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Role of plastics in decoupling municipal solid waste and economic growth in the U.S.

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ABSTRACT

Analysis of data from the US Environmental Protection Agency (EPA) on municipal solid waste (MSW) generation rates correlated to personal consumption expenditure (PCE) uncovers a decoupling event occurring between 1997 and 2000. A comparison of waste generation rates for each material category found in MSW reveals that plastics increased by nearly 84 times from 1960 to 2013 while total MSW increased only 2.9 times. The increase in plastic waste generation coincides with a decrease in glass and metal found in the MSW stream. In addition, calculating the material substitution rates for glass, metal and other materials with plastics in packaging and containers demonstrates an overall reduction by weight and by volume in MSW generation of approximately 58% over the same time period. A quantitative calculation of a scenario where plastics were not used in packaging and containers to replace glass, metal, and other materials demonstrates that MSW generation rate rises equally with PCE. Therefore, this study has determined that the increase of plastic use is a contributing factor to the decoupling of MSW generation from PCE.

1. Introduction

There has been a general trend regarding average MSW generation increasing with nominal Gross Domestic Product (GDP) of a region or country. The correlation has given rise to hypotheses that affluent societies consume more materials and resources and therefore, have a commensurately higher increase in MSW generation rates than less affluent societies. A more detailed inspection of the data indicates that actual MSW generation falls within a range of 2–6 lb per person per day (lb/person/day) over a range of GDP from $5000 to $110,000, respectively (Hoornweg and Bhada, 2012). This suggests that, regardless of region or income, there is a fairly consistent rate of material use that eventually is discarded as waste, applying a stress to the environment. Generally, more affluent regions or nations can counteract the environmental impact of development and waste generation by attempting to decouple MSW generation with GDP, productivity, standard of living increase or personal consumption expenditure (PCE).

Many developed and affluent nations have established material recovery programs (e.g. recycling) to attempt to decouple their continued increase in standard of living with an associated increase in MSW generation (Hopewell et al., 2009). The adaption of the Economic Kuznet Curve (EKC) to waste has resulted in a generally accepted Waste Kuznet Curve (WKC) (Fischer-Kowalski and Amann, 2001; Seppälä et al., 2001). The WKC has developed in the same way as the EKC describing a trajectory where initial increases of income per capita or GDP are directly correlated to increases in pollution or environmental degradation. Eventually, a transition begins where continued rises in per capita income result in a decrease in environmental degradation. Initially, there is a relative decoupling where waste generation rates rise more slowly than per capita income followed by an absolute decoupling where waste generation rates actually decline with a rise in per capita income.

A number of studies have been done on waste generation decoupling, mostly in the European Union (EU). In Europe, it is has been observed that decoupling potentially exists due to policy implementation, regulations, and tax penalties. Although the evidence is uneven, there does appear to be segments that experience a relative decoupling in recent years. However, a couple of studies (Cole et al., 1997; Seppälä et al., 2001) found no evidence of a transition to the inverted U-curve segment associated with a WKC.

A report by Mazzanti and Zoboli concludes that while there is no trend for waste generation (i.e. no observed WKC), policy directives in the early stages of implementation may work. They observe some early positive signals in favor of a relative de-linking for waste generation and associated landfill diversion (Mazzanti et al., 2006; Mazzanti and Zoboli, 2008). In another report by Mazzanti et al., they

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conclude that there is no relative WKC observed however there is evidence of absolute decoupling, specifically regarding wastes that are landfilled (Mazzanti et al., 2012; Mazzanti and Nicolli, 2011). Regarding landfill diversion, the decoupling observed is driven by factors related to structural (population density) and economic (opportunity costs) parameters.

A more specific analysis done by Montevecchi et al. investigates the effectiveness of environmental policy instruments to decouple waste generation using a case study in Slovakia. They find an absolute decoupling occurs primarily via policy and tax drivers but also recognizes that raising awareness and education campaigns appear to help (Montevecchi, 2016). Zorpas et al. determined that regardless of the wealth of a country or region, motivation is needed for the citizens to alter their behavior regarding waste impacts on the environment. The primary motivations were identified as tax penalties or financial incentives (i.e. income to the consumer) (Zorpas et al., 2014). Other cases studies find similar outcomes (Sjöström and Östblom, 2010).

Triquero et al. found that there is a combination of government and market based incentives that could improve regulatory framework to minimize waste. Implementing a proactive and preventive approach to enhance responsibility while involving all stakeholder groups could decouple waste generation from economic growth (Triguero et al., 2016). Finally, Poulios and Latinopoulos attempted to determine if a WKC relationship exists using time-series data over a 15 year-period from the Thessaloniki region of Greece. They uncovered evidence that enacted legislation related to waste management has not proven successful however, high gate fees and landfill bans had an immediate impact on waste diversion (Katsifarakis et al., n.d).

Based on the cited studies, it is evident that factors such as policy and awareness can contribute to reduce MSW generation and landfill diversion but the US is driven by consumer demand and the cost of associated desired goods. Therefore, reduction in materials consumption in the US is not likely. Importantly, due to the lack of a national policy/directive or tax in the U.S. on MSW generation, the only implication for the decoupling between MSW generation and economic growth must be due to material stream changes. The biggest change in the composition of the MSW material stream over time has been in the plastics content, therefore, it is possible that the decoupling is correlated to plastics entering the consumer materials stream. This study has determined that the increase in plastic products across nearly all consumer sectors aligns with the possibility to yield lower cost consumer items and results in a decoupling of the waste generation to GDP and PCE. This is the first possible direct correlation where the substitution of one type of material (e.g. plastic for glass, metal, and other materials) enables the MSW decoupling that is pursued by policy or central actions. In this study, multiple pieces of evidence are presented that suggest a relative decoupling between MSW generation and economic growth, which in this case was defined by PCE. The MSW generation also serves as a surrogate for MSW disposal because there is assumed to be no accumulation of MSW at the individual or local level. In other words, all MSW generated is disposed (i.e. reused, recycled, combusted for energy recovery, and landfilled), according to the average rates for each part of the waste management hierarchy. An assessment of changes in the MSW composition in the US is also presented along with hypotheses as to why this MSW decoupling is occurring regardless of any specific policy or law implemented to reduce MSW in the US.

