Climate impact of forest bioenergy: contributions from biogenic CO_2 and albedo

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Abstract

Production of biomass for bioenergy can alter biogeochemical and biogeophysical mechanisms, thus affecting local and global climate. Recent scientific developments mainly embraced impacts from land use changes resulting from area-expanded biomass production, with several extensive insights available. Comparably less attention, however, is given to the assessment of direct land surface-atmosphere climate impacts of bioenergy systems under continuous management such as in existing plantations and forested ecosystems, whereby land use disturbances are only temporary. Here, following IPCC climate metrics, we assess bioenergy systems in light of two important dynamic land use-climate factors, namely, the perturbation in atmospheric carbon dioxide (CO_2) concentration caused by the timing of biogenic CO_2 fluxes, and temporary perturbations to surface reflectivity (albedo).
Results show the importance of specifically addressing the climate forcings from biogenic CO_2 fluxes and changes in albedo, especially when biomass is sourced from forested areas affected by seasonal snow cover. The climate performance of bioenergy systems is highly dependent on biomass species, local climate variables, time horizons, and the climate metric considered. Bioenergy-related climate policies and accounting mechanisms should rapidly adapt to address these issues and the complexity of the outcomes.

1. Introduction

This paper summarizes key contributions we developed in the field of the climate impact of CO_2 emissions from bioenergy and biomaterials. The work is structured as follows. In the following section we show the concepts at the basis of treatment of emissions in climate sciences, with applications to direct bioenergy from biomass (section 2) and bioenergy as an "end of life" treatment of biomaterials (section 3). Section 4 investigates the effects due to timing of biogenic CO_2 emissions from oxidation of biomaterials, while section 5 analyzes the role of forest residues. In section 6, site specific climate metrics for biogenic CO_2 emissions are computed, also estimating contributions from temporary changes in surface albedo, and applied to selected case studies producing heat from stationary applications (results are compared with fossil reference systems). In section 7, we briefly discuss bioenergy performance according to different climate metrics.

2. Biogenic CO_2: IRF and GWP

We treat biogenic CO_2 emissions as the other greenhouse gases (GHG) following IPCC climate metrics based on the concept of radiative forcing and Global Warming Potential (GWP). This approach is the most common way to deal with GHG emissions in environmental impact studies, life-cycle assessment (LCA) studies, and climate impact accounting mechanisms.
Climate metrics refer to the impact of a pulse emission of the GHG to the atmosphere. This is assessed by predicting the atmospheric decay of that pulse emission using the so-called Impulse Response Function (IRF), which is the fraction of the emission pulse remaining in the atmosphere over time [1, 2]. We have therefore elaborated IRF for biogenic CO_2 emissions as a function of the biomass rotation period, integrating the biomass system with the global carbon cycle, and simulating an idealized scenario where all the above ground standing biomass is harvested [3, 4]. Figure 1 shows the atmospheric decay of biogenic CO_2 from regenerative biomass, and Table 1 shows the GWPs.

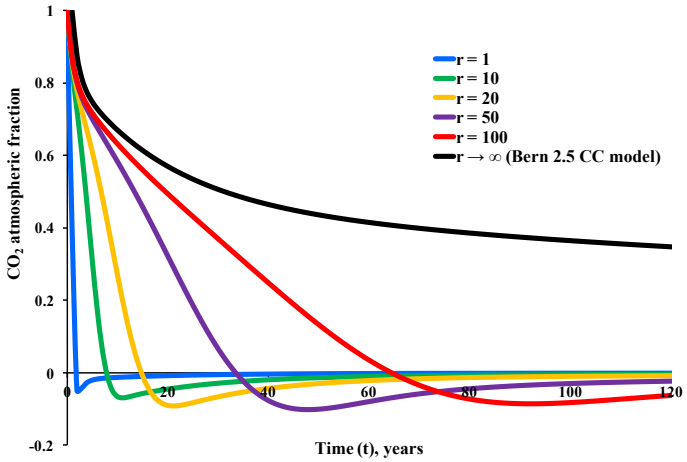

Fig. 1 IRF of biogenic CO_2 from regenerative biomass in comparison with the decay of fossil CO_2 (or from deforestation), and as a function of the biomass rotation period (r). Source: [3].

