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Industrial greenhouse gas emissions: Does CO_2 from combustion of biomass residue for energy really matter?

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ABSTRACT: Woody biomass fuel combustion for industrial heating and processing is increasing in northwestern North Carolina. Sources are mainly biomass waste and residues, including sawdust and chips from the furniture and wood processing industries, greenwood chips from construction sites and right-of-way clearing operations, and wood removed from landfill streams. This paper evaluates 5 hypothetical scenarios for use and disposal of biomass waste to demonstrate effects of industrial combustion of this biofuel on the greenhouse gas emissions bundle. Conclusions are that use of biomass residue as a fuel can be a positive strategy for mitigating greenhouse gas emissions.

KEY WORDS: Biomass combustion · Industrial biofuel · Industrial fuel switching · Greenhouse gas

1. INTRODUCTION

Combustion of biomass for energy is gaining popularity as an industrial substitute for coal and electricity to provide heat and steam for space heating and materials processing (EIA [US Energy Information Administration] 1994). Inexpensive and abundant regional biomass fuel is increasingly being used as a feed stock in industrial boilers, however, the relative impacts of this practice upon greenhouse gas (GHG) emissions has received only modest attention.

The Intergovernmental Panel on Climate Change (IPCC 1995) and United States Environmental Protection Agency (USEPA 1995) guidelines do not count industrial use of biomass fuel as part of the GHG equation because carbon in biomass is part of a closed carbon cycle with zero net emissions. Research seeking a standard methodology for GHG balances of bioenergy systems in comparison with fossil energy systems concludes that '...increased reliance on bioenergy systems, in place of fossil-fuel-based energy systems, could result in net emission savings of greenhouse gases to the atmosphere' (Schlamadinger et al. 1997).

In their assessment of energy comparisons, Schlamadinger et al. (1997) recognized that bioenergy: (1) may be lower in efficiency than fossil fuels, (2) may require additional fossil fuel energy inputs into transportation and conversion, (3) may be produced as a by-product as well as a main product, (4) may not always displace the use of fossil fuels to the extent expected because of 'leakage', and (5) may produce not only CO_2 during processing and use, but CH_4 and N_2O as well.

Other significant research also recognizing the significance of bioenergy's association with GHGs and its substitution for fossil fuel energy includes Eriksson & Hallsby (1992), Gustavsson & Johansson (1994), Gustavsson et al. (1995), Marland & Schlamadinger (1995),

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Borjesson (1996), Schlamadinger & Marland (1996), Marland & Schlamadinger (1997) and others. These researchers have analyzed biomass in considerable detail, but with the exception of Schlamadinger et al. (1997) and Marland & Schlamadinger (1997) few compare GHG emissions from alternative uses of biomass residue, these being by-products of other industrial and commercial processes. Once biomass residue becomes available, choices for its use and disposal become limited, and emissions from these choices may vary considerably.

This study analyzes several alternatives for biomass residue use and disposal in order to compare their GHG emissions. Alternative energy sources compose a major part of most strategies to eliminate waste, to efficiently utilize all components of industrial materials, and to conserve fossil fuels (Johansson & Sipila 1991, Frosch 1992, Jelinski et al. 1992, Patel & Kumar 1992).

2. BACKGROUND

Biomass consists of all organic materials that can be effectively burned, including wood and wood products (woodfuel), crop residues and by-products, and animal waste and by-products. As an industrial fuel, biomass has several advantages over fossil fuels, not the least of which is the fact that it is a renewable resource. While charcoal served as a fuel for early metallurgy, most of the world's growth in fuel use since the Industrial Revolution has been associated with fossil fuels. Recently, however, biomass has attracted the attention of industry again because it is locally or regionally available, diverse in character, and relatively inexpensive, and its combustion can be 'environmentally benign' (EIA 1994).

In 1992, use of biomass as a fuel represented 3% of the total US energy consumption. Of that biomass used, 81% was wood. The EIA (1994) predicted that by year 2010 biomass might represent 5% of the kilojoules (kJ) generated in the United States (EIA 1993, 1994). Energy from wood alone should rise from 2373 trillion kJ in 1992 to 4077 trillion kJ in 2010, for an increase of 72% in 18 yr (EIA 1994).

In the United States, the South was the largest biomass-for-energy use region for 1992 with 49 % of the total consumption. The West, at 21%, follows, with the Northeast and Midwest consuming 15% each of the country's total. Seventy-one percent of the woodfuel use in the country occurred in the industrial sector. Although the paper and allied industries consume a large portion of the industrial woodfuel, mostly as a black liquor, a by-product of pulp and paper processing, other solid woodfuels are increasingly being used to fire industrial boilers (EIA 1994).