2. Materials and methods

The analyses conducted were based on public and internal data compiled by the American Chemistry Council (ACC) Plastics division, the US EPA, EREF, and the Earth Engineering Center at City College of New York (EEC|CCNY). This section provides a brief explanation of the primary calculations that were performed to identify correlations between the MSW material streams and MSW generation trends that are discussed in the Results and Discussion section of this study.

2.1. Volume calculations

Calculations were performed to determine the volume of MSW generated in the US over time. The volume of MSW was calculated using different methods and was crosschecked to compare the accuracy of final calculated reported values. One such method was based on the densities of material streams in MSW and the other utilized the volume-to-weight conversion factor for MSW provided by the EPA. For the first method, average densities reported in the literature of materials in MSW were used to convert the material stream tonnages to volumes (the material stream tonnages were calculated based on the percent material breakdown of MSW reported by the EPA for each given year). The total volumetric generation of MSW was calculated as the summation of the individual volumes of the material streams. The material densities that were used are shown in Table 1 and they are the average of reported low, medium, and compacted densities for each material.

The second method used a volume-to-weight conversion factor reported by the EPA in the April 2016 report, “Volume-to-Weight Conversion Factors”. The conversion factor used was for “Uncompacted, Mixed MSW – Residential, Institutional, Commercial”, which is reported to range from 250 to 300 lb per cubic yard (lb/yd^3); therefore, the average of the lower and upper bound, 275 lb/yd^3, was used in the calculations of this study.

An additional method that was employed to check the primary volume calculations used an average density of 0.18 ton m^{-3} obtained from data from the US EPA Landfill Methane Outreach Program (LMOP). The density estimation was determined combining US EPA data of actual tons landfilled (i.e. waste in place) amounting to 7,418,578,787 tons with the amalgamated average MSW density. The average MSW density was developed using a weighted average of each category based on a typical composition of MSW from years ranging from 1960 to 2013. A second calculation was performed to obtain the density of MSW by applying the formula, $0.305 \times \rho_{paper} + 0.061 \times \rho_{glass} + 0.107 \times \rho_{metal} + 0.066 \times \rho_{plastics} + 0.0142 \times \rho_{food} + 0.181 \times \rho_{yard} + 0.138 \times \rho_{other}$ to the waste stream densities in Table 1 and resulted in a value of 0.17 tons m^{-3}. These are in close agreement therefore, an average value of 0.175 tons m^{-3}. Please refer to Supplemental Information for further detail on the methodologies that were used to confirm volume generation of MSW in the US.

Table 1
Densities for each category of MSW[a]. *Source:* Waste Materials – Density Data, Environmental Protection Authority Victoria.

Category	kg m^{-3}	Tons m^{-3}
ρ paper	152	0.167
ρ glass	331	0.364
ρ plastics	101	0.111
ρ metal	130	0.142
ρ food	629	0.692
ρ yard	254	0.280
ρ other	93	0.103

[a] The densities reported in the table are different from physical material densities because they represent material densities in the waste stream. Therefore, factors such as moisture content and waste material compaction will contribute to variation from the physical material density.

2.2. Material substitution scenario

To understand the impact of plastics on MSW, this study quantitatively analyzed hypothetical scenarios in which plastic was removed from the waste stream and was substituted with glass, metal and other materials in its product applications. For US packaging, the combined weight of alternative packaging that would be needed to substitute US plastic packaging is about 4.5 times more than the weight of the plastic packaging that is replaced (see Supplemental information for details on the determination of this value). For all other product applications, the plastics material substitution ratio is 3.2, meaning that it would require 3.2 times more material by mass for the same product if plastic was replaced (Franklin Associates, 2014) [17]. Please refer to the Supplemental Information for additional details on the material substitution calculations that were performed in this study.

3. Results

Comparisons were made of MSW generation tonnage and PCE as a function of time to provide an initial understanding of the potential for decoupling. Fig. 1 shows the comparison between PCE and two different estimates of MSW generation in the US. One estimate is from the EPA and the second is from the Biocycle studies, which use a different methodology than EPA to determine MSW generation. The values are indexed to 1989 (the earliest year that the Biocycle survey has data for) to enable a direct comparison between the two estimation processes.

Evident in Fig. 1 are two different times where the estimated MSW generation data deviates from the PCE data corresponding to the two estimation methods. If there was no relative decoupling, the slope of the MSW generation tonnage data would be similar to the slope of the PCE data for the entire time range. It is apparent that by using the EPA estimation data, a decoupling seems to occur approximately in 1995, whereas the Biocycle data exhibits the decoupling occurs near 2000. The proximity of these time frames suggests that relative decoupling occurs regardless of the estimation method. The time difference between the two methodologies, while measureable, is not considered significant. The clear identification of the decoupling time frame is more important. Therefore, EPA values will be used for further comparisons and analyses in this study because they are determined from a consistent and long-standing methodology. The important aspect is the time frame, not necessarily the exact timing. The waste stream changes gradually because it is influenced by policy decisions and consumer behavior related to socio-economic variations and trends. The decisions and behavioral changes are realized over an extended period, on the order of 5 years, therefore a delayed or damped signal will be observed in the characteristics of the waste stream.

