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Urban Residential Refuse Composition and Generation Rates for the 20th Century

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Examination of historical data shows that 3.5×10^8 tonnes (t) of residential refuse was discarded in New York City (NYC) during the 20th century. Maximum and minimum rates of per capita mass discard of residential refuse during this time are reported in 1940 (940 kg per capita yr^{-1}) and 1961, 1963 (320 kg per capita yr^{-1}), respectively. Since 1980, per capita residential refuse discard rates have been steady and comparatively low (430 kg per capita $yr^{-1} \pm 2.5\%$). Fuel ash accounted for approximately 34% of residential refuse in NYC during the century. A decline of refuse bulk density (as collected) from approximately 500 to 200 kg m^{-3} and an increase in refuse organic matter content from 20% to 80% (by mass) is reported between 1920 and 1990 and is due largely to mass fraction reductions for fuel ash and increases for paper and plastic. Approximately 4.9×10^8 t of refuse was disposed in NYC during the 20th century (including commercial and residential refuse), representing a total pool of about 8.0×10^7 t of organic carbon (as C) that has entered city landfills and incinerators.

Introduction

Understanding of the composition and per capita mass discard rate of urban residential refuse (solid waste), and their tendency to change over time, is important for all aspects of refuse management (*1*, *2*). Past studies of residential refuse composition have typically examined characteristics at a local-, regional-, or national-scale at a single point in time (*1*). Studies were often performed to assist in the development of waste management programs within one or more urban waste-sheds. Methods consisting of collection of refuse, sorting into classes, and characterization by mass fraction have been used most frequently to examine refuse content (*2*). More recently, materials flow methods have been used to provide gross estimates for national average content of refuse (*3*). Factors reported to influence spatial variability in the composition and per capita discard rate of urban refuse include local geography and climate, season, character of population and local industry, efficiency of refuse collection (*4*), character of neighborhoods, living habits, market methods, type and layout of residential property, economic conditions, frequency of collection (*5*), and socioeconomic status (*6*). Some researchers have studied waste composition changes over relatively short (decadal) time scales and attempted to identify causal mechanisms (*4*, *5*, *7*−*9*). However, no studies could be found in the literature that examined the composition and discard rates of residential refuse in an urban area over a long (century) time interval.

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Data on refuse composition and discard rates reported for many U.S. cities in the early 20th century have been criticized for poor record keeping and reporting, incomplete collection of discards (*10*), use of volumetric measurements that tended to overestimate mass (*4*, *10*, *11*), and, more recently, incomplete or absent explanation of methodology (*12*). Municipal records for New York City (NYC) have been reported to be among the most accurate measure of urban refuse in the U.S. during the early- and mid-20th century due to near-complete collection of discards (necessitated by a high percentage of land development (*11*)), periodic testing of the relationship between waste volume and mass, maintenance of records for separate collections for ash, garbage (putrescible refuse including mainly food refuse), and rubbish (a practice that was not performed in most U.S. cities), comprehensive reporting of data on an annual basis (*13*), and laws prohibiting residential in-sink garbage disposal systems. Records of the total mass of refuse discarded in NYC are available for most years in the 20th century and have been used elsewhere to quantify patterns of refuse combustion (*14*) and landfill development (*15*, *16*). New York City's population density and total refuse discard rates have been high compared to other cities throughout the century and have necessitated frequent modernization of refuse management practices (*14*, *17*). To accomplish this, studies using collection, sort, and weigh methodology for quantitative examination of residential refuse composition have been performed periodically in NYC under municipal sponsorship (1905 (*11*); 1939 (*7*); 1971 (*18*); 1979 (*19*); and 1989 (*20*)). Collectively, this is probably the most comprehensive set of data of its kind available for a U.S. city for the past century.

In this study, historical data are used to quantify the composition and rates of per capita discard of residential refuse in NYC as a function of time and examine principal controls on urban residential refuse characteristics during the 20th century.

Methods

Data from municipal waste management records and historical literature are examined to quantify the rates of discard of residential refuse mass in NYC over the time period 1900 to 1999. During this period, refuse collections in NYC were consistently divided into two classes based on source: residential and commercial (*21*). Municipal agencies have collected residential refuse and private carting companies have collected commercial refuse. For the purpose of this study, refuse is defined as the material collected from these sources. Residential refuse represents post-consumer discards and does not include commercial wastes (from hotels, restaurants, stores, etc.) or process residuals from refining or manufacturing (i.e., industrial waste). Mass measurements of residential refuse collected by NYC agencies are available in municipal records for most years during the century. These data are used to quantify annual mass rates of per capita residential refuse discard. Measurements of commercial refuse collections were included in NYC municipal records only if the material was taken to a disposal facility (landfill, incinerator, etc.) in NYC. These commercial refuse discard data are quantified in this study to determine the mass of residential plus commercial refuse disposed in NYC during the study period. This mass does not include commercial and residential refuse transported outside NYC for disposal. Most commercial and residential refuse discarded in NYC before about 1960 was also disposed within the city (*21*), and municipal records compiled in this study are a good measure of the total refuse mass discarded in NYC before that time