With the exception of black liquor and perhaps very limited crop residues, industrial-use biomass in the US South consists mainly of sawdust and chipped or ground wood, hereafter called biomass residue. Sources include residue from wood products industries (chips and sawdust), wood packaging material waste (e.g. pallets, boxes and packing), ground or chipped construction and demolition materials, and chipped greenwood from the clearing and landscaping of construction sites and right-of-ways. Most of these products, formerly considered waste by the producers, are now recognized as a valuable alternative industrial fuel, selling at $10 or 11 per tonne in 1997 (J. M. Kennedy pers. comm.). To date there is no evidence in the study area of the practice of chipping standing timber for sale as industrial biofuel.

Dry biomass residue produces about 17 to 20 million kJ t^{-1} when burned, while wet (or green) residue contains as little as 10 million kJ t^{-1} (Harris et al. 1986, USEPA 1995, R. A. Harris pers. comm.). For example, kiln-dried wood produces high energy output per unit, while greenwood tree trimmings produce less due to higher moisture content. For each percent of moisture contained in wood, energy content declines by approximately 1% (Kennedy pers. comm.).

Use of biomass residue as a fuel by manufacturing industries varies in many ways. A small North Carolina furniture plant may combust sawdust and scrap in unsophisticated boilers or even wood stoves to supply energy for space heating or drying green wood in a kiln. In a large plant relying upon biomass residue as a major fuel source, however, computer-controlled boilers may efficiently combust a wide range of biomass under strictly controlled conditions. These efficient industrial boilers heat the residue until it vaporizes, burn the resulting volatile gases, then use scrubbers and electrostatic precipitators to collect particulate matter. Unlike open biomass burning, industrial boilers are monitored by air quality regulatory agencies and produce little particulate matter or visible smoke.

All combustion of biomass produces CO_2. Depending upon the completeness of combustion and other factors, 1 t of biomass produces an average of 1.5 t of CO_2. There are, however, other methods of disposal for biomass residue, including landfilling or using it as a landscaping material. In each of these cases, the ensuing decay process also generates GHGs.

Questions posed in this study are: (1) whether combusting biomass as an industrial fuel is an environmentally sound practice; (2) how the CO_2 equivalent emissions from biomass combustion compare with those of alternative disposal and use scenarios; and (3) whether industrial biomass fuel use should be considered a GHG mitigation strategy.

3. STUDY AREA

3.1. Landscapes and land use

The initial data used to study a cross-section of biomass-burning industries came from the Blue Ridge-Piedmont study area in the NASA-funded study ‘Global Change in Local Places’ (no. NAGW-4932).

This study area is located in northwestern North Carolina and consists of 12 counties containing a total of 5037 square miles (13 023 sq. km), with physical landscapes ranging from mountains to rolling hills (Fig. 1). Most of the 1990 population of 742 484 was scattered in small towns and cities and across a rural landscape. The only large city is Winston-Salem, located in Forsyth County on the eastern edge of the study area.

Research on the ‘Global Change in Local Places’ grant provided us an opportunity to analyze the use of industrial biomass fuel within a limited study area. Of considerable interest were the magnitude of this practice, the range of technology being used, and the sources of fuel.

In total, 59 % of the study area is forested and about one-third is considered managed forest. Consequently, wood products industries are a major part of the economy. The study area contained 1 billion m^3 of merchantable live timber 12.7 cm diameter at breast height (Brown 1993). Assuming North Carolina’s harvest rate for the study area to be about 0.5 % of the total growing stock, approximately 5.3 million m^3 of timber is harvested annually (Brown 1993). Waste from harvest and from manufacturing processes may amount to at least one-half of the wood weight, or 2.7 million m^3 of biomass residue within the study area, much of which is typically left on the harvest site as limbs and stumps. The study area is also home to nearly half of North Carolina’s furniture industry, generating considerable dried wood waste in the form of end-pieces, shavings and sawdust.

Population growth and associated industrial and commercial expansion have been rapid in the study area, with population increases averaging 1.4 % yr^{-1} between 1970 and 1990. The processes of clearing residential lots and industrial/commercial sites generate large amounts of chipped greenwood biomass useable in industrial boilers.

3.2. Uses of industrial biomass residues

The authors sought interviews with several of the leading biomass users within the study area, finding 2 plant engineers (1997-98) who were very knowledgeable about biomass residue combustion and emissions: James M. Kennedy of Corn Products, Inc., Winston-Salem, North Carolina, and Thomas J. Gibson Jr of Thomasville Furniture Industries, Inc., Lenoir, North Carolina. Additionally, we talked to Bob Harris (phone interview, July 24, 1997) of The Strom Thurmond Institute, Clemson University, Greenville, South Carolina, well known for his work in developing industrial biomass boiler projects.

