Technical overview of the Waste Impact Calculator

Martin J. Brown & Peter Canepa
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Materials Management Program
700 NE Multnomah St.
Suite 600
Portland, OR 97232
Phone: 503-229-5696
800-452-4011
Fax: 503-229-6124
Contact: Martin Brown

www.oregon.gov/DEQ

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State of Oregon
Department of Environmental Quality

This report prepared by:

Oregon Department of Environmental Quality
700 NE Multnomah Street, Suite 600
Portland, OR 97232
1-800-452-4011
www.oregon.gov/deq

Contact:
Martin Brown
503-229-5502
Martin.Brown@state.or.us

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Abstract

The Waste Impact Calculator (WIC) is an analytical framework for estimating the life cycle environmental impacts of solid waste materials and for projecting the effects of solid waste management decisions. WIC was created with Oregon users in mind, but may be useful to others as well.

WIC is intended to be a practical and accessible tool for sustainability and waste managers. Solid waste has traditionally been measured, managed, and understood in terms of sheer weight, but the newer perspective of sustainable materials management requires an understanding of the life cycle environmental impacts of waste materials. However, the quantification of such impacts involves life cycle assessment, a specialized discipline which many do not have the time or experience to pursue.

WIC is intended to bridge the two perspectives. As input, it takes traditional, weight-based solid waste data, as might be obtained from recycling surveys and waste sorts. It then applies a simplified form of life cycle assessment to that data, and outputs impacts in some detail. WIC also allows the comparison of management scenarios, for example “increased recycling” or “reduced food waste.” WIC requires some analytical experience, and in many cases some programming or database skill, but no experience with formal life cycle assessment.

WIC is extendable in form and intended to be published in multiple modules. This paper serves as documentation for the base module, which may be used on its own or serve as the basis for more user-friendly or intricate elaborations of the WIC concept. This document includes a general description of the WIC framework, specifications for the form and content of WIC’s essential data tables, and guidelines for producing impact results.

The authors will publish additional modules for WIC as time and resources allow. Motivated users are encouraged to improve WIC and create their own modules, as WIC’s concept, code and essential data are published freely.

Related resources

Two complementary documents provide additional detail and illustration. *Impact Modelling for the Waste Impact Calculator* has extensive details on the life cycle inventories that underlie the impact calculations for individual materials, while *Example Applications of the Waste Impact Calculator* shows how the framework may be used to create diverse types of output.

WIC’s source code and data are published on github at https://github.com/OR-Dept-Environmental-Quality/wic-base. Check there for updates.

Introduction

The "problem" of solid waste

For decades municipal solid waste has been a focus of environmental concern, activism, and management. Solid waste is often used as a symbol for resource consumption, and waste management activities such as recycling are perceived as ways to reduce environmental impacts such as greenhouse gas emissions.[1] The role and treatment of solid waste is also a prominent part of comprehensive approaches to the environmental effects of materials, such as "circular economy" (CE)[2] and "sustainable materials management" (SMM).[3]

For sustainability analysts, there is appeal in studying the solid waste stream. Waste studies have the advantage of a broad scope. They can quantify a notable portion of material use at a city, national, or even global scale. Moreover, as archaeologist William Rathje pointed out, waste data is not theoretical: it represents materials that have unarguably been used by humans. It can thereby serve as a useful correction to humanity's more abstracted and idealized conceptions of self.[4]

Nonetheless the full environmental effect of solid waste, and the way that solid waste management decisions influence it, remains unclear. The breadth provided by the solid waste perspective comes with a lack of precision. As this paper will illustrate, waste streams are complex mixtures which resist precise characterization, and the diversity of end-of-life "treatments" for waste, especially when recycling is considered, is large and ever-changing.

Models that estimate the life cycle impacts of solid waste materials and management, including the one described in this paper, cannot entirely overcome these sources of imprecision. But the relevance and practicality of impact results may make the modeling effort worthwhile.

Weight-based vs. lifecycle perspectives

Currently there is a gulf between the way solid waste is quantified and the kind of results managers and analysts want. The parties who study and track waste (typically local governments, occasionally other large organizations) nearly always quantify waste in terms of weight, measured shortly after collection from households, businesses, etc.

However, managers and analysts want results in terms of environmental impacts, such as greenhouse gas emissions and toxicity scores. In particular, sustainability analysts and waste managers want to use

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[1] e.g. Daniel Hoornweg, Perinaz Bhada-Tata, and Chris Kennedy, "Environment: Waste Production Must Peak This Century," *Nature News* 502, no. 7473 (October 31, 2013): 615, https://doi.org/10.1038/502615a; Abi Bradford, Sylvia Broude, and Alexander Truelove, "Trash in America: Moving from Destructive Consumption to a Zero-Waste System," 2018, https://uspirgedfund.org/sites/pirg/files/reports/US%20-%20Trash%20in%20America%20-%20Final.pdf; Sustainable Materials Management Coalition, "Reducing the Environmental Impact of Materials Use," November 2016, https://www.michaeldbaker.com/MDB_WP_live_site/wp-content/uploads/2016/11/SMMC_Reducing_the_Impact_Final_508.pdf.