Table 1 Characterization factors for biogenic CO2 emissions from bioenergy sourced from regenerative biomass. Source: [3].

Rotation (years)	GWP TH = 20	GWP TH = 100	GWP TH = 500
1	0.02	0.00	0.00
10	0.22	0.04	0.01
20	0.47	0.08	0.02
30	0.68	0.12	0.02
40	0.80	0.16	0.03
50	0.87	0.21	0.04
60	0.90	0.25	0.05
70	0.93	0.30	0.05
80	0.94	0.34	0.06
90	0.95	0.39	0.07
100	0.96	0.43	0.08

3. GWPs of biogenic CO_2 for bioenergy from biomaterials

Harvested biomass can be used as materials and stored in the anthroposphere for a certain number of years before being used for bioenergy production. In this case, biogenic CO_2 emissions from bioenergy occur at the end of life of the biomaterials, while the sequestration in the new stand occurs immediately after harvest, so sequestering CO_2 from the atmosphere before than the harvested biomass is combusted. Table 2 shows the value of the GWP (TH = 100) to characterize biogenic CO_2 emissions as a function of the biomass rotation period and of the storage period in the anthroposphere [5]. Figure 2 shows that the value of GWP is almost zero (i.e., no effect on climate) when the harvested biomass is stored for approximately half of the rotation period [5].

Table 2 GWP factors for biogenic CO_2 emissions tabularized for several rotation/storage period combinations using a 100-year time horizon. Source: [5].

Rotation period (years)	Storage period in the anthroposphere (years)										
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
1	0.00	-0.07	-0.15	-0.23	-0.32	-0.40	-0.50	-0.60	-0.71	-0.84	-0.99
10	0.04	-0.04	-0.12	-0.20	-0.28	-0.37	-0.46	-0.57	-0.68	-0.80	-0.96
20	0.08	0.00	-0.08	-0.16	-0.24	-0.33	-0.42	-0.53	-0.64	-0.76	-0.92
30	0.12	0.04	-0.04	-0.12	-0.20	-0.29	-0.38	-0.48	-0.60	-0.72	-0.88
40	0.16	0.09	0.01	-0.08	-0.16	-0.25	-0.34	-0.44	-0.55	-0.68	-0.84
50	0.20	0.13	0.05	-0.03	-0.12	-0.21	-0.30	-0.40	-0.51	-0.64	-0.80
60	0.25	0.17	0.09	0.01	-0.07	-0.16	-0.26	-0.36	-0.47	-0.59	-0.75
70	0.29	0.22	0.14	0.06	-0.03	-0.12	-0.21	-0.31	-0.42	-0.55	-0.71
80	0.34	0.26	0.18	0.10	0.02	-0.07	-0.17	-0.27	-0.38	-0.50	-0.66
90	0.38	0.31	0.23	0.15	0.06	-0.03	-0.12	-0.22	-0.33	-0.46	-0.62
100	0.44	0.37	0.29	0.21	0.12	0.032	-0.06	-0.16	-0.27	-0.4	-0.56

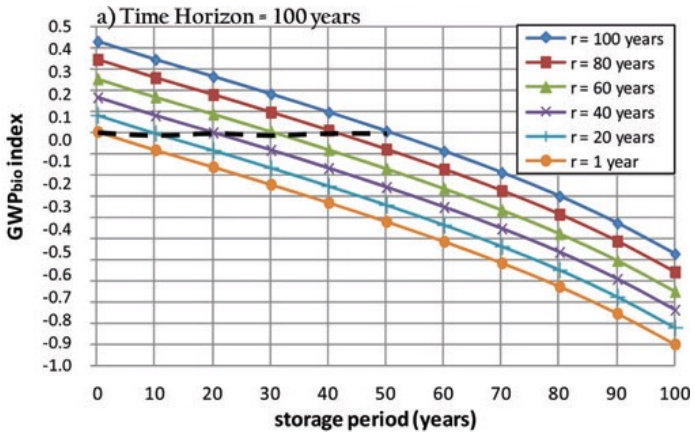

Figure 2 GWP factors (TH = 100) for 6 rotation periods (r) as a function of biomass storage period in the anthroposphere. The black broken line shows when the storage period is equal to half the rotation period. Source: [5].

