

Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills

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Abstract. The objective of this research was to measure the amount of carbon associated with the major biodegradable components of municipal solid waste (MSW) that remains in long-term storage after anaerobic decomposition in landfills. Tests were conducted in quadruplicate in 2-L reactors operated to obtain maximum decomposition. Measured carbon storage factors (CSFs) for grass, leaves, branches, food waste, coated paper, old newsprint, old corrugated containers, office paper, and MSW were 0.32, 0.54, 0.38, 0.08, 0.34, 0.42, 0.26, 0.05, and 0.22 kg C sequestered dry kg⁻¹, respectively. These values were then used to estimate an overall CSF for MSW that varied from 0.274 to 0.302 kg C sequestered wet kg⁻¹ for waste mixtures that exclude and include recycling, respectively. On the basis of an overall CSF for MSW and data on global MSW generation, global carbon sequestration from MSW burial is estimated to be at least 119 million metric tons per year.

1. Introduction

Municipal solid waste (MSW) is composed of 40 to 50% cellulose, 9 to 12% hemicellulose, and 10 to 15% lignin on a dry weight basis, and the cellulose plus hemicellulose (carbohydrates) account for about 90% of the biodegradable fraction [Barlaz *et al.*, 1989, 1990]. With the burial of MSW in a landfill a complex series of chemical and microbiological reactions is initiated [Barlaz *et al.*, 1990]. The oxygen entrained in the refuse at burial is rapidly depleted, leading to the development of an anaerobic ecosystem. In the absence of nitrate and sulfate or once these electron acceptors are depleted, methanogenesis is the dominant electron sink process. The terminal products of refuse decomposition in a landfill are carbon dioxide and methane.

Cellulose decomposition in landfills is well documented [Booker and Ham, 1982], and the relationship between cellulose and hemicellulose loss and methane production has been described [Barlaz *et al.*, 1989]. However, even under optimal conditions for biodegradation, complete carbohydrate decomposition cannot be expected because of the presence of lignin. Lignin is at best only slowly degradable under anaerobic conditions, and it limits access of the hydrolytic bacteria to some carbohydrate material [Colberg, 1988; Dehority and Johnson, 1961; Stinson and Ham, 1995; Tong *et al.*, 1990]. Thus landfills represent a net carbon sink not only for biologically recalcitrant materials such as plastic, rubber, and leather but also for some fraction of the biomass-derived components including paper, food waste, and yard waste [Bogner, 1992; Bogner and Spokas, 1995].

The global carbon cycle is not well understood, and closing a global carbon balance requires a terrestrial sink of 1–2 Gt C

yr⁻¹ [Post *et al.*, 1997; den Elzen *et al.*, 1997; Thompson *et al.*, 1996; Tans *et al.*, 1990]. Several models of terrestrial carbon storage have been published [Bruno and Joos, 1997; Post *et al.*, 1997; Thompson *et al.*, 1996; Schimel *et al.*, 1994]. However, “the global uptake of anthropogenic carbon by the terrestrial system has been mainly deduced by difference to balance the global carbon budget ...” [Bruno and Joos, 1997]. Thus direct measures of terrestrial carbon storage should improve models of global carbon cycling. Here we report on the amount of biomass-derived carbon that does not degrade even under optimal conditions in a simulated landfill. These data are used to evaluate the impact of various recycling strategies on carbon storage and to develop a direct estimate of global carbon sequestration from MSW burial.

2. Experimental Methods

2.1. Experimental Design

The components selected for study were the major biodegradable components of MSW [U.S. Environmental Protection Agency (EPA), 1994] and included grass, leaves, branches, food, coated paper, old newsprint, old corrugated containers, and office paper as well as MSW. Experiments were conducted in quadruplicate in 2-L reactors. A seed of well-decomposed refuse, henceforth referred to as the seed, was used to initiate the decomposition of each component except MSW, which was tested without a seed. Seed made up 30% by volume of each reactor except for the food reactors in which tests were conducted with 70% seed because initial tests with 30% seed were not successful [Barlaz *et al.*, 1997; Wang *et al.*, 1997]. Four control reactors containing seed only were used to measure methane production and carbon storage attributable to the seed. Two additional control reactors (seed 2) were initiated with the food reactors that were set up after the other component reactors. Control reactors were operated until all test reactors had been dismantled.