As discussed in the introduction, there is evidence that relative, and perhaps absolute, decoupling is occurring in the EU primarily due to policy directives related to material that must be excluded from landfill. Those drivers do not exist in the US; therefore, other factors contribute to the decoupling displayed in Fig. 1. During the time frame between 1995 and 2000, the US MSW waste stream began to change; the increase in generation tonnage does not correspond directly to PCE or GDP (not shown in Fig. 1) growth rates. The decoupling is fairly significant since the PCE slope remains relatively constant at 0.047 while the MSW generation slope, based on EPA, is 0.019 from 1995 and later. In other words, using the EPA MSW generation estimates, beginning in 1995, the MSW generation growth rate is about 40% of the PCE growth rate.

A similar relative decoupling is observed when including the volume of the MSW generated. The volume data is important because landfill capacity is largely based on the volume of waste that can be contained. Fig. 2 presents mass and volume data indexed to 1960, the year EPA started to publish their state of waste reports. The Biocycle values are re-indexed to match the EPA indexed value in the year 1989, again the first year Biocycle began to publish MSW generation rates. Since the MSW generation data is reported on a weight basis, two methods to determine volume were used. The first calculated based on material densities of MSW stream categories and the weighted MSW composition percentage as provided by the EPA. The second used an aggregate mass to volume conversion factor of 5.6 m^3 per ton reported by the EPA

Fig. 2 shows the indexed values of weight and volume from 1960 to 2013, the latest data available with the required

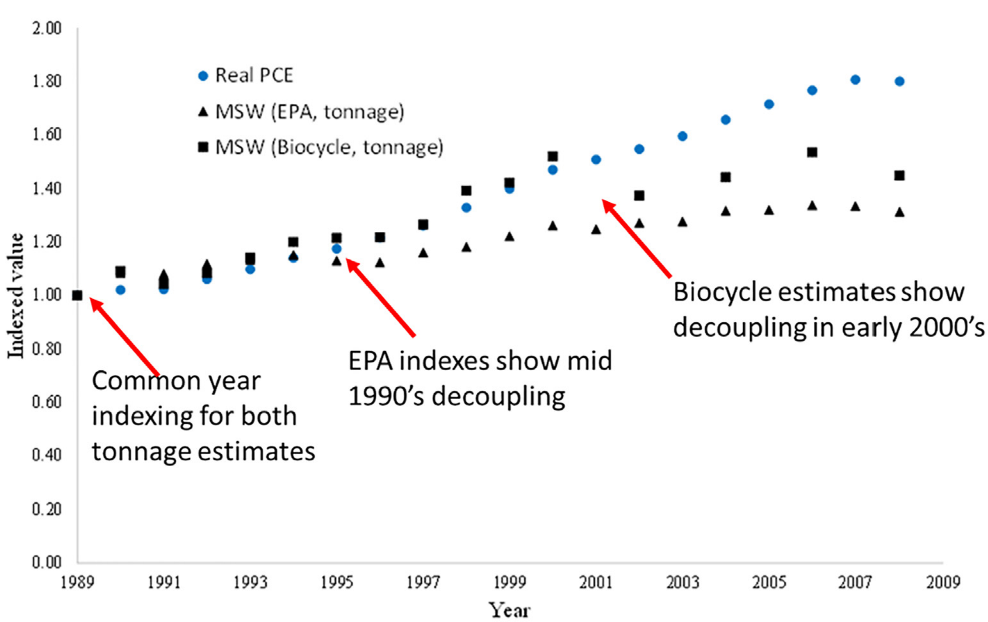

Fig. 1. Indexed comparison of PCE and MSW tonnages generated based on EPA and Biocycle estimation methodologies for MSW generation.

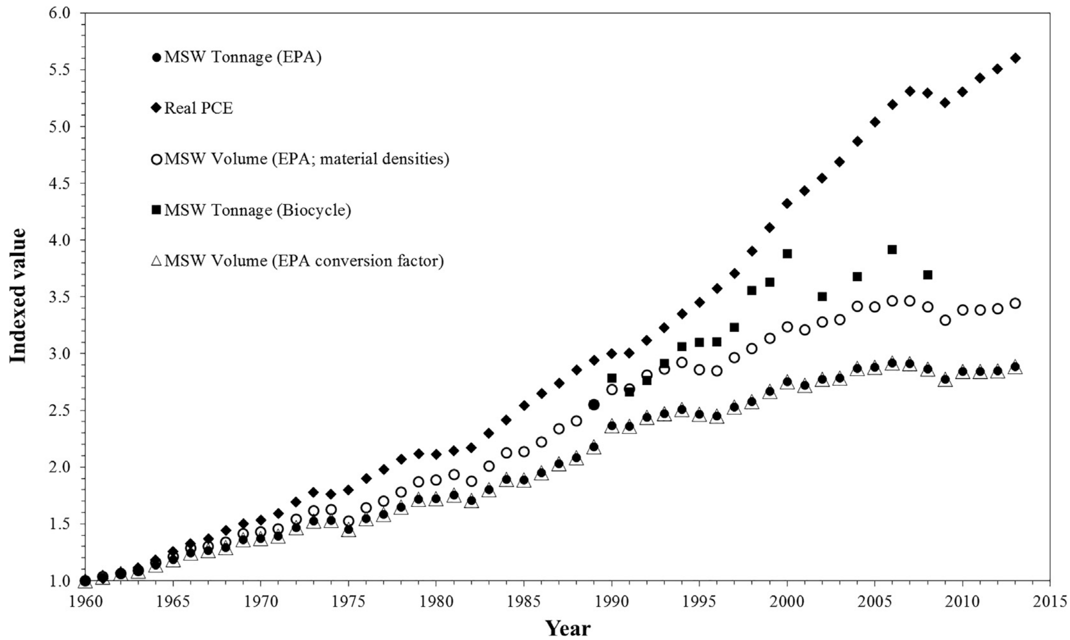

Fig. 2. Indexed comparison for MSW generation based on tonnage, weight, and PCE as a function of time.

