Arnold Schwarzenegger
Governor

BIOMASS TO ENERGY:

FOREST MANAGEMENT FOR WILDFIRE REDUCTION, ENERGY PRODUCTION, AND OTHER BENEFITS

APPENDIX 9

PIER FINAL PROJECT REPORT

January 2010
CEC-500-2009-080-AP9

Appendix 9: Landscape Carbon Model

1. Author:

Gregg Morris, Future Resources Associates

Notice of Change in Scenario Naming Conventions

Key assumptions, modeling structures and terminology were altered and refined to accommodate new thinking during the course of this study. The reader will observe in the appendices that the scenarios are referred to as "Scenarios 1, 2 and 3" or "S1, S2 and S3."

In both the main text of the Final Report and in the Life Cycle Assessment appendix (Appendix 4), the former Scenario 1 (S1) was renamed to the "Reference Case." Scenario 3 (S3) has been renamed the "Test Scenario." Scenario 2 (S2), focused on the relative contributions and impact of Industrial Private Forestry (IPF) has been eliminated from most of the analyses that make up the entire study. These changes better reflect the focus of the study, which is fundamentally about the landscape level changes in wildfire, habitat, and other dynamics. The modification of terminology do not substantively affect the findings or recommendations of the study.

Introduction

The B2E life-cycle analysis (LCA) project is concerned with the host of social, economic, and environmental issues surrounding the sustainable management and use of forest resources in California. A key issue of investigation for the project is: what are the implications of various forest treatment regimes for atmospheric greenhouse gas levels? Carbon is exchanged rapidly and continuously between the earth's biomass and atmosphere. From a greenhouse gas perspective, forest treatments to reduce risks associated with destructive wildfires have the immediate effect of removing a significant amount (e.g. 20 – 25 %) of carbon from the forest, and transferring most of the removed carbon to the stock of greenhouse gases in the atmosphere via combustion. On the other hand, compared with a fire-prone, overgrown forest, the treated forest has an increased net annual growth rate, and decreased probabilities of both fire occurrence and severity. Over time, a treated forest tends to reduce atmospheric greenhouse gases by sequestering carbon at a greater rate than the overgrown forest, and by reducing fire damage. The Carbon Domain of the LCA effort dynamically models the stocks and flows of carbon associated with the forests on the B2E beta landscape over a forty year period, either with or without forest treatment operations being performed to reduce fire risks and improve the functioning of watersheds.

The Carbon Domain of the B2E study shows that under all three scenarios constructed for the study region, the beta landscape is a net absorber of atmospheric carbon dioxide throughout the forty-year timeframe of the study. The two scenarios that include treatment operations, scenarios 2 and 3, both show enhanced landscape-wide carbon sequestration compared with the no-treatment scenario (scenario 1), with increasing levels of treatment showing increasing enhancement of sequestration. However, this increased level of sequestration comes at the expense of an initial increase in biogenic greenhouse gas levels associated with the landscape, due to fuel use of the fraction of the treatment removals that cannot be used for the production of wood products. The net result is that performing landscape treatments has a small net

impact on biogenic greenhouse gas levels in the atmosphere, while avoiding a significant amount of fossil carbon additions to the atmosphere. In the short term treatment operations increase biogenic greenhouse gases, but in the long term, treatment operations decrease biogenic greenhouse gases by enhancing forest health and growth, and by making the forest more resilient to fire, insect and disease losses. This report begins with background on the global carbon cycle, and the essential role played by forests in the carbon cycle. The forestry resources on the beta landscape are characterized with respect to the long-term impacts of forest treatments on carbon flows. The landscape carbon model is then described, and the results of modeling the three B2E scenarios are discussed.

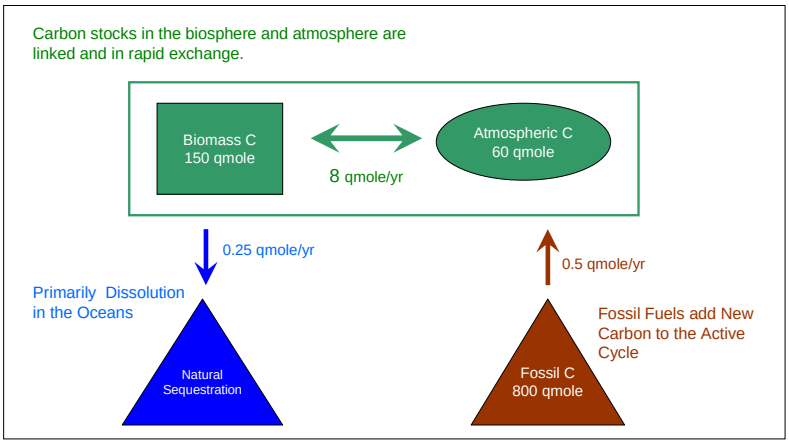
The Global Carbon Cycle

Carbon is the essential element for life on earth. The earth contains well over one million qmoles of carbon,[1] most of which is safely locked away in geological storage, inaccessible to the atmosphere. Only a tiny fraction of the earth's carbon is in the atmosphere, where it is found mainly in the form of the two principal greenhouse gases, carbon dioxide (CO_2) and methane (CH_4). CO_2 is currently found in the atmosphere at a concentration of ~ 380 ppm. CO_2 has an atmospheric residence time that is estimated at between 100 – 200 years, and contributes approximately one-half of the greenhouse gas forcing effect of all atmospheric gases. Methane is found in the atmosphere at a concentration of ~ 1.7 ppm, but has a greenhouse forcing effect that is twenty-five times greater than that of CO_2 on a per-carbon basis.[2] CH_4 has a 12-year residence time in the atmosphere, and its mode of clearance from the atmosphere is by conversion to atmospheric CO_2.

Carbon gases in the atmosphere (~ 60 qmoles of C) are in rapid exchange with carbon in the earth's biomass (~ 150 qmoles of C in terrestrial biomass, mostly forests, divided almost equally between living and dead organic matter). Approximately 8 qmoles of C are exchanged between the earth's biomass and atmosphere annually, with flows roughly in balance. Carbon is taken up by biomass through photosynthesis, and returned to the atmosphere by a combination of respiration, decomposition, and fire. The stock of carbon that is part of the active carbon cycle is thus about 210 qmoles, of which approximately 30 percent is in the air, and 70 percent is in the biomass (living and dead organic matter) at any given time. Figure 1 shows the global carbon cycle graphically as it relates to atmospheric carbon. The active circulation part of the global carbon cycle is enclosed by the green rectangle in the figure. The carbon circulating within the green rectangle is called biogenic carbon.

Figure 1: Global Carbon Cycle

[1] 1 qmole = 1 x 10^{15} moles of carbon, weighing approximately 13.25 billion tons.
[2] J.T. Houghton, ed., *Climate Change 1995: the Science of Climate Change*, published for the Intergovernmental Panel on Climate Change by Cambridge University Press, 1996.



Approximately 800 qmoles of carbon are deposited inside the earth in the form of fossil fuels, including natural gas, petroleum, coal, oil shales, and peat. Fossil fuels are the world's principle commercial energy sources. However, the downside of fossil energy use from a greenhouse gas perspective is that it entails removing carbon from geologic storage, where it is unavailable to the atmosphere, and injecting it directly into the atmosphere, adding it as new carbon to the carbon that is already in the active carbon cycle. Clearly, the amount of carbon in fossil fuels is enough to seriously unhinge the active carbon cycle (inside the green rectangle in the figure) that regulates the earth's climate, as well as life on earth.

Carbon Neutral

The greenhouse gas emissions produced at biomass and biogas generating facilities comes from carbon that is already a part of the stock of the linked atmospheric – biospheric carbon cycle (biogenic carbon—see green rectangle in Figure 1). This is in stark contrast to fossil fuel combustion, which removes carbon from permanent geologic storage, and adds it as net new carbon to the carbon already in the atmospheric – biospheric circulation system. Fossil-fuel combustion adds new carbon to the linked stocks of atmospheric and biospheric carbon. Biomass energy production makes use of biogenic carbon that is already part of the atmospheric – biospheric stock. Most people focus on this aspect of bioenergy production, and proclaim it to be "Carbon Neutral."

Existing greenhouse gas tracking and trading systems, such as those of RGGI in the Northeast U.S., and the system used by the EU, consider biomass energy to be a zero-greenhouse-gas-emitting technology. These tracking systems, which are among the world leaders in greenhouse gas tracking and trading, are concerned only with accounting for greenhouse gas emissions from fossil carbon use. Emissions of CO_2 from biomass are considered carbon neutral, and are not counted towards a facility's or a retail seller's greenhouse gas emissions in either of these pioneering tracking systems. California's tracking system, which is still in development, will be different. According to current plans, California's tracking system will track emissions of biogenic carbon as well as fossil carbon, but it will consider biogenic carbon to be a separate category of emissions than fossil carbon, and will not require the retirement of biogenic greenhouse gas emissions against AB 32[3] emissions allowances.