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Coated paper, old newsprint, old corrugated containers, and office paper represent 4.2, 6.6, 12.2, and 3.3%, respectively, of MSW as generated [U.S. EPA, 1994]. Newsprint is a mechanical pulp that contains all of the initial lignin, while office paper is a chemical pulp in which most of the lignin has been removed. Old corrugated containers and coated paper contain both mechanical and chemical pulp, and coated paper contains a clay coating to provide a smooth, glossy finish. Since lignin will inhibit carbohydrate decomposition, the papers selected for testing should represent the range of biodegradabilities associated with different types of paper. In addition, these four papers represent the four highest categories of paper discarded [U.S. EPA, 1994].

Experiments were designed to measure the ultimate biodegradability of each component tested under conditions that simulate enhanced decomposition in a landfill. Actual decomposition in a traditional landfill designed to minimize moisture infiltration would be lower. Experimental conditions included shredding most components (see section 2.2), seeding, incubation at about 40°C, and leachate recycling and neutralization. In addition, phosphate and ammonia concentrations were maintained above 5 mg P L⁻¹ and 100 mg N L⁻¹, respectively, to minimize the potential for nutrient availability to limit biodegradation. All reactors were monitored until they were no longer producing measurable methane, except the old corrugated container reactors in which the methane yield increased by less than 2% over the final 80 days of operation. The monitoring period varied from 135 days for grass and leaves to 671 days for office paper.

2.2. Materials

For each component the objective was to test the material as it would have been discarded prior to contamination with other refuse components. Grass was obtained from a compost facility in Orlando, Florida, because freshly cut grass was not growing in Raleigh, North Carolina, during the winter when this experiment began. Both leaves and branches (less than 5 cm diameter) were collected from compost facilities in Raleigh, North Carolina. Food waste was collected by individual graduate students from their houses for the 1-week period prior to initiation of the experiment. Coated paper, old corrugated containers, and office paper were collected from local recycling centers. Old newsprint was collected from the North Carolina State University library and represented about 50 different newspapers to minimize the influence of different sources of pulp. The seed was excavated from a landfill known to be in an active state of methane production [Wang *et al.*, 1997].

Except for grass and coated paper all components were shredded with a slow-speed, high-torque shredder (Shredpax AZ-7H, Wood Dale, Illinois) to obtain a uniform sample size no greater than about 2 cm wide by 5 cm long. Grass was not shredded because it was already well mixed. Coated paper was not shredded because of concern that the shredded edges of the paper would allow access to uncoated parts of the paper that might be more bioavailable. Instead, magazines were opened and the center two pages were used.

2.3. Experimental Equipment, Reactor Operation, and Analytical Methods

The reactor system, including the 2-L reactors, the leachate collection and recycling apparatus, and the gas collection bag, has been described previously [Barlaz *et al.*, 1997; Wang *et al.*, 1997; Rhew and Barlaz, 1995] and is summarized here. Experiments were conducted in 2-L-widemouthed plastic jars. A port was installed in the bottom of each jar to allow leachate drainage to a 1-L intravenous bag. Ports were installed in the reactor lid to allow for leachate to be recycled to the top of the reactor and for a gas outlet. Gas was collected in tedlar gas bags. Gas composition was measured by a gas chromatograph equipped with a thermal conductivity detector and a HayeSep Q 80/100 column (Gow-Mac, Bound Brook, New Jersey). Gas volume was measured by evacuation from the gas bag with a 1-L syringe.