resolution. The volume reported in Fig. 2 is based on the conversions using only the EPA MSW generation tonnage estimates. The indexed value for the EPA estimates of tonnages are identical to the calculated volume using the EPA conversion factor because a constant value of 5.6 m^3 per ton is used. These are shown in Fig. 2 by the overlapping open up-triangle and the filled circles. The indexed volume values determined using the material densities exhibit a different divergence time. Nonetheless, this data still shows that there is a relative decoupling based on MSW volume generation compared to PCE occurring somewhere between 2000 and 2005. This time frame overlaps with the tonnage time frame shown in Fig. 1.

Comparing the PCE and EPA tonnage values on a parity plot as a function of time, shown in Fig. 3, provides a more precise indicator to identify when decoupling occurs. The data presented in Fig. 3 compares the EPA MSW generation values in millions of tons generated and the PCE values in billions of 2009 chained dollars. Here, MSW generation rate and PCE are directly correlated until 1989, 1994 and 1998–2000, as shown by the thin equal slope line. In 1989, there is briefly an observed increase in MSW generation compared to the PCE rates. During the 1990–1992 time frame, the divergence plateaus and then begins to reverse in 1994. This reversal lasts long enough to bring the MSW generation and PCE back into alignment. The next divergence observed begins between the years 1998 and 2000 and is maintained for the remainder of the data set. Since these values are not indexed, they can be considered a quantitative measurement of when the MSW generation rate, using the EPA estimates, deviates from economic growth, as measured by PCE. Therefore, a decoupling between waste generation and economic growth occurs precisely between the years 1998 to 2000. Finally, upon close inspection, a further departure from the PCE growth curve is observed starting in 2010, which may suggest the beginning of an absolute decoupling.

The evidence presented above includes all categories of the waste stream. However, recently there has been a large effort to remove green waste from the MSW stream. For example, over 19 million tons of yard trimmings were composted in 2012 whereas only 4.2 million tons were composted in 1990 (US EPA, 2015).

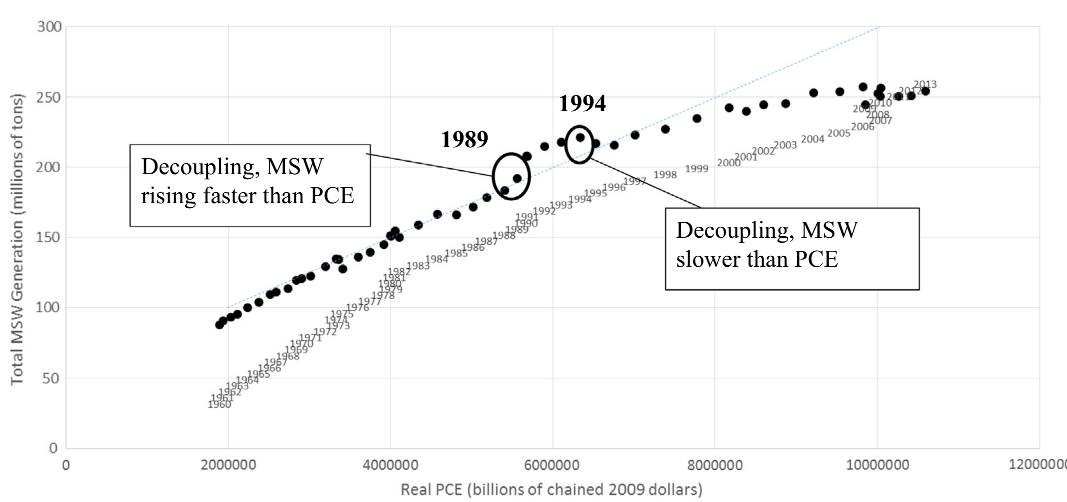

Fig. 3. Parity plot for total tons of MSW generated and PCE.

