ISSUE BRIEFING PAPER

DRAFT

A GLOBAL META-ANALYSIS OF FOREST BIOENERGY GREENHOUSE GAS EMISSIONS ACCOUNTING STUDIES (1991-2012)

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EXECUTIVE SUMMARY

- We conducted a literature review of 39 studies (representing 79 cases) published between 1991 and 2012 that investigate the Greenhouse Gas (GHG) emissions (primarily CO2) of forest-based bioenergy systems. The studies ranged from global to local scales and varied in temporal and analytical boundary setting.
- The majority of literature reviewed concluded that biomass utilization for energy is atmospherically CO2 ("carbon") neutral over time when compared to fossil fuel equivalent energy sources. That is, there is an initial carbon debt to the atmosphere that is paid back as forests sequester carbon compared to fossil fuel energy sources that continue to emit greenhouse gases. This was a consistent major finding of studies published over the past 22 years.
- Overall, 59 of the cases (75%, n=79) reviewed concluded that forest-based bioenergy systems were neutral over time, while 7 cases (9%) assumed that the biogenic carbon cycle of these systems GHG neutral by definition, and 10 cases (13%) concluded that forest-based bioenergy systems are not GHG neutral at all.
- Studies with conclusions of carbon neutral over determined that the carbon debt payback periods are highly influenced by 1) comparative fossil fuel type, 2) conversion technology, 3) feedstock source (including use of additional harvests or residues and plantation vs. natural forest management), 4) disturbance regimes (including wildfire, pest outbreaks, and climatic events) and 5) history of biomass infrastructure on existing landscapes.
- The use of dynamic as well as reference point baselines has been persistent throughout the period studied, and conclusions are fairly consistent across a variety of ecosystem types/climatic zones and regions.
- Studies that evaluated the use of logging residue as the primary feedstock exhibited a lower variability in results and shorter payback period than additional harvest cases.
- Recent studies (2010-2012) show a divergence in approaches towards quantifying a balanced biomass utilization life cycle assessment (LCA) that integrates upstream emissions of both bioenergy and fossil fuel. Use of the concept of a "carbon payback period" is becoming a commonplace metric to describe the GHG impact of bioenergy systems.
- There does not appear to be any recent agreement on the confidence of using specific temporal scales. For example, 9 out of 31 authors who determined carbon neutrality over time modeled >100 years into the future. At the same time nearly half of these studies (14 out of 31) use hypothetical data, this percentage is even higher for those who model >100 years (5 out of 9).

- The scope of individual studies varies widely in analytical detail. For example, carbon pools considered, leakage not considered in any of the cases, product substitution was only considered in 3 cases. Both pools are highly contentious and can have major impacts on overall results.

INTRODUCTION

Many comprehensive biogenic greenhouse gas (GHG) emissions studies of forest biomass energy systems relative to fossil fuel energy systems have been published in the peer reviewed and gray literature since 1991. We conducted a quantitative meta-analysis of these studies to document common assumptions and conclusions related to the atmospheric benefits of switching from fossil fuels to forest-based woody biomass energy. The intent of this analysis is to benchmark the current peer-reviewed and selected scientific grey literature and articulate the trends in the published findings. Our goal was to understand the key drivers influencing study results on the greenhouse gas benefits of using forest biomass instead of fossil fuels for various types of energy around the world.

Recent policy and social debates have centered on the issue of the "carbon neutrality" of woody biomass energy. Here, carbon neutrality is achieved when a biologically-based energy feedstock does not contribute to an increase in net CO2 relative to a defined baseline. The literature we reviewed defines baselines in various ways. A "reference point" baseline (Figure 1) establishes as the baseline the carbon stock on a given land area or at a given point in time (EPA 2011). A "dynamic" (or "anticipated future") baseline (Figure 1) involves the definition of a business-as-usual (BAU) condition that is projected without any new use of biogenic feedstocks for energy. In addition to determining carbon stock changes under bioenergy scenarios relative to these two types of baselines, many studies then evaluate changes in atmospheric CO2 of the bioenergy scenario compared to a fossil fuel energy baseline (Figure 2). These types of studies generally defined a "carbon debt" to the atmosphere relative to fossil fuel scenarios that could be "paid back" over time. The point at which the emissions scenarios were equal to each other is also often referred to as carbon neutrality.

This briefing paper summarizes the most obvious trends but does not attempt to attribute statistical significance to the patterns nor advocate specific energy pathways or policies. It is also important to note that most studies looked at the impacts of developing new biomass energy facilities and do not evaluate the GHG implications of energy production from existing facilities. Below we summarize the key results and briefly describe the methods used in our meta-analysis.