Sufficient deionized water was added to each reactor initially to ensure production of about 800 mL of leachate. Additional deionized water was added when the volume of leachate decreased below 500 mL because of sample removal. Leachate was neutralized 6 days a week until the pH stabilized at or slightly above 7. It was recycled 6 days per week throughout the monitoring period. NH₃-N and PO₄-P concentrations were monitored semimonthly, and concentrations were adjusted as necessary to the aforementioned target levels.

Once methane production was complete, the reactors were dismantled. The decomposed solids, as well as fresh samples of each component tested, were dried at 65°C and ground in a wiley mill to pass a 0.5-mm screen for use in solids analysis. Cellulose and hemicellulose were analyzed by acid hydrolysis of a sample followed by analysis of monomeric sugars by a high performance liquid chromatograph equipped with a pulsed amperometric detector [Pettersen and Schwandt, 1991]. The technique for lignin analysis was modified from that described by Effland [1977]. Total carbon analyses were performed by using a Perkin Elmer 2400 CHN elemental analyzer. Cellulose, hemicellulose, and lignin analyses were performed in duplicate and carbon analyses were performed in triplicate.

2.4. Calculation of Carbon Storage

A carbon storage factor (CSF) was calculated to represent the mass of carbon that was stored (not degraded) per initial dry mass of component. The mass of solid phase carbon added to and removed from each reactor was calculated from the measured masses and carbon concentrations. To calculate a CSF for each component, it was necessary to correct for carbon storage that could be attributed to the seed because each component except MSW was tested as a mixture with seed. The CSF for each component was calculated by using (1).

$$CSF_i = \frac{C_{out} - (CSF_s \times W_s) \frac{Y_i}{Y}}{M} \quad (1)$$

where CSF_i is the carbon storage factor for component *i*; C_{out} is the mass of carbon remaining after decomposition; CSF_s is the carbon storage factor for the seed; W_s is the mass of seed in a

Table 1. Ratio for Correction of Seed Carbon Storage Factor

Reactor Series	Days of Operation	Correction Ratio ^a
Seed	670	NA
Grass	135	0.55
Leaves	135	0.55
Branches	573	1.0
Food	187	1.0 ^b
Coated paper	219	0.75
Old newsprint	430	0.98
Old corrugated containers	470	0.99
Office paper	670	1.0
MSW	391	NA ^c

NA, not applicable; MSW, municipal solid waste.

^aRatio of the average methane yield in the four seed reactors at the time of component reactor dismantling, divided by the ultimate (day 670) average methane yield in the seed reactors. This is Y_i/Y in equation (1).

^bA second set of control reactors was operated in parallel to the food waste reactors. Hence the correction ratio is 1.0, although the food waste reactors were only operated for 187 days.

^cSeed was not used in the MSW reactors.

component reactor; Y_i is the average methane yield of the seed reactors at the time that the four component i reactors were dismantled; Y is the average final methane yield of the seed reactors; and M is the initial dry mass of component i in each reactor. The term Y_i/Y represents a correction factor on carbon storage attributable to the seed, signifying that many component reactors were dismantled prior to the seed reactors. The value of Y_i/Y is given in Table 1. The calculation procedure described here assumes that carbon storage for the seed was the same, whether the seed was present in the control or component reactors.

3. Results and Discussion

3.1. Carbon Storage

The carbon concentrations and CSFs for each component tested are presented in Table 2. The initial carbon concentration of the seed was lower than that of any refuse component. This is indicative of decomposed material and is consistent with the seed having been excavated from a landfill. Seed 2 was stored in the laboratory for approximately 6 months after

Table 2. Solids Concentration and Carbon Storage Factors (CSF) for Refuse Components