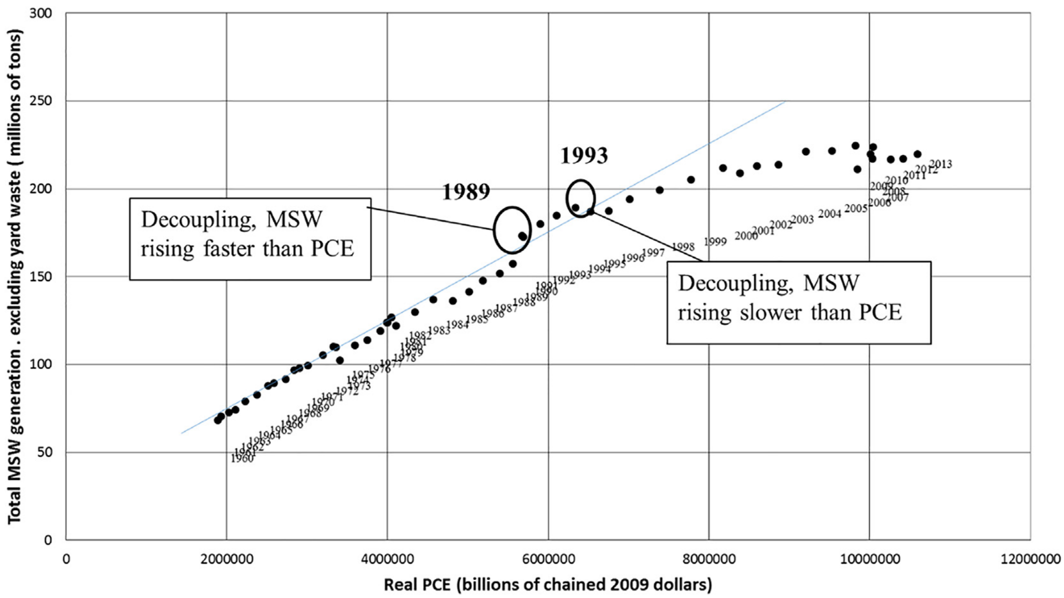

Fig. 4. Parity plot of total tons of MSW generated, excluding yard waste, and PCE.

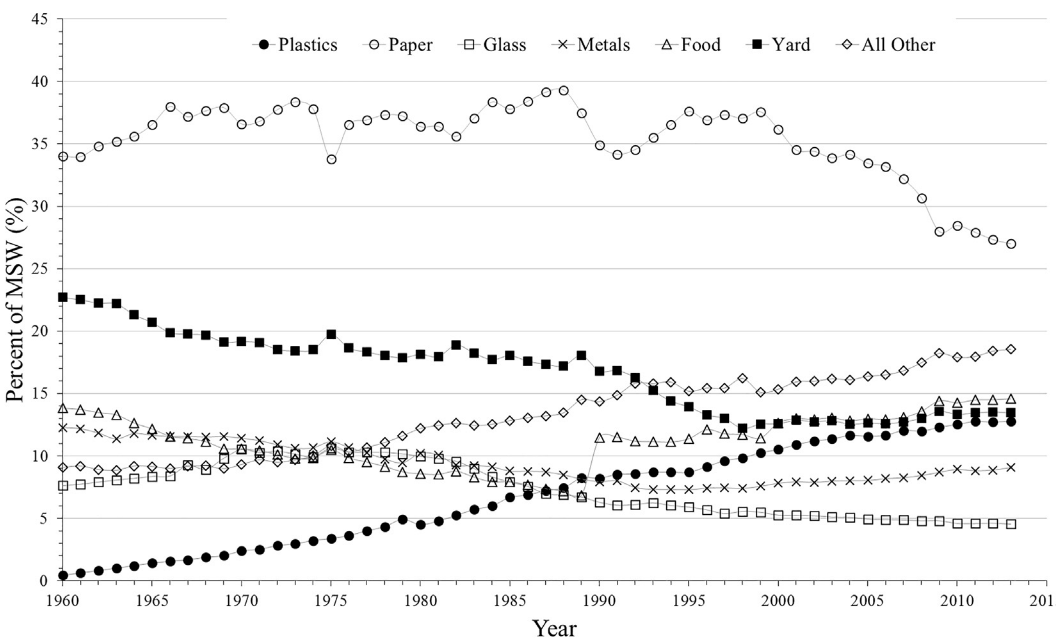

Fig. 5. Material categories comprising overall MSW, absolute percent.

Currently, the recovery and composting of yard wastes is nearly 58% of the MSW generation compared to 1990 when it was only 12%. However, the amount of yard trimmings remained nearly constant over this time, changing from 35 million tons in 1990 to 33 million tons in 2012. Therefore, the MSW generation data shown in Fig. 3 was adjusted by removing yard waste to enable comparisons without the variable component of yard waste. Fig. 4 presents that adjusted data.

Even with removing yard waste from MSW, the finding that there is a relative decoupling still holds, although it begins slightly earlier. MSW generation rate and PCE are directly correlated until 1993 without yard trimmings. The relative decoupling is observed to begin between 1997 and 2000, representing a consistent offset associated with the removal of yard waste. In Fig. 4, the total amount of MSW is adjusted down from 88 million to 68 million tons in 1990. This was determined by calculating the yard waste using the percent composition in the MSW stream reported by EPA and subtracting it from the total MSW. Based on Fig. 4, it can be seen that removing compostable yard waste from the waste stream is not the cause of the relative decoupling observed.

To uncover a potential causation for the observed relative decoupling that occurs in the 1998–2000 time frame, comparisons of the separate waste material categories versus PCE were explored. Fig. 5 shows the trends in the different material categories that comprise the MSW stream from 1960 until 2013.

The data shows that for nearly all categories except 'Plastics' and 'All Other' that their percentage in MSW declines. The 'Food' data set shows an abrupt increase in the year 1990 due to a change in EPA's estimation methodology for food waste. Metals generally decline from 1960 to the 1990s, plateau during the 1990s and then