TABLE 1. Details of Sort and Weigh Studies of Residential Refuse Performed in NYC during the 20th Century

year source	1905[a] (*11*)	1939[b] (*7*)	1971[c] (*18*)	1978−1979[d] (*19*)	1989[e] (*20*)
county[f]	NY	Bx, Q, K	NY, Q, K	Q, K	NY, Q, Bx, K, R
sampling period	Oct	monthly (1 year)	April	Oct, 1978 March, 1979	quarterly (1 year)
quantity sampled	24 t	1155 t[g]	0.63 t	na	39 t[h]

[a] Detailed analysis of rubbish component only, ash and food refuse reported elsewhere (Table SI-1, Supporting Information (*21*)); rubbish reported to comprise 6.7% of NYC refuse in 1905 (*21*). Ash and food waste constitute the remainder. [b] Refuse sampled before salvage/recycling. [c] Truckloads inspected for 7 days prior to sampling; refuse subsampled by successive quartering. [d] Average of two survey results. [e] Samples collected over 5−6 day period in each quarter (Aug, 1989; Oct, 1989; Jan, 1990; April, 1990; sample areas chosen to exclude effect of municipal recycling. [f] Counties: NY, New York (Manhattan); Bx, Bronx; Q, Queens; K, Kings (Brooklyn); R. Richmond (Staten Island). [g] Estimated mass of contents of 168 truckloads. [h] Estimated mass of 346 samples studied, assumes 250 pounds per sample (reported as 200 to 300 pounds per sample. na: information not available.

(i.e., commercial plus residential refuse). Between 1960 and the end of the century, the percentage of commercial refuse exported for disposal outside of the city increased (*21*, *22*), and municipal records compiled in this study become unreliable as a measure of the total mass of refuse discarded in NYC during this period. Some residential refuse was exported from NYC in the years 1997−1999 (*22*). Industrial wastes are not included in this study. Municipal records of refuse discards for years prior to 1930 do not include Queens or Richmond County. On the basis of per capita discard estimates and population, exclusion of refuse from these counties will underestimate total NYC refuse mass for this period (1900−1929) by about 11%.

Refuse discards were reported in volumetric measurements in most municipal records prior to 1947, and conversions to mass in this study are based on reported refuse density (unit weight) measurements. Refuse was formerly segregated by NYC residents into three distinct classes for separate collection: ash (including about 12% nonash street sweepings (*11*, *23*)), garbage, and rubbish. For most years between 1900 and 1938, municipal records report refuse mass discard for these separate classes (*21*). For years prior to 1936, conversions assume densities for ash, garbage, and rubbish of 686 (±9.3%), 650 (±5.1%), and 89 (±17.3%) kg m^{-3}, respectively. These conversion factors are computed as the average of 24 density measurements for each class reported for years between 1900 and 1912 (*4*, *10*, *11*, *21*, *24*−*28*). For years prior to 1918, refuse measurements were reported by volume as the number of cartloads of standard size. Conversion to volume in this study is based on reported cart volume measurements. Conversion factors of 1.33 (±10.9%), 1.31 (±10.4%), and 5.68 (±1.7%) m^3 $cart^{-1}$ are used for ash, garbage, and rubbish, respectively. These conversion factors are computed as the average of 16−18 measurements reported for years between 1902 and 1917 (*21*). For years between 1937 and 1948, conversion from volume to mass assumes linear change of bulk (combined) density of refuse from 451 kg m^{-3} (1937) to 266 kg m^{-3} (1948), based on reported values for those years (*21*). Municipal recycling programs for residential refuse were begun in NYC in the late 1980s (*22*), and the mass of recycled materials collections are included in total and per capita residential refuse discard data reported here.

Data for the total mass of refuse disposed in NYC (i.e., the sum of residential plus commercial refuse) are available for most years. The mass of the residential refuse fraction was not always reported in municipal records and is quantified in this study from the reported sum of residential and commercial refuse for various periods using computed ratios for nearest years with full data. The following residential refuse ratios (residential refuse mass/(residential + commercial refuse mass)) are used: 1906−1919, 0.80; 1931−1939, 0.85; and 1941−1944, 0.9). For years 1900 and 1901, the mass of residential refuse discarded is computed by linear extrapolation from reported values. Data for the mass of residential refuse discarded in NYC are normalized to population (per capita mass of refuse discarded) on an annual basis for detailed examination. Population data were obtained from the U.S. Census Bureau (*29*). Linear interpolation is used to estimate population between reported decadal census values. Per capita estimates exclude Queens and Richmond County for years prior to 1930.

Composition of refuse as a function of time is examined by comparing reported results from refuse composition studies performed in NYC at different times (*7*, *11*, *18*−*20*). Details of these studies are reported in Table 1. These data represent waste composition estimates drawn from different sampling periods, sample quantities, and sample locations within NYC. Consequently, these values should be viewed as general approximations for comparative purposes. Waste classification used here conforms to a scheme reported by Hickman (*6*) and includes metal, glass, paper, food waste, yard waste, wood, plastic, rubber and leather, textiles (cloth and synthetics), ash, and miscellaneous materials. Results of past sort and weigh studies are segregated into these general classes. Data for each class are reported in mass fraction (mass percent of the sum of all refuse classes). All references to relative abundance of waste classes in this text relate to mass fraction, unless otherwise noted.