Within the study area, there are 3 main sources of wood that become biomass residue: (1) wood removed from the landfill stream; (2) greenwood chips from clearing land and maintaining right-of-ways; and (3) sawdust, scrap, and bark from wood products factories.

Wood removed from the landfill stream includes a wide range of wood materials brought in by residential, industrial, and commercial landfill customers, who pay a tipping fee of about \$11 t^{-1} to unload in a special part of the landfill. This wood includes waste from construction projects, used or broken industrial pallets and crates, household furniture, landscaping timbers, and tree trimmings. Specialized equipment in landfill operations is then used to grind the wood into ragged pieces that are easier to handle and burn more readily than whole pieces. Landfill operators sell this biomass residue to industries for combustion, generally receiving about \$10 t^{-1} in 1997. Sometimes, however, the material includes too much soil and metallic debris, which users reject because it can damage their boilers and associated equipment (Kennedy pers. comm.).

There has been an increase in the use of greenwood chips by industries with modern boilers of 600 hp or more (Harris pers. comm.). This biomass residue comes

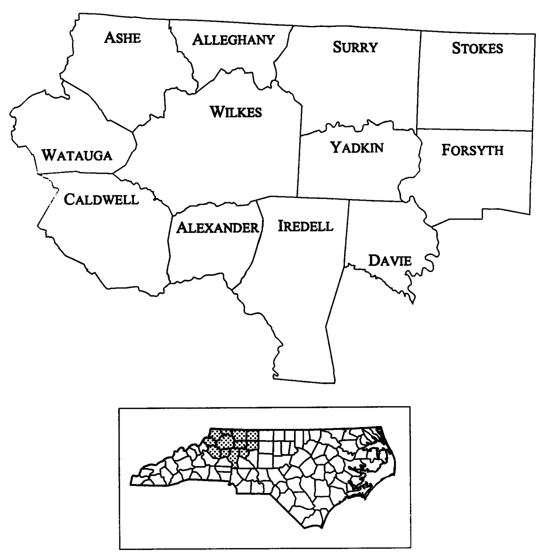

Fig. 1. Global Change in Local Places (GCLP) study area, northwest North Carolina

almost exclusively from clearing green wood from construction sites and right-of-ways. Crews may indiscriminately strip all the wood from a construction or right-of-way site and chip it into small pieces. Generally, industrial biomass residue users contract with construction companies and utilities to buy these chips by weight. The value of the chips varies somewhat, depending upon the quality, dependability, and volume of the source, the cutting and chipping process, and the distance the product is hauled. Excepted alternative disposals of such material in the study area have been to burn it on-site or sell it as landscaping mulch.

Finally, sawdust is used by several industries. For the most part, this residue is used by the same wood products industries that generate it. Many furniture plants rely upon in-house sawdust production to fuel their boilers, dry their wood (kilns), and heat their work spaces (Gibson pers. comm.). As a general rule, these plants consume all surplus sawdust during the winter, but may sell some of the surplus to larger biomass users during the summer. Sawdust is generally a high quality biomass residue having a high energy content. Consequently, it is in greater demand as an industrial fuel than other biomass residues because it contains no dirt and little moisture (Kennedy pers. comm.).

Within the study area, the availability of useable biomass residue continues to increase, largely because of an increasing awareness of the market. As a general rule, biomass residue could be trucked within a radius of 80 km to a user in 1997 and remain profitable for the supplier (Kennedy pers. comm.). However, as demand for the fuel increases, haul distances may also increase.

3.3. Industrial combustion of biomass

Data on industries using biomass residues as a fuel within the Blue Ridge-Piedmont study area came from the Aerometric Information Retrieval System (AIRS Database) (1996). IPCC and USEPA guidelines disregard CO_2 from combusting biomass in emissions totals, but it is useful here to include it for comparison purposes.

If emissions from biomass combustion are included in the GHG emissions bundle for the state of North Carolina in 1990, GHG emissions from all sources totaled 137.6 million t of CO_2 equivalent. Fossil fuel consumption was the largest source of GHG, but biomass combustion accounted for 11.5 % of the total. Industry, commerce and institutions accounted for 89 % of the biomass-burning emissions (AIRS Database 1996).