Refuse Component	Carbon, %	CSF ^a	Cellulose, %	Hemicellulose, %	Lignin, %	Volatile Solids, %	(C Plus H) (VS) ^{-1, b} %	Extent of Decomposition ^c
Seed	27.37	0.18 (0.01)	23.4	4.7	22.5	48.2	58.3	21.8
Seed 2	25.93	0.20 (0.01)	18.3	3.7	22.1	42.4	51.9	6.3
Grass	44.87	0.32 (0.02)	26.5	10.2	28.4	85.0	43.2	94.3
Leaves	49.4	0.54 (0.06)	15.3	10.5	43.8	90.2	28.6	28.3
Branches	49.4	0.38 (0.02)	35.4	18.4	32.6	96.6	54.7	27.8
Food	50.8	0.08 (0.04)	55.4	7.2	11.4	93.8	66.7	84.1
Coated paper	34.3	0.34 (0.02)	42.3	9.4	15.0	74.3	69.6	39.2
Old newsprint	49.2	0.42 (0.02)	48.5	9.0	23.9	98.5	58.4	31.1
Old corrugated containers	46.9	0.26 (0.01)	57.3	9.9	20.8	98.2	68.4	54.4
Office paper	40.3	0.05 (0.01)	87.4	8.4	2.3	98.6	97.2	54.6
MSW	42.0 ^d	0.22 (0.01)	28.8	9.0	23.1	75.2	50.3	58.4
MSW	50.2 ^d	0.22 (0.01)						

^aData represent the average for each reactor set with the standard deviation (s.d.) presented parenthetically. Units are kg C sequestered dry kg⁻¹.

^bThe percentage of the volatile solids attributed to cellulose plus hemicellulose.

^cThe extent of decomposition is the measured methane yield divided by the yield calculated assuming conversion of 100% of the cellulose and hemicellulose (and protein in the case of food waste) to methane and carbon dioxide.

^dThe initial carbon concentration of the MSW tested is not known because the original sample was lost. The CSF for MSW was calculated using a value of 42.0% measured on another sample of residential MSW and also calculated using a value of 50.2% [Tchobanoglous *et al.*, 1993].

the initial seed; hence its lower carbon concentration was expected. The carbon concentration in the seed was also likely influenced by the presence of soil that was used to cover the refuse at burial. Among the MSW components the coated paper had the lowest carbon content, which can be explained by the presence of a clay coating.

The CSF ranged from lows of 0.05 for office paper and 0.08 for food waste to 0.54 for leaves. The highest CSF was measured for leaves which had a total carbohydrate concentration of only 25.5%, corresponding to 28.6% of the volatile solids (VS), while lignin comprised 48.6% of the VS. The remaining VS were not accounted for by the cellulose, hemicellulose, and lignin analyses. In addition, even the carbohydrates that were present exhibited a relatively low extent of decomposition (Table 2). The extent of decomposition is a measure of the fraction of the carbohydrates present that were converted to methane plus carbon dioxide. Thus the initial solids composition and extent of decomposition for leaves are consistent with a high CSF.

Old newsprint (0.42), branches (0.38), and coated paper (0.34) had the next highest CSFs. Each of these components had a substantially higher carbohydrate concentration than leaves but exhibited a relatively low extent of decomposition. In contrast, grass (CSF=0.32) had a relatively low carbohydrate concentration and a low fraction of the VS attributable to carbohydrates (43.2%). However, grass underwent more thorough decomposition than all other components. In previous work it was determined that the lignin in grass is not as restrictive to microorganisms as the lignin in other MSW components [Eleazer *et al.*, 1997]. Office paper and food waste had the lowest CSF measurements. These waste components are characterized by high carbohydrate and low lignin concentrations and relatively high extents of decomposition: 54.6% for office paper and 84.1% for food waste.