Refuse composition studies in 1939 and 1989 were designed in a manner to exclude the effects of municipal recycling programs. However, examination of the mass fraction of refuse classes will be affected by selective diversion of some waste materials prior to collection, for salvage (*4*, *10*), combustion for fuel value or convenience (*8*, *11*), and for beverage container deposit redemption (*22*). Ash from fuel combustion was the most abundant refuse component prior to about 1950, and the fuel-ash-free composition of refuse is also computed to examine the character of refuse composition unrelated to fuel use. Data for separate collections of residential refuse classes prior to 1938 enabled more detailed examination of fuel ash discards for this time interval. These segregated data probably have an error of about 5−10% due to incomplete refuse separations by residents (*13*, *21*) and prescribed combination of different classes, such as tin cans (*10*) and other inert material (broken crockery, etc. (*30*)) in ash.

Mass fraction of total organic matter in NYC residential refuse is obtained from the literature (*25*, *31*) and computed from reported refuse composition data (*7*, *11*, *18*−*20*) as the sum of all organic matter-based classes (paper + wood + plastic, etc.). Residual organic matter in ash is excluded. Density data for bulk (mixed) NYC residential refuse (as collected) is obtained from the literature (*21*) and computed from reported measurements of ash, garbage, and rubbish by assuming their respective densities, as described above. Gross estimates of the total mass of fuel ash, paper, and organic matter in residential refuse in the 20th century are computed from reported data. Values for years without reported data are estimated by linear interpolation. Resi-

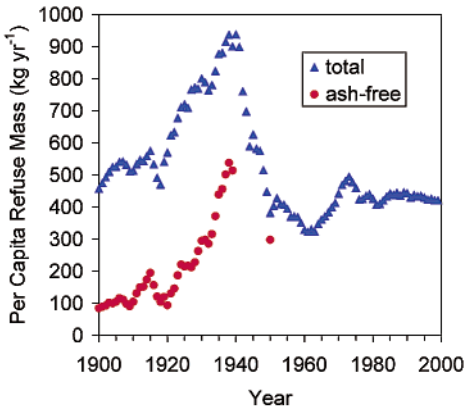

FIGURE 1. Per capita mass discard rate of residential refuse (kg yr^{-1}) in NYC for the 20th century (blue triangles). Per capita rates corrected for fuel-ash content (i.e. ash content removed) are also shown (red circles). Sources in Table SI-1, Supporting Information.

dential fuel ash is assumed to be negligible after 1971 because ash content was not reported in refuse composition studies (<1.5−3% (*18*−*20*)).

Results and Discussion

Residential Refuse Discard Rates. Approximately 3.5×10^8 tonnes (t) of residential refuse was discarded in NYC during the 20th century (Table SI-1, see Supporting Information). The mass of residential refuse discarded on an annual basis fluctuated between 1.6×10^6 t yr^{-1} and 8.2×10^6 t yr^{-1} during the century (Table SI-1, see Supporting Information). Maximum and minimum rates of per capita discard of residential refuse mass in NYC are observed in 1940 (940 kg per capita yr^{-1}) and 1961, 1963 (320 kg per capita yr^{-1}), respectively (Figure 1; Table SI-1, see Supporting Information). Average annual rates of per capita discard of residential refuse mass, calculated on a decadal basis, is highest in the 1930s (860 kg per capita yr^{-1} ± 7.4%) and 1920s (695 kg per capita yr^{-1} ± 9.9%) and lowest in the 1960s (360 kg per capita yr^{-1} ± 9.2%) and 1950s (390 kg per capita yr^{-1} ± 6.1%). Variability between years is greatest between 1900 and 1975. Per capita refuse discard rates have been steady and comparatively low since 1980 (430 kg yr^{-1} ± 2.5%; includes residential recycling collections). This finding for NYC is not consistent with earlier reports that per capita refuse discard rates in the U.S. increased after 1980 (*35*, *36*).

The two longest time intervals with sustained increase in rates of per capita mass discard of residential refuse in NYC during the study period (1920−1930 and 1963−1973) correspond to periods of economic prosperity in the U.S. Economic decline after these time periods corresponds to interruption of ascending patterns. Reduction in per capita refuse discard rates in NYC is observed during World War I (WWI, 1914−1918) and WWII (1941−1945) and can be explained, in part, by war-related fuel and materials conservation and refuse salvage and recycling programs during these periods (*4*, *37*−*39*).

A total of 4.9×10^8 t of refuse was disposed in NYC during the 20th century (commercial plus residential refuse). This value is at least 10% less than the total mass of residential and commercial refuse discarded in NYC, due to out-of-city disposal of a fraction of commercial and residential refuse and lack of records for Queens and Richmond Counties prior to 1930. Residential refuse constitutes about 70% of all refuse disposed in NYC during the study period.

Refuse Composition

Fuel Ash. Refuse composition data are reported in Table 2. Fuel ash constituted about 34% (1.2×10^8 t) of the mass of all residential refuse discarded in NYC during the 20th century (Figure 2; Table SI-1, see Supporting Information). Between 1900 and 1940, fuel ash accounted for more than 60% of residential refuse mass discards, suggesting that high per capita discard rates observed during this period were controlled mainly by the high ash content of residential fuels (mainly coal) used for space heating and cooking.

