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Climate mitigation comparison of woody biomass systems with the inclusion of land-use in the reference fossil system

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ABSTRACT

While issues of land-use have been considered in many direct analyses of biomass systems, little attention has heretofore been paid to land-use in reference fossil systems. Here we address this limitation by comparing forest biomass systems to reference fossil systems with explicit consideration of land-use in both systems. We estimate and compare the time profiles of greenhouse gas (GHG) emission and cumulative radiative forcing (CRF) of woody biomass systems and reference fossil systems. A life cycle perspective is used that includes all significant elements of both systems, including GHG emissions along the full material and energy chains. We consider the growth dynamics of forests under different management regimes, as well as energy and material substitution effects of harvested biomass. We determine the annual net emissions of CO_2, N_2O and CH_4 for each system over a 240-year period, and then calculate time profiles of CRF as a proxy measurement of climate change impact. The results show greatest potential for climate change mitigation when intensive forest management is applied in the woody biomass system. This methodological framework provides a tool to help determine optimal strategies for managing forests so as to minimize climate change impacts. The inclusion of land-use in the reference system improves the accuracy of quantitative projections of climate benefits of biomass-based systems.

1. Introduction

Earth's climate is essential for our life on the planet, though the way we live is changing the climate. Human society releases greenhouse gas (GHG) emissions to the atmosphere while providing heat, mobility, housing and industrial production. Most anthropogenic GHG emissions come from combustion of fossil fuels, but land-use changes also contribute significantly to total emissions [1]. Increased atmospheric concentration of GHG contributes to global climate change and its associated ecological and social impacts. The forest ecosystems play an increasing role in climate mitigation strategies by capturing and storing solar energy and carbon dioxide (CO_2) in woody biomass. If managed sustainably, forests can be an important element in reducing net GHG emission and the effects of climate change [2].

Forest systems can affect the climate in many ways, such as fossil fuel substitution [3], material substitution [4], and carbon stock changes in biomass and soil [5]. A limiting factor

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for biomass feedstock availability can be the area of land for solar energy collection and biomass production. This spatial limit implies that the use of biomass in one application will reduce the amount available for other applications. The efficiency of replacing different fossil fuels in different sectors with solid biomass can vary widely. For example, using solid biomass instead of fossil fuels in a large stationary plant will reduce GHG emission more than using such biomass to substitute fossil transportation fuels [6].

Robust analyses of forest bioenergy systems will necessarily consider issues of forest land-use [7–12]. The development of assessment methodologies for land use in LCA has been the subject of lively debates [10,13,14]. Changes in land use and vegetation coverage can change physical parameters, such as albedo and evapotranspiration rates, that directly affect the absorption and disposition of energy at the surface of the earth and thereby affect local and global temperatures [14]. Most of the prior studies have focused on agriculture land-use change [9,12,15]. However, little attention has heretofore been paid to the forest land-use in reference fossil energy systems, when comparing bioenergy and fossil energy systems [9].

In this study we estimate and compare time profiles of GHG emissions and cumulative radiative forcing (CRF) of woody biomass-based systems and reference fossil systems with explicit consideration of land-use carbon flows in the reference fossil system. Three different forest management regimes are considered: conventional forest management, intensive fertilized forest management, and unmanaged forestry regime. In the latter case the forest land in the reference fossil system is left unharvested, with varying levels of equilibrium carbon storage. The differences in the time profiles of GHG emissions and CRF among the different management strategies are then analyzed and compared.

2. Methods and data

2.1. Dynamic life cycle perspective

A methodological framework is needed to accurately compare fossil energy systems and bioenergy systems with the aim to minimize the net GHG emissions to the atmosphere. In such a comparison, the complete energy supply chains from natural resources to energy services must be considered in both systems. Comparing GHG balances of bioenergy and fossil energy systems is a complex process integrating both biological and technological features. The GHG emissions of a bioenergy system depend on the source of the biomass feedstock and the technical systems used to transport, process and convert the feedstock to end-use energy service. To perform a robust comparison, not only the elements of the bioenergy system must be considered, but also the fossil reference system must be described and defined clearly [3]. The exact location of system boundaries in terms of activity, time or place can influence the final outcome. Moreover, the temporal system boundaries should include all aspects of the wood life cycle such as the dynamics of forest growth including regeneration and carbon saturation, the availability of residue biofuels at different times, and the duration of carbon storage in products [16].

Here we conduct a dynamic life cycle analysis of a biomass system and a reference fossil system, considering emissions of CO_2, nitrous oxide (N_2O) and methane (CH_4) along the full energy and material chains. We quantify the biological and fossil carbon flows related to the establishment, growth, and harvest of the forest biomass supply chain. Annual carbon stock changes per hectare of forest land are determined for living biomass, harvested products, litter and soils. Furthermore, in the reference fossil system we estimate the biological carbon changes in living biomass, dead biomass and soil of the unused forest land. Appropriate biological decay rates are used for stumps, roots, branches and needles remaining in the forest. For the technological parts of both systems we assess all GHG emissions from extraction, refining, transport and combustion of the biomass or fossil fuel as well as for forest management activities. An overview of the framework for comparing GHG emissions of biomass systems and reference fossil systems is presented in Fig. 1.

2.2. Woody biomass system

We model three different forest management alternatives: 1) conventional forestry, 2) fertilized forestry, and 3) unmanaged and unharvested forest (see Table 1). In all studies, we consider one unit hectare of Norway spruce (*Picea abies*) forest land located in northern Sweden, with a Site Index of 16.

In the conventional alternative, the forest is managed following conventional Swedish practices, with three thinnings in years 50, 68, and 87, and final clear-cut harvesting after a rotation period of 109 years. Estimates of forest biomass production are made using the DT model [17]. When the stand is harvested the woody biomass is used for energy and material purposes, substituting non-wood fuels and materials. We disaggregate the total tree biomass into stems, branches and tops, stumps, needles, coarse roots, and fine roots. We assume that 60% of stem-wood is large-diameter ("sawtimber") and 40% is small-diameter ("pulpwood"), and that all large stem-wood is harvested and used to produce wood construction material. We consider the additional wood use for a wood-framed building compared to a concrete-frame building [18]. To be able to compare the woody biomass

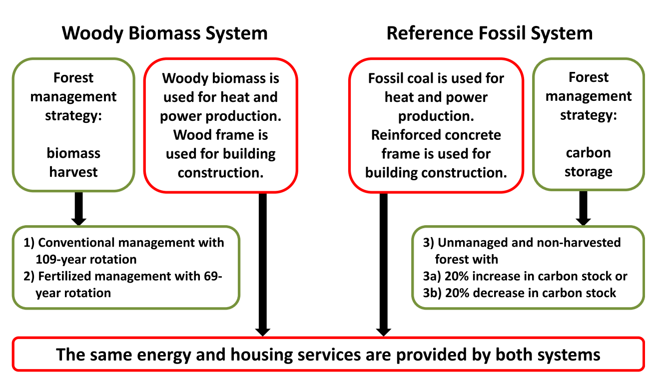

Fig. 1 – Overview of GHG emission comparison of woody biomass and reference fossil systems with consideration of land-use in both systems.