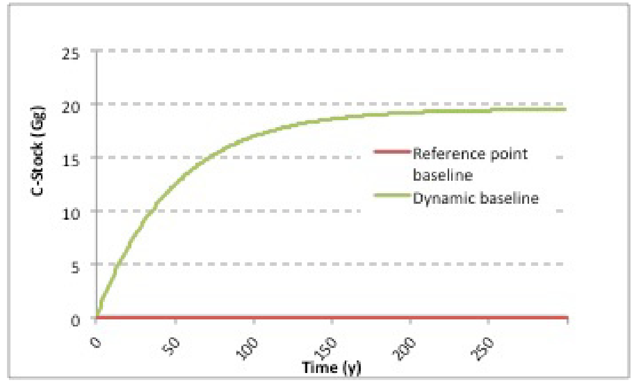

Figure 1: Dynamic and reference point baselines.

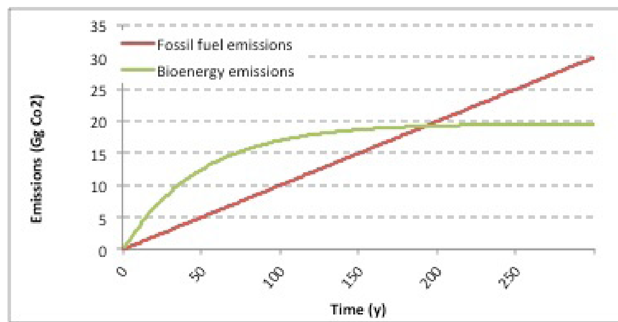

Figure 2: Bioenergy emissions from additional fellings (green line) based on a dynamic baseline compared to alternative fossil fuel emissions (dotted, gray line). The point where both lines converge determines the payback period (adapted from Zanchi et al. 2012).

FINDINGS

1.1 Baseline choices

The choice of a baseline has profound impacts on the GHG balance of bioenergy systems compared to reference scenarios. Dynamic as well as reference point baselines were both applied throughout the study period starting in 1991 (Figure 1). The dynamic baseline approach was most notably spearheaded in Europe by Schlamadinger et al. (1995). Coinciding with the publication of the "Manomet Report" (Manomet Center for Conservation Sciences 2010), bioenergy GHG accounting studies multiplied in numbers applying a variety of baseline approaches.

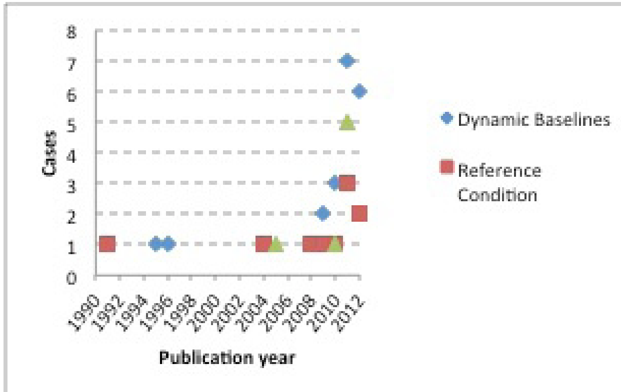

Figure 3: Baseline choice by study and publication year.

1.2 Study results: Is forest-based bioenergy GHG neutral?

Throughout the studied period starting in 1991, outcomes suggested that forest-based bioenergy systems can be neutral over time (Figure 2). Starting in 2009, we observed that study results became more contentious. While the outcome 'neutral over time' still dominated over all cases investigated, an increasing number of cases resulted in outcomes classified as 'neutral by definition' as well as 'not neutral'.

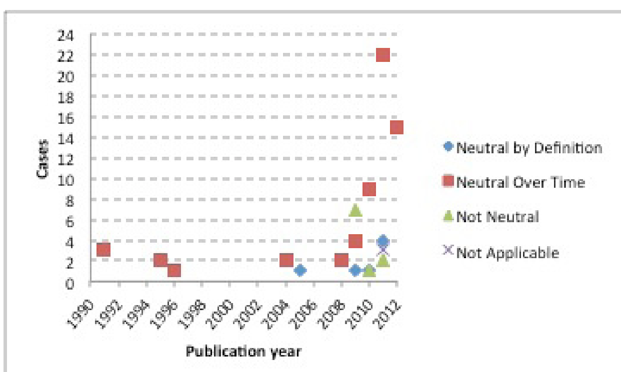

Figure 4: Key result by publication year (count of cases).