Comparably high percentages of ash in residential refuse were reported for other cities in the northern U.S. for the first four decades of the century (*4*, *10*, *21*, *37*), although considerable divergence is probable in cities in the southern U.S., and others that did not use coal as their principal residential fuel (*8*). Replacement of coal with lighter and more convenient fuels that produce little ash (oil and natural gas) is reported to have begun in NYC in the 1920s (*21*) and is evident in Figure 2 as a progressive decrease in ash content for refuse discarded between 1920 and about 1960. Ash

TABLE 2. Mass Fraction of Residential Refuse from Five Sort and Weight Studies Performed in NYC in the 20th Century[a,b]

refuse class	1905[c] percent (*11*)	1905[c] percent ash free	1939[b] percent (*7*)	1939[d] percent ash free	1971[b] percent (*18*)	1978[b] percent (*19*)	1989[b,l] percent (*20*)
food refuse	13.4	67.0	17.0	29.8	15.6	17.8[g]	14.1
ash	79.9		43.0		2.8[f]	1.5[f]	2.3[f]
paper	5.0	25.0	21.9	38.4	35.5	32.9	34.7
plastic					2.7	8.8	9.9[i]
metal	0.2	1.0	6.8	11.9	11.1	13.3	5.3[i]
glass	0.2	1.0	5.5	9.6	23.1[j]	9.4[h]	5.5[i]
textiles	1.0	5.0			3.9	5.7	5.2
hazardous							0.4
rubber and leather	0.1	0.5			3.5		0.2
wood	0.1	0.5	2.6	4.6	1.2	4.5	2.4
yard refuse					0.7	4.7[g]	4.7
miscellaneous			3.2	5.6		1.5	15.2[k]
total organic content[e]	19.6		41.5		63.1	74.4	78.3

[a] Details of studies are reported in Table 1. [b] Reported values are mass fraction in percent of total refuse mass examined. [c] From detailed analysis of rubbish component; assumes that rubbish accounts for 6.7% of all residential refuse as reported in ref *21*; ash and food waste are reported from ref *21*, Table SI-1, see Supporting Information. [d] Mass fraction on an ash-free basis; computed using values in column to left. [e] Computed as sum of food, paper, plastics, textiles, household hazardous, rubber and leather, wood, and yard refuse. [f] Reported in source as miscellaneous fines and represents an upper bound since it also includes other inerts (dirt, etc.). [g] Reported in source as combined food and yard waste; value listed here assumes 4.7% yard waste (*20*) and remainder as food waste. [h] Reported in source as combined glass and ceramics; value listed here assumes 0.2% ceramics (*20*). [i] Value listed does not include plastics and aluminum diverted by beverage container deposit redemption. [j] Value includes ceramics and stones. [k] Includes diapers (3.8%) and organic fines (2.6%) and undifferentiated refuse (8.8%). [l] Calculated for bulk-free refuse; bulk reported to account for 9.9% of collections.

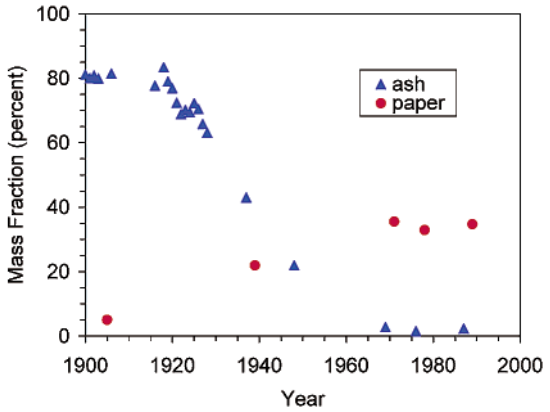

FIGURE 2. Mass fraction of ash (blue triangles) and paper (red circles) in residential refuse in NYC for the 20th century (sources in Tables 2 and SI-1, Supporting Information). Ash content shown after 1960 constitute maximum (upper bound) abundance.

constituted less than 3% of NYC's residential refuse mass by 1971 (*18*). A similar shift in fuel usage has been reported for other cities in the northern U.S. (*5*, *9*) and comparable effects on their refuse composition are likely. As the mass fraction of ash approached minimum values in the early 1960s, per capita rates of mass discard of residential refuse reached a minimum for the 20th century (320 kg per capita yr^{-1}).

Incinerator Ash. Use of domestic residential incinerators in NYC increased steadily between 1910 and 1971 (*14*, *17*) and was responsible for a progressively larger rate of refuse mass diverted from discards during this time. Peak use of domestic incinerators in NYC occurred in 1971 (1.3×10^6 t yr^{-1} (*14*)) and resulted in a mass reduction equal to about 25% of all residential refuse discarded in that year (i.e., mass reduction equals mass lost during combustion; assumes ash residue production equals 37% of combusted mass (*40*)). Ash from domestic incineration of refuse in NYC during the 20th century (1.2×10^7 t (*14*)) accounts for about 3.5% of all residential refuse discarded during that time. Municipal and domestic incinerators combusted 1.1×10^8 t of commercial and residential refuse in NYC during the 20th century (*14*) and account for a total refuse mass reduction of 8.0×10^7 t. This is equivalent to about 16% of all refuse disposed in NYC during the 20th century (includes residential and commercial refuse and the following assumptions from ref *14*: municipal incineration, 8.1×10^7 t combusted and 26% residue production; domestic incineration, 3.3×10^7 combusted and 37% residue production).

