In contrast, changes in the earth's mean surface temperature lag behind changes in radiative forcing (Berntsen and Fuglestvedt, 2008), so temperature change breaks even after radiative forcing.

Economic damages due to climate change can be estimated as a function of the mean global temperature rise and the global GDP in a given year (Nordhaus, 1992). Under this common assumption, with a specified economic growth scenario, economic damage is proportional to temperature change and breaks even at the same time. However, cumulative economic damages depend on the integral of temperature change. The carbon debt causes a greater immediate temperature change for the alternative fuel scenario, meaning that the integrated temperature curves and thus the cumulative economic damages must break even at some time after temperature change, depending on the rate of economic growth and the magnitude of the temperature changes in each scenario. Because a fraction of emitted CO_2 remains permanently in the atmosphere, this implies that present CO_2 emissions result in greater cumulative damages than future emissions at any specified time in the future.

A discount rate can be applied to convert future economic damages to present value, though the appropriate discount rate for climate damages is a subject of considerable debate (Weisbach and Sunstein, 2008). Discount rates of 1–3% are recommended when intergenerational effects are to be considered (Stern, 2006; U.S. Office of Management and Budget, 2003), with higher discount rates placing relatively higher value on the welfare of the current generation. Because the carbon debt causes higher emissions in the short term, higher discount rates move the breakeven point for cumulative economic damages further into the future.

This is the first assessment of biofuels from managed forests that fully incorporates changes in harvest cycle time, possible disruptions to wood product carbon pools, and the climatic and economic consequences of carbon debt (Havlík et al., 2011; McKechnie et al., 2011; Mitchell et al., 2012). This study evaluates the carbon debt breakeven time and the breakeven times for radiative forcing, temperature change, and economic damages for producing liquid fuels from woody biomass sourced from managed forests, with varying harvest cycles and wood product scenarios. Using multiple breakeven metrics provides a broad perspective for climate policies affecting forest management, while the harvest cycle and wood product scenarios serve to identify the management practices suited for environmentally beneficial biofuel production. We calculate breakeven times for dedicated plantations of Loblolly pine (*Pinus taeda*) in the southeastern United States. Loblolly pine is one of several yellow pine species that are grown on dedicated plantations for forest products in that region, any of which could be used as a candidate biomass feedstock because of their rapid growth rate. We specifically chose Loblolly pine as it is the predominant species for timber production in the southeastern United States (NC State University, 2014).

2. Methods

Transient CO_2 emissions from biofuels production are estimated using a comparative analysis with a business-as-usual forestry scenario. Carbon pools are tracked with a forestry model of stand growth, harvest, and decomposition of litter and wood products. The resulting emissions profiles are used as inputs to a climate response model to determine radiative forcing, temperature change and economic damage as a function of time.

2.1. Forest Carbon Model

Carbon pools in the managed forest are tracked with a carbon flow model adapted from Dewar (1991), Dewar and Cannell (1992), and Magnani et al. (2009), who present an analytical model of stand growth, litter generation and decomposition. The main changes to the model involve treating short- and long-lived wood products as separate pools (as opposed to a single wood product pool), and developing input parameters specific to Loblolly pine growth and harvest. More detailed carbon models can be found in the literature (McKechnie et al., 2011), but this model has been shown to agree with average values for mid-latitude tree plantations (Dewar and Cannell, 1992). Since the model has not been significantly modified, it is applicable to this scenario without the need for recalibration. Carbon pools are