4. Effect of timing of biogenic CO_2 emissions from harvested wood products on GWP

Another paper investigates the different options to model biogenic CO_2 emissions from biomass harvested for biomaterials, considering three wood applications with different lifetime: fuel (lifetime = 2 years), nonstructural panels (lifetime = 30 years), and housing construction materials (lifetime = 150 years) [6]. CO_2 emissions from wood oxidation are modeled using the following probability distributions: a) a delta function (δ), used to simulate emissions at the end of the lifetime, as in the section above; b) an uniform distribution (υ), where emissions are equally spread over a certain number of years (equal to two times the lifetime); c) an exponential distribution (ε), following IPCC practices for harvested wood products; d) a chi-square distribution (χ), where the emissions are distributed around the expected lifetime. Figure 3 shows on the left the profiles of the CO_2 emission rate given by the different probability distributions for wood use as nonstructural panel, and on the right the resulting changes in atmospheric CO_2 concentration, i.e. IRF (that is labeled PRF in the figure) [6]. Table 3 shows the corresponding values of GWP [6].

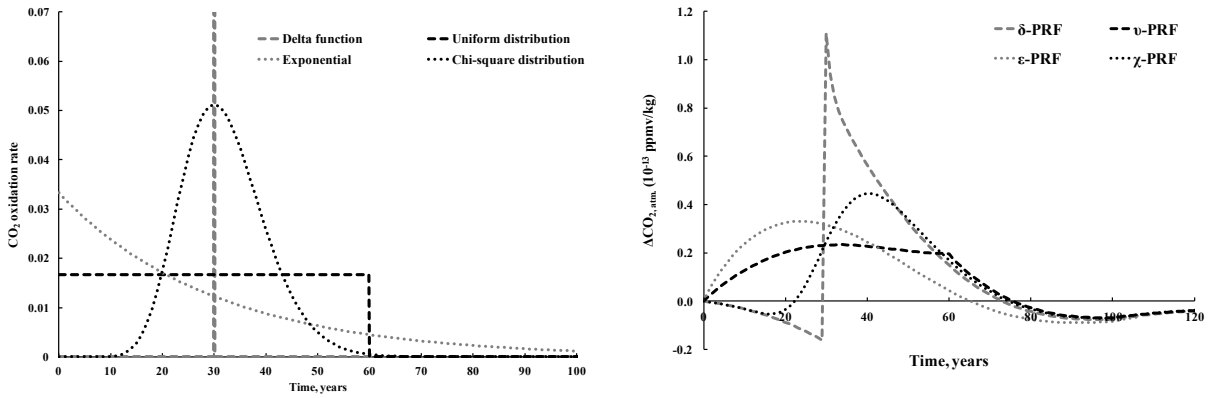

Figure 3 Oxidation rates according to different probability distributions for wood use as nonstructural panel on the left. Corresponding changes in atmospheric CO_2 concentration are shown on the right. Source: [6].

Table 3 GWP for three wood uses using different probability distributions as emission functions. Source: [6].

	GWP		
	TH = 20	TH = 100	TH = 500
Wood as fuel			
Delta function	0.96	0.43	0.07
Continuous distribution	0.87	0.41	0.07
Exponential distribution	0.87	0.40	0.07
Chi-square distribution	0.79	0.39	0.07
Wood as non structural panels			
Delta function	-0.04	0.19	0.03
Continuous distribution	0.14	0.18	0.03
Exponential distribution	0.25	0.18	0.03
Chi-square distribution	-0.04	0.17	0.03
Wood as housing construction material			
Delta function	-0.04	-0.57	-0.15
Continuous distribution	-0.01	-0.34	-0.16
Exponential distribution	0.03	-0.26	-0.14
Chi-square distribution	-0.04	-0.58	-0.16

5. Role of forest residues for IRF and GWP

The influence for GWP of biogenic CO_2 of harvesting forest residues along with the stems is investigated in [7] (case study: Norwegian spruce forest). Figure 4 shows the resulting different IRFs resulting from various forest residue removal scenarios. Table 4 shows the corresponding values of GWP.