Paper. Based on available data, paper accounted for 24% of residential refuse discarded in NYC during the 20th century (by mass) and was the second most abundant refuse class during this time. High salvage value has been reported for waste paper in the first several decades of the century (*41*), and the diversion of paper for recycling probably lowered the relative content reported here for 1905. The use of paper by manufacturers for consumer products and packaging rose considerably after WWI (*37*) and contributed to the overall rise in fuel-ash-free per capita refuse discards (Figure 1). Paper replaced fuel ash as the most abundant residential refuse class in NYC by about 1950 (Figure 2).

With the exception of plastics, paper is the only major refuse class in NYC that did not decline substantially in mass fraction during the century. On a fuel-ash-free basis, the mass fraction of paper appears to have been relatively steady throughout the century, ranging between about 25 and 40%. Mass fractions of paper in NYC residential refuse are generally consistent with reports of regional and national averages for most of the century (*1*, *3*, *4*, *8*, *9*).

Plastics. Plastics are not reported in NYC residential refuse in waste surveys conducted in 1905 and 1939 but increase

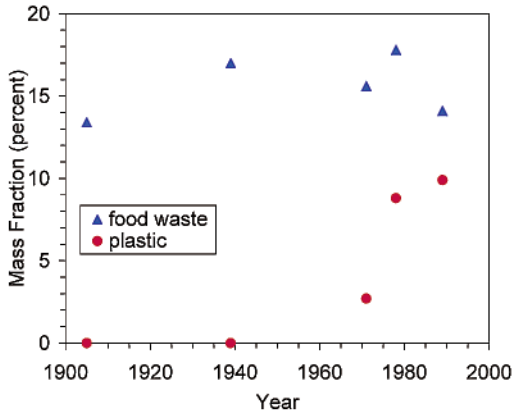

FIGURE 3. Mass fraction of plastic (red circles) and food waste (blue triangles) in residential refuse in NYC for the 20th century (sources in Table 2). Plastics content shown for 1989 does not include material diverted by beverage container deposit redemption.

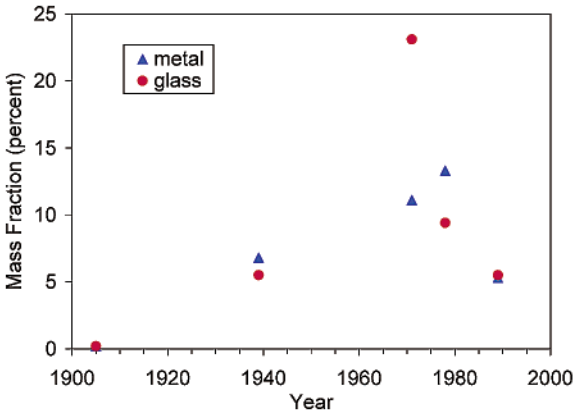

FIGURE 4. Mass fraction of metal (blue triangles) and glass (red circles) reported in residential refuse in NYC for the 20th century (sources in Table 2).

to 3% of residential refuse mass by 1971 (*18*) and 10% in 1989 ((*20*) Figure 3). This increase in mass fraction is consistent with reported national trends (*3*). Lightweight plastics and aluminum replaced much heavier material in consumer products and packaging (steel, glass, etc. (*3*, *41*)). Since the 1970s, the mass of plastic in some common refuse items (milk containers, beverage bottles, etc.) is reported to have decreased substantially (*41*). Despite this shift to lighter-weight materials and legislation mandating deposits on most beverage containers in the mid-1980s (*22*), the rate of per capita mass discard of residential refuse in NYC has not changed over the last two decades. This suggests that these factors, which would otherwise reduce per capita discards, have played a role in offsetting increases in refuse mass from other quarters and thus were instrumental in stabilizing per capita discard rates after 1980.

Glass and Metal. Glass and metal have combined to account for about 10−35% of NYC's residential refuse mass since 1939 (Figure 4), based on available data. Tin cans and glass bottles are reported to account for most metal and glass discarded in NYC prior to the 1970s (*9*−*11*, *42*) and illustrate the historical importance of food and beverage containers in determining the character of urban residential refuse. Reusable glass beverage containers were used extensively in the U.S. until they were replaced by nonreturnable steel and glass containers in the late 1960s (*43*). This probably explains much of the rise in mass fraction of metal and glass in residential refuse in NYC by the early 1970s (Figure 4). Increased abundance of metal and glass was reported for residential refuse in other U.S. cities in the late 1960s (*43*).

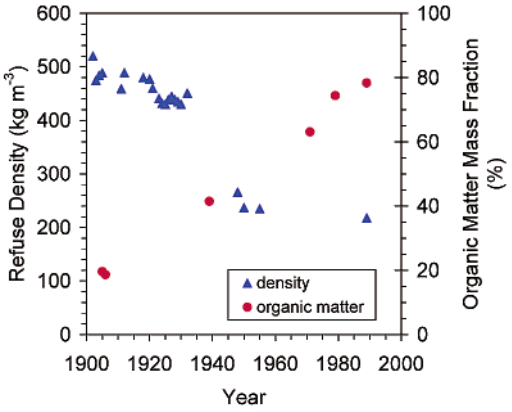

FIGURE 5. Bulk density (blue triangles, left scale) and mass fraction of organic matter (red circles, right scale) in NYC residential refuse for the 20th century (sources for density in Table 2, SI-1 (Supporting Information), and 1, 45 and 46; and for organic matter content in 25 and 31).