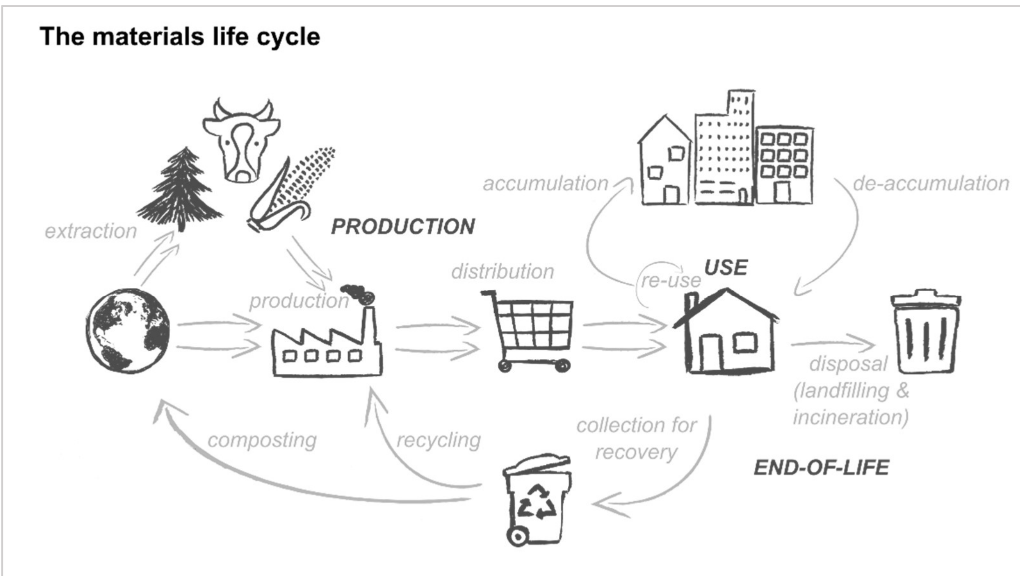
[2] Ellen MacArthur Foundation, *Re-Thinking Progress: The Circular Economy*, 2011, https://www.youtube.com/watch?v=zCRKvDyyHmI.

[3] Joseph Fiksel, "A Framework for Sustainable Materials Management," *JOM* 58, no. 8 (August 1, 2006): 15–22, https://doi.org/10.1007/s11837-006-0047-3; United States Environmental Protection Agency, "Sustainable Materials Management: The Road Ahead," June 2009, https://www.epa.gov/sites/production/files/2015-09/documents/vision2.pdf.

[4] William L. Rathje and Cullen Murphy, *Rubbish!: The Archaeology of Garbage* (University of Arizona Press, 2001).

impact quantities to inform practical waste management decisions, answering questions like "which waste materials represent the biggest impacts?"; "how will impacts change if we compost more?"; and "which is more effective, reducing waste generation or increasing recycling?"

The analytical discipline that calculates such impacts is life cycle assessment (LCA).[5] LCA asserts that every product or material can be linked to impacts due to emissions across multiple stages of a "materials life cycle," illustrated schematically below. The materials life cycle includes production (comprising extraction, manufacturing, distribution), use, and end-of-life treatment (landfilling, recycling, etc). The sum of impacts across all those stages– or some defined subset of them – is the "life cycle impact."[6] To date, LCA has frequently been applied to individual waste materials and processes,[7] but rarely to realistic municipal waste streams.



The fields of solid waste, SMM, and CE need LCA-based tools that convert conventional weight-based waste information into estimated life cycle impacts. To be practical, such tools must be tolerant of the variable quality, scope, and specificity of solid waste data. Some users will know a great deal about the contents of their waste streams, or have a strong influence over the way it is managed. Others will not.

One tool that addresses this challenge is the Waste Reduction Model (WARM) from US EPA.[8] WARM is both popular and well-documented. Unfortunately, current expressions of WARM are not well suited to the purposes of the Oregon Department of Environmental Quality (DEQ), where waste is approached

[5] International Organization for Standardization, "ISO 14044:2006: Environmental Management — Life Cycle Assessment — Requirements and Guidelines," 2006, https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/84/38498.html; "Life-Cycle Assessment," in *Wikipedia*, October 24, 2017, https://en.wikipedia.org/w/index.php?title=Life-cycle_assessment&oldid=806786959.

[6] Life cycle assessment, by definition, calculates "potential environmental impacts" (see later section Uncertainties inherent to solid waste data and their implications, as well as ISO 14044:2006). This paper uses "environmental impacts" without explicit mention of "potential" for brevity.

[7] e.g. David A. Turner, Ian D. Williams, and Simon Kemp, "Greenhouse Gas Emission Factors for Recycling of Source-Segregated Waste Materials," *Resources, Conservation and Recycling* 105, Part A (December 2015): 186–97, https://doi.org/10.1016/j.resconrec.2015.10.026.

[8] United States Environmental Protection Agency, "Waste Reduction Model (WARM)," accessed September 29, 2016, https://www.epa.gov/warm.

from a comprehensive SMM perspective. DEQ needs to calculate impacts associated with waste management scenarios, while WARM focuses on *differences* in impacts between management scenarios. WARM version 14 does not display impacts from the production phase of the materials life cycle in a straightforward fashion, though the more recent version 15 has begun to correct this. Both WARM versions 14 and 15 are limited to two management scenarios and two environmental impact categories, GHG emissions and energy use.

The Waste Impact Calculator

This paper introduces a new framework for estimating the life cycle impacts of solid waste, one that suits Oregon's particular needs and may be useful to others as well. DEQ's "Waste Impact Calculator" (WIC) creates a bridge between the weight and impact perspectives of waste, and allows users to estimate the impacts associated with a large variety of materials and waste management scenarios.

As input, WIC uses standard solid waste data, where mixed waste streams are described in terms of tons of component materials going to specific end-of-life fates. This is the type of data that typically results from municipal recycling surveys and "waste sorts." For example, a very simple waste stream might be described with the following entries: "10 tons of food waste going to landfill, 6 tons of food waste going to composting, 5 tons of steel going to landfill, and 4 tons of steel going to recycling."[9]

WIC applies a summary form of LCA to such data, and outputs estimated life cycle impacts in a useful amount of detail, dividing life cycle impacts into components representing production, transportation to end-of-life treatment, and end-of-life treatment itself. Similar to WARM, WIC excludes impacts from the use stage of the materials life cycle, as will be explored in the section <u>Uncertainties inherent to solid waste data and their implications</u>.