The IRFs and GWP factors appear to be sensible to the amount of forest residues harvested. When all residues are left in the forest (red line in Figure 4) they freely decompose over time, so that the biogenic CO_2 decay is slower for some decades than that of fossil CO_2. When all residues are collected (light purple line in Figure 4), the decay is faster and perfectly overlap with that shown in the second section above.

For a 100-year time horizon, the GWP factors suggest that between 44 and 62% of biogenic CO_2 emissions at the energy conversion plant should be attributed to causing equivalent climate change potential as fossil-based CO_2 emissions.

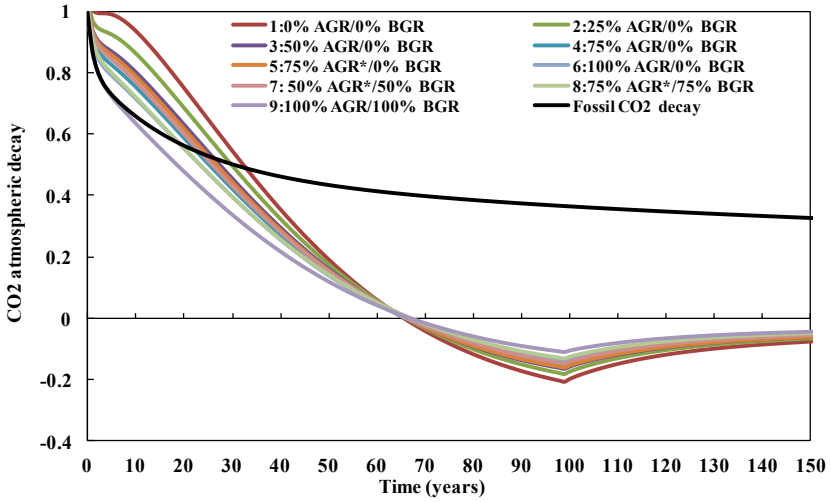

Fig. 4 Atmospheric CO_2 decay profiles due to a unit CO_2 pulse of bioenergy at conversion site with consideration of CO_2 emissions due to decomposition of the fraction of forest residues that remain upon the forest floor. AGR = Above Ground Residues; BGR = Below Ground Residues. % refers to the fraction of residue that is harvested. Source: [7].

Table 4 Characterization factors for biogenic CO_2 emissions from bioenergy sourced from regenerative biomass according to different forest residue management scenarios. Source: [7].

Residue extraction scenario	GWP TH = 20	GWP TH = 100	GWP_b TH = 500
1. 0% AGR/ 0% BGR	1.30	0.62	0.09
2. 25% AGR/0% BGR	1.22	0.58	0.09
3. 50% AGR/0% BGR	1.15	0.54	0.09
4. 75% AGR/0% BGR	1.09	0.51	0.08
5. 75% AGR*/0% BGR	1.13	0.53	0.09
6. 100% AGR/0% BGR	1.05	0.49	0.08
7. 50% AGR/50% BGR	1.11	0.52	0.09
8. 75% AGR/75% BGR	1.06	0.49	0.08
9. 100% AGR/100% BGR	0.96	0.44	0.08

