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Carbon debt and payback time – Lost in the forest?

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ABSTRACT

In later years the potential contribution of forest bioenergy to mitigate climate change has been increasingly questioned due to temporal displacement between CO_2 emissions when forest biomass is used for energy and subsequent sequestration of carbon in new biomass. Also disturbance of natural decay of dead biomass when used for energy affect the carbon dynamics of forest ecosystems. These perturbations of forest ecosystems are summarized under the concept of carbon debt and its payback time. Narrative reviews demonstrate that the payback time of apparently comparable forest bioenergy supply scenarios vary by up to 200 years allowing amble room for confusion and dispute about the climate benefits of forest bioenergy. This meta-analysis confirm that the outcome of carbon debt studies lie in the assumptions and find that methodological rather than ecosystem and management related assumptions determine the findings. The study implies that at the current development of carbon debt methodologies and their lack of consensus the concept in it-self is inadequate for informing and guiding policy development. At the management level the carbon debt concept may provide valuable information directing management principles in a more climate benign directions.

1. Introduction

In later years the contribution of forest bioenergy to potentially mitigate global warming has been increasingly questioned [1] due to the temporal displacement between CO_2 emissions when forest biomass is used for energy and subsequent sequestration of carbon in new biomass. Disturbance of natural decay of dead biomass and growth of living biomass when used for energy affect the carbon dynamics of forest ecosystems. These perturbations of forest ecosystems are summarized under the concept of carbon debt and its payback time. A number of recent narrative reviews discussed the implications of carbon dynamics and carbon debt of forest bioenergy with reference to climate impact and policy development [2–4]. Lamers and Junginger [3] demonstrated that the carbon payback time of apparently comparable forest bioenergy scenarios vary by up to 200 years allowing amble room for confusion and dispute about the potential climate benefit of forest bioenergy.

The birth of the carbon debt concept is often attributed a paper in Science in 2008 [5], which did not treat forest bioenergy but potential forest clearing as a consequence of agricultural expansion driven by increased demand for biofuels. The underlying mechanisms describing how forest carbon dynamics may be influenced by increased demand for bioenergy was however treated much earlier [6,7]. An analysis from 1996 by Leemans et al. [8] developed to support the second assessment report of the IPCC [9] describe the now well-known pattern of a transition period, where increased deployment of bioenergy increases CO_2 emissions to the atmosphere followed by an extended period with reduced emissions. More recent papers describe the same pattern conceptually; see e.g. Mitchel et al. [10]. While few if any argue against the existence of a potential carbon debt, quantification of same remains controversial. Naudts et al. [11] reported a carbon debt of Europe's forest of 3.1 Pg C since 1750 because of forest management compared against an untouched forest baseline. Nabuurs et al. [12] contested the relevance of an untouched forest baseline assumption and find no carbon debt in the outlooks for Europe's forest for the same reason, forest management.

Carbon debt and payback time studies aim to inform scientists, policy makers, forest managers, the utility sector and other stakeholders on the climate consequences of extracting more biomass from forests to meet an increased demand for non-fossil energy. In the vast body of literature one can find support for almost any view on the climate impact of forest bioenergy, from being instantly beneficial to analyses showing that it will not in the next 10,000 years contribute to global warming mitigation. The objectives of this review are a) to identify patterns and commonalities in assumptions and outcomes across the current scientific literature on forest bioenergy, carbon dynamics and global warming mitigation potential; b) to identify factors influencing carbon debt and payback times of energy production based on forest biomass; and c) to provide guidance to policy and decision makers on how to understand and treat the carbon debt

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concept with reference to forest management, energy resource procurement and energy policy development. Buchholz et al. [13] demonstrated recently that reported carbon debt payback times of forest bioenergy are particularly influenced by inclusion of wildfire dynamics in the analyses and models. This review follows in the line of Buchholz et al. [13], but considerably more scenarios or cases are included (245 here vs. 123 in Buchholz et al.) and emphasis is put on exploring how applied methodology and assumptions influence the outcome of carbon debt studies.

2. Materials and methods

Carbon debt is caused by a number of factors. With respect to forest biomass factors of particular relevance are:

Temporal displacement between CO_2 emission from biomass conversion to energy and subsequent CO_2 sequestration in new biomass. The long rotations in forestry increase the importance of this factor [14,15].

Additional harvest of biomass perturbate the forest ecosystems and may change growth and decay rates of living and dead biomass.

Upstream fossil CO_2 emissions from resource production and extraction are different than those associated with the extraction of fossil resources displaced by biomass.