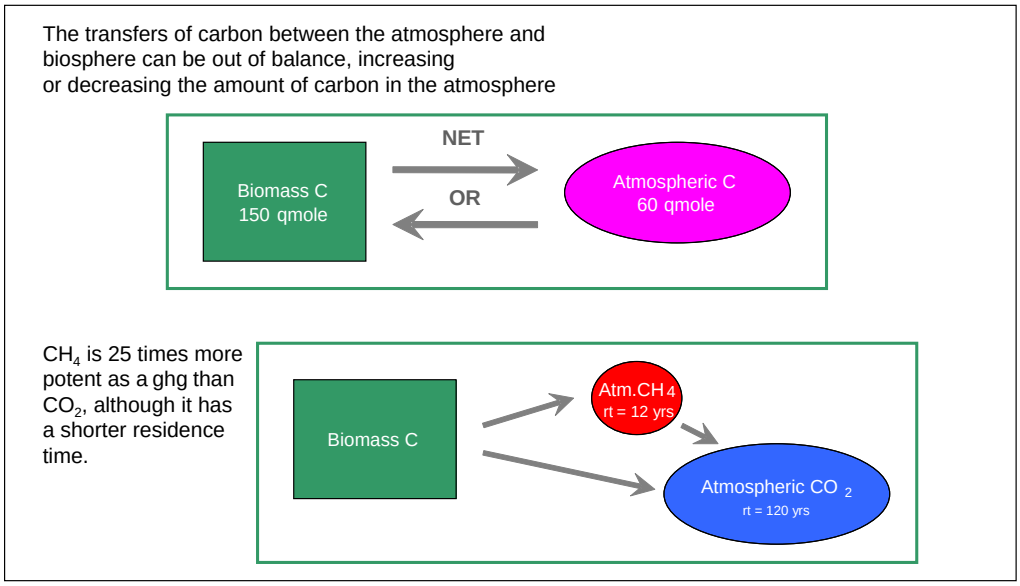
Beyond Carbon Neutral

[3] AB 32 is the California Global Warming Solutions Act of 2006.

Carbon neutrality, while an important intrinsic characteristic of bioenergy production, is only part of the story of the greenhouse gas implications of biomass. In addition to being carbon neutral by virtue of using biogenic carbon, biomass energy production can affect atmospheric greenhouse gas concentrations in two important ways. First, the total amount of carbon that is sequestered in terrestrial biomass affects the amount of carbon in the atmosphere. By contributing to forest health and fire resiliency in currently at-risk, overstocked forests, in the long term energy production from forest fuels can increase the amount of carbon that is stored on a sustainable basis in the earth's forests, making a positive contribution to efforts to control atmospheric greenhouse gas levels. Second, biomass energy production can change the timing and relative mix (oxidized vs. reduced) of carbon forms emitted to the atmosphere associated with the disposal or disposition of the biomass resources. From a greenhouse gas perspective reduced carbon (CH_4) is twenty-five times more potent than oxidized carbon (CO_2) on an instantaneous, per-carbon basis, so the form in which carbon is transferred from the biomass stock to the atmospheric stock is critically important from the standpoint of greenhouse forcing impact. In the long-term, CH_4 has a 12-year residence time in the atmosphere, and its clearance involves conversion to atmospheric CO_2.

In current carbon tracking and trading systems, which are primarily focused on fossil CO_2, the potential greenhouse gas benefits of biomass energy production related to the disposal of biomass resources, including healthier and more fire- and disease-resilient forests, and the substitution of natural CH_4 emissions with CO_2 emissions, are categorized as Greenhouse Gas Offsets. These concepts are illustrated graphically in Figure 2. The accounting rules for greenhouse gas offsets are in the early stage of development, and will be extremely important for the future of biomass energy production and use.

Figure 2: Offsets for Biomass GHG Abatement



Biomass Energy Resources from the Beta Landscape

The B2E project beta landscape, which is described in detail elsewhere in this report, is located in a heavily forested region of northern California. The 2.7 million-acre landscape houses

several existing biomass power plants and sawmills, and is split fairly evenly between public and private forestlands. The study looks at performing either no treatment anywhere in the landscape (Scenario 1), or two different levels of treatment on the forests in the beta landscape (Scenarios 2 & 3). Merchantable timber in the removals is used for the manufacture of wood products, while the remaining removals are used as power plant fuel. The sawmill residues resulting from the production of wood products from the merchantable material is also used as power plant fuel for purposes of the carbon modeling domain of the B2E project.

The carbon model follows the flows of carbon associated with treatment removals of forest biomass for both wood products and fuels applications, as well as due to forest growth and periodic fire losses in the forest. The B2E project has assumed that forest treatment removals would be used for their highest-valued application, with all of the merchantable material used for the manufacture of wood products, and the remainder used for energy production, including wood manufacturing residues.

In-forest biomass residues include two major categories of materials: residues that are generated in the forest when timber is harvested for wood products, which is often called slash, and material naturally occurring in forests in the form of overgrowth material, whose removal would provide environmental benefits to the remaining forest. Harvesting residues include the tops and limbs of harvested trees, bark (especially when debarking takes place in the forest), and cull logs that are cut and removed during harvesting operations. The cheapest form of management for this material is to leave it in the forest as it is generated, but that is also the worst management practice from a forestry perspective, as leaving harvesting residues in the field retards regrowth of the forest, and represents a substantial fire hazard. Virtually all timber harvesting contracts in California require loggers to manage the slash they generate. Slash that is generated close enough to an operating biomass energy plant can be collected and used as fuel. The alternative is to collect the slash and burn it in piles. Open burning leads to much higher levels of emissions of smoke, particulates, and other air pollutants, including greenhouse gases, than combustion in a controlled boiler.

The other major category of in-forest residue is overstocked material that exists in vast areas of California's forests. Due to poor forestry practices and aggressive fire-fighting efforts during most of the past century in California, today vast areas of the state's forests are overstocked with stressed biomass. This material presents an enhanced risk of destructive wildfires, an enhanced vulnerability to disease and pest attacks, and generally degrades the healthy functioning of the forest ecosystem. Overstocked forests benefit greatly from thinning operations.

The B2E project constructed three different forestry treatment scenarios for the beta landscape, in order to study the effects of treatment on the forest ecosystem, and on the community. The first scenario, which is the control case, entails no treatment operations anywhere on the landscape over the forty-year timeframe of the analysis. The second scenario entails treatment operations on only the private commercial forestlands that are part of the beta landscape, while the third scenario adds treatment operations on the public lands to the scenario-2 treatments on the private lands. Thus, the third scenario represents the most extensive level of landscape treatment over the forty-year framework of the analysis.

Analytical Approach

Two detailed dynamic atmospheric concentration models have been developed for analyzing the time-dependent greenhouse gas concentrations associated with biomass energy production. Both models are built as Excel spreadsheets. Atmospheric concentrations of the greenhouse

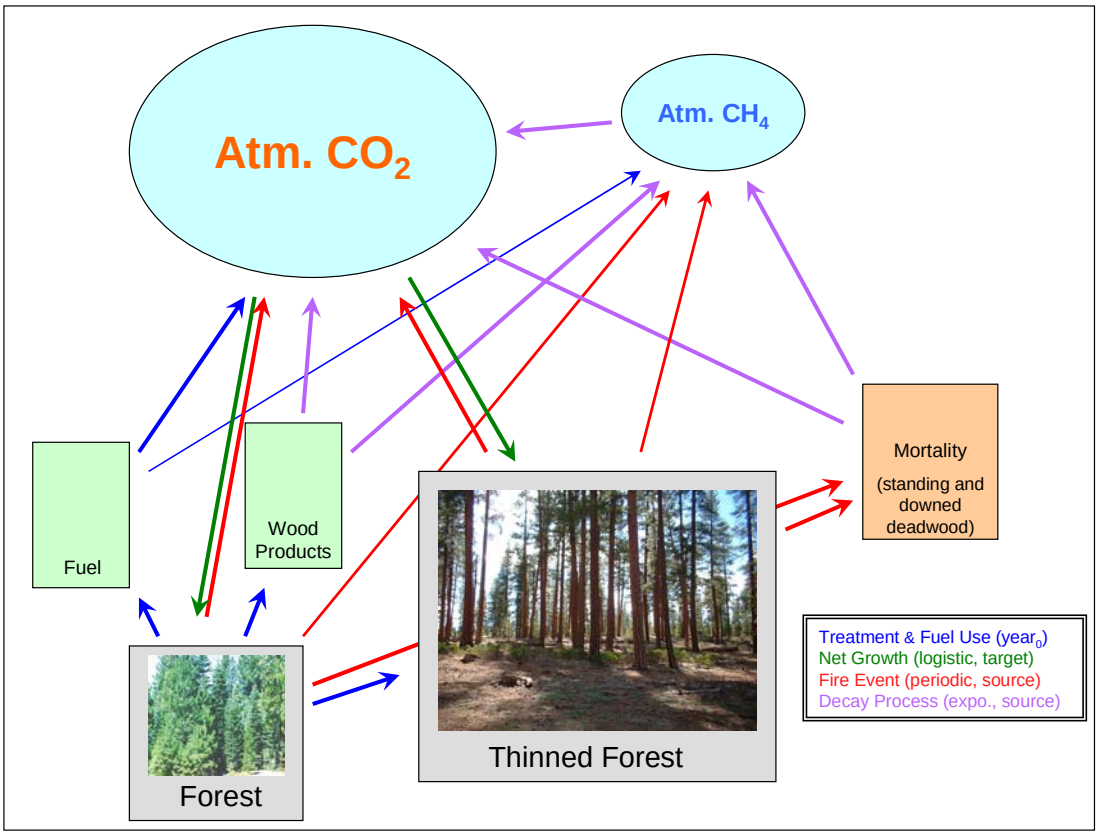
gases associated with the biomass energy production pathway can be compared with the atmospheric greenhouse gas levels associated with alternative means of disposal or disposition of the same biomass residues, combined with production of the same amount of energy using fossil fuels. The model computes the time-dependent atmospheric stocks of CO_2 and CH_4 that are associated with the biomass residues used for energy production, or subjected to alternative disposal or disposition pathways. Atmospheric concentrations of the carbon-containing greenhouse gases are followed over a time horizon of up to 100 years. One model tracks the concentrations of greenhouse gases associated with sustained management of biomass for energy production over an entire landscape. The other model tracks the long-term atmospheric greenhouse gas concentrations resulting from a single year's worth of biomass fuel use. Fossil-carbon greenhouse gases and biogenic-carbon greenhouse gases are tracked in separate accounts.