6. Site-specific GWP and the importance of albedo

The peer reviewed literature about climate impacts from forest management reports important contributions from changes in biophysical factors like surface reflectivity (albedo), longwave radiation fluxes, evaporation and others [8-12]. As one example, the albedo effect is found to be the dominant direct biogeophysical climate forcing on the global scale, particularly in areas affected by seasonal snow cover, and can sometimes more than offset the global warming induced by deforestation [10, 12-14]. In a recent paper, we assess the contributions to direct global warming of various bioenergy case studies from temporary climate forcings as changes in atmospheric CO_2 concentration and surface albedo, in addition to direct greenhouse gas (GHG) emissions throughout the value chain [15]. The analysis focuses on CO_2 from bioenergy sourced from a stand where biomass is kept under continuous rotation (no land use change), and a LCA perspective is undertaken. Table 5 shows the resulting site-specific GWP for biogenic CO_2 emissions, given by the contributions from the temporary increase in atmospheric CO_2 and changes in surface albedo [15]. Figure 5 shows the contributions for the various case studies when biomass is used for production of heat in stationary plants [15]. When biomass is sourced from areas affected by seasonal snow cover, albedo contributions are significant, and in some cases they can more than offset the global warming induced by GHG emissions, so giving a net cooling effect also in the very short term (e.g., see CA case study).

Table 5 GWPs for the selected biomass case studies and time horizons. GWP values for CH_4 and N_2O differ from that reported in the 4th IPCC Assessment report [1] because here the effective radiative forcing is used as basis. Abbreviations: PNW = mixed forest in Pacific Northwest (US); WI = aspen forest in Wisconsin (US); CA = pine forest in Canada; NO = spruce forest in Norway; fr = with harvest of 75% of above ground forest residues. Source: [15].

		GWP TH = 20	GWP TH = 100	GWP TH = 500
CO_2		1.00	1.00	1.00
CH_4		96.3	34.5	10.6
N_2O		336	348	179
	Bio CO_2, NO	1.25	0.62	0.11
	Albedo, NO	-0.94	-0.42	-0.13
Net, NO		0.32	0.20	-0.02
	Bio CO_2, NO (fr)	1.07	0.51	0.09
	Albedo, NO (fr)	-0.85	-0.38	-0.12
Net, NO (fr)		0.22	0.12	-0.03
	Bio CO_2, US PNW	1.04	0.58	0.10
	Albedo, US PNW	-0.14	-0.07	-0.02
Net, US PNW		0.90	0.51	0.08
	Bio CO_2, US WI	1.08	0.32	0.06
	Albedo, US WI	-1.10	-0.38	-0.12
Net, US WI		-0.02	-0.06	-0.06
	Bio CO_2, CA	1.13	0.42	0.08
	Albedo, CA	-1.60	-0.61	-0.19
Net, CA		-0.47	-0.18	-0.11
Bio CO_2, willow		0.09	0.02	0.00

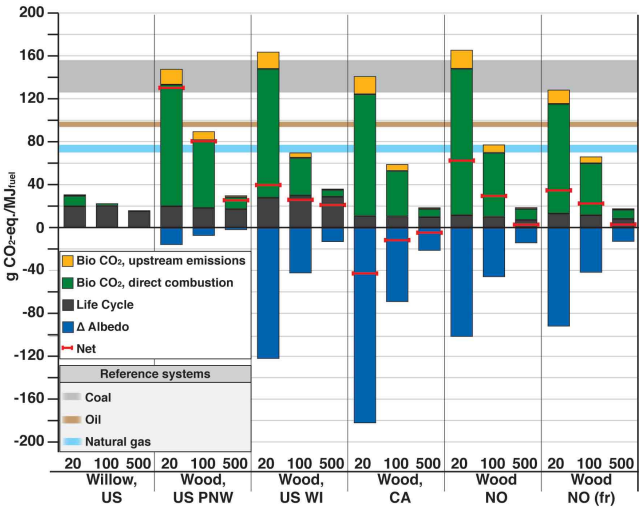

Figure 5 Direct contributions to global warming of the different bioenergy options for stationary applications. Three time horizons (20, 100 and 500 years) are considered. Fossil fuels (coal, oil and natural gas) per MJ of fuel combusted are shown to benchmark our results. Lower and higher limits of the bands for the fossil systems represent the impact for TH = 500 and TH = 20, respectively. Abbreviations: see caption of Table of Table 5. Bio CO_2 = biogenic CO_2 emissions, i.e. emissions from oxidation of biomass harvested for bioenergy; Upstream emissions = emissions from biomass losses through the value chain and biofuel processing; Direct combustion = emissions from combustion of biofuels at plant. Source: [15].