Within the Blue Ridge-Piedmont study area, GHG output (CO_2 equivalent) was 20.6 million t in 1990, 20.1 % of which came from biomass combustion. Manufacturing accounted for 96 % of the biomass combustion emissions, while residential biomass combustion generated only 4 % (AIRS Database 1996). Industrial

Table 1. Biomass fuel use point sites in northwestern North Carolina (1990) in tons. Source: AIRS Database (1996)

County	Point site	CH_4	CO_2	N_2O	CO_2 equiv. total
Forsyth	(1) Corn Products	6	2 546 795	7	2 548 870
Wilkes	(2) Abtco Inc.	9	798 213	0	798 419
Caldwell	(3) Kincaid Furniture Plants (1, 4, 6, 8)	2	129 518	0	129 558
Caldwell	(4) Broyhill Furniture Corp. (6 plants)	1	89 003	0	89 130
Caldwell	(5) Bernhardt Furniture Plant (1, 2, 3, 5, 7)	1	73 574	0	73 637
Wilkes	(6) American Drew Plant (11, 12, 13, 14)	1	67 443	11	70 523
Caldwell	(7) Singer Furniture Plant (7)	1	51 655	0	51 698
Caldwell	(8) Thomasville Furniture	0	35 934	0	35 976
Davie	(9) Thomson Crown Wood Products Company	0	25 086	0	25 107
Caldwell	(10) Nu Woods	0	24 704	0	24 731
Forsyth	(11) Collingwood Furniture	0	17 967	0	17 967
Ashe	(12) Thomasville Furniture	0	16 260	0	16 264
Forsyth	(13) Brady Furniture	0	13 475	0	13 475
Alexander	(14) Hickory White-Chaircraft	0	8 983	0	8 986
Iredell	(15) Thomasville Furniture	0	8 983	0	8 986
Iredell	(16) Godfrey Lumber Company	0	8 983	0	8 986
Davie	(17) Lexington Furniture Plant (11)	0	8 310	0	8 312
Caldwell	(18) Hammary Plant (14)	0	7 007	0	7 009
Alexander	(19) Bassett Upholstery Plant (9)	0	6 738	0	6 739
Iredell	(20) Bassett Furniture	0	6 738	0	6 739
Iredell	(21) Bernhardt Plant Furniture (4)	0	5 390	0	5 390
Iredell	(22) Dixie Seating Company	0	2 695	0	2 695
Total		22	3 953 453	19	3 959 196

boilers that can use biomass appear to be expanding in both numbers and size within the study area (Harris pers. comm.).

The top 22 biomass-burning emitters of CO_2 within the study area in 1990 included 17 furniture industries, 3 wood and wood products plants (particle board and lumber), a textile plant, and a food processor (Table 1, Figs. 2 & 3). In total, these 22 companies emitted 4.0 million t of CO_2 equivalent. As a comparison, this total equals nearly 60% of the emissions by Duke Power's only coal-fired thermoelectric generating plant in the study area, which emitted 6.7 million t (AIRS Database 1996).

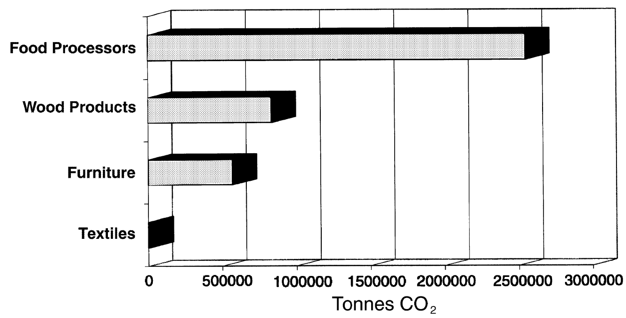

Fig. 2. Major biomass burning emitters in northwestern North Carolina by sector

4. METHODOLOGY

The large amounts and upward trend of GHG produced by industrial biomass combustion within the study area convinced us of the need to compare the emissions of several biomass disposal alternatives. This allowed us to analyze relative atmospheric impacts of industrial biomass combustion.

We determined that there were 4 principal alternatives for dealing with woody biomass residue: combusting it in industrial boilers, landfilling or long-term storage on-site, using it as a landscaping material (mulch), and using it in manufactured material.

Using these 4 alternatives, we developed 5 comparative scenarios for biomass residues and analyzed the GHG emissions from each. These included: (1) combustion in an industrial boiler; (2) landfilling it without flaring methane (CH_4); (3) landfilling it and flaring off or using CH_4 as a fuel; (4) using it as landscaping material; and (5) using it in production of a manufactured product. In order to standardize the calculations for