The biomass greenhouse gas models are stock and flow models that incorporate the exponential decay function for carbon loss from relevant stocks of carbon. The carbon stocks analyzed in the model include the atmospheric stocks of CO_2 and CH_4, and various stocks of fixed biomass carbon in storage, including carbon fixed in living forest biomass, carbon fixed in standing and downed mortality, etc. For each landscape treatment scenario the biomass carbon is initially partitioned among three stocks: atmospheric CO_2, atmospheric CH_4, and carbon in the appropriate storage reservoir. The carbon in storage then is subjected to long-term decay into CO_2 and CH_4. The CO_2 and CH_4 emitted by the carbon-in-storage are added to the atmospheric stocks over time, in accordance with the characteristic half-life of the carbon in the storage reservoir. The atmospheric CO_2 and CH_4 stocks are themselves subjected to exponential-decay removal processes. The removal pathway for atmospheric CH_4 is conversion via oxidation to atmospheric CO_2. CO_2 is removed from the atmosphere via multiple pathways, including conversion to biomass, and dissolution in the oceans.

The Landscape Greenhouse Gas Model

The B2E project performed detailed forest growth and fire modeling for the 2.7 million acre beta landscape under the three treatment scenarios constructed for the study. This modeling work produced a wealth of data on the inventories of living and dead biomass in the forest, biomass flows to sawmills and power plants, and net annual growth and fire consumption losses, under each scenario. The project modeling looked at treatment removals, fire events, and standing biomass inventories over a forty-year timeframe, with data such as inventories, removals, and fire losses determined as if all changes and activities for each decade occur in the first year of the decade. The B2E project forestry and fire modeling provides the primary inputs that are used in the landscape greenhouse gas model.

The landscape greenhouse gas model accepts inventory, treatment, and fire data on the same once-per-decade basis as is available in the B2E Jumbo data files. However, the landscape greenhouse gas model tracks stocks and flows of carbon on an annual basis. The consequence is that the results of the modeling in many categories look like step functions. Carbon flows are tracked for several stocks of fixed carbon, and for CO_2 and CH_4. Carbon stocks examined in the model include living biomass, mortality biomass, biomass in wood products, and the stocks of the two major carbon-based greenhouse gases, CO_2 and CH_4, in the atmosphere. Fossil-carbon greenhouse gases and biogenic-carbon greenhouse gases are tracked in separate accounts. Figure XX illustrates graphically the carbon stocks and flows that are tracked in the landscape greenhouse gas model.



The model is controlled from the input panel worksheet, which is duplicated in Figure xx. The cells that are outlined and printed in blue are the cells that require user input information. The inputs on this page include information about diesel fuel use in forest treatment operations, the storage characteristics of carbon in wood products, in deadwood in the forest, in wood products, and in the atmosphere in its two principal forms, and the relevant characteristics of avoided fossil fuels.

Model Inputs Module

Fuel Production. (th.bdt/yr)	2006	2016	2026	2036	Total
Scenario 2	5,868	6,056	5,523	5,557	23,005
Scenario 3	8,384	8,692	7,104	7,005	31,185

Diesel Fuel Consumption (gal / bdt)					4.5
Fuel Production	2.5	2.5	2.5	2.5	
Fuel Transportation	1.5	1.5	1.5	1.5	
On-Site Fuel Handling	0.5	0.5	0.5	0.5	

Fate of C if use	Initial Fate CO_2	Initial Fate CH_4	Storage	In Storage (yr) ½ Life	In Storage (yr) Res.Time	Loss from Storage CO_2	Loss from Storage CH_4	Accum. in Storage
mortality			100.0%	20.8	30.0	53.3%	26.7%	20.0%
product			100.0%	55.5	80.0	48.0%	12.0%	40.0%
Biomass Energy	99.0%	0.1%	1.0%	10.0	14.4	60.0%	5.0%	35.0%

Avoided Fossil Fuel C	% avoided	mmkWh/y	ton / mmkWh CO_2	CH_4	Storage	
Coal	50%	15,592	1,100	0.15	3.0	
N. Gas / ST & GT	25%	7,796	570	0.04		
N. Gas / Comb. Cycle	25%	7,796	450	0.10		
Diesel			22.0	0.005		lb/gal

Carbon in Atmosphere	½ Life	Res. Time	Rad.Eff.
CO_2	83.2	120.0	1
CH_4	8.3	12.0	25

Electric Generation Efficiency	1.00	bdt/MWh
Biomass Electricity Produced	31,185	mmkWh/yr
% of dry Biomass that is Carbon		48%

The changing inventories of biomass during the study timeframe across the beta landscape for the three scenarios are determined on three nearly-identical worksheets. These worksheets track carbon stocks of living and mortality biomass, carbon in wood products, and the two carbon-based greenhouse gases in the atmosphere, CO_2 and CH_4. Figure xx shows the worksheet used for Scenario 1, which is the no-treatment scenario. This scenario does not include any wood products or energy production. For scenarios 2 and 3, which do include treatments and the use of the treatment removals, additional worksheets are used to track the carbon flows from the fossil fuel use that is avoided, and from the biomass power plants that use the treatment-produced fuels.

Untreated Forest Module (all quantities thousands of tons except as noted)

	Inventory	C to Storage (forest)			Mortality	CO2 to atmosphere			CH4 to atmosphere			CO2 equiv	St.Mort.	C to Storage (standing mortality)		
Year	th.bdt/yr	Input	Output	EOY	th.bdt/yr	Input	Output	EOY	Input	Output	EOY	EOY Burder	th.bdt/yr	Input	Output	EOY
2005				83,937												
2006	174,870	1,248	1,110	84,075	2,313	1,220	4,581	(3,361)	35	1	34	(1,024)	1,588	762	13	750
2007	0	1,248	0	85,323		58	4,548	(7,851)	9	3	40	(5,124)		0	25	725
2008	0	1,248	0	86,571		57	4,511	(12,304)	9	4	45	(9,239)		0	24	700
2009	0	1,248	0	87,819		57	4,473	(16,721)	8	4	49	(13,364)		0	23	677
2010	0	1,248	0	89,067		56	4,437	(21,101)	8	4	52	(17,496)		0	23	654
2011	0	1,248	0	90,315		56	4,400	(25,446)	8	5	56	(21,630)		0	22	633
2012	0	1,248	0	91,563		55	4,364	(29,755)	7	5	58	(25,763)		0	21	612
2013	0	1,248	0	92,811		54	4,328	(34,029)	7	5	60	(29,892)		0	20	591
2014	0	1,248	0	94,059		53	4,292	(38,268)	7	5	62	(34,014)		0	20	571
2015	0	1,248	0	95,306		52	4,257	(42,473)	7	5	63	(38,128)		0	19	552
2016	198,555	1,100	958	95,449	1,996	1,398	3,687	(44,762)	44	7	100	(37,858)	1,190	571	28	1,096
2017	0	1,100	0	96,549		96	3,662	(48,328)	13	9	104	(41,144)		0	37	1,059
2018	0	1,100	0	97,650		94	3,633	(51,866)	13	9	108	(44,454)		0	35	1,024
2019	0	1,100	0	98,750		93	3,603	(55,377)	12	9	110	(47,782)		0	34	990
2020	0	1,100	0	99,850		91	3,574	(58,859)	12	10	113	(51,125)		0	33	957
2021	0	1,100	0	100,951		89	3,545	(62,315)	11	10	114	(54,478)		0	32	925
2022	0	1,100	0	102,051		88	3,516	(65,743)	11	10	115	(57,837)		0	31	894
2023	0	1,100	0	103,151		86	3,487	(69,144)	11	10	116	(61,199)		0	30	864
2024	0	1,100	0	104,252		84	3,459	(72,520)	10	10	116	(64,561)		0	29	835
2025	0	1,100	0	105,352		82	3,431	(75,868)	10	10	116	(67,921)		0	28	808
2026	219,484	987	1,822	104,517	3,796	2,821	2,999	(76,047)	86	13	188	(63,111)	2,154	1,034	44	1,797
2027	0	987	0	105,504		163	2,987	(78,871)	21	17	193	(65,610)		0	60	1,737
2028	0	987	0	106,492		160	2,963	(81,675)	21	17	197	(68,162)		0	58	1,680
2029	0	987	0	107,479		157	2,940	(84,458)	20	17	199	(70,759)		0	56	1,624
2030	0	987	0	108,466		154	2,917	(87,221)	19	17	201	(73,396)		0	54	1,569
2031	0	987	0	109,453		151	2,894	(89,964)	19	18	202	(76,066)		0	52	1,517
2032	0	987	0	110,440		147	2,871	(92,688)	18	18	203	(78,763)		0	51	1,467
2033	0	987	0	111,428		144	2,848	(95,392)	17	18	202	(81,482)		0	49	1,418
2034	0	987	0	112,415		141	2,826	(98,077)	17	18	202	(84,219)		0	47	1,370
2035	0	987	0	113,402		137	2,803	(100,743)	16	17	200	(86,970)		0	46	1,325
2036	236,254	802	2,074	112,129	4,322	4,096	2,118	(98,765)	123	22	302	(78,036)	1,936	929	60	2,194
2037	0	802	0	112,931		215	2,118	(100,667)	26	26	301	(79,952)		0	73	2,121
2038	0	802	0	113,733		210	2,102	(102,559)	25	26	300	(81,914)		0	71	2,050
2039	0	802	0	114,535		205	2,086	(104,441)	24	26	299	(83,915)		0	68	1,982
2040	0	802	0	115,337		200	2,071	(106,311)	23	26	296	(85,948)		0	66	1,916
2041	0	802	0	116,138		195	2,055	(108,171)	23	26	293	(88,008)		0	64	1,852
2042	0	802	0	116,940		190	2,040	(110,020)	22	25	290	(90,091)		0	62	1,790
2043	0	802	0	117,742		186	2,024	(111,858)	21	25	286	(92,192)		0	60	1,731
2044	0	802	0	118,544		181	2,009	(113,686)	21	25	282	(94,308)		0	58	1,673
2045	0	802	0	119,346		176	1,994	(115,504)	20	24	277	(96,434)		0	56	1,617
2046	248,637	802	0	120,147		171	1,978	(117,311)	19	24	273	(98,567)		0	54	1,563