Large reductions in mass fractions for glass (75% between 1971 and 1989) and metal (60% between 1979 and 1989) are observed at the end of the century, based on available data (Figure 4). Decline in glass and metal content was reported for refuse in the U.S. during this period based on materials flow analysis and was explained by replacement of steel and glass containers by lighter-weight plastic and aluminum and by diversion from refuse discards due to beverage container deposit legislation (*3*). These factors probably also explain much of the decline in glass and metal content reported here for NYC.

Food and Other Organic Wastes. On an ash-free basis, food waste accounted for about 65% of NYC's residential refuse in the early 1900s but declined to 30% by 1939 (Table 2). Increased use of automotive vehicles in the early century extended the distribution area of food products by reducing cost and increasing speed of food transport, thus making fruits and vegetables readily available in U.S. cities during all seasons (*44*). Inefficient refrigeration during this period favored increased food waste discards due to spoilage and retention of trim materials for removal in the household after sale. The mass fraction for food waste declined to 16% in 1971 (*18*) and 13% in 1989 ((*20*) Figure 3). This decline can be partly attributed to the emergence of improved refrigeration, which reduced spoilage and trim waste (*44*). By the 1950s, manufacture of frozen foods resulted in the sale of fewer untrimmed vegetables and an overall decrease in residential food waste discards (*5*, *9*) while presumably increasing paper and other food packaging waste. Increased use of chemical preservatives in foods lengthened product shelf life and reduced rates of discard due to spoilage.

Manure from horses used for public and commercial transportation during the first decade of the century is reported to account for one-third of street cleaning debris in NYC (*11*, *23*) and was therefore equivalent to about 6% of the total mass of refuse disposed. Use of horses for transportation in NYC began to decline after about 1910 and was substantially complete by the mid-1930s (*21*). This is consistent with reports for other U.S. cities (*37*).

Density and Total Organic Matter Content. Maximum reported bulk density (520 kg m^{-3}) and minimum total organic matter content (19% by mass; excludes residual organic matter in ash) for residential refuse in NYC are observed during the first decade of the century (Figure 5) and correspond to high mass fractions for fuel ash. A 50% decrease in density and a 4-fold increase in organic matter content of residential refuse is observed between about 1920 and 1990 (Figure 5). This can be attributed to the decrease in fuel ash content and increase in mass fractions for paper and plastics

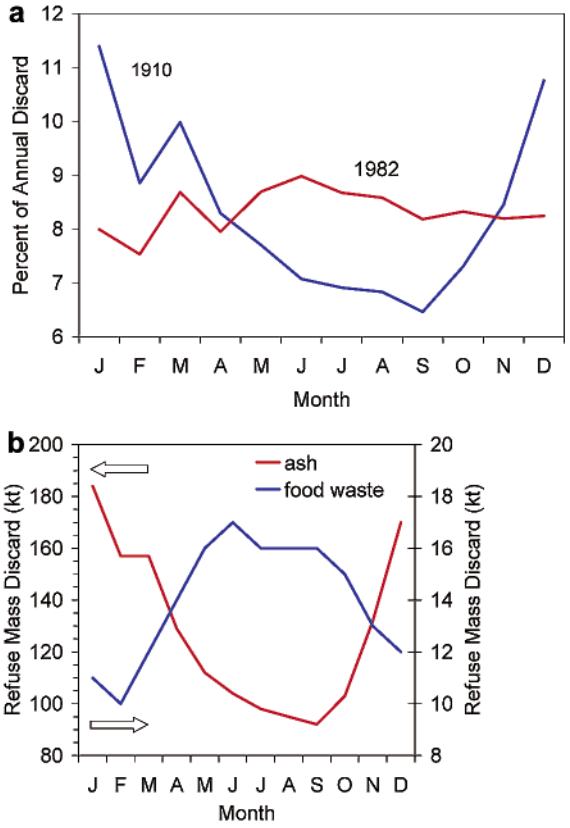

FIGURE 6. a: Monthly variation in the relative discard rate of residential refuse mass in NYC for 1910 (blue line) and 1982 (red line; data are from refs *21* and *31*, respectively). Monthly values are reported as percent of total annual mass, normalized to a 30-day month. b: Monthly mass discard rate of residential ash (red line, left scale) and food waste (blue line, right scale) in New York City in 1910 (data from ref *21*).

during this time. These long-term changes for NYC are consistent with smaller changes reported for shorter time intervals for other U.S. cities for refuse organic matter content (as measured by the combustible fraction of refuse (*3*, *43*, *45*, *46*)) and density (*5*, *9*, *47*).

Seasonal Variation. In the early 20th century, the rate of mass discard of residential refuse in NYC fluctuated throughout the year (Figure 6a). Maximum rates occurred in winter, due mainly to high rates of ash production from coal use for space heating (Figure 6b (*7*, *11*, *13*, *30*)). Maximum rates of food waste discard occurred in late summer due to greater availability of fruits and vegetables (Figure 6b (*11*, *13*, *30*)). Annual mass fluctuation for food waste was equal to about 10% of the fluctuation for fuel ash. Seasonal changes in rates of mass discard of residential refuse declined between 1920 and about 1960, mainly through reductions in the use of fuels with high ash content and improvements in methods of food preprocessing, preservation, and transport. By the 1970s, seasonal differences in refuse discard rates in NYC were small ((*34*) see Figure 6a). Attainment of seasonal consistency in the discard rate of residential refuse in NYC by this time corresponds to increased uniformity for other refuse characteristics on a nationwide basis, including composition (*1*, *41*, *48*) and chemical characteristics of refuse (*12*) and chemical characteristics of particles emitted from refuse incinerators (*49*).