WIC also allows the user to estimate and compare the impacts linked to management scenarios they may be considering, for example "increased recycling" or "reduced food waste."

The most likely users of WIC are analysts who are familiar with life cycle thinking and approaches like CE or SMM, but who are not full time practitioners of LCA – for example, sustainability planners and waste managers in local governments, corporations, and NGO's.

The goals of the WIC project are to create a system that:

- Creates reasoned, credible estimates of the life cycle environmental impacts of solid waste materials and streams;
- Clearly illustrates the contributions of major life cycle stages to total impacts;
- Allows analysts who are not experienced LCA practitioners to calculate such impacts;
- Calculates such impacts at all the levels of detail relevant to a state or local SMM program, for example statewide totals, subtotals linked to geographic areas, material classes, life cycle stages, years, and legal classification as either "disposed" or "recovered" material;
- Allows the user to project the impacts associated with "what-if" scenarios such as "increased recycling" or "reduced food waste";
- Can answer the most common questions waste managers and sustainability officers have about management options and life cycle impacts (notably, questions involving changing the amount of material recovered, changing recovery or disposal dispositions, reducing waste generation, and changing end-of-life transport distances);

[9] Though this example is particularly simplistic, real field data describing solid waste often lacks precision in the way it characterizes materials, as will be explored in the section "The nature of solid waste and solid waste data."

- Is as transparent, open, and adaptable as practical, given the limits of its creators' time, resources, and programming skill; and
- Reports results in a large and flexible number of impact categories or inventory metrics (GHG emissions, water use, ecotoxicity, etc).

Publications and modules

WIC is intended to be extendable and will be published in multiple modules.

This document is part of the *wic-base* module, published at https://github.com/OR-Dept-Environmental-Quality/wic-base, on which all other WIC modules will likely depend. This document describes the concepts behind the WIC framework, details the proper format of WIC's essential data files, and demonstrates procedures necessary to produce credible results.

Two complementary documents, also part of the *wic-base* module, provide additional detail.

Impact Modelling for the Waste Impact Calculator has extensive details on impact calculations for individual materials. It includes topics of technical interest to LCA practitioners such as system boundary, material definitions, data sources, and the approach for allocating impacts during recycling.

Example Applications of the Waste Impact Calculator shows how the framework may be used to create diverse types of output. That document contains at least two examples using the R language: a simple report in R Markdown, which shows how to avoid the most likely pitfalls in data processing; and screenshots from an interactive web application written with R's "Shiny" package.[10]

Together, this documentation should be sufficient to allow readers with suitable skills to produce impact results using *wic-base* and their own solid waste data. Especially motivated readers may go on to create and publish their own modules extending WIC, perhaps modules that produce sophisticated output or are especially user-friendly.

DEQ itself plans to publish additional modules for WIC, including an interactive web app for nonprogrammers. Check the wic-base repository at https://github.com/OR-Dept-Environmental-Quality/wic-base for updates. The authors of WIC (Martin J. Brown and Peter Canepa) welcome both improvements to their own code and completely different expressions of the framework.

The nature of solid waste and solid waste data

The waste stream and weight-based statistics

The subject of WIC is solid waste and its management.

- ***Solid waste*** means the diverse organic and inorganic waste matter collected at homes, businesses, depots, and other operations and variously described as "trash," "rubbish," "yard debris," "recyclables," etc.
- ***Solid waste management*** means the various end-of-life processes, or ***dispositions***, that are applied to these materials, such as landfilling, recycling, composting, and combustion (aka "incineration"). Solid waste management also includes transport starting at the household or other "generator" of the waste.

[10] https://shiny.rstudio.com/

- ***Solid waste stream*** means the compiled list of materials and quantities being managed, along with their dispositions. To give a simplistic example, a solid waste stream might be "10 tons of steel to be recycled, 6 tons of HDPE to be combusted, and 5 tons of food waste to be landfilled." (In reality most waste streams have dozens of components.) The word "material" has a fluid definition that will be explored below.

Solid waste management covers a large variety of materials and processes, making it an unusually broad topic for LCA, which is more commonly associated with comparisons of specific products and services.[11] Despite this breadth, it is important to note that solid waste statistics do not represent the entirety of waste or material consumption. Some high-impact materials, such as concrete, have long lives in the technosphere before ever showing up in waste statistics, if they show up at all.

Definitions of solid waste vary by jurisdiction. Published waste statistics rarely if ever include mining and forestry waste, though almost all solid waste statistics include the familiar "municipal" waste from residential collections.[12] There is considerable variation among jurisdictions in the extent to which they include commercial waste (e.g. from stores and restaurants) and construction materials.

Oregon's definition of solid waste, as applied in the calculation of waste statistics required by state law,[13] includes municipal waste, commercial waste, and a few construction materials. Oregon's statistics notably exclude *inert* construction materials (e.g. concrete, dirt), and industrial and agricultural waste.

Governments and other entities typically summarize their waste streams with weight-based statistics. This paper will follow Oregon's vocabulary and definitions for those statistics (though WIC itself does not require users to follow Oregon's usage). In Oregon, ***waste generation*** is the total tonnage collected, no matter where it is destined – for landfilling, recycling, composting, etc. The amount ***recovered*** is the tonnage recycled, composted, or (for a few specific materials) combusted with energy recovery. The amount ***disposed*** is the tonnage of everything else, which includes all of the waste landfilled and most of the waste combusted. The ***recovery rate*** is a percentage: the tons recovered divided by the tons generated.[14]

Other governments and entities calculate similar statistics with slightly different names and definitions. "Recycling rate" may refer to the percentage of generation which is recycled or composted (perhaps omitting combustion). "Diversion rate" may refer to the percentage of generation that is not landfilled.