The model determines, on an annual basis, both the biogenic- and fossil-carbon greenhouse ~~gas flows associated with the landscape under study over a forty-year period. Per the B2E~~ modeling efforts, forest treatments and fires occur during the first year of each decade in the simulation, while net forest growth is a continuous annual function. Net greenhouse gas levels for treatment scenarios 2 and 3 are plotted vs. the greenhouse gas levels associated with the control (no treatment) case (scenario 1). Biogenic greenhouse gases are accounted for separately from fossil greenhouse gases, consistent with the reporting protocols being developed under AB 32.

In order to illustrate how the model works, we describe the equations used in row no. six of the worksheet, which is the grey row for the year 2006 in the figure. The worksheet tracks stocks and flow for carbon in four reservoirs: carbon in biomass in the living forest (inventory), carbon in standing and downed mortality biomass in the forest (st.mort.), carbon dioxide (CO_2) in the atmosphere, and methane (CH_4) in the atmosphere. Each reservoir is represented by three columns: input, output, and EOY (end of year inventory). Carbon in the two solid-form (biomass) reservoirs is denominated in terms of thousands of tons of carbon. CO_2 is denominated in terms of thousands of tons of CO_2, and CH_4 is denominated in terms of

thousands of tons CH_4. The stock of carbon in the forest inventory is based on the total biomass inventory across the beta landscape, based on the output of the fire and growth modeling conducted for this project. The carbon stocks in the other three reservoirs is tracked only in terms of the marginal stocks and flows associated with the beta landscape over the forty-year timeframe of the B2E study. Most of the model inputs are entered into the Model Inputs Module, but several key forest-related inputs are entered directly into the scenario modules. These forest-related inputs are derived from the SFA fire modeling that has been performed for the B2E project. These inputs are shown in white type in the figure.

Following row no. six from left to right, the first data entry after the date (2006) is the starting inventory of living biomass on the beta landscape (col. B), a model input, expressed in terms of thousand bdts per year of total biomass. The other two inputs in row no. six are the total mortality (col. F) and standing mortality (col. P) due to fires in the first decade of the simulation, also expressed in terms of thousand bdts per year of total biomass. The total mortality measure is generated directly by the SFA modeling, while the standing mortality is derived from the SFA modeling output, calculated as the total mortality plus the amount of duff and litter that is volatilized, less the total amount of volatilization (which includes duff and litter).

The three columns to the right of the inventory column track the stocks and flows of carbon in the forest inventory across the beta landscape. Carbon input to the forest biomass through net growth is annualized based on an assumption of linear growth during each decade included in the simulation. All of the mortality for each decade is assumed to occur during the opening year of the decade, consistent with the SFA modeling. The equations used in cols. C – E are:

Carbon to Storage (forest)
Input = (Inventory end of decade – Inventory beginning of decade + Mortality) / 10
Output = Mortality biomass * % of biomass that is C
EOY = Previous-year's Inventory + Input – Output

Columns Q, R and S, the right-most columns in the figure, track the marginal stocks and flows of carbon in the standing and downed mortality biomass associated with the B2E simulation across the beta landscape. Input to this carbon reservoir is the non-volatilized portion of mortality from the SFA modeling. Output is based on the residence time of carbon in dead wood in the forest. The equations used in cols. Q – S are:

Carbon to Storage (standing mortality)
Input = Standing and down mortality biomass * % of biomass that is C
Output = Average inventory for year / residence time for C in reservoir
EOY = Previous-year's Inventory (= 0 for 2006) + Input – Output

Columns H – J and K – M track the marginal stocks and flows of the two carbon-containing greenhouse gases in the atmosphere (CO_2 and CH_4 respectively) associated with the B2E simulation across the beta landscape. Methane inputs to the atmosphere result from the volatilization of forest biomass during fire events, and from the degradation of standing and down mortality biomass. Carbon dioxide inputs to the atmosphere result from these two sources, and from the oxidation of previously-emitted CH_4 (methane is cleared from the atmosphere via oxidation to CO_2). Fire emissions data generated for the B2E project suggest that of the carbon volatilized, one-fifteenth is emitted in the form of CH_4, and the remainder in the form of CO_2. The equations used in cols. H – M are:
CH_4 to atmosphere (H – J)
Input = ((forest output - st. mort. output) / 15 + st. mort. output * % to CH_4) * 16/12
Output = Average inventory for year / residence time for C in atmospheric CH_4
EOY = Previous-year's Inventory (= 0 for 2006) + Input – Output

CO_2 to atmosphere (K – M)
Input = ((forest output - st. mort. output) / 15*14 + st. mort. output * % to CO_2) * 44/12
+ CH_4 output * 44/16
Output = Average inventory for year / residence time for C in atmospheric CO_2 +
forest C input * 44/12
EOY = Previous-year's Inventory (= 0 for 2006) + Input – Output

The final column in the figure, column O, shows the total greenhouse gas burden in the atmosphere associated with the study landscape, expressed in CO_2 equivalents. This number is calculated as the sum of the EOY CO_2 burden, plus the EOY CH_4 burden multiplied by the radiative effectiveness multiplied by 44/16 (the weight ratio to convert to carbon equivalent basis, which is the basis for the radiative effectiveness ratio of 25 in the input module).

The One-Year Greenhouse Gas Model

The one-year greenhouse gas model is more generalized than the landscape model, and includes a wider variety of biomass fuels (sawmill residues, forest residues, agricultural residues, urban waste wood, manure, and landfill gas). In this report, we emphasize the one-year greenhouse gas model's forest fuels modules, and the results and insights it provides regarding the performance of forest treatment operations in California.

The model begins with an inventory of the types of biomass fuels used for energy production. Factors for partitioning each type of biomass into alternative fates (open burning, landfilling, etc.) are then entered, and the amounts of biomass that would be subject to each category of alternative fate is determined. The model follows the carbon flows for each alternative fate over a one-hundred year time period, and the atmospheric concentrations of the carbon-based greenhouse gases, CO_2 and CH_4, are compared for the energy production alternative, and for the alternative fates for the biomass residues, should energy production not be performed. The greenhouse gas emissions of fossil fuel use that is avoided by biomass energy production are also determined. Fossil carbon greenhouse gases and biogenic carbon greenhouse gases are tracked in separate accounts. Figure xx shows graphically the logic flow of the model. Biomass resources under consideration are either used for energy production, or they meet some alternative fate, typically a conventional disposal option.