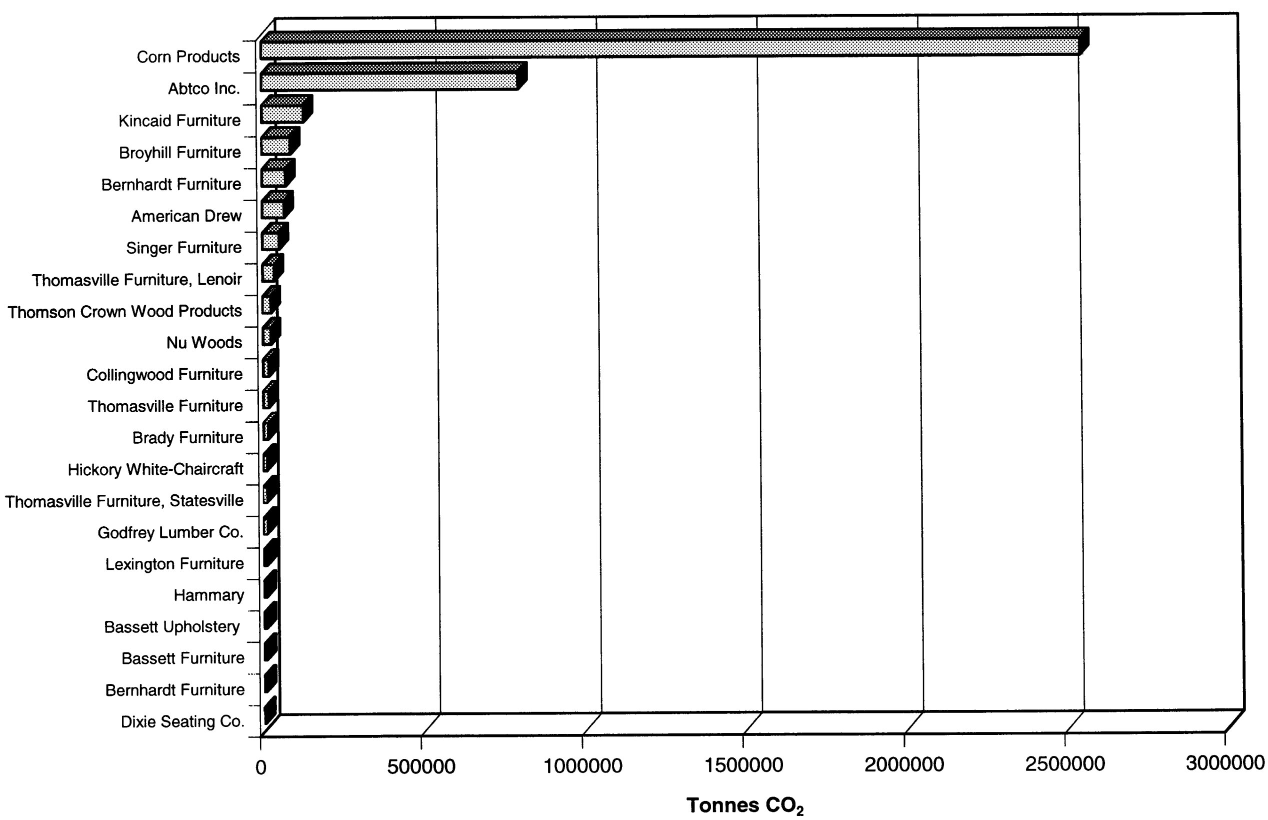

Fig. 3. Major biomass-burning emitters in northwestern North Carolina

each scenario, all emissions are calculated as CO_2 equivalents (USEPA 1995).

With the exception of Scenario 1, all other scenarios assume that the energy of 0.7 t of coal must be substituted for each tonne of biomass used for some purpose other than industrial fuel.[1] This was based on heats of combustion of dry pine compared to average heats of combustion of typical Virginia coal (Hodgeman 1956). Although other fossil fuel energy sources, including fuel oil and natural gas, are also possible substitutes for biomass fuels, coal is used here because of similarities in boiler design and because this is a common comparison in other biomass fuel research (Marland & Marland 1992, Marland & Schlamadinger 1997).

In the first scenario, the total CO_2 emissions stand independently. In the other 4 scenarios, where biomass residue is allowed to decay or is stored, the equivalent amount of coal for fuel is calculated to replace energy of the biomass. Therefore, the CO_2 equivalent for each is the total from the decay or storage of biomass and from the burning of coal as a replacement.