7. Importance of climate metrics

GWP is a form of cumulative metric, i.e. it considers the cumulative/integrated effect over time of a perturbation in terms of radiative forcing. When instantaneous metrics are considered (i.e., the instantaneous impact at a specific point in time), such as instantaneous radiative forcing or global surface temperature change, the impact from bioenergy is shorter in time than that from fossil CO_2. Figure 6 shows the case studies presented above for production of heat in comparison with fossil systems using the temporal changes in instantaneous radiative forcing over time [15]. In the short term, impacts from bioenergy can be lower than that of fossils, or even net negative (i.e., yielding a cooling effect). Concerning the medium and long term, bioenergy impacts are basically temporary, as they tend to be very low after some decades, while those from fossil fuels are consistently higher.

Figure 7 compares the global average surface temperature response to a pulse emission of fossil CO_2 and biogenic CO_2 sourced from regenerative biomass (rotation period = 100 years) [16]. The curves show that CO_2 emissions from deforestation or combustion of fossil fuels induce a response that warms global average surface temperature for millennia, while CO_2 emissions from forest bioenergy warm climate only temporarily. Should increases in the demand for forest bioenergy lead to reduced carbon stocks rather than full recovery of the pre-harvest forest, the resulting climate response should still be understood as being principally different from that of fossil CO_2 or from deforestation, having a profile that lies somewhere in between the two cases presented in Fig 7.

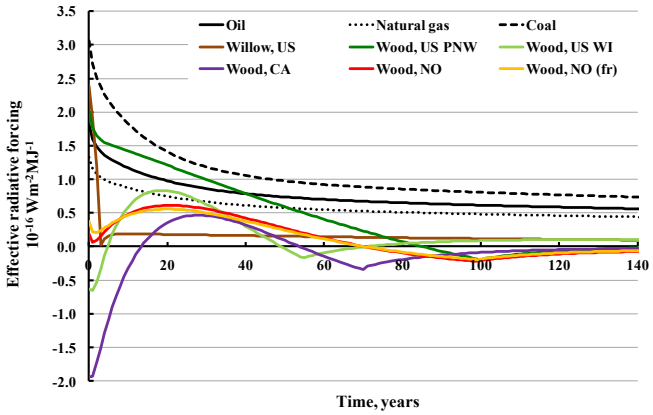

Figure 6 Net effective radiative forcing (instantaneous) for the different bioenergy options for stationary applications and fossil reference systems. Abbreviations: PNW = Pacific Northwest (US); WI = Wisconsin (US); CA = Canada; NO = Norway; fr = with harvest of 75% of above ground forest residues. Source: [15].

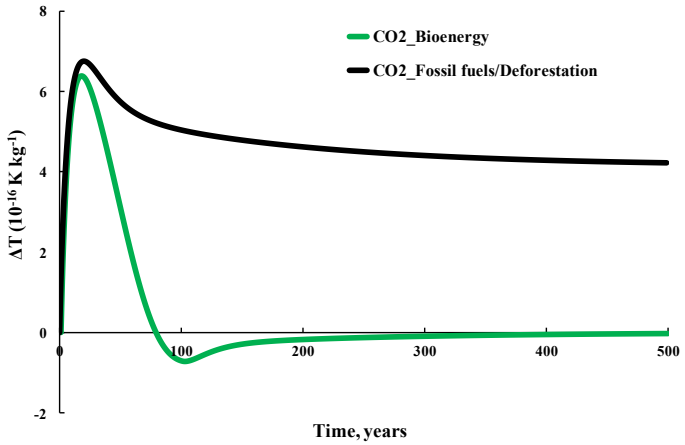

Figure 7 Global surface temperature response to a pulse emission of fossil CO2 in relation to the same pulse from bioenergy sourced from a forest in which the carbon stock is regenerated over a 100-year rotation period. Source: [16].

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