The nature of "materials" in solid waste

Solid waste streams are nearly always mixtures of different substances, even when some sorting is applied by the generator or processor of the waste. They are rarely uniform in chemical makeup or physical form. For example, a household may separate its waste into "trash" and "recyclable" bins. Each of these bins in turn contains a mixture. The recycling bin might be sorted by a recycling operator into several fractions, for example glass, paper, and plastic.

For some end-of-life applications such broad "materials" categories may be sufficient, but for others additional separation is necessary. A collection of unseparated mixed "plastic" is difficult to recycle as-is

[11] e.g Quantis, "Comparative Environmental Life Cycle Assessment of Hand Drying Systems: The XLERATOR Hand Dryer, Conventional Hand Dryers, and Paper Towel Systems," July 29, 2009, https://www.exceldryer.com/wp-content/uploads/2017/02/LCAFinal9-091.pdf.
[12] Figure 3.1 in United Nations Environment Programme and International Solid Waste Association, *Global Waste Management Outlook*, 2015, https://wedocs.unep.org/handle/20.500.11822/19339.
[13] ORS 459A.010, "Policy" (2015), 010, http://www.oregonlaws.org/ors/459A.010.
[14] ORS 459A.010, 010.

– though one proprietary process claims to do so, converting pulverized plastics into bulky products like pallets.[15] For recycling into more conventional products, such as new containers, separation by chemical compound (PET, HDPE, etc.) often is required. Even these relatively "pure" classifications may themselves be mixtures, whose components affect options for waste management. For example, as of this writing, blow-molded PET is more commonly recycled than thermoformed PET.

The word ***material*** is thus a generic term whose breadth depends on context. WIC uses the word "material" to refer to any identifiable class of matter, narrow or broad, which appears in Oregon's legally defined solid waste stream *and* for which it has characterized environmental impacts. For example WIC has characterized impacts for specific plastic compounds including PET and HDPE, and also a more generic material category called "RigidPlastic." See section Available materials and dispositions for a complete list of materials. If the user can input their waste stream in terms of specific plastic compounds, they will get more representative impact outputs. If not, they can use the more generic category, and their results will represent impacts for an assumed mixture of specific compounds.

The output of weight-based waste studies

The way that governments study and quantify solid waste demonstrates the fluid definition of "material."

In Oregon and other jurisdictions, every truckload of waste destined for disposal is weighed before its contents are landfilled or incinerated. The total of such measurements is the total tons disposed. However, the materials making up that waste are much less frequently characterized. Getting that detail requires a study often described as a "waste sort," where samples of disposed waste are separated into distinct material categories and weighed.

Waste sorts are highly laborious,[16] especially if a high specificity of material categories is desired, so waste sorts tend to be conducted infrequently. Oregon DEQ conducts one every five or six years, and uses more than 100 material categories[17] – though for the purpose of analysis and reporting, the 100+ categories are often collapsed into a smaller number.

Recycling and other recovery is harder to study than disposal, because the marketplace for recovered materials is complex. Recovered materials are collected by a variety of parties: garbage haulers, scrap metal collectors, grease handlers, etc. These materials may then be sold and bought multiple times in different states of separation and/or processing. The ultimate user of the material may be local, or many hundreds of miles away.

State and local governments have various ways of extracting information from this marketplace and summarizing it. In Oregon, law[18] requires participants in the recycling marketplace to report to DEQ,[19] which summarizes and de-duplicates the records. But regardless of the reporting and analysis system, the end result is a list of tonnages for specific materials that are destined for recovery.

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[15] "Wimao Ltd.," Wimao, accessed January 29, 2021, https://www.wimao.fi/; Plastics Recycling Show Europe, "Welcome to New Exhibitor WIMAO...," Twitter, December 2, 2019, https://twitter.com/PRS_Europe/status/1201423276028911616.

[16] e.g. CalRecycle, "2018 Facility-Based Characterization of Solid Waste in California," May 15, 2020, https://www2.calrecycle.ca.gov/Publications/Download/1458.

[17] Oregon Department of Environmental Quality, "Statewide 2016 Waste Composition Study: Excel Results Files Updated June 20, 2018 [Sheet P16TOT]," 2018, https://www.oregon.gov/deq/FilterDocs/A01-StatewideWCS16.xlsx.

[18] ORS 459A.010, Policy.

[19] Oregon Department of Environmental Quality, "Individual Material Collection Report [2015 Oregon Material Recovery Survey]," 2015, http://www.deq.state.or.us/lq/pubs/forms/sw/PrivateRecyclerSurvey.pdf.

If recovery data is harmonized with disposal data – usually by creating a common set of material categories -- a unified picture of the waste stream can be created in a single table. For example a simple waste stream with three materials might be characterized this way:

material	disposition	legalClassification	tonsWeight
FoodWaste	composting	recovery	17
FoodWaste	landfilling	disposal	29
Electronics	recycling	recovery	5
Electronics	combustion	disposal	4
WoodWaste	combustion	recovery	105
WoodWaste	landfilling	disposal	16

This example shows an important quality of waste streams and of WIC's approach to them. The disposition of waste (the technical process with which the waste is treated, such as landfilling or combustion) should be recorded independently of its legal classification (in Oregon, the words "recovery" and "disposal" are used, but in other jurisdictions "diversion" and similar terms may apply). This is necessary because jurisdictions differ in the way they apply these terms. In Oregon, combustion is usually classed as disposal, but not always – note the difference between "WoodWaste" and "Electronics."

More significantly, favorable-sounding legal classifications do not guarantee favorable environmental outcomes. Managers might *assume* that legal classifications of "diversion," "recycling," etc. will be associated with lower environmental impacts. One use of WIC is to test such hypotheses.