Differences in efficiency between fossil and biomass conversion technologies. Heat and to some extent electricity can be generated as efficiently with forest biomass as with fossil resources. Biomass with high content of chlorine (Cl), potassium (K_2O) and sodium (Na_2O) causes corrosion, slagging and fouling of boilers, heat exchangers and super heaters [16,17]. Problems increase with increasing temperatures, why biomass boilers often operate at lower steam temperatures. This is particular true for straw fired boilers, but a high share of bark, leaves and twigs in forest biomass can also reduce attainable operating temperatures.

The oxygen to carbon ratio is higher in biomass than in fossil hydrocarbons [16]. Fossil material (old biomass) is in a more reduced state than living or recently dead plant tissues. Consequently CO_2 emission per energy unit from combustion is higher from biomass than from coal, oil and natural gas irrespective of conversion efficiencies.

Carbon debt is comparable to financial debt in that it can be paid back over a period of time. Increasing harvest of biomass from forests may for a shorter or longer period of time reduce the amount of carbon stored in the forest, either in living or dead biomass. If increased harvest change the hydrology of forest ecosystems due to reduced evapotranspiration increased emissions of methane and nitrous oxide may be observed [18]. When increased harvest of forest biomass is done with a purpose of displacing other resources, GHG emissions from extraction and use of these are avoided. The payback time of carbon debt is modelled as the number of years it takes to reach parity between the cumulated additional emissions from biomass harvest and use, and avoided emissions from extraction and use of displaced resources [10].

This review builds on the scientific literature published in the last 20+ years reporting payback times of using forest biomass to displace fossil resources for energy generation. A total of 245 scenarios are included and characterized relative to a number of descriptive variable presented in Table 1. Data are extracted from [6,7,10,19–46].

2.1. Payback time

In this review I included payback times reported in reviewed literature in the form of tabulated data, clearly legible graphs or payback times described or discussed in-text. Consequently a few publications were disregarded and not all scenarios in all publication are included. E.g. Mitchel et al. [10] analyze 1764 different scenarios for increased harvest in Ontario, 14 of these are included here as they are specifically discussed in the paper.

2.2. Scale and data

Lamers and Junginger [3] distinguished between three different scales when analyzing carbon debts. Same distinction is used here. Stand scale indicate that carbon dynamics is modelled for a uniform even-aged mono-culture. When harvested, the entire stand is cut and the wood is used for materials and/or energy. Analyses applying a fixed landscape scale attempts to counteract the obvious simplification of stand scale studies by assuming a hypothetical landscape of uniform even-aged compartments of monoculture, where each compartment is displaced in time but otherwise modelled as described for stand scale studies. In the fixed landscape the compartments in the forest landscape describe a so-called normal forest where all successional stages from regeneration to final harvest are equally represented [47]. The dynamic landscape representation is based on a true representation of an actual forest landscape encompassing diversity in e.g. species, ages, and rotation lengths. Data underlying the studies are based on either hypothetical data or spatially explicit data, usually from forest inventories.

2.3. Model

A range of models are used to model the carbon dynamics of increased biomass harvest. In this study 13 different named models were found as well as a number of un-named models. Only named model were included, but the methodology accounts for missing values by attributing arbitrary values to the un-named models.

2.4. Biome and geography

Here I distinguish between three different biomes from boreal to temperate. Sub-tropic and tropic biomes are not represented specifically in the literature on carbon debt repayment. A few scenarios included in this review have a global scope and include the sub-tropics and tropics indirectly. Particularly scenarios from North America and Europe dominate the review (Fig. 1), reflecting well that these are the regions that dominate use, production or trade of solid biofuels [48].

2.5. Species class and land use history

The studies included here model a wide range of tree species and forest types, some as monocultures and others as mixed species forests or stands. In this review the modelled stands or landscapes are characterized as either coniferous, broadleaves or mixed species.

The history of land use prior to the stand or landscape being harvested for energy purposes may have an influence on the payback time. Particularly if former land use was agriculture, a large mass of carbon have been sequestered from the atmosphere and stored in living and dead biomass. Natural forests store large amounts of carbon, but may not contribute much to further sequestration of carbon [49,50]. Here I distinguish between three different types of land use history; agriculture, natural forest or plantation forest.

2.6. Counterfactuals

Carbon debt studies analyze the impact of bioenergy scenarios as an alternative to other energy supply scenarios. In the studies included here the bioenergy is an alternative to fossil energy. Setting up such alternatives requires a number of 'what if' assumptions. What if the forest was not managed for bioenergy production; how would the forest then have been managed? What if biomass (living or dead) was not harvested for energy; what would have happened to it? These 'what if' assumptions are usually termed counterfactuals.

Mitchel et al. [10] distinguished between carbon debt repayment and carbon offset parity. Carbon debt repayment represents the time it takes a forest bioenergy system to offset temporary