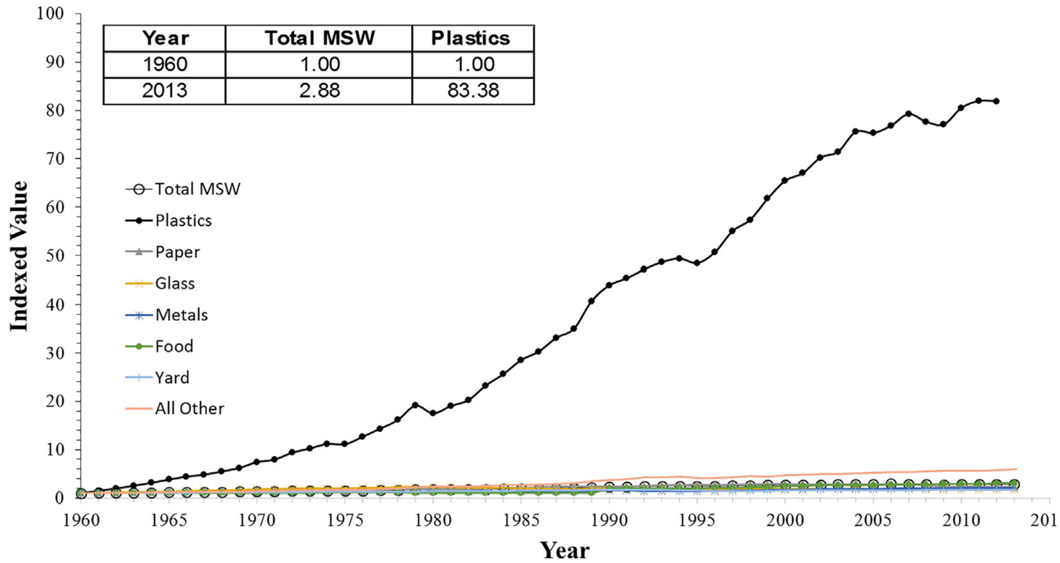

Fig. 6. Material categories comprising MSW indexed to 1960 values.

slightly increase in the beginning of the 2000s. Glass demonstrates an initial increase followed by a smooth decline from approximately 1975 until a general plateauing or very slight increase in the early 2000s. 'Paper' remains range-bound between 35 and 40% for a much longer period of time, yet definitively experiences a decline approximately in the year 2000. This is coincident with the 1998 to 2000 time frame established for the decoupling. However, this decline does not account for the divergence observed in Figs. 3 and 4. 'Yard Waste' shows a slight but steady decline from 1960 until 1990 after which its contribution to the waste stream declines dramatically due to the efforts to divert it to composting, as mentioned previously. The yard waste trend is a result of one instance where a policy implemented at the municipal level throughout the country resulted in a demonstrable outcome (US EPA, 2015).

The 'All Other' category rises during the same time frame as the other material categories decrease. This is an outcome of the methodology that EPA uses to calculate generation rates. The defined categories cannot be precisely estimated. Therefore, as the MSW generation rate increases any discrepancy resulting from the category estimation must be balanced by the 'All Other' category. However, the 'Plastics' stream, which is well classified, is the only other material stream to increase during this time.

To examine the relative changes in the material categories that comprise the MSW stream, values were indexed to 1960 (similar to what was done in Figs. 1 and 2). Fig. 6 shows each material category of MSW indexed to 1960 based on the EPA estimation method. In other words, the ratios presented are the tonnage of the material stream in a given year to its value in 1960. From Fig. 6, it becomes obvious that the material that has experienced the largest increase in its fraction of the MSW stream is plastics. Every other category changes by less than a factor of three while simultaneously plastics increase by nearly an two orders of magnitude. The table inset in Fig. 6 shows that from 1960 to 2013, the overall MSW generation has increased by 2.88, on a weight basis, whereas plastic generation has increased by 84 times on a weight basis.

The data shown in Fig. 6 provides the strongest evidence that plastics could be a likely contributing reason for the decoupling observed in Figs. 1–4. This large increase in plastics entering the waste stream is aligned with the general reduction of glass, metal and paper. The materials that have been shown to be replaced by plastics are primarily metals and glass in containment and packaging products (US EPA, 2015). While plastics have experienced an ever increasing penetration into the consumer market for the past century, it was not until the 1960s that economical and safe mass production of plastics became available (American Chemistry Council, Plastic Resins in the United States, 2014). Since that time, plastic substitution of materials, especially glass and metals in the food packaging and toy industries, has steadily increased (American Chemistry Council, Plastic Resins in the United States, 2014). For example, in the container and packaging sector, the plastic contribution in the waste stream went from 120,000 tons in 1960 to 13,980,000 tons in 2013. That is an increase of approximately 13.9 million tons while simultaneously, glass increased by only approximately 3.1 million tons, from 6,190,000 to 9,260,000 tons, and metal decreased by approximately 2.3 million tons, from 4,660,000 to 2,400,000 tons. This large increase in material replacement with plastics has occurred even with a simultaneous downgauging or thinning of the plastic packaging and materials. Initial thicknesses of plastic packaging material averaged approximately one-third of the weight of the combined glass and metal replacement until the year 2000. Starting in 2000, the plastic packaging continuously decreased by about 3% per year, further reducing the weight exchanged until the ratio reached one quarter of the combined replacement weight (Franklin Associates, 2014). Even with this significant increase in plastics, the total MSW generation did not increase significantly as is shown in Fig. 6. Please refer to the Supplemental Information for an example of this calculation.