Uncertainties inherent to solid waste data and their implications

Real solid waste data, gathered and summarized as described above, is sometimes not as detailed or assured as analysts might desire. The vagaries and uncertainties characteristic of solid waste data have consequences for the design of a model like WIC or WARM.

It is often unclear how collected waste materials have been *used*, which makes estimating impacts from the "use stage" of the materials life cycle a guessing game. This is because waste studies tend to list materials by commodity categories, for example "10 tons of steel." Such entries can represent a range of products, for example soup cans and stove parts. Both provide steel for end-of-life processes such as recycling, but the "use phase" impacts for these products could be dramatically different.

Impact totals reported by WIC, as well as WARM, exclude impacts from the use stage. This is a substantial exclusion. The use stage is a large source of impacts for several important classes of products, such as personal computers[20] and clothing.[21] Omitting the use stage may further give the impression that calculation of impacts for production and end-of-life processes is precise, when it may not be. Collected wastes, even within a commodity category, may have been produced over a range of time and with a variety of techniques. More precision would be desirable, but the ambiguous nature of the material mixes

[20] Anders S. G. Andrae and Otto Andersen, "Life Cycle Assessments of Consumer Electronics — Are They Consistent?," *The International Journal of Life Cycle Assessment* 15, no. 8 (September 1, 2010): 827–36, https://doi.org/10.1007/s11367-010-0206-1.

[21] Kirsi Laitala, Ingun Grimstad Klepp, and Beverley Henry, "Does Use Matter? Comparison of Environmental Impacts of Clothing Based on Fiber Type," *Sustainability* 10, no. 7 (July 2018): 2524, https://doi.org/10.3390/su10072524; A. P. Periyasamy, J. Wiener, and J. Militky, "Life-Cycle Assessment of Denim," in *Sustainability in Denim*, ed. Subramanian Senthilkannan Muthu, The Textile Institute Book Series (Woodhead Publishing, 2017), 83–110, https://doi.org/10.1016/B978-0-08-102043-2.00004-6.

composing solid waste makes excluding the use phase a practical necessity. (For more on WIC's "system boundary," see *Impact Modelling for the Waste Impact Calculator*.)

Likewise, it is not always clear exactly what ultimately *happens* to waste materials. While waste managers can have direct knowledge of the landfills and incinerators receiving materials for disposal, they may find it impossible to learn the final dispositions of materials collected for recovery.

The sheer number of recovery dispositions is voluminous. For example, food waste may be composted aerobically or anaerobically digested. Glass can be melted and reformed into new containers, or crushed for use as roadbed. Aluminum cans might be recycled into new cans, or made part of a lower-quality cast alloy. Moreover, the marketplace for recovered materials is active and complex, with materials in various states of separation being sold, stockpiled, and resold. Materials can disappear into that market, making the ultimate method of recovery unknowable.

This uncertainty presents a design challenge for both WARM and WIC. The users of these tools want to know about the impacts linked to specific dispositions – but users may not always know which technical processes apply to those dispositions, especially in the realm of recycling. In addition, the creators of the tools have limited resources – they cannot characterize impacts for every conceivable process.

WARM responds by defining a relatively small number of recovery dispositions, with generic names such as "recycling." The impact modeling for these dispositions typically represents the most common reasonable case – for example glass containers are recycled into glass containers, rather than the more unusual fiberglass, though both are technically and economically realistic. The simplicity of this arrangement allows WARM to be presented to the user as a spreadsheet tool.

WIC attempts to be more flexible. For users with less specific data or interests, WIC provides a reasonable and self-consistent set of default values for recovery dispositions. (See *Impact Modelling for the Waste Impact Calculator* for the rationale behind these defaults.) For users with more specific data or interests, WIC's impact database should provide an increasing number of options. Any number of dispositions can be defined and applied for any individual material, and the impact database can be updated at any time. For better or worse this strategy makes a spreadsheet implementation unworkable.

Impact calculations

The nature of LCA impact results

This paper will not provide an overview of LCA. However, it seems relevant to emphasize one fundamental characteristic of impact numbers (i.e. Life Cycle Impact Assessment results) produced by LCA.

When LCA assigns impact quantities to products, materials or services (including the waste materials and management choices included in WIC and WARM), these impacts should be understood as "estimated" and "potential" impacts. They are "estimated" in the sense they can reasonably and objectively be associated with a process (say, landfilling a ton of food waste), but not necessarily the *exact* impacts associated a particular instance of that process (say, landfilling a *particular* ton of food waste).

These impacts are also "potential impacts," in the vocabulary of ISO 14044,[22] rather than absolute, precise, or guaranteed. Modeling environmental impacts inherently involves uncertainty, and some of the impacts modeled occur in the future, rather than the present.

[22] International Organization for Standardization, "ISO 14044."

This paper refers to impacts without further qualifying them as “potential,” “estimated,” etc.

Total impact and its parts

What follows is a general description of WIC’s approach to converting weight-based solid waste data to life cycle impacts. LCA specialists interested in technical matters such as system boundary and allocation linked to recycling should see *Impact Modelling for the Waste Impact Calculator*.

Within a given impact category, WIC defines the total impact of a solid waste stream as the sum of impacts from all materials in the waste stream. For materials *i=1 to m…*

$$IMPACT_{waste\ stream} = \sum_{i=1}^{i=m} IMPACT_i$$

The impact of a single material *i* is the sum of impacts from three life cycle stages:

$$IMPACT_i = PROD_i + EOLT_i + EOL_i$$

Where

- PROD = Production, which is used in the broad sense, and includes extraction of resources, manufacturing or other processing, distribution and transport to retail;
- EOLT = End-of-life transport, which encompasses only the transport between the collection point (e.g. a home or business) and the waste management facility. For disposed materials, the waste management facility will be the landfill or incinerator. For recovered materials, the waste management facility will be the first meaningful participant in the marketplace for recovered materials. For mixed recyclables this first participant is likely to be a MRF (material recovery facility). Other first participants include steel businesses (for scrap metal collections) and composting and anaerobic digestion facilities.
- EOL = End-of-life treatment, such as landfilling, incineration, recycling, etc. The end-of-life treatment phase may include additional transportation, after the material has left the control of the collector.[23] End-of-life treatment emissions may be positive, for example when organic material is disposed in a landfill and decays, or negative, for example, when steel is recycled and a recycling credit, based on a material’s so-called embodied burden, has been applied.