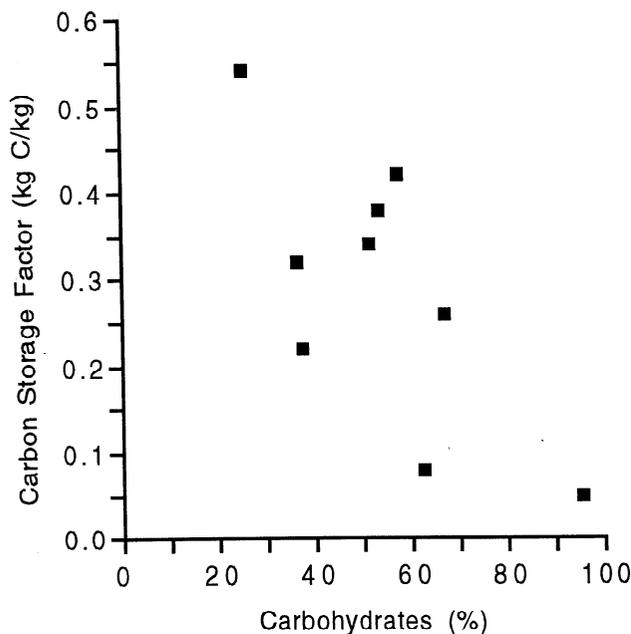


Figure 1. Relationship between carbon storage factor and carbohydrate concentration.

Table 3. Fraction of Total Carbon Stored Attributable to the Seed

Reactor Series	Fraction, %
Grass	21.4
Leaves	11.7
Branches	16.8
Food	90.2
Coated paper	36.3
Old newsprint	20.9
Old corrugated containers	16.9
Office paper	53.8
MSW	NA ^a

NA, not applicable; MSW, municipal solid waste.

^aNo seed was used in the MSW reactors.

The relationship between the carbohydrate concentration and CSF is presented in Figure 1. A perfectly linear relationship would suggest that carbohydrates are the only component degraded and that there was no interference from lignin. The relatively weak relationship, $r^2 = 0.50$, indicates that factors in addition to carbohydrate concentration influence the extent of carbon sequestered. The CSFs of the seeds are reported in Table 2 but are not included in Figure 1 because their behavior would not be similar to that of fresh components. Other aspects of solids decomposition patterns have been presented previously [Eleazer *et al.*, 1997].

3.2. Uncertainty in Carbon Storage

The CSFs presented in Table 2 were calculated by assuming that the seed underwent similar decomposition in the control and component reactors. To assess the potential impact of the seed on the calculated CSFs, the fraction of the total carbon stored in each reactor series that was attributed to the seed is presented in Table 3. These values range from 12 to 54% except for the food waste (90.2%), indicating that, except for the food waste, the CSFs are not highly sensitive to the mass of stored carbon that was attributed to the seed. The food CSF is highly sensitive to the mass of carbon storage attributed to the seed because the food waste reactors contained more seed initially.

3.3. Effect of Recycling on Carbon Storage

The CSFs reported in Table 2 may be used to estimate carbon sequestration from MSW and the impact of changes in MSW composition on carbon sequestration in landfills. This analysis assumes that the MSW composition presented by the U.S. EPA [1994] is representative of waste actually buried in landfills. This assumption is imperfect because many other wastes are buried in landfills including construction and demolition waste, water and wastewater treatment sludges, and some nonhazardous industrial waste. Nonetheless, this analysis suggests the direction and potential magnitude of changes in carbon sequestration that could result from changes in MSW composition.

A model was developed to calculate carbon sequestration from MSW as a function of waste composition, CSFs, and re-

Table 4. Estimate of Carbon Sequestration Rates as MSW Composition Is Influenced by Recycling and Composting

Component	Composition, ^a % wet wt	Recycle, ^b %	H ₂ O, ^c %	Carbon Sequestered, ^d kg C kg ⁻¹ wet MSW
Grass	7.95	19.8/60	70	base case no recycling, 0.274
Leaves	3.98	19.8/60	30	
Branches	3.98	19.8/60	10	
Wood	6.6	9.6/40	20	national average recycling rates, 0.285
Food	6.7	0/0	70	
Plastic	9.3	3.5/5	2	hypothetical local recycling rates, 0.302
Metal	8.3	30.4/50	3	
Glass	6.6	21.8/50	2	
Other	9.0	13.2/26 ^e	7 ^f	
Coated paper	1.9 ^g	11/19 ^g	5	
Old newsprint	9.9 ^g	29/41 ^g	5	
Old corrugated containers	20.3 ^g	35/44 ^g	5	
Office paper	5.5 ^g	23/31 ^g	5	

^aBased on MSW as generated [U.S. EPA, 1994] and an assumption that yard waste is 50% grass, 25% branches, and 25% leaves.