A scenario was developed to explore how the relative decoupling observed during the 1998 to 2000 time frame would be impacted if glass, metal and other materials were not substituted by plastic. Details of the calculation are in the Supplemental Information and a brief description is provided here. Based on data obtained from plastic manufacturers (Franklin Associates, 2014), a mass conversion estimate was developed. The estimated weight ratio, using amalgamated data obtained from the major U.S. manufacturers, for non-plastic containers and other products to plastic ones is 3.2. In other words, the weight of material that would be needed to replace plastics for the same product applications, such as containers, would be 3.2 times more than if plastics were used. The ratio used for packaging applications ranged from 3.32 in 1960 to 4.5 in 2013. The increase in the weight ratio is a result of the downgauging or thinning of the plastic packaging material from

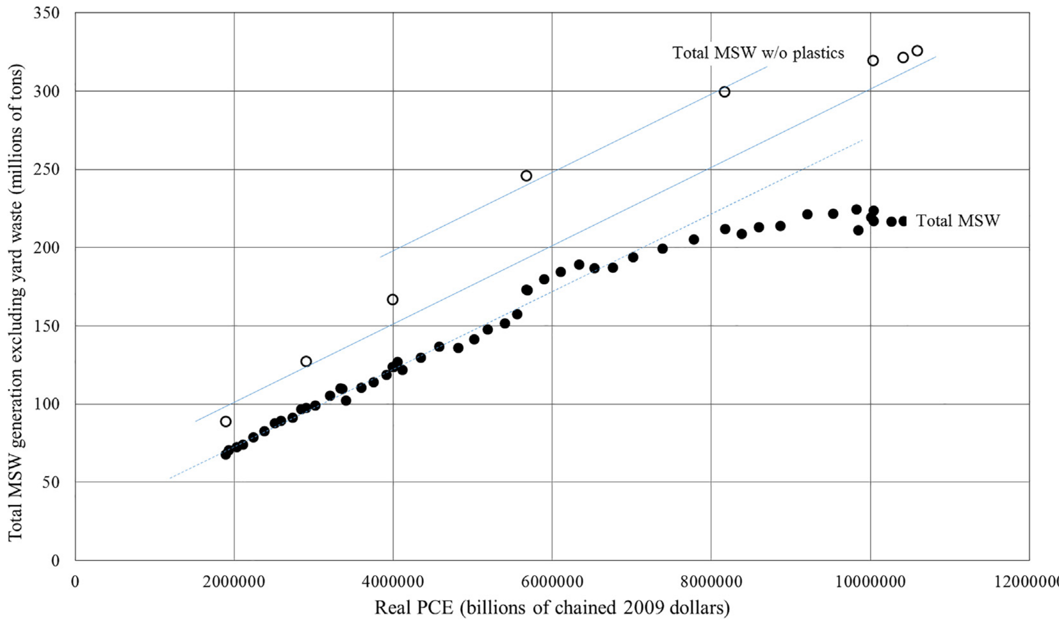

Fig. 7. Parity plot for scenario of total tons of MSW generated, excluding yard waste, without plastic substitution for glass and metal packaging and containers and PCE growth.

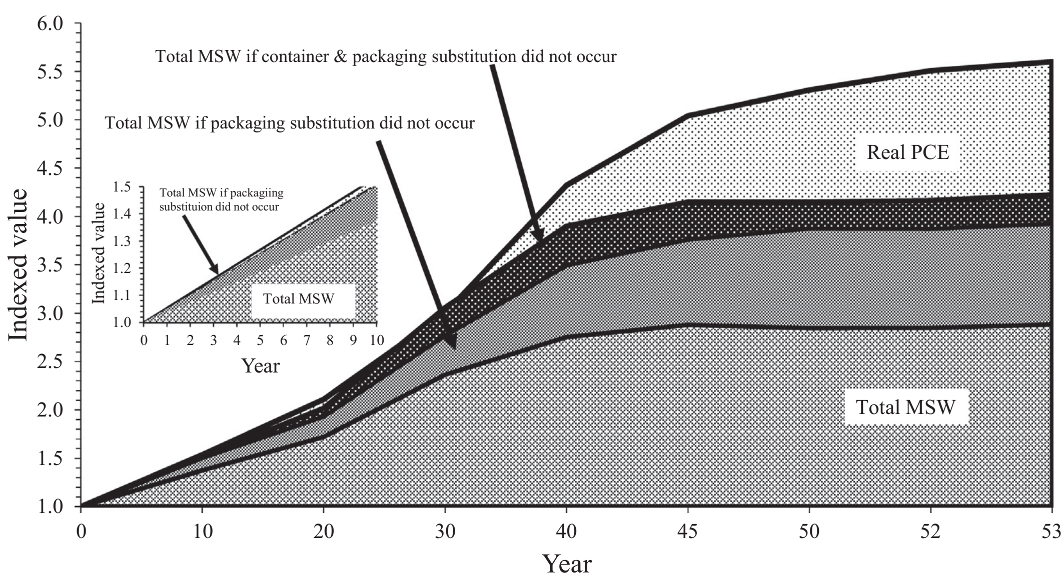

Fig. 8. Wedge contributions for metal, glass, and other material substitution if plastics were removed from MSW, indexed to show time frame.

2000 to 2013. In other words, as the plastic containers and packaging were made thinner, substitution by other materials, such as metals, glass, and paper, increases on a mass basis because less weight of plastic material is required for the same packaging applications compared to the other materials.

The results of this substitution scenario analysis are shown in Fig. 7 as a parity plot using the same data as shown in Fig. 4. The additional data where plastic is removed from MSW and consequently not used to substitute metal, glass, and other materials for packaging, containers, and other product applications is shown as open circles with two parity lines to aid in comparison.

The first observation from Fig. 7 is that in the early years (from 1970 to 1985), the total MSW generation on a mass basis increases faster than PCE. Instead of starting in 1989, it appears to begin closer to 1975 and continues until 2000. After 2000, there is a decrease over the next ten years but only to the rate that corresponds to the PCE rate on a one-to-one basis. The remainder of the data, 2010 to 2013, continues to show the same rate of increase in MSW generation and PCE. This analysis demonstrates that if glass, metal and other materials were not substituted by plastics in the packaging and container categories, MSW generation would remain coupled to PCE growth.

The results of the substitution scenario are shown on an indexed basis in Fig. 8, with the mass indexed values on the y-axis and the years as indexed from 1960 on the x-axis.