20th Century Trends. The most significant trends in the composition of residential refuse in NYC during the 20th century are the decline in mass fractions for four of six major waste classes (fuel ash, food waste, metal, and glass), rising mass fractions for plastics, and sustained of high mass

fractions for paper. These factors were instrumental in the gradual conversion of residential refuse from mostly inorganic matter in the first half of the century to mostly organic matter in the second half, and a consequent decrease in refuse density. These changes had profound implications for all aspects of refuse collection, transportation, and disposal. Replacement of glass and metal with plastics during the last several decades has added to the chemical complexity of refuse and increased relative energy yield during waste combustion. Four-fold increase in refuse organic matter content has increased the available substrate for thermal oxidation in incinerators and microbiological mineralization in landfills, with resultant increases in the greenhouse gas production potential per unit of refuse mass. Assuming similar organic matter content for residential and commercial refuse and excluding residual organic matter in fuel ash, the total mass of organic matter in refuse disposed in NYC during the 20th century is approximately 2.4×10^8 t. If a moisture content of 25% and an average content of cellulose ($C_6H_{10}O_5$) are assumed, refuse disposed in NYC during the century has constituted a pool of 8×10^7 t of carbon (as C).

Changes in the composition and per capita mass discard rate of urban residential refuse during the 20th century have been the product of many factors. Influential factors suggested by this study are the ash content of residential fuels, use of new materials (i.e. plastics) and products (i.e. fuel oil), war, status of the economy, diversion of materials before discard for recycling, domestic incineration, and changes in the methods employed by product manufacturers and distributors for preprocessing, preservation, containerization, packaging, and transportation of consumer goods.

When viewed more broadly, the most influential factor affecting urban refuse characteristics in the 20th century appears to have been the evolution of technologies used by product manufacturers and distributors of consumer goods and, in particular, development of lighter and more convenient products for the marketplace. This movement has been driven by strong market forces (most notably, lowered transportation costs) and appears to have been instrumental in the decline of the four major waste classes noted above. Of the five principal waste classes for residential refuse in NYC prior to WWII, only paper has maintained high mass fractions through the end of the century. Similar to coal at the start of the 20th century, paper is now the most abundant consumer product in NYC, and, likewise, its replacement or elimination represents the greatest potential for reduction in product distribution costs and increase in consumer convenience. Trends observed for the 20th century suggest that technological advances will continue to shape urban refuse characteristics in the future, with the most significant changes being the progressive replacement of paper and other heavy refuse components by lighter and more chemically complex materials.

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Supporting Information Available