^bThe percentage of each component generated that is recycled. The first value is based on national average data [U.S. EPA, 1994], and the second value is a hypothetical rate for a community with a curbside recycling program. Values include composting plus recycling.

^cTypical values presented on a wet weight basis [Tchobanoglous et al., 1993].

^dCalculated using the CSFs in Table 2 and the CSFs for other components presented in the text.

^eAverage of values for textiles, rubber, leather, and other [U.S. EPA, 1994].

^fAverage of values for textiles, rubber, leather, and ash [Tchobanoglous et al., 1993].

^gThe compositions of the four paper components analyzed in this study were adjusted to total 37.6%, the total paper concentration in MSW. The paper recycling rates given are "effective" rates. They were decreased from the national average and hypothetical rates because the waste composition of each paper component presented here includes that component plus the amount by which it was increased so that total paper is 37.6%.

cycling rates. The major input data, assumptions, and model results are presented in Table 4. CSFs for the biodegradable components of MSW were based on the results presented in Table 2. The CSF for metal and glass was 0 since these constituents are inorganic. The CSF for the plastic mix present in MSW was calculated based on a weighted average percent car-

bon for individual plastic types and the assumption that all plastics are 100% recalcitrant. Data on the composition of individual plastics in MSW have been published [U.S. EPA, 1994], and the carbon concentration in each plastic was calculated from chemical formulas [Merck and Company, Inc., 1996]. The weighted average CSF for plastic is 0.82. This

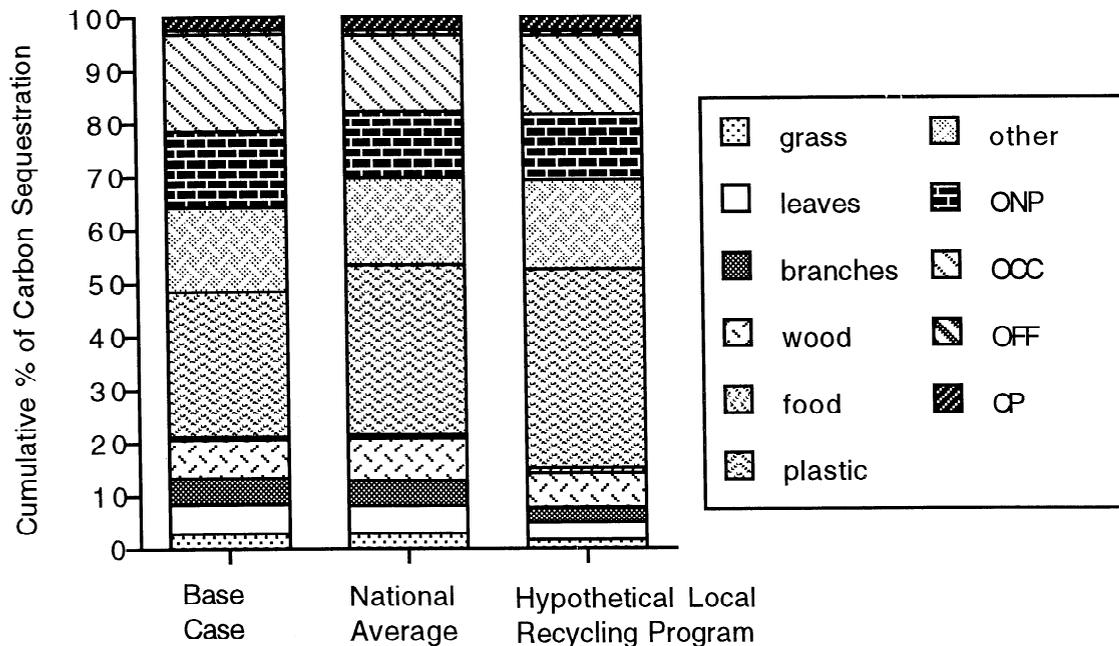


Figure 2. Sensitivity of total carbon sequestration to individual MSW components. No carbon sequestration is associated with glass and metal, and these components are not shown.