Key results were strongly correlated with the choice of the baseline (Figure 3). Only cases applying a dynamic baseline partly concluded that forest-based bioenergy systems are not GHG neutral. Overall, 59 (75%) of the cases reviewed concluded that forest-based bioenergy systems were neutral over time, while 7 cases (9%) assumed that the biogenic carbon cycle of these systems is GHG neutral by definition, and 10 cases (13%) concluded that forest-based bioenergy systems are not GHG neutral at all.

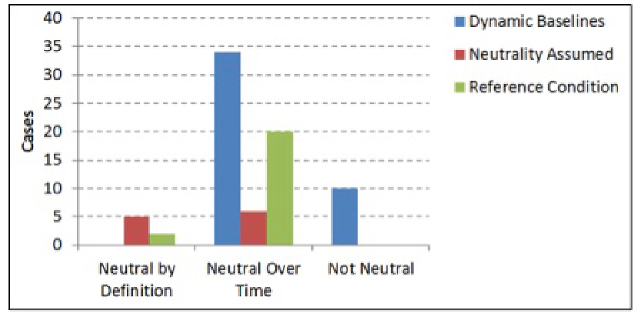

Figure 5: Key result by baseline choice (count of cases).

1.3 Key factors determining length of payback period

1.3.1 Types of displaced fossil fuels and energy type

Over 50% of all reviewed cases analyzed electricity production scenarios (Figure 4) followed by liquid transportation fuel, heat, and combined heat and power (CHP) scenarios. For all energy types, the majority of cases attested a 'neutral over time' result. This result suggests that energy types are weak predictors of key results.

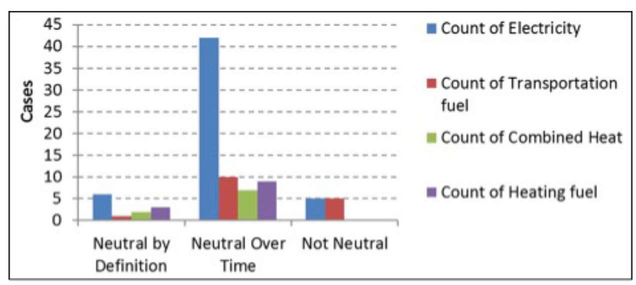

Figure 6: Count of cases by key result and energy type.

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[1] One complicating factor is the inclusion of the Mitchell et al 2012 study which does not assign a specific technology or displaced fuel to its scenarios and calculates a payback of 20 to >1,000 years. It assumes an efficiency scale between 20-80%. Clearly, the higher end is reached by CHP and heat more easily than by the other scenarios. Due to the small case load of 'heat', this one number distorts the mean.

Table 1: Payback periods by fossil fuel replaced and energy type. We considered only those cases that i) resulted in 'neutral over time' or 'not neutral', ii) are based on biomass from additional harvests and iii) exclude cases that only consider biomass from plantations.

	Displaced Fuel	Count	Min (Years)	Max (Years)	Mean (Years)
Electricity	Coal	14	0	230	53
	Fuel mix	9	0	>1,000	~161
	Natural gas	5	0	400	82
	Oil product	4	40	295	166
	Total*	29	0	>1000	~102
Liquid Transport Fuel	Fuel Mix	1	20	>1,000	~510
	Oil Product	11	0	459	165
	Total*	12	0	>1,000	~200
Combined Heat and Power (CHP)	Coal	3	12	100	45
	Fuel mix	1	20	>1,000	~510
	Oil product	4	0	100	21
	Total*	7	0	>1000	~94
Heat	Coal	2	40	100	70
	Fuel mix	1	20	>1,000	~510
	Natural gas	2	17	37	27
	Oil product	4	0	100	35
	Total*	7	0	>1000	~130

1.3.2 Additional harvests vs. logging residues

A clear distinction in payback period outcomes can be made when separating cases that look at logging residues only vs. cases that examine the implications of additional harvests including subsequent logging residues (Table 2). Cases that relied on additional harvests resulted in payback periods ranging in average from 70 to 114 y, while cases examining logging residues only averaged in a lower and narrower range from 15 to 26 y.

Table 2: Payback period by biomass type.

BIOMASS TYPE	CASES	MEAN OF LOW PAYBACK PERIOD (YEARS)	MEAN OF HIGH PAYBACK PERIOD (YEARS)
Additional harvests incl. residues	64	70	114
Residues only	16	15	26
Total	80	57	93

1.3.3 Biomass from natural forests and newly established plantations

Over five times more cases focused on biomass sourced from natural forests compared to cases that examined biomass derived from newly established plantations (Table 3). The mean of the lower and upper payback period for plantation-based biomass was considerably below the equivalent numbers for biomass from natural forests.