WIC delimits these three stages based on practical considerations from the waste manager’s perspective.

All production-stage impacts, including extraction, processing, and distribution to market, are combined into one figure. This reflects the reality that waste managers have little influence over the way materials are produced or distributed. If waste managers want to reduce PROD, the main “management option” they can advise is that waste generation be reduced.

After production, impacts likely occur in the use stage of the materials life cycle. Waste managers have little influence over these impacts. Use stage impacts are not calculated by WIC, as explained in the section Uncertainties inherent to solid waste data and their implications.

The end-of-life-transport and end-of-life stages are where waste managers are likely to have the most influence. Managers can influence end-of-life-transport impacts (EOLT) by choosing to transport waste

[23] For a description of how transportation impacts in WIC’s underlying LCA model are parsed into the EOLT and EOLT stages, see the section *Introduction to the impactFactors table; transport-related adjustment to LCA output*.

different distances, and end-of-life impacts (EOL) by changing the dispositions to which wastes are assigned. WIC keeps these phases distinct to reflect those points of influence.

Estimating impacts from weight

$PROD_i$, $EOLT_i$ and EOL_i are not measured directly. Rather, the solid waste stream is characterized by the weights, or masses, of each material found in solid waste records and sampling programs. (WIC uses the terms weight and mass interchangeably.[24]) Those masses are converted to $PROD_i$, $EOLT_i$ and EOL_i using ***impact factors*** relating impacts to unit weights, for example "3.2 kg CO_2 equivalents of greenhouse gas emissions per short ton of waste."

Production-related impacts for each material ($PROD_i$) are straightforward to calculate, as the product of the total mass of waste generated for that material ($MASS_i$) and a production impact factor (PIF_i):

$$PROD_i = MASS_i \times PIF_i$$

End-of-life treatment impacts for each material (EOL_i) are more complex, because materials have multiple plausible dispositions at the end of their useful lives, each of which has distinct impact characteristics. For material *i* and its dispositions $j=1$ to d…

$$EOL_i = \sum_{j=1}^{j=d} MASS_{i,j} \times EIF_{i,j}$$

That is, to find the total end-of-life treatment impact for each material, the mass of each unique combination of material and disposition ($MASS_{i,j}$) must be multiplied by the matching impact factor ($EIF_{i,j}$), and those products summed.

End-of-life-transport impacts are calculated in a similar way, using an end-of-life-transport impact factor ($TIF_{i,j}$), but with the addition of a scaling factor that allows users to customize transport distances (in relation to a default distance supplied by WIC).

$$EOLT_i = \sum_{j=1}^{j=d} MASS_{i,j} \times TIF_{i,j} \times \frac{custom\ distance_{i,j}}{WIC\ default\ distance_{i,j}}$$

This calculation process can be applied for a waste stream of any size – from the waste produced by a single household or business to the waste produced by a state or industry. WIC anticipates that users will want to compare waste streams representing different places ("Dane county vs. Smith county"), materials ("Steel vs. wood"), and management scenarios ("Business as usual vs. increased composting") – so its data files are set up to allow processing of multiple streams, as described below.

[24] Though physics makes a distinction between the two, where weight is a force and mass is a quantity of matter, in the everyday practice of solid waste management they are effectively the same: things are weighed and those weights are used to represent quantities of matter.

Data tables and their processing

Computing platforms

DEQ performs WIC analyses using the open-source computer language R,[25] as shown in *Example Applications of the Waste Impact Calculator*. However, WIC need not be expressed with R. Conceivably, any computer language or system that has the following qualities could be used. The system should:

- Contain basic data analysis features, such as utilities for importing/exporting data file formats, summary functions, basic statistical functions, etc.;
- Allow controlled joins of data tables, based on key values in named columns;
- Allow creation of calculated columns; and
- Filter and de-duplicate tables based on flexible criteria.

In addition, most users will want the ability to create graphical output – though it is not strictly necessary.

The authors recommend any expression of WIC utilize open-source software and scripted code rather than menu-driven commands or point-and-click interfaces. Though simple analyses could conceivably be executed in a spreadsheet or GUI-driven database, these will likely be difficult to debug and inflexible to alter. Open-source, scripted analyses are more transparent, reproducible, and adaptable to changes in scope and parameters.

Elements of the WIC framework

WIC is better described as a "framework" than a "model." It has only three basic elements:

- a data table containing weight-based solid waste information;
- a data table containing "impact factors," multipliers that relate weight to impacts;[26] and
- some sort of code or interface that connects the two data tables and filters and sums results.

This is a flexible arrangement that allows a large variety of analyses to be performed. Users can calculate the impacts associated with:

- Single waste materials or waste streams composed of collections of materials;
- A wide array of end-of-life treatments;
- The transport of waste *to* end-of-life treatment; and
- Any number of management scenarios.

The drawback of this flexibility is that it is possible for users to make mistakes, especially if they are coding entirely new analyses. New users should read this paper, and study the companion document *Example applications of the Waste Impact Calculator*, to see how the framework can be properly applied.

WIC executes the impact calculation scheme described earlier in this paper by merging its two essential data tables and processing the result. In general, in WIC, $masses \times impact\ factors = impacts$, but the details of processing matter.