Table xx: Logic Flow in Greenhouse Gas Model

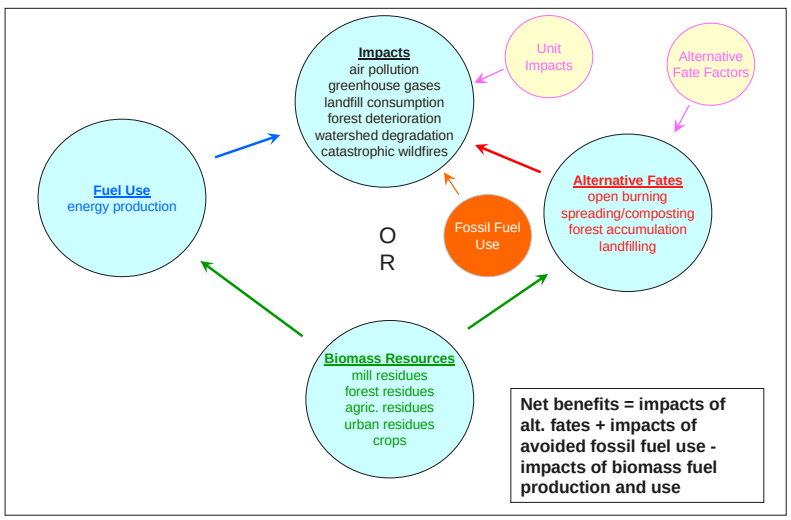
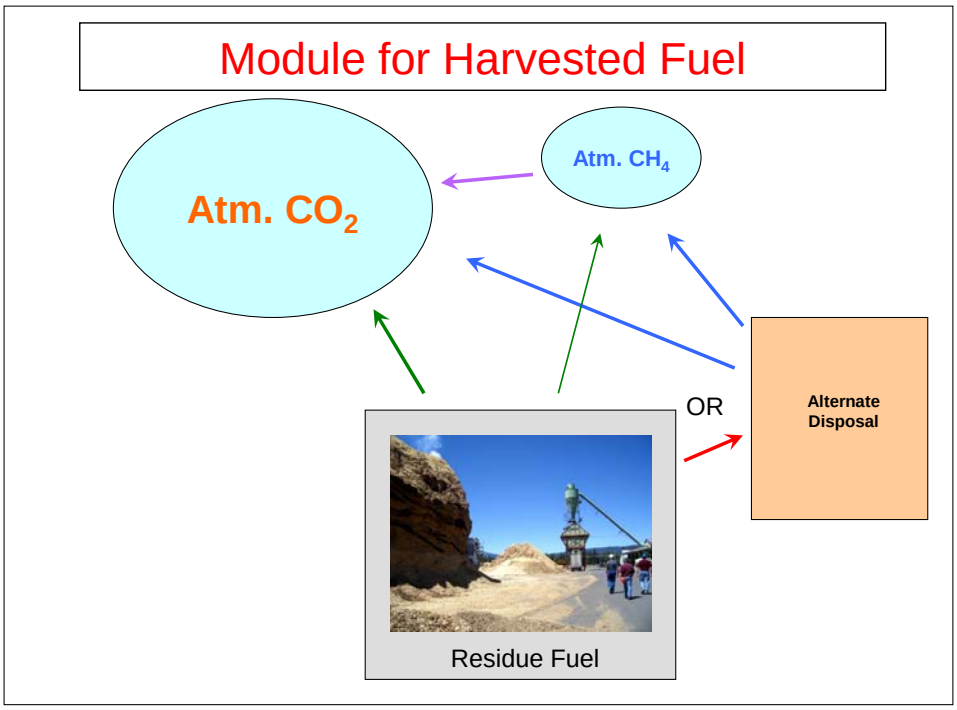


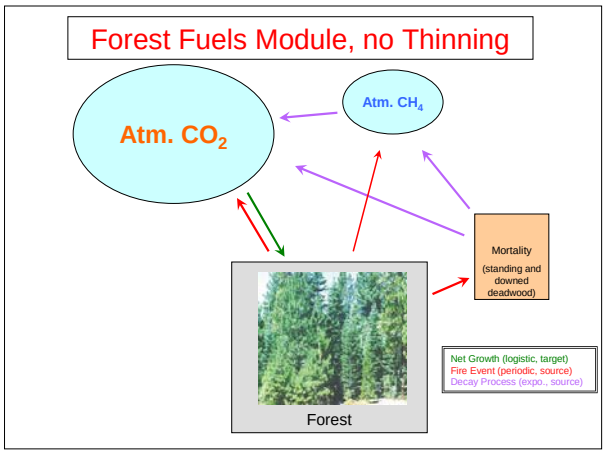
Figure xx shows the stock and flows in the Biomass Greenhouse Gas Model's harvested fuel module. This is the model's basic module, and is used for all of the alternative fates considered in the model with the exception of fuels left in the forest as overstocked material. The emissions of CO_2 and CH_4 from alternative disposal include both immediate and delayed emissions. Virtually all of the emissions from biomass energy production are immediate.

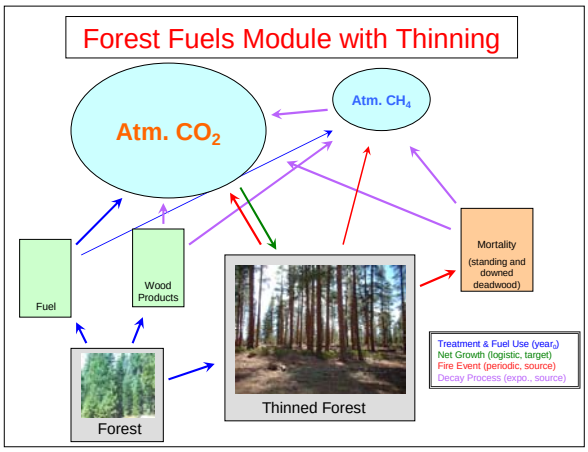
Figure xx: Harvested Fuel Module



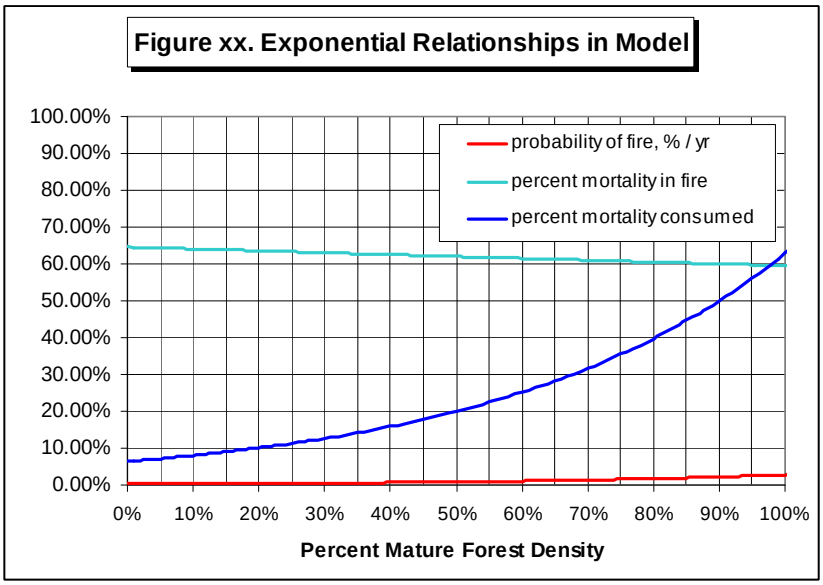
Analyzing the greenhouse gas fate of biomass that is left in the forest as overstocked material is more complicated than that of already harvested biomass, because living biomass sequesters CO_2 from the atmosphere, as well as being a source of carbon emissions during wildfires and insect or disease events.[4] Left in the forest, overstocked biomass initially is treated as having entered into a long-term storage reservoir, which is the overstocked forest itself. The overstocked forest has a higher probability of destructive wildfires than a thinned forest, and is on a part of the growth curve where net annual growth (bdt/ac) is lower than in a thinned forest. When a wildfire does occur, it consumes not only some of the overstocked material that would have been removed in a thinning, but also a portion of the growing stock that would have remained in the forest after a thinning. For modeling purposes, the greenhouse gas impact of leaving biomass in the forest as overstocked material is determined as the difference between the emissions of greenhouse gases from overstocked forests, and the emissions that occur from thinned forests. Biomass carbon in a thinned forest has a longer residence time than in the overstocked situation (lower annual probability of fire), thinned forests grow faster than overstocked forests in terms of net annual growth, and fires in thinned forests cause less extensive damage to the growing stock than fires in overstocked forests. Figure xx shows the model's forest-fuels modules.

[4] Fire is used in this Report as a proxy for a variety of vectors that hit overstocked and stressed forests harder than healthy forests, including insect infestations and disease outbreaks.

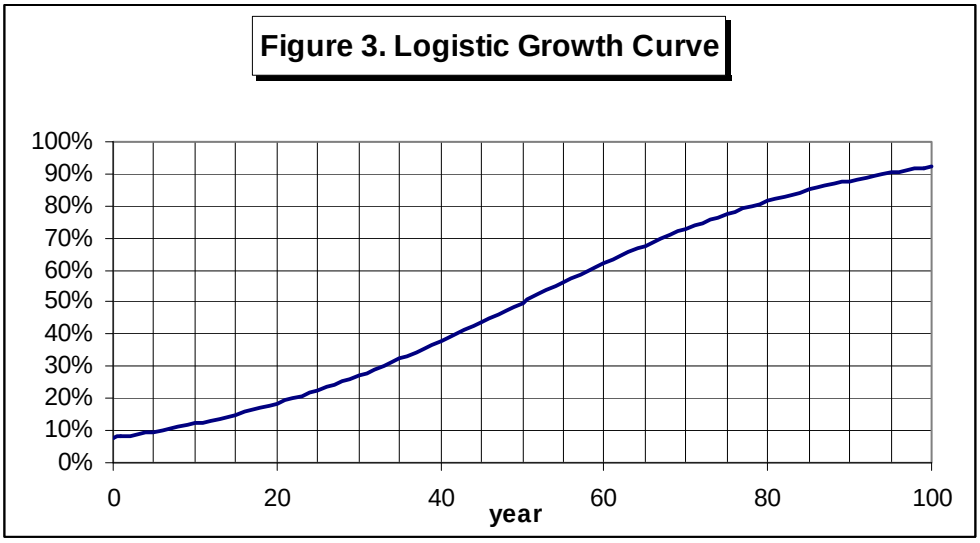




The model incorporates exponential decay mechanics for the loss of carbon from biomass stocks in the model, such as losses of carbon stored in forest biomass due to periodic events, like fires. The B2E project, of which this study is a part, developed a series of detailed, 40-year fire scenarios for the 2.7 million acre beta landscape in northern California that is representative of many regions in the state that have extensive needs for forest thinning operations. The relationships for fire probability, fire mortality, and percent of total mortality that is consumed, all as a function of forest density, are derived from the B2E project Jumbo data files. Figure xx shows the base-case exponential relationships that are used by the one-year greenhouse gas model.