Table 3: Payback periods by forest type.

FOREST TYPE	CASES	MEAN OF LOW PAY-BACK PERIOD (YEARS)	MEAN OF HIGH PAY-BACK PERIOD (YEARS)
Existing Natural Forest	46	83	128
New Plantation	8	6	60
Total	54	70	117

1.3.4 Differences by region and climatic zones

Overall, of all the 70 cases that calculated payback periods, the lower and higher payback period averaged at 57 and 93 years, respectively. Over 80% all cases were located in Europe (n=28) and the US (n=31), with each having a fairly equal share (Table 4). Mean lower and upper payback periods were considerably shorter for European cases than for US cases. Canadian cases (n=5) showed similarities in results to European cases.

Table 4: Payback period by region.

REGION	CASES	MEAN OF LOW PAY-BACK PERIOD (YEARS)	MEAN OF HIGH PAY-BACK PERIOD (YEARS)
Africa	1	2	3
Canada	5	37	52
Europe	28	45	85
Global	1	13	28
US	31	78	119
N/A	4	21	41
Total	70	57	93

Over 80% of all studies focused on the temperate or cold zones (Table 5). For the cold zone, the range between the average low and high payback periods (29 to 57 years) was within the range of the average low and high payback period for the temperate zone (15 to 66 years). In other words, both zones produced comparable payback periods on a first glance, with a higher variability characterizing studies located in the temperate zone.

Table 5: Payback period by climatic zone.

CLIMATIC ZONE	CASES	MEAN OF LOW PAY-BACK PERIOD (YEARS)	MEAN OF HIGH PAY-BACK PERIOD (YEARS)
Tropical	2	8	16
Dry	8	5	147
Temperate	33	15	66
Cold	26	29	57
Total	69*	22	65

* Double counting occurred in ten cases where studies investigated simultaneously areas where dry/temperate and temperate/cold zones overlapped

1.4 Additional insights

1.4.1 LCA boundaries

Fossil fuel vs. bioenergy

Setting comparable LCA boundaries is paramount for a meaningful comparison amongst alternative fuel scenarios. While we observed a balanced setting of LCA boundaries in most studies, i.e. covering similar upstream and downstream GHG fluxes for fossil fuel as well as bioenergy scenarios, the eight cases that were characterized by more detailed bioenergy scenarios were all published in the last two years (Figure 5).

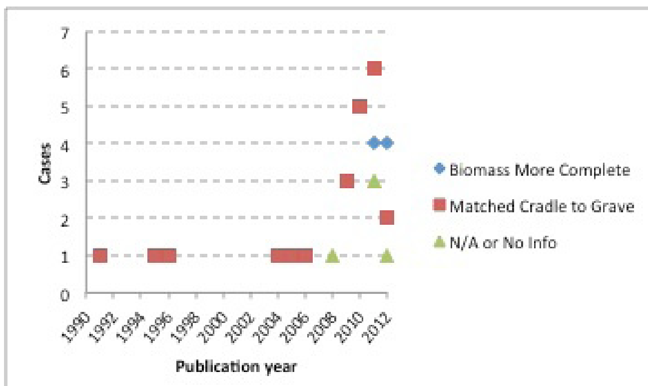

Figure 7: LCA boundaries for reference and bioenergy scenario.

C-pools considered

We screened each case to determine which carbon pools were considered in the analysis. Seven carbon pools were restricted to the forest ecosystem (Above ground live biomass, Aboveground standing dead biomass, Belowground live biomass, Belowground dead biomass, Forest floor,

Merchantable timber, Harvest residue), four described the processing of material (Forest treatment operations, Recovery of biomass in the forest, Transport, Mill residue), while two described product fate (Wood products in use, Wood products in landfill), and two described indirect effects (Leakage, Product substitution). The dataset was characterized by a very inconsistent inclusion of these carbon pools in each case ranging from an inclusion of just one of these carbon pools to up to 14 carbon pools. The average case included eight carbon pools. Leakage was not considered in any of the studies while product substitution benefits were considered in only three cases.