Table 5. Estimate of Global MSW Generation and Carbon Sequestration Rates

Region	MSW Generation ^a	C Sequestration: Base Case ^b	C Sequestration: 5% Plastics ^b	C Sequestration: 10% Increase in CSF _m ^b
Africa	82	2.79	4.5	2.79
Asia	579	17.2	30.3	17.6
Europe	298	49.3	52.8	53.6
North and South America and the Caribbean	110	9.81	11.9	10.4
Oceania (Australia and New Zealand)	14.4	4.07	4.08	4.48
United States	188	35.5	35.5	39.0
Total	1271.4	118.7	139.1	127.9
Subtotal for fully developed countries ^c	471	91.4	91.4	100.6

Data are in millions of metric tons per year. The complete data set may be obtained as a Microsoft Excel file on request from the author.

^aThe MSW generation and composition data were adopted from earlier studies [U.S. EPA, 1994, U.S. EPA, 1995]. In many cases, generation and/or waste composition data for one country in a region were assumed to be valid for the entire region. Such assumptions were required for much of Africa, Asia, South America, and the Caribbean.

^bCalculated from equations (2) and (3). CSF_m (0.302) was calculated in Table 4. The CSF for yard waste (0.228) was calculated as the weighted average of the CSFs for grass, leaves, and branches, assuming that they represent 50%, 25%, and 25% of yard waste, respectively. The CSF for food waste (0.024) was adopted from Table 2. The CSF for paper (0.262) was calculated from the weighted average of the CSFs for coated paper, old newsprint, old corrugated containers, and office paper. Their compositions are presented in Table 4. The CSF for plastic is 0.82 (see text). The CSFs given here are per wet kilogram of component.

^cFully developed countries include Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Israel, Italy, Japan, Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, United Kingdom, and the United States.

value neglects the presence of small amounts of additives. The CSF for "other," 0.51, is based on the average percent carbon for textiles, rubber, leather, and sweepings [Tchobanoglous *et al.*, 1993] and the assumed complete recalcitrance of these components in landfills.

Carbon sequestration factors were calculated for three scenarios: (1) MSW composition in the absence of any recycling or composting, (2) MSW composition after adjustment to reflect national average recycling and composting rates, and (3) MSW composition after adjustment to reflect hypothetical local recycling and composting rates. As presented in Table 4, carbon sequestration varies from 0.274 kg C sequestered wet kg⁻¹ MSW buried in the case with no recycling or composting to 0.285 and 0.302 kg C sequestered wet kg⁻¹ MSW when waste composition is varied to reflect national average and location-specific recycling rates, respectively. The carbon sequestration rate increases as recycling rates increase because the plastics composition of MSW increases with increased recycling and the carbon in plastic is completely sequestered. As illustrated in Figure 2, the amount of carbon in MSW that is sequestered is most sensitive to assumptions regarding both the plastic and "other" components of MSW because these components contain substantial amounts of carbon and were assumed to be 100% recalcitrant.

3.4. Global Carbon Sequestration from MSW

Carbon sequestration from MSW burial on a global scale was estimated by using (2) and (3) for fully developed and developing countries, respectively, and the results are presented in Table 5.

$$C_{\text{seq}i} = G_i \times LF_{\text{fr}i} \times \text{CSF}_m \quad (2)$$

$$C_{\text{seq}i} = G_i \times LF_{\text{fr}i} \times \left\{ \left(\text{CSF}_{\text{yw}} \times YW_{\text{fr}} \right) + \left(\text{CSF}_{\text{pa}} \times Pa_{\text{fr}} \right) + \left(\text{CSF}_f \times F_{\text{fr}} \right) \right\} \quad (3)$$