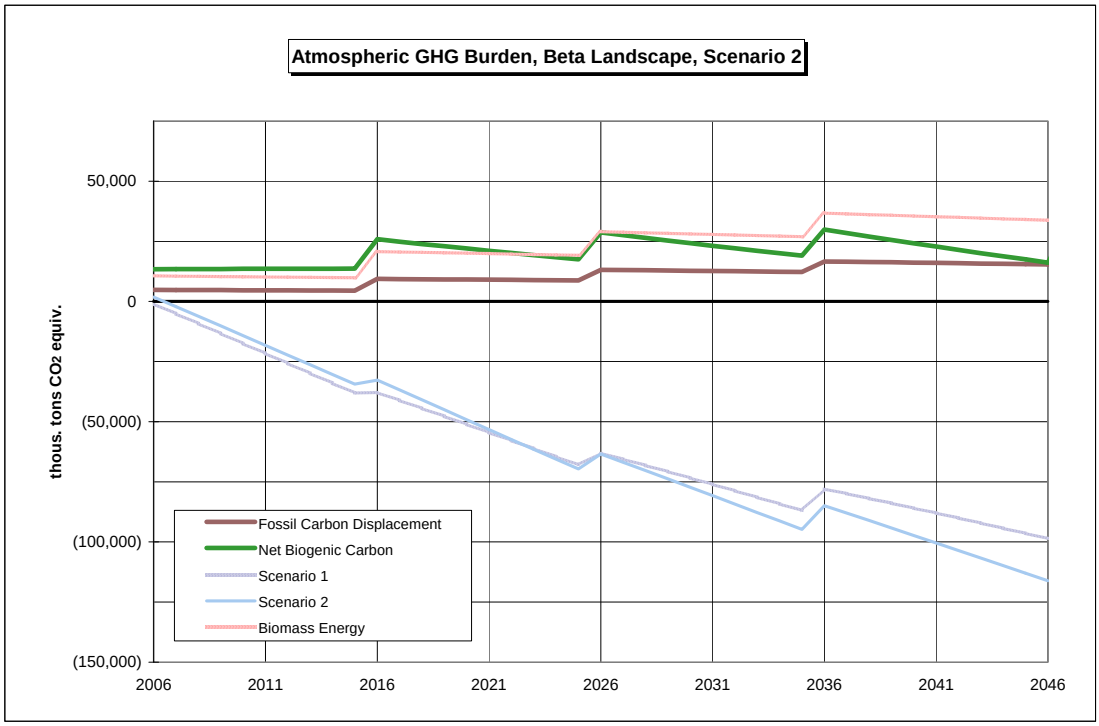


Net annual forest growth in the one-year greenhouse gas model is based on logistic growth mechanics, in which net growth is expressed as a function of standing forest density. Logistic growth is defined by two parameters, a rate parameter, the length of time for growth to proceed from a level of ten percent of maximum forest density (density of forest at zero net annual growth, or stasis) to ninety percent of maximum density, and a magnitude parameter (bdt per acre at stasis). As in the case of the fire data, the dynamics of the growth curve used in the model are derived from the B2E Jumbo data. Figure xx shows the base-case logistic growth curve that is used in the model.



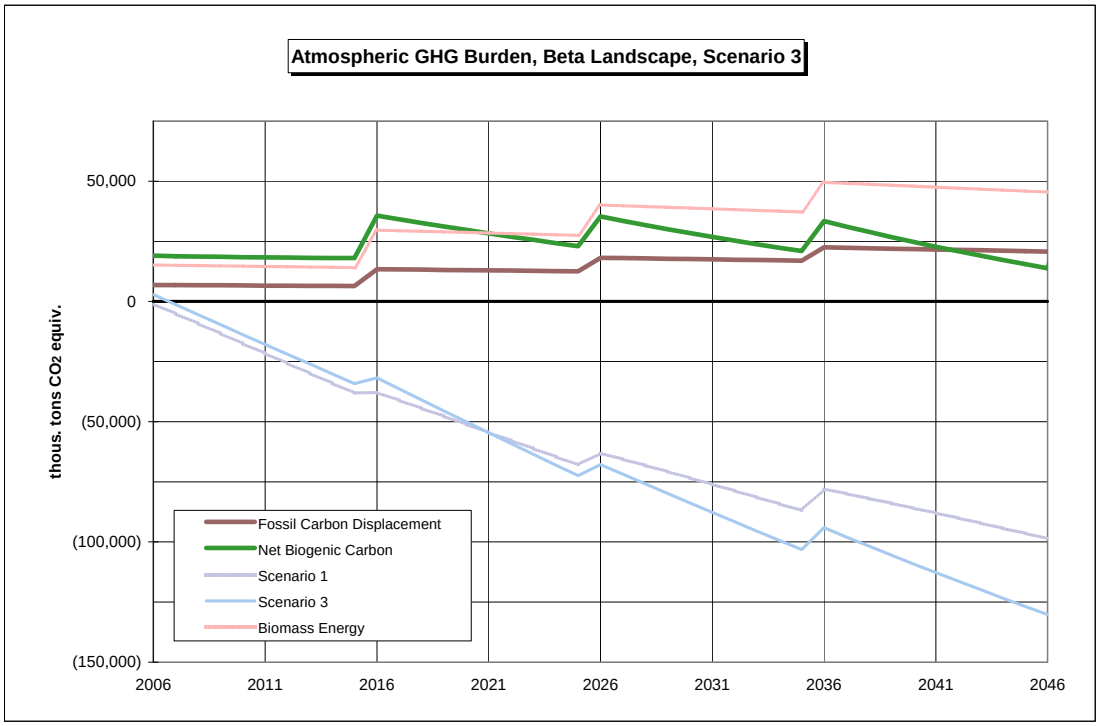
The Greenhouse Gas Implications of Forestry Treatments on the Beta Landscape

The landscape-level model provides insights about the net carbon flows associated with the beta landscape due to two different levels of forest treatment, vs. no treatment at all. In both treatment-based scenarios the immediate greenhouse gas consequence of treatment is to increase biogenic greenhouse gases associated with the landscape, compared with no treatment, due to the use of a portion of the treatment removals as power-plant fuel. Over the long term the treated acreage has a higher net growth rate than the same acreage left untreated, and is more fire resilient. However, at the end of each decade in the B2E study a new cycle of treatment is carried out, in effect boosting biogenic atmospheric greenhouse gas levels associated with the landscape through biomass energy production even as the previously treated acreage is acting as a net absorber of biogenic atmospheric carbon, compared with not having performed the earlier treatments. Figure xx shows the results of the landscape-wide greenhouse gas profiles for Scenario 2 of the B2E project.



In scenario 2, in which only private commercial lands receive treatment operations, the net biogenic atmospheric greenhouse gases associated with the landscape are higher in the treatment scenario (scenario 2) than in the no-treatment scenario (scenario 1) throughout the timeframe of the study. After approximately 40 years the elevated biogenic greenhouse gases fall to the level of the fossil carbon they displace, although it is important to keep in mind the fundamental difference between biogenic carbon, which is already part of the atmospheric carbon cycle, and fossil carbon, which is not part of the atmospheric carbon cycle unless it is removed commercially from geological storage for purposes of energy production.

In scenario 3, shown in Figure xx, in which treatments are performed on both private commercial lands and public forestlands, the net biogenic atmospheric greenhouse gases associated with the landscape are initially higher in the treatment scenario (scenario 3) than in the no-treatment scenario (scenario 1), but heads towards zero by the end of the study timeframe. In scenario 3, the enhanced biogenic greenhouse gases fall below the fossil greenhouse gases they displace after about thirty-five years of the forty-year simulation.