Table for NYC on the annual mass of total refuse disposed, residential refuse discarded, residential ash discarded, residential garbage discarded, sources of data, per capita residential refuse discarded, and refuse bulk density and population (Table SI-1). This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Niessen, W. R.; Chansky, S. H. In *Proceedings of 1970 National Incinerator Conference*; American Society of Mechanical Engineers: New York, 1970.
(2) Tchobanoglous, G.; Theisen, H.; Vigil, S. *Integrated Solid Waste Management, Engineering Principles and Management Issues*; Irwin McGraw-Hill: New York, 1993.
(3) Franklin, W. E.; Franklin, M. A. In *Proceedings Municipal Solid Waste Technology Conference*; Greenblott, J., Ed.; United States Environmental Protection Agency: Washington, DC, San Diego, CA, 1989; Vol. 1, pp 2−1.
(4) Hering, R.; Greeley, A. S. *Collection and Disposal of Municipal Refuse;* McGraw-Hill: New York, 1921.
(5) Bloodgood, D. E. *Refuse Removal J.* **1960**, *May*, 17.
(6) Hickman, H. L. *Scrap Age* **1969**, *Feb.*, 305.
(7) Eliassen, R. *Am. J. Pub. Health* **1942**, *32*, 1029.
(8) *Refuse Collection Practice;* Committee on Refuse Collection and Disposal, American Public Works Association: Chicago, IL, 1941.
(9) *Refuse Collection Practice*, 3rd ed.; Committee on Solid Wastes, American Public Works Association, Public Administration Service: Chicago, IL, 1966.
(10) Morse, W. F. *The Collection and Disposal of Municipal Waste*; Municipal Journal and Engineer: New York, 1908.
(11) Parsons, H. deB. *The Disposal of Municipal Refuse;* John Wiley & Sons: New York, 1906.
(12) Haynes, B. W.; Law, S. L.; Campbell, W. J. *Metals in the Combustible Fraction of Municipal Solid Waste*; Report of Investigations 8244; Bureau of Mines, U.S. Department Interior: Washington, DC, 1977.
(13) Fetherston, J. E. *Final Disposition of Refuse*; Report to Committee on Refuse Disposal; New York City Board of Estimate and Apportionment: New York, 1916.
(14) Walsh, D. C.; Chillrud, S. N.; Simpson, H. J.; Bopp, R. F. *Environ. Sci. Technol.* **2001,** *35*, 2441.
(15) Walsh, D. C. Ph.D. Dissertation, Rensselaer Polytechnic Institute, 1996.
(16) Walsh, D. C.; LaFleur, R. F. *Ground Water* **1995,** *33(4)*, 556.
(17) Walsh, D. C.; *Environ. Sci. Technol.* **2002**, *36* (15), 316a.
(18) Kaiser, E. R.; Kasner, D.; Zimmer, C. *Incinerator Grate Deterioration: Causes, Cures and Costs;* Final Report to City of New York Environmental Protection Administration; New York University: New York, 1972.
(19) Study of Municipal Solid Waste Quantity, Composition and Heating Value-Spring Creek Area, Brooklyn, New York; Port Authority of New York and New Jersey: New York, 1979. In *The Waste Disposal Problem in New York City: Proposal for Action*; New York City Department of Sanitation: New York, 1984.
(20) *New York City Waste Composition Study (1989−1990) Final Report;* New York City Department of Sanitation: New York, 1992.
(21) *Annual Reports of the New York City Department of Sanitation*; New York City Department of Sanitation: New York, selected years 1898−1964.
(22) *Mayor's Management Report*; New York City Office of the Mayor: New York, biannual report for years 1975-1999, inclusive.
(23) Very, E. D. *Proc. Am. Soc. Civ. Eng.* **1908**, *28(8)*, 378.
(24) Parsons, H. DeB. *Proc. Am. Soc Civ. Eng.* **1908**, *28(8)*, 376.
(25) Fetherston, J. T. *Proc. Am. Soc Civ. Eng.* **1908**, *28(8)*, 380.
(26) Craven, M. *Brooklyn Eng. Club* **1901**, Paper 29.
(27) Allen, K. A. *Am. Soc. Civ. Eng.* **1927**, *91*, 838.
(28) Parsons, H. deB. *Am. Soc. Civ. Eng. Trans.* **1906**, LVII, Paper 1027, 45.
(29) *United States Census;* Department of Commerce, Bureau of the Census: United States Printing Office: Washington, DC, decadal reports from 1900 through 2000, inclusive.
(30) Fetherston, J. T. *Am. Soc. Civ. Eng. Papers Discussions* **1907**, *33(9)*, 940.
(31) Solid Waste Sampling Program, CSI Resource Recovery Systems, Inc. for New York City Department of Sanitation: New York, 1982. In *The Waste Disposal Problem in New York City: Proposal for Action*; New York City Department of Sanitation: New York, 1984.
(32) Fenton, R. *An Analysis of the Problems of Sanitary Landfills in New York City*; Bureau of Sanitary Engineering, New York City Health Department: New York, 1947.
(33) *Statistical Waste Disposal Reports*; New York City Department of Sanitation: New York; annual reports for years 1957-1971, and 1973.

(34) *Solid Waste Disposal Operations Plan*; New York City Department of Sanitation and Wehran Engineering: New York, 1981.
(35) U.S. Congress, *Facing America's Trash*; OTA-O-424; Office of Technology Assessment, U.S. Govt. Printing Office: Washington, DC, Oct., 1989.
(36) USEPA, *Decision Makers Guide to Solid Waste Management*; EPA/530-SW-89-072; U.S. Govt. Printing Office: Washington, DC, Nov., 1989.
(37) Melosi, M. V. *Garbage in the Cities: Refuse, Reform, and the Environment, 1880−1980*; Texas A&M University Press: College Station, TX, 1981.
(38) Pearl, R. *J. Ind. Eng. Chem.* **1918**, *Nov.*
(39) Eliassen, R. *Eng. News-Rec.* **1942**, *June 4*, 72.
(40) Kaiser, E. R.; Halitsky, J.; Jacobs, M. B.; McCabe, L. C. *J. Air Pollut. Control Assoc.* **1959**, *9*, 85.
(41) Rathje, W.; Murphy, C. *Rubbish! The Archaeology of Garbage*; HarperCollins: New York, 1992.
(42) Kaiser, E. R.; Zeit, C. D.; McCaffrey, J. B. In *Proceedings of 1968 National Incinerator Conference*; American Society Mechanical Engineers: New York, 1968.
(43) *Solid Waste Disposal*; Ohio Legislative Service Commission: Akron, OH, 1970; Staff Research Report 100.
(44) Herberger, A. H. *Collection and Disposal of Refuse in New York State Municipalities*; Bureau of Training and Research, New York State Conference of Mayors: Albany, NY, 1935; Publication 36.
(45) Greeley, A. A.; Clarke, S. M.; Gould, R. H. *Am. City* **1955**, *May*, 102.
(46) Rogus, C. A. *Civ. Eng. (NY)* **1952**, *Dec.*, 54.
(47) Stephenson, J. W.; Cafiero, A. S. In *Proceedings of 1966 National Incinerator Conference*; American Society Mechanical Engineers: New York, 1966.
(48) Niessen, W. R.; Alsobrook, A. F. In *Proceedings of 1972 National Incinerator Conference*; American Society Mechanical Engineers: New York, 1972.
(49) Greenberg, R.; Gordon, G. E.; Zoller, W. H.; Jacko, R. B.; Neuendorf, D. W.; Yost, K. J. *Environ. Sci. Technol.* **1978**, *12*, 1329.

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