It is clear that without plastic substitution for glass, metal and other materials in the packaging and container categories, there would be a much later and much smaller decoupling, if any at all. Fig. 8 provides more resolution on the impact of material substitution by plastic as it presents the scenarios where only packaging was not substituted and then both packaging and containers were not substituted. The Total MSW wedge is the MSW generation excluding yard waste where decoupling appears to start about one year after the indexed year. The next wedge is the scenario where only packaging was not substituted using plastic, but containers were substituted. This scenario shows decoupling would start somewhere near year 4, or nearly 3 years after the case where substitutions did occur. The third wedge shows the results of the scenario when neither containers nor packaging were substituted with plastics. Decoupling does not occur until nearly 32 years after the indexed year. Based on the finding that decoupling does not occur until the 1998 to 2000 time frame, a delay of nearly 30 years is consistent with the analysis shown in Fig. 7 that decoupling likely would not be observed.

4. Discussion

It is important to note that no other material category in MSW either correlates or can be used to explain the observed decoupling shown in Figs. 1–4. The only other category that increased over the investigated time was the 'All Other' category. Materials that are included in that category range from lead-acid batteries to MSW organics for composting. Furthermore, the 'All Other' category only increased by about 5.6 times (approximately 39 million tons) from 1960 to 2013 and is more than offset by the decline in the defined waste stream categories.

The evidence provided here suggests that increased plastic usage may be enabling a relative decoupling between MSW generation and economic growth. The increase in plastic in the consumer market, which consequently contributes to the increased plastics fraction in MSW and the fact that plastic is the major substitution material for objects, such as glass and metal, in the packaging and container sectors correlates to the decrease in tonnage and volume of MSW generated, with a simultaneous increase in PCE. In addition, through our investigation using quantitative substitution ratios the application of plastic is clearly a significant contributor to the observed decoupling. Since the US does not have a national waste policy or directive, this decoupling is strongly linked to consumer behavior. The overwhelming majority of material substitution occurring in the consumer market is the replacement of metal and glass with plastics (American Chemistry Council, Plastic Resins in the United States, 2013). This investigation focused on the connection between plastics substitution and its increased prevalence in the MSW waste stream resulting in a relative decoupling of MSW generation and economic growth in the US.

Reviewing cross-sectional differences, similar to Kinnaman et al. (2014), provides insight into possible other factors that can contribute to the decoupling of MSW generation that may be related to different activities across the US. For example there are plastic shopping bag bans enacted in California that have alerted consumers to the issue of plastic impacts and waste management in general. In addition 31 states, concentrated on the east coast, manage a portion of their plastic waste using waste to energy facilities. The amount varies considerably from 57% to only 0.4% with an average of 13%. It has been demonstrated that regions that employ waste to energy facilities have higher recycle rates and generally lower generation rates. Therefore it is expected that states with more facilities would realize more decoupling.

Finally, to put the plastic substitution into an environmental context, information reported by Franklin et al. on six categories for the US and Canada determined a significant reduction in energy demand and global warming potential. The six categories are (i) caps & closures, (ii) beverage containers, (iii) stretch & shrink, (iv) carrier bags, (v) other flexible and (vi) other rigid. Thus, for example beverage containers that normally would be glass were replaced with plastic and caps & closures that would be metal were replaced with plastic. The environmental impact in the US, where the total material weight replaced (i.e. weigh reduction using plastic replacement material) was 49.6 million kg over the six categories, resulted in an 80% reduced energy demand and a 130% reduced global warming potential impact. The situation for Canada, where the replacement amount was 5.5 million kg over the six categories, resulted in approximately 1/2 the energy consumption and 1/2 of the global warming potential impact.

Plastics pose environmental challenges for end-of life disposal however alternatives to landfilling exist such as pyrolysis conversion systems. Pyrolysis thermally decomposes the plastics into useable oils that can become part of the fuel supply infrastructure. As a result, plastics that go to pyrolysis processes at the end of their useful life provide two benefits; the intended use as a consumer product and the intrinsic energy recovered when thermally converted into oil. Together, recycling and thermal conversion technologies can reduce the overall pollution and carbon footprint of plastics.

In terms of the energy consumption of plastics production, one must take into account the overall energy savings that are achieved as a result of plastics substitution. For example, plastic substitution in automobiles reduces the overall weight up to 30% leading to a commensurate reduction in fuel consumption and emissions. Plastic packaging also conserves energy and natural resources compared to its alternatives. Specifically it would require 1.5 times more aluminum, 4 times more steel, and 20 times more glass than plastic to carry the same volume of a beverage. Furthermore, plastic use in building and construction materials saved more than 467 trillion BTUs in a year compared to alternative materials, which is equivalent to the average annual energy demand of 4.6 million households in the US.

5. Conclusion

Since the introduction of plastics into the economy there has been a significant replacement of glass and metal containers and packaging. Although the benefits of plastic materials has been shown through numerous applications, the impact on waste generation has not been very clear. The amount of plastics in the MSW has increased by 83 time the amount it was in 1960 while total MSW is only 2 times the amount. This study quantitatively evaluated correlations between the amount of plastics in the waste stream with PCE and total waste generation rates. The correlation with PCE demonstrates that since the late 1990s (approximately 1998) there has been a decoupling of MSW generation rates with PCE or economic growth. Plastics play a role in the decoupling due to materials substitution that reduce the overall weight of MSW and down-gauging that reduces the amount of material needed. Decoupling would still occur without plastics but it would be delayed by an estimated 32 years. This indicates that other factors are influencing the decoupling as well and should be further understood.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.wasman.2018.05.003.

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