- One data table, ***massProfiles***, describes the waste stream(s) under consideration by listing the weights of materials that compose them, their end-of-life dispositions, and relevant end-of-life transport distances. These records can be labelled with additional classification variables such as management scenario name, geographic place, year, etc. The ***massProfiles*** table must be created

[25] "R: The R Project for Statistical Computing," accessed February 18, 2021, https://www.r-project.org/.

[26] "impact factors" might be characterized more formally as "LCIA profiles" – see *Impact Modeling for the Waste Impact Calculator*

and provided by the user. A simple example of a ***massProfiles*** table is provided later in this document, and applied in the R Markdown document in *Example applications of the Waste Impact Calculator*.

- Another data table, ***impactFactors***, contains the impact factors described earlier in this paper, relating weight to impacts. This file is provided as part of WIC.
- ***massProfiles*** and ***impactFactors*** are merged based on material and disposition names, and end-of-life-treatment impacts are calculated by multiplying mass by impact factor. Additional records are created as necessary to represent impacts in the end-of-life-transport and production phases of the life cycle.
- The result is a merged table, called here ***impactsInDetail***, containing tonnages and impacts of waste in maximum available detail.
- ***impactsInDetail*** is then filtered and summarized to produce desired results.

In practice, the code or database instructions that merge the files and produce usable output can be very simple. Most of the user's effort will go into creating a ***massProfiles*** table that is well suited to their purposes and passes checks for internal consistency.

File formats

WIC requires no particular file format for the ***massProfiles*** and ***impactFactors*** tables, though the WIC project prefers nonproprietary formats (see project goals). In its current practice, DEQ plans to publish ***impactFactors***, and any pre-packaged ***massProfiles***, as simple CSV text files. DEQ may also publish data in the RData format.

DEQ's WIC code consists of R scripts and R Markdown documents – which are nonproprietary, plain text documents readable with any text editor.

The key role of massProfiles

Creation of a credible, internally consistent ***massProfiles*** table is essential, because in the basic expression of WIC, this table is the <u>main and often only way</u> the user provides input to the system. (The only other way would be for the user to create custom code.) The material names, weights, disposition names, scenario names, etc. in ***massProfiles*** must completely and accurately describe the scenarios and waste streams the user wants to study. For example, when comparing an "increased recycling" scenario to a "baseline" scenario, the "increased recycling" scenario should show increased tonnages for recycling dispositions and decreased tonnages for disposal dispositions. It is the user's responsibility to assure that ***massProfiles*** describes their management ideas accurately.

Structure and logic of massProfiles

Here is a simple ***massProfiles*** table, expressing waste streams for the 5 scenarios in *Example Applications of the Waste Impact Calculator*.

massProfiles for Anytown's analysis of food waste

scenario	wasteshed	material	disposition	umbDisp	tons	miles
baseline	Anytown	FoodWaste	landfilling	disposal	7669	178
baseline	Anytown	YardDebris	composting	recovery	9000	4
compostFW585	Anytown	FoodWaste	composting	recovery	585	77
compostFW585	Anytown	FoodWaste	landfilling	disposal	7084	77
compostFW585	Anytown	YardDebris	composting	recovery	9000	77
compostFW1000	Anytown	FoodWaste	composting	recovery	1000	77
compostFW1000	Anytown	FoodWaste	landfilling	disposal	6669	178

compostFW1000	Anytown	YardDebris	composting	recovery	9000	77
reduceFW03	Anytown	FoodWaste	landfilling	disposal	7439	178
reduceFW03	Anytown	YardDebris	composting	recovery	9000	4
reduceFW06	Anytown	FoodWaste	landfilling	disposal	7209	178
reduceFW06	Anytown	YardDebris	composting	recovery	9000	4

In the ***massProfiles*** table, *tons* is the critical field. This is a mass of some waste material, in short tons. All the other fields serve to identify or qualify where the *tons* came from, which management scenario they represent, what life cycle stage they represent, etc.

wasteshed is meant to identify a geographic source of the tonnage data (e.g. tons from "City A", "City B"), but it could also be used to identify tons from other types of sources (e.g. tons from "Company A", "Company B"), or periods of time ("2020" vs. "2021").

material is the name of the material, e.g. "Aluminum." Remember, as discussed before, that material names may represent broader or narrower categories which often overlap. PET bottles, for example, are common in municipal waste. If the waste stream data has specific detailed entries for PET, that material name can be used, but if the bottles are mixed with other plastics a more generic material category like "RigidPlastic" might be more appropriate. <u>Tons of materials should not be counted twice</u>.

disposition describes what happens to the tons at the end-of-life. It is important to recall that *disposition* names refer to specific technical processes, not generic concepts of disposal or recycling. For example, the common word "composting" can actually refer to two different processes, anaerobic digestion (called "anaerobicDigestion" by WIC), or aerobic composting (called "composting" by WIC).

WIC's *material* and *disposition* names are fully described in the companion document *Impact modeling for the Waste Impact Calculator*.

umbDisp is short for "umbrella disposition." This field allows the user to group dispositions into convenient umbrella categories. This field is not necessary to identify what happens to *tons* at end-of-life (*disposition* indicates that), or to calculate environmental impacts. However, it is provided to assist analysts required to report on solid waste within various legal categories. For example, Oregon law requires reports distinguishing "recovered" materials from "disposed" ones. Other jurisdictions might utilize legal categories such as "diverted" or "recycled." Governments differ in which *dispositions* they consider to be recycling or diversion, so the user sets *umbDisp* to reflect their local conditions.

miles is an optional field related to end-of-life transportation impacts. If *miles* are not entered, WIC will use the standard distances in its database. If entered, *miles* should contain the distance traveled for end-of-life dispositions like recycling, composting, or landfilling. Specifically:

- For disposal dispositions such as landfilling and combustion, and for composting dispositions such as composting and anaerobic digestion, *miles* should contain the number of miles between pickup of the material (often at a house or business) and treatment (i.e. landfill, composter, or incinerator).
- For recycling dispositions it should include the miles between pickup and the first participant in the recycling market (e.g. a MRF).
- As elaborated earlier, *miles* should reflect the portion of end-of-life transportation that waste managers can actually influence.