where $C_{\text{seq}i}$ is carbon sequestration from MSW in country i ; G_i is the mass of MSW generated in country i ; $LF_{\text{fr}i}$ is the fraction of waste generated in country i that is buried in landfills; CSF_m is 0.302 based on U.S. waste (Table 4); and CSF_{yw} , CSF_{pa} , and CSF_f and YW_{fr} , Pa_{fr} , and F_{fr} are the carbon storage factors and waste composition fractions for yard waste, paper, and food waste, respectively. Both G_i and the CSFs are based on wet weight. The assumptions required to calculate component specific CSFs are presented in Table 5. Data on MSW generation rates and composition and the fraction of MSW buried in landfills were adopted from U.S. EPA [1995] except for U.S. data that were adopted from a country-specific estimate [U.S. EPA, 1994].

Equation (2) was used for fully developed countries (listed in Table 5) for which it was assumed that the U.S. waste composition and CSF could be applied. The CSF of 0.302 that was applied to these countries includes plastics. This is important given the high CSF for plastic (0.82) and the sensitivity of estimates to plastic (Figure 2). In contrast, carbon sequestration for all other countries was calculated using (3). Only stored carbon associated with yard waste, paper, and food waste was considered because no waste composition data were available for plastic or other waste components.

Global carbon sequestration due to MSW burial is estimated to be $118.7 \times 10^6 \text{ t yr}^{-1}$ (Table 5). Countries considered to be fully developed account for 77% of this carbon. Many countries that were not considered to be fully developed for this model have some large urban areas for which waste composition may approach that of the United States. Thus some further consideration of plastic is important. If it is assumed that the countries modeled by (3) have a plastics concentration of 5%, then global carbon sequestration increases by 17.2% (Table 5).

The CSFs presented in Table 2 and the carbon sequestration estimates presented in Tables 4 and 5 represent the minimum sequestration based on thorough decomposition of each component tested. These values are based on laboratory experiments in which reactors were operated to achieve maximum decomposition. Carbon buried in landfills operated to minimize moisture infiltration will exhibit higher levels of carbon sequestration. Increasing the CSF for fully developed countries by 10% results in an increase in global sequestration to $127.9 \times 10^6 \text{ t}$. The estimate of carbon sequestration presented here represents a refinement and significant increase relative to an earlier estimate of $31.6 \times 10^6 \text{ t}$ [Bogner, 1992].

Carbon sequestration estimates presented here are based on a steady state model that uses waste generation rates for 1994 for the United States and the early 1990s for other countries. While historical information on global waste generation was not readily available, it is certain that waste generation is increasing over time. For example, in the United States, waste generation increased by 236% between 1960 and 1993 [U.S. EPA, 1994]. As the fraction of the world's population living in fully developed countries increases, waste generation rates will increase. In addition, the fraction of waste buried in landfills will likely increase as landfills generally represent the least expensive disposal alternative, at least from a short-term perspective. In parts of Asia, Africa, and Latin America, where living standards have the potential to increase, the fraction of waste currently buried in landfills was generally about 40%. To simulate future development, carbon sequestration was calculated assuming that 70% of waste in these regions is buried in landfills and the waste contains 5% plastics. Even with no population increase, carbon sequestration increases to $151.3 \times 10^6 \text{ t}$. This may be counteracted to some extent by a movement among some European countries to decrease the burial of degradable organic wastes in landfills, although this trend is difficult to quantify.

The estimate of carbon sequestration developed here ($-0.12 \text{ Gt C yr}^{-1}$) is 5–10% of the 1–2 Gt C yr^{-1} of missing carbon identified previously [Post et al., 1997]. It is expected

that these data will be useful for refinement of models of terrestrial carbon storage.

Carbon sequestration is one factor that should be considered in comparing the environmental benefits and liabilities associated with landfills in specific and MSW management strategies in general. Other factors include gaseous emissions from MSW decomposition and from the equipment used for landfill operation, energy consumed during landfill construction and operation, and the potential recovery of methane for energy. Of course, alternatives to landfills will also have associated environmental benefits and liabilities.

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