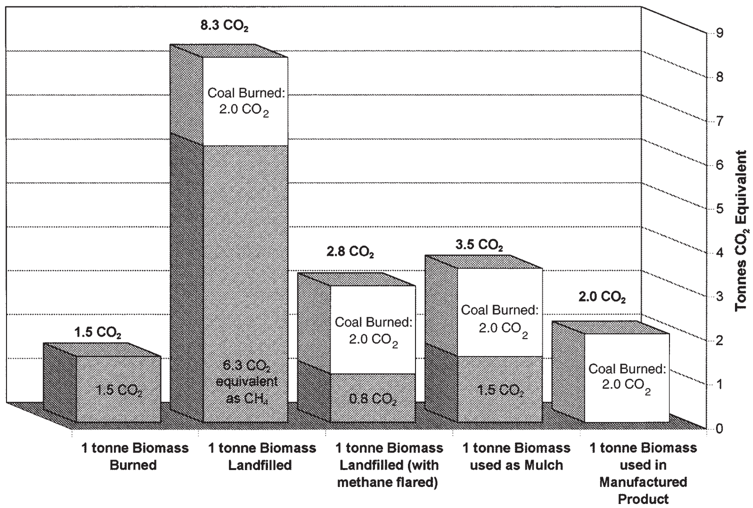

Fig. 4. CO_2 and CO_2 equivalents for alternative biomass scenarios (all totals are estimated averages by the authors)

5. COMPARISONS OF BIOMASS BURNING TO ALTERNATIVES

Fig. 4 compares the 5 scenarios, beginning with the combustion of 1 t of biomass residue being burned in an industrial boiler under ideal conditions.

In the first scenario, 1 t of combusted biomass generates about 1.5 t of CO_2, comparing favorably with CO_2 released during natural biomass decay. In other words, if trees were left to die and decay *in situ* in the forest, the resulting CO_2 emission would be about 1.5 t per tonne of wood, although the sequestered carbon would be released more slowly than if it were burned. As a general rule, the production of thermo NO_x during biomass combustion is not an issue because most industrial boilers operate at temperatures below 1100°C.

In the second scenario, the biomass is placed in a landfill without flaring CH_4. Not only must valuable landfill space be used to store the biomass, but under landfill conditions it emits CH_4, a gas with more than 21 times the radiative forcing of CO_2 (IPCC 1995, USEPA 1995, Houghton et al. 1996, Wiley Barbour, USEPA, pers. comm. 1997). Cellulose, the principal component of biomass, contains 44% carbon. Under the anaerobic conditions found in landfills, about half of the carbon can be converted to CH_4 over the biomass decay cycle. Under controlled laboratory experiments,'...landfill gas generated from the degradation of cellulose, one principal metabolizable component of forest products, yielded 51% methane and 49% carbon dioxide' (O'Leary & Walsh 1991, as cited in Micales & Skog 1997).

Assuming 1 t of landfilled biomass produces 0.3 t of CH_4 and that CH_4 is 21 times more effective as a GHG than CO_2, the landfill-produced CO_2 equivalent from Scenario 2 is approximately 6.3 t. Coal will still be necessary to supply fuel needs, bringing the total CO_2 equivalent to 8.3 t. (The total does not include additional emissions associated with mining, processing and transportation of the coal.) This scenario generates the highest CO_2 equivalent (Table 2) of any of the scenarios.

The third scenario involves combusting the CH_4 by either flaring it off or capturing it as an energy source for industrial processing or space heating. If the methane is simply flared off, the maximum CO_2 ultimately produced is 2.8 t, including 0.8 t from combusting CH_4 and 2.0 t from replacement coal. If, on the other hand, the CH_4 is utilized as fuel (no replacement coal is necessary), total CO_2 is only 0.8 t, less than the simple biomass decay scenario.

The majority of the CH_4 from a landfill would potentially be produced from woody biomass during the first

[1]Although Marland & Marland (1992) assumed 0.6 units of coal to substitute for 1.0 units of 'harvested wood', the authors assumed 0.7 units of coal to substitute for 1.0 units of woody biomass residue used by industries in the Blue Ridge-Piedmont study area. This slightly higher coefficient accounts for some of the wood residue being kiln-dried sawdust and wood pieces with higher kJ per unit than harvested wood

Table 2. CO_2 equivalent for burning biomass and alternatives (all totals are estimated averages by the authors), na: not applicable

Source	Amount (t)	Process	kJ ($\times10^6$)	Gas (t)	CO_2 equiv. (t)
Coal	0.7	Burned	17	2.0 CO_2	2.0
Biomass	1	Burned	17	1.5 CO_2	1.5
Biomass	1	Decayed	na	1.5 CO_2	1.5
Biomass	1	Landfilled	na	0.3 CH_4	6.3
Biomass	1	Landfilled (methane flared)	14.4	0.8 CO_2	0.8

20 to 40 yr, but could continue asymptotically thereafter depending to a large degree on the amount of water available in the landfill (Rees 1980, Halvadakis et al. 1988, Augenstein 1992, Suflita et al. 1992, Bogner & Spokas 1993, Micales & Skog 1997). Thus, as much as 75% of the carbon in biomass residue may be permanently sequestered in landfills (Bogner & Spokas 1993, Doorn & Barlaz 1995, Micales & Skog 1997).