1.4.2 Temporal scales, large-scale carbon pulses, and data quality

The temporal scale of analysis for all studies analyzed ranged from 20 to 500 years with an average of 149 years. The lowest temporal scale was applied by Hudiburg et al. (2012) to avoid the risk of 'overstretching data'. No neutrality was achieved over these 20 years in this study. All other authors seemed to have enough confidence in their assumptions, datasets and models to investigate carbon fluxes over longer time scales although only a few cases included episodic carbon pulses that occur on large temporal and spatial scales such as wildfire (included in 17 out of 80 cases), insect outbreaks or storm events. Those studies that looked at longer temporal scales tended to use hypothetical data (17 out of 39 or 44% of all studies). Amongst those studies that modeled neutrality over time on temporal scales surpassing 100 years, five out of nine or 56% used hypothetical data.

1.4.3 Metrics to assess neutrality

Calculating a payback period as a metric to describe the GHG impact of alternative scenarios is becoming standard practice outnumbering other metrics frequently employed such as tons of carbon displaced per energy unit of biomass fuel (e.g. Hall et al. 1991, Schmidt et al. 2011), carbon emissions for various scenarios over a given timescale (e.g. Domke et al. 2008), or a carbon neutrality factor that measures GHG emissions in percent of a baseline scenario over a given period of time (e.g. Kilpeläinen et al. 2012, Winford and Gaither 2012, US Forest Service 2009, Zhang et al 2010, Schlamadinger et al. 1995). Payback period was the principal metric in 59 cases out of a total of 79 cases that compared bioenergy scenarios to fossil fuel scenarios.

CONCLUSIONS

There was a consistent major finding of 39 studies published over the past 22 years, that forest-based biomass utilization for energy is atmospherically carbon neutral over time when compared to fossil fuel equivalent energy sources. Overall, 59 of the cases (78%) reviewed concluded that forest-based bioenergy systems were neutral over time, while 7 cases (9%) assumed that the biogenic carbon cycle of these systems GHG neutral by definition, and 10 cases (or 13%of all cases reviewed) concluded that forest-based bioenergy systems are not GHG neutral at all.

Carbon debt payback periods are highly dependent on a variety of factors. In general, cases that evaluated the use of logging residue as the primary feedstock exhibited a lower variability in results and lower payback than additional harvest cases.

The use of dynamic as well as reference point baselines has been persistent throughout the period studied, and conclusions are fairly consistent across a variety of ecosystem types/climatic zones and regions. In recent years, conclusions as well as applied methodologies became more contentious.

Studies converge considerably on the temporal scale considered in the modeling efforts as well as in the use of datasets (hypothetical or real) and boundary settings for LCA analysis. The inclusion of episodic large scale events such as wildfires was sporadic.

Notably, a broadening of GHG implications using bioenergy systems was largely absent. The inclusion of other GHG relevant emissions and factors such as methane or atmospheric particles, surface albedo, or discounting approaches to account for the release of GHG emissions along a temporal scale (e.g. Cherubini et al. 2011) is not common practice.

METHODS

Literature search

Searching for literature starting in 1991 to 2012, we identified 35 peer-reviewed studies that investigated forest-based bioenergy systems on their GHG neutrality on a temporal scale, as well as five influential studies in the grey literature. Using the search engine Scopus, we added influential grey literature to the dataset as well.

Case classification and attributes

For studies analyzing multiple scenarios such as a range of forest ecosystems, fossil fuels offset (coal, mix, natural gas, oil product), or energy types (electricity, liquid transportation fuel, combined heat and power, heat), we divided the study into cases. If results were not directly attributable to specific cases, each case was associated with the overall result.

Attributes included Source Authors, Year Published, Key Result ('Neutral by definition', 'Not neutral', and 'Neutral over time' whereas the payback period was less than 100 y or the authors concluded with a comparable statement), Lower and Upper Bound Payback Period, Scale, Jurisdiction, Geographic Region, Vegetation Type, Climatic Zone (Tropical, Dry, Temperate, Cold based on an aggregation of the Köppen classification), Lifecycle Analysis (LCA) pools considered, Baseline Assumption (Dynamic or Reference point baseline), Biomass Source (Additional harvests or Current logging residues only), Energy Types Compared, Fossil Fuel Replaced, Inclusion of Wildfire Dynamics, Forest type (Natural Forest or Plantations), LCA boundaries, Temporal Scale, Analytical Spatial Scale (Stand, Forest, Landscape), Data Used (Hypothetical, Regional, Field data), Notes.

For cases where attributes were not applicable, e.g. no payback period was calculated but neutrality was investigated over a given time scale in comparison to fossil fuel alternatives, we transcribed results in the 'Notes' section.

ANALYSIS

We created the database using Microsoft Office 2010 Access and used Microsoft Office 2010 Excel Pivot charts and graphs for the analysis.

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APPENDIX

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