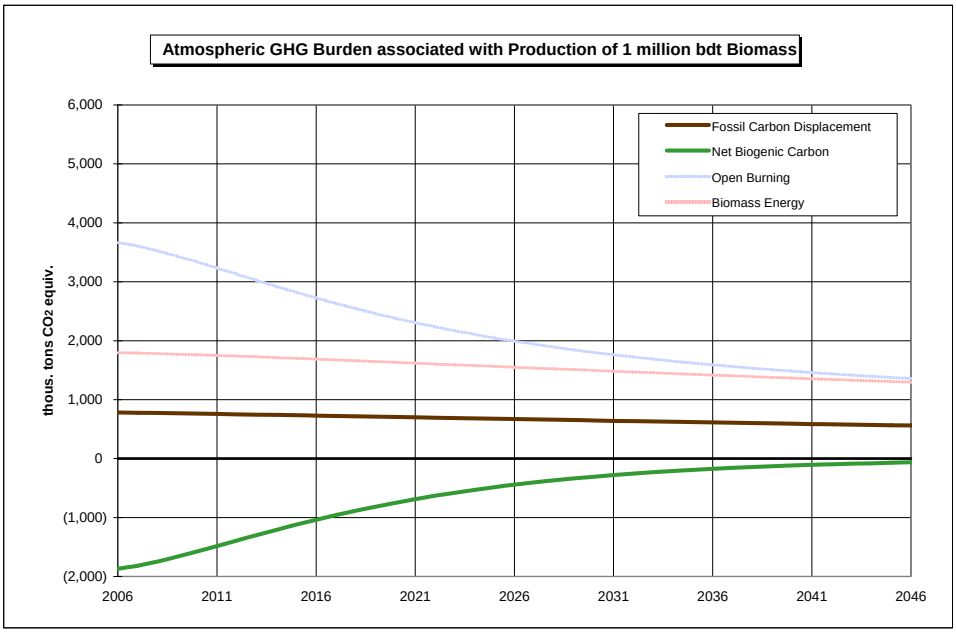
In all three scenarios considered in the B2E study, the beta landscape is a net absorber of atmospheric carbon throughout the study timeframe. The untreated landscape (scenario 1), shown in dark blue in the two figures above, is the same curve in each figure. Over the forty-year timeframe of the study the untreated landscape (scenario 1) removes approximately 100,000 tons of CO_2 from the atmosphere, while the scenario 2 landscape removes approximately 115,000 tons, and the scenario 3 landscape removes more than 125,000 tons. These rates of CO_2 removal translate into standing biomass increases across the beta landscape of almost 50,000 bdt (scenario 1), almost 60,000 bdt (scenario 2), and more than 70,000 bdt (scenario 3), for the respective scenarios.

For the heavier-treatment scenario, scenario 3, by the end of the fourth decade the net atmospheric level of biogenic greenhouse gases associated with the beta landscape, including the power plant emissions from the treatment fuels, is headed towards zero. Presumably in the long term continued periodic treatments across the landscape would result in net negative biogenic greenhouse gas levels (projecting the curve forward). In addition, after forty years the high-treatment scenario has resulted in atmospheric greenhouse gas levels that are lower by 8 million tons of fossil CO_2 equivalents as compared to the no-treatment scenario.

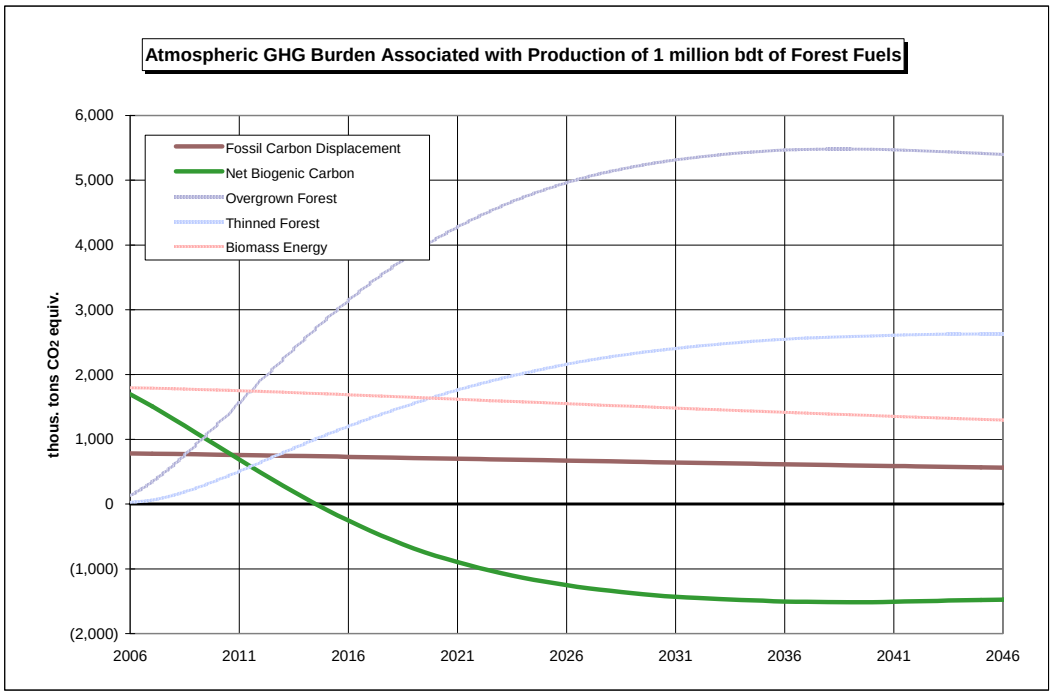
Burning Forest Biomass in the Forest vs. in the Power Plant

The question of whether it is better, from a greenhouse gas perspective, to burn forest biomass in the forest vs. in the power plant can be interpreted in two different ways. On the one hand a comparison can be made between the alternatives of thinning with on-site pile burning of the residues, vs. thinning with energy production from the residues. In this comparison, shown in Figure xx, initially the greenhouse gas levels associated with the biogenic carbon in the pile burn alternative (blue) are approximately twice as high as with the power plant alternative (red), an advantage that virtually disappears over the 40-year B2E study timeframe. The emissions are initially higher because incomplete combustion in the pile burn alternative, for example

smoldering around the edges of the burning piles, leads to emissions of significant amounts of methane as well as CO_2. Over time, the methane in the atmosphere converts to atmospheric CO_2.



On the other hand, as illustrated in Figure xx, a comparison can be made between the alternatives of not thinning (leaving the forest without treatment and letting the biomass eventually burn in a wildfire) vs. thinning with energy production from the residues. In this comparison, initially the greenhouse gas levels associated with no treatment are lower than the levels associated with treatment, because the immediate consequence of treatment and energy production is to transfer carbon from the forest to the atmosphere. Over time, however, the treated forest is more fire resilient than the untreated forest, and net annual growth rates are higher, the combined results of which are that for the first 8 – 9 years after thinning biogenic greenhouse gas levels are higher due to thinning than they would have been without thinning, although by five years after treatment they drop below the level of the fossil carbon emissions they displaced.



By fifteen years after the thinning net biogenic greenhouse gas levels associated with the treatment have been reduced by a greater amount than the fossil greenhouse gases they have displaced through biomass energy production from the residues. At this point, the total reduction in atmospheric greenhouse gases is approximately twice as great as the amount of fossil greenhouse gases associated with the no-treatment scenario. Projected out, the net biogenic greenhouse gas reduction associated with the treatment remains greater than 1 ton of CO_2 equivalents per bdt of treatment removal (1 mil ton per mil bdt in the figure) for more than one-hundred years.

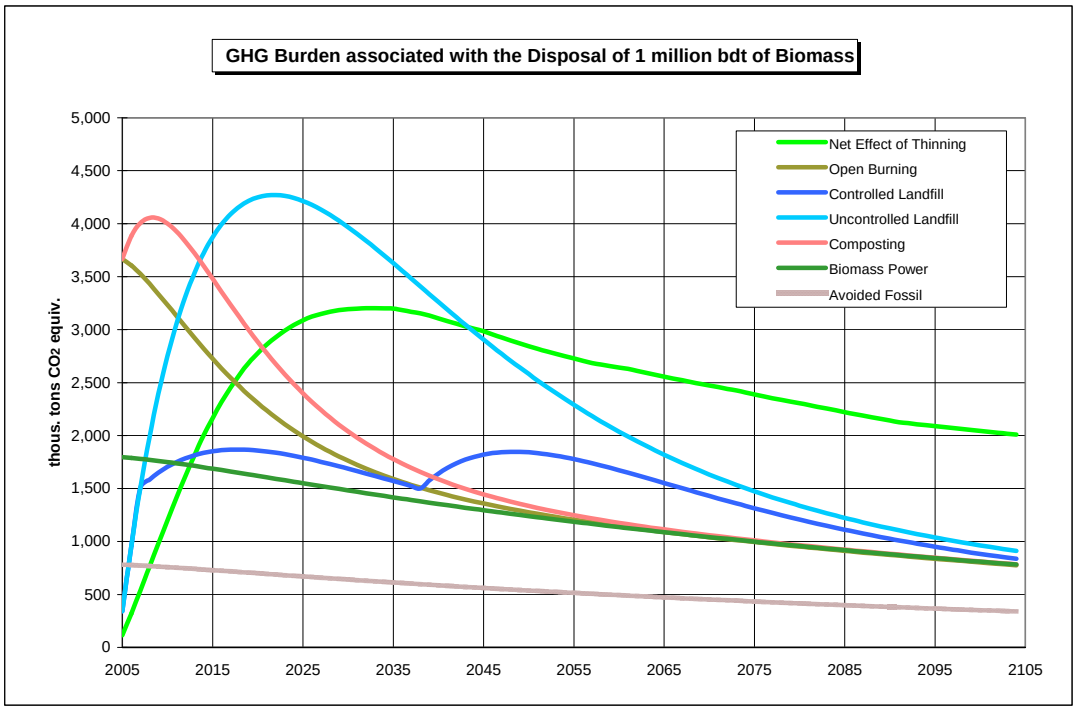
Designing Treatments to Maximize Sequestration

Both models suggest that more intensive treatments, both in terms of removals (bdt) per acre, and total acres treated, lead to greater greenhouse gas benefits in the long term. Of course maximizing the amount of the treatment removals that are used for product manufacturing rather than as fuel has a positive effect on associated greenhouse gas emissions. In view of recent research suggesting that global warming already underway is increasing the risks and severity of California wildfires,[5] a phenomenon that is not reflected in the B2E modeling, it is likely that the greenhouse gas advantages of forest treatment operations will increase in the future over what is shown in the B2E simulations.