In the fourth scenario, biomass is used as landscaping material spread thinly around scrubs and flowers. This generates CO_2 at about the same rate as normal decay, or approximately 1.5 t per tonne of biomass. Because the biomass residue is not piled in deep layers, little or no CH_4 is generated. Coal will still be necessary, bringing the total to 3.5 t.

In the fifth scenario, biomass residue is used to produce a manufactured material, such as particleboard, which would prolong the sequestration of carbon. Sequestration of carbon in manufactured products is certainly useful as a GHG mitigation strategy, although the actual value varies. For example, when biomass is used as a packing material, sequestration tends to be for short periods of time; but a more durable product, such as particleboard door, may sequester carbon for 30 or more years. Ultimately, in either case, CO_2 should be released at levels similar to normal decay unless the material is landfilled or combusted. Assuming the biomass is used in a manufactured good, coal will still be burned, bringing the total CO_2 emitted to 2.0 t.

Finally, rough cost and energy comparisons of coal and biomass provide an interesting backdrop to the scenarios above (Table 3). Per estimates by local North Carolina coal companies in the winter of 1998, a tonne of pulverized bituminous coal, a common boiler feed, delivered without cost from West Virginia cost $31, and contained about 27 million kJ. Assuming a medium grade of woody biomass residue at $10 ton and 15 to 16 million kJ (delivered without cost from source), the cost advantage of biomass as a fuel is apparent. At these 1998 rates, 1 kJ generated from coal costs $1.15, while 1 kJ from biomass cost $0.66, a cost savings of 42% of biomass over coal.

Table 3. Cost comparisons of fuel alternatives (all totals are estimated averages by the authors)

Fuel	Cost ($ t^{-1})	kJ ($\times10^{-6}$)
Stoker coal	36	28
Pulverized coal	31	27
Biomass (dried)	13	16–18
Biomass (moderate)	10	15–16
Biomass (wet)	9	9

6. CONCLUSIONS

GHG emissions are a major concern in global climate change, leading society to seek mitigation options for outputs of carbon dioxide and methane. To the question, ‘Does CO_2 from combusting biomass residues really matter?’, the answer is ‘Yes, but in a positive way.’ Although combusting biomass in industrial boilers is an increasing source of CO_2 emissions, it will, in fact, actually serve to reduce total long-term CO_2 emissions by serving as a substitute for fossil fuels.

Given 5 scenarios of biomass residue disposal and use, industrial biomass combustion appears to be an efficient and environmentally sound practice when compared to the other uses/disposal methods. Although combustion does complete the cycle of CO_2 emission more quickly than the other methods, the total amount of GHG emitted is considerably less than the other scenarios, with 1 exception. Producing CH_4 from landfilled biomass and using the natural gas as a fuel produces less CO_2 than direct biomass combustion if all of it can be captured. The landfill costs, fugitive gases, and production time, however, could well outweigh the apparent advantages.

Landfilling biomass, without flaring the CH_4, results in the highest long-term CO_2 equivalent emissions of all of the scenarios considered. Assuming CH_4 is 21 times as radiatively active as CO_2, 6.3 t of CO_2 equivalent emissions could potentially be released from each tonne of biomass under ideal conditions. Even if 75%

of the carbon in landfilled wood is sequestered long-term, this scenario requires an equivalent amount of coal be combusted as a substitute, adding an additional 2.0 t of CO_2 to the atmosphere for a total CO_2 equivalent of 8.3 t.

Carbon sequestration remains one of the major topics of ongoing research and can bear directly upon biofuel choices. Other questions deal with the life cycles of industrial products.

As a renewable fuel resource, biomass residue is increasingly being recognized for its potential value to industry, rather than merely waste to be disposed of. When used as an industrial fuel, biomass is substituted for fossil fuels, thus representing a saving of non-renewable resources.

When biomass residue is combusted as a substitute for fossil fuels, carbon in coal and petroleum remains sequestered. The short-term sequestration of carbon in plants is already an active part of the carbon cycle, while carbon from fossil fuels does not become an active part of the cycle until it is combusted.

Locally available biomass has real cost advantages over coal as a fuel. There may be hidden costs, however, including the need for different boiler technology to burn only biomass, as well as environmental concerns. Cutting standing timber solely for use as biofuel is a concern because this timber not only represents sequestered carbon, but may also serve as a sink for future atmospheric carbon.

There are also the related issues of culling forests of non-commercial trees for biofuel. Such trees serve as valuable wildlife habitat, making them critical to survival of some forest species. The argument for using biomass residue rather than standing timber as an industrial fuel is certainly stronger.

Empirical inventories of biomass residue as a potential fuel source, particularly involving distance-decay and transportation costs, would be valuable in assessing the realistic limits of biomass as an industrial fuel.

As a result of this study, we conclude that the use of biomass residue as an industrial fuel is a viable mitigation strategy in efforts to reduce GHG emissions.

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LITERATURE CITED

AIRS Database (Aerometric Information Retrieval System) (1996) Air Quality Section, North Carolina Department of Environment and Natural Resources (DENR), Raleigh, NC

Augustein D (1992) The greenhouse effect and US landfill methane. Global Environ Change Dec:311–328

Bogner J, Spokas K (1993) Landfill CH_4: rates, fates, and role in global carbon cycle. Atmosphere 25:369–386

Borjesson B (1996) Energy analysis of biomass production and transportation. Biomass Bioenergy 11:305–318

Brown MJ (1993) North Carolina's forests, 1990. Southeastern Forest Experiment Station, Asheville, NC

Doorn MRJ, Barlaz MA (1995) Estimate of global methane emissions from landfills and open dumps. US Environmental Report EPA-600/r-95-019. USEPA, Washington, DC

EIA (1993) Annual energy review 1992. DOE/EIA–0384(92). EIA, Washington, DC

EIA (1994) Estimates of US biomass energy consumption 1992. DOE/EIA–0548(92). EIA, Washington, DC

Eriksson H, Hallsby G (1992) Biomass fuels—effects on the carbon dioxide budget. Nutek, Stockholm report R 1992: 10

Frosch RA (1992) Industrial ecology, a philosophical introduction. Proc Nat Acad Sci USA 89:800–801

Gustavsson L, Johansson B (1994) Cogeneration: one way to use biomass efficiently. Heat Recov Syst CHP 14:93–103

Gustavsson L, Borjesson P, Johansson B, Svenningsson P (1995) Reducing CO_2 emissions by substituting biomass for fossil Fuels. Int J Energy 20:1097–1113

Halvadakis CP, Findikakis AN, Papelis C, Leckie JO (1988) The Mountain View controlled landfill project field experiment. Waste Manag Res 6:203–114

Harris RA, McMinn JW, Payne FA (1986) Calculating and reporting changes in net heat of combustion of wood fuel. For Prod J 36:6:57–60

Hodgeman CD (ed) (1956) Handbook of chemistry and physics. The Chemical Rubber Publishing Company, Cleveland, OH

Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (eds) (1996) Climate change 1996, the science of climate change. Cambridge University Press, Cambridge

IPCC (Intergovernmental Panel on Climate Change) (1995) Climate change 1994; radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios. Cambridge University Press, Cambridge

Jelinski LW, Graedel TE, Laudise RA, McCall DW, Patel CKN (1992) Industrial ecology: concepts and approaches. Proc Nat Acad Sci USA 89:793–797

Johansson A, Sipila K (1991) New ecologically acceptable methods for fuel and power production from biomass and peat. Energy Sources 13:87–93

Marland G, Marland S (1992) Should we store carbon in trees? Water Air Soil Pollut 64:181–195

Marland G, Schlamadinger B (1995) Biomass fuels and forest-management strategies: how do we calculate the greenhouse-gas emissions benefits? Energy 20:1131–1140

Marland G, Schlamadinger B (1997) Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. Biomass Bioenergy 13(6):389–397

Micales JA, Skog KE (1997) The decomposition of forest products in landfills. Int Biodeterioration Biodegradation 39 (2-3):145–158

O'Leary P, Walsh P (1991) Landfilling principles. Waste Age 23:81–88

Patel C, Kumar N (1992) Industrial ecology. Proc Nat Acad Sci 89:798–799

Rees JF (1980) The fate of carbon compounds in the landfill disposal of organic matter. J Chem Tech Biotechnol 30: 161–175

Schlamadinger M, Marland G (1996) The role of forest and bioenergy strategies in the global carbon cycle. Biomass Bioenergy. 10(5/6):275–300

Schlamadinger B, Apps M, Bohlin F, Gustavsson L, Jungmeier G, Marland G, Pengoud K, Savolainen I (1997) Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems. Biomass Bioenergy 13(6):359–375

Suflita JM, Gerba CP, Ham RK, Palmisano AC, Rathje WL, Robinson JA (1992) The world's largest landfill. Environ Sci Technol 26:1486–1495

United Nations Environment Programme (1985) An assessment of the role of carbon dioxide and of other greenhouse gasses in climate variations and associated impacts. World Meteorological Organization, Geneva

USEPA (United States Environmental Protection Agency) (1995) State workbook: methodologies for estimating greenhouse gas emission, 2nd edn. USEPA, Washington, DC

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