Comparison to Other Forms of Biomass Fuels

[5] Westerling, Hidalgo, Cayan, and Swetnam, *Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity*, **Science**, volume 313, pages 940 – 943, August 18, 2006.

Figure XX compares the profile over time of the greenhouse gas burdens associated with biomass energy production from forest fuels, labeled “net effect of thinning” in the figure, with the profiles for other biomass fuels and their avoided fates, and avoided fossil fuel emissions, with all curves scaled to the use or disposal of one million bdt of biomass residues. As can be seen in the figure, the atmospheric greenhouse gas profile over time is very different for the energy production alternatives (biomass vs. fossil fuel), and for the alternative disposal pathways shown in the figure.



The curves for the biomass energy and fossil-fuel energy alternatives are based on the immediate release of virtually all of the fuel-bound carbon in the form of CO_2, followed by its gradual clearance from the atmosphere. The conversion of one million bdt of biomass leads to emissions of 1.75 million tons of biogenic CO_2, while avoiding emissions of 0.75 million tons of fossil fuel CO_2, based on the assumed California mix of avoided fossil fuel use due to biomass energy production (50 percent avoided coal, 50 percent avoided combined-cycle gas). Over the long term, all of the alternative disposal options for the biomass residues produce higher levels of biogenic greenhouse gas levels than use of the material for electricity production, none more so than forest fuels from forest treatment operations.

For biomass that is buried in landfills, the resulting greenhouse gas emissions occur over a period of decades, which is in stark contrast to the diversion of this material for use as a power-plant fuel, where it would be converted immediately and entirely to CO_2. However, in the landfill the slow decomposition process produces approximately equal amounts of CO_2 and CH_4, a much more potent greenhouse gas mixture than pure CO_2. Many landfills are required to collect and burn (flare or engine) their gases, although only a portion of the total landfill gases are collected, typically about 70 percent.

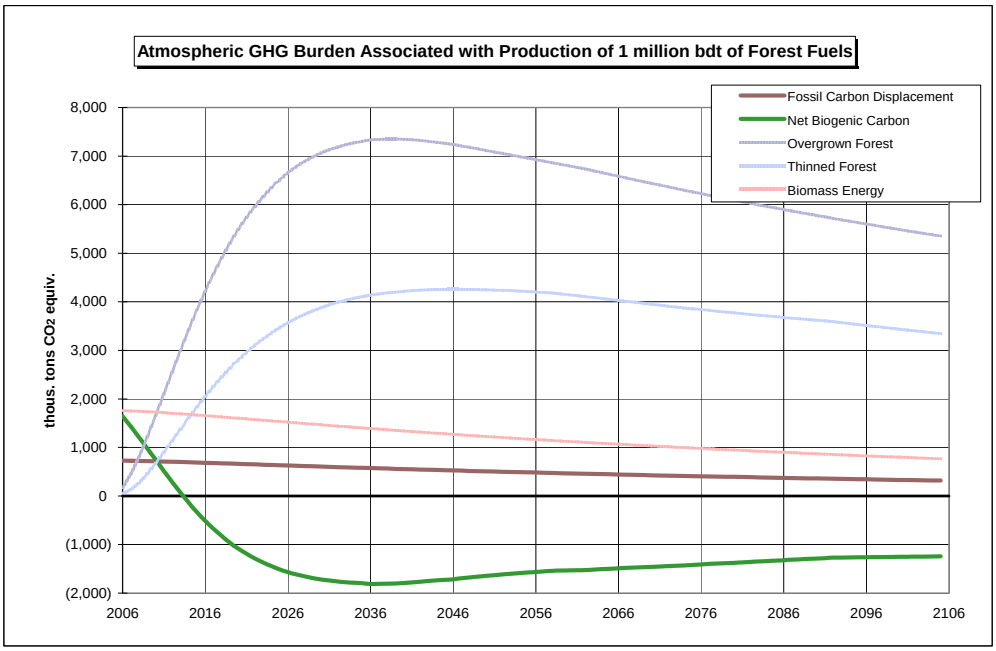
The delay in the onset of greenhouse gas benefits from using forest residues that would otherwise accumulate in the forest is even more pronounced than in the case of diverting waste

wood from landfill disposal. The greenhouse gas benefits associated with the use of forest thinnings,[6] which result from both enhanced net biomass growth in the treated forest, and reduced risk of destructive forest fires and insect and disease infestations, doesn't peak until approximately thirty years after the forest treatment is performed. Assuming that the treated forest continues to receive periodic treatments over time, a practice that is not reflected in the modeling, the use of this type of biomass for energy production has a large positive impact on biogenic greenhouse gas emissions much further into the future than is the case for the other categories of biomass fuels. This is mainly a result of the fact that thinning the forest protects the bulk of the remaining growing stock from fire and disease risks, and enhances net annual forest growth. In the absence of thinning an overgrown forest, when a wildfire or disease outbreak does occur it tends to consume and kill far more total biomass, and thus release far more carbon, than would have been removed by thinning and protecting the bulk of the forest biomass.

California's forests are highly diverse. Overgrown forests that are ideal candidates for thinning operations exist in all of the state's major forest regions, although the types and extent of treatments that are needed vary greatly. We have attempted to construct a base-case dataset for the one-year greenhouse gas model that is representative of the options available for the B2E beta landscape.

Figure xx shows the base-case greenhouse gas profiles for the use of one million bdt of forest treatment fuels in 2006, versus failing to perform the treatments that would produce this fuel. The production of one million bdt of forest fuel using base-case assumptions is associated with the treatment of 61,000 acres of overgrown forest. Treatment of these 61,000 acres of California forest in 2006, presumably scattered around the state, would lead to a reduction in biogenic greenhouse gas levels of nearly two million tons of CO_2 equivalents twenty five years later, as well as avoiding approximately 0.9 million tons of fossil CO_2 emissions in 2006, which would leave a residual level of fossil CO_2 in the atmosphere of approximately 0.75 million tons 25 years later.

[6] Net benefit is used in the sense of expected net benefits, with a probability distribution of wildfire assigned to the in-forest residue fuel that is left as overgrowth material in the forest.



Increasing the amount of material that is removed during treatment has the potential to increase the resulting net biogenic greenhouse gas benefit. The base-case dataset assumes that the treatments remove an average of 20 bdt of biomass per acre. The majority of treatments currently performed in the state are on private forestlands, which are generally is better condition than public forestland in the state. Assuming that the needier public lands in the state become more amenable to having treatment operations performed in the future, it is likely that the average amounts of removals (bdt per ac) will also increase. The base case assumes 20 bdt per acre are removed. If removals are increased to an average of 35 bdt per acre, the biogenic emissions benefits are increased by about fifty percent as compared with the base case benefit shown in the figure.

Treatment of Bioenergy in Greenhouse Gas Reduction Programs

Existing greenhouse gas reduction programs are geared toward reducing emissions of fossil carbon to the atmosphere, and properly so. Continuing to add new (fossil) carbon to the carbon that is already in circulation between the atmosphere and the biosphere is the fundamental driver of human-caused global climate change. Although the California's AB 32 system for reducing greenhouse gas emissions is still being developed, several fundamental principles appear to have been established with respect to the treatment of biogenic emissions within the grand scheme of greenhouse gas controls.

The first principle is that in California, biogenic carbon will be reported and tracked as a separate category of greenhouse gases than fossil carbon gases. Fossil carbon emissions will need to be matched with emissions allowances, which will be denominated in units of CO_2 equivalents. Biogenic carbon emissions will not have to be retired against emissions allowances.

The second principle is that greenhouse gas offset credits can be created for net-negative biogenic carbon emissions, as have been demonstrated above for virtually all bioenergy

production pathways. Precisely how these kinds of offsets may be used in the future is still to be determined.

Conclusion

The carbon domain of the B2E project demonstrates that the beta landscape is a better absorber of atmospheric greenhouse gases if carefully planned forest treatment operations are conducted, and that the greater the proportion of the landscape that receives treatment, the greater the benefits in term of overall carbon sequestration. However, it is important to note that the net benefits of enhanced carbon sequestration across the landscape due to forest treatment have to be balanced against the release of the biogenic carbon at the biomass power plants. With an ongoing program of forest treatment across the landscape the net effect on biogenic greenhouse gas levels associated with the landscape is an increase for the first several decades, followed eventually by a long-term decrease in atmospheric greenhouse gases associated with ongoing, sustainable management of the landscape, compared with no treatment of the landscape. This is in addition to the avoidance of fossil carbon emissions due to the production of energy from the unmerchantable forest biomass removals.

Looked at from the perspective of the impacts on the actual land that receives treatment operations, the treated acreage itself becomes neutral with respect to associated biogenic greenhouse gas levels in approximately eight years, and positive thereafter, in comparison to no treatment on the same acreage. Again, this is in addition to the avoidance of fossil carbon emissions due to use of the removal fuels for power production.