WIC will compare any custom distances to standard distances in its database and scale end-of-life transport impacts in a linear way.

Note: in many cases, end-of-life transport impacts for waste materials are small compared to impacts from other life cycle phases. <u>Users may want to preview impact results using default mileages before committing extensive labor to determining exact transport distances.</u>

scenario is the last variable which helps classify the weight recorded in *tons*. *scenario* is a name which identifies a solid waste management strategy which has been expressed by values of *tons* linked to various combinations of *wasteshed*, *material*, and *disposition*.

Addition of production and end-of-life-transport tonnages

As described above, the records of ***massProfiles*** represent tons of materials handled at the end-of-life phase of the life cycle. Yet, according to the impact calculation formulae described earlier, impacts also occur in two other phases of the materials life cycle: end-of-life transport and production. Waste masses must also be associated with those phases.

One approach, illustrated by the R Markdown document in *Example Applications of the Waste Impact Calculator*, is to supplement ***massProfiles*** with additional records representing those stages. To do this, WIC makes a simple assumption: the number of tons produced, or transported to end-of-life treatment, is the same as the number handled (and measured) at end-of-life-treatment itself.

This assumption is a logical, practical way to apply a life cycle approach to real waste streams composed of diverse materials. It stands to reason that all the tons that are handled at end of life must previously have been produced and transported to end-of-life-treatment. This assumption does *not* imply that WIC assumes material losses during production or end-of-life-transport are zero. They likely are not. Rather, in WIC, if there are material losses in any stage, the consequences of those losses should be reflected in the relevant impact factors – given that *tons* are measured at end-of-life-treatment.

Introduction to the impactFactors table; transport-related adjustment to LCA output

The ***impactFactors*** table contains all the impact factors DEQ makes available to users of WIC. Each record contains one impact factor, describing impact per short ton of waste material, classified by impact category, reference units (e.g. "joules"), material name, life cycle stage, and disposition.

These impact factors are the summarized results of original life cycle assessment work by Oregon DEQ, work described in detail in *Impact modeling for the Waste Impact Calculator*. While that life cycle assessment work contains certain assumptions that are specific to Oregon, ***impactFactors*** should nonetheless be useful to many outside of Oregon.

The ***impactFactors*** table provided with WIC is usable as-is. However, it does differ slightly from the direct output of DEQ's LCA software, which is available as part of the *wic-base* repository. The direct output of the LCA software is altered in two ways before it is saved in the ***impactFactors*** table. These transformations serve the purpose of making WIC's life cycle stages (production, end-of-life-transport, and end-of-life) relevant to processes waste managers can actually influence. In particular:

<u>Production transportation impacts are merged with production process impacts.</u> The direct LCA output distinguishes between "production" impacts and "production transportation" impacts. However, WIC's typical user (a manager of solid waste) has little influence over production transportation distances, so when the ***impactFactors*** table is created, these are summed together to create a total production impact.

<u>Some end-of-life-transportation impacts are assigned to end-of-life process impacts.</u> The direct LCA output gives end-of-life-transportation impacts for the whole end-of-life transport chain from local pickup (e.g. at curbside) to final processing (e.g. landfill or user of recycled material). The way this full transport

chain is modelled is described in the *Impact Modelling* document. But this full distance is not always under the control of local waste managers. For disposal (landfilling and incineration) and composting (aerobic and anaerobic) local waste managers have a good idea of the final destination, so for these dispositions end-of-life transport factors are left unaltered.

However, for recycling dispositions, recovered materials enter an active marketplace where they may change hands numerous times and travel many hundreds of miles before the material is actually used. The local waste manager only has power over the first part of this journey – before the material enters the recycling market. Therefore for recycling dispositions, the end-of-life-transport factor is split into two parts. The part of that factor that can be influenced by the local waste manager is approximated by the landfilling end-of-life-transport factor for that material (in Oregon, this represents truck transport of about 180 miles). The remaining portion of the end-of-life transport factor represents transport impacts that are beyond the influence of the local waste manager, so this portion is added to the end-of-life-treatment impact factor for that material and disposition.

All the end-of-life transport factors, whether subject to the transformation above or not, may be scaled by *miles* values input by the user.

Structure and logic of the impactFactors table

The ***impactFactors*** table is thousands of lines long, but the first 20 lines demonstrate its format:

First 20 lines of the impactFactors table

material	LCstage	disposition	corporateSource	impactCategory	impactUnits	impliedMiles	impactCategoryLong	impactFactor	gabiExportDate	wicImportDate
AcceptedOtherSteel	endOfLife	incinerationNoER	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	85.14568	2020-11-06	2021-02-11
AcceptedOtherSteel	endOfLife	landfilling	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	39.36742	2020-11-06	2021-02-11
AcceptedOtherSteel	endOfLife	recyclingGeneric	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	-1455.27759	2020-11-06	2021-02-11
AcceptedOtherSteel	endOfLifeTransport	incinerationNoER	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01883	2020-11-06	2021-02-11
AcceptedOtherSteel	endOfLifeTransport	landfilling	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01883	2020-11-06	2021-02-11
AcceptedOtherSteel	endOfLifeTransport	recyclingGeneric	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01883	2020-11-06	2021-02-11
AcceptedOtherSteel	production	production	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	2213.56286	2020-11-06	2021-02-11
Aluminum	endOfLife	incinerationNoER	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	142.37133	2020-11-06	2021-02-11
Aluminum	endOfLife	landfilling	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	39.36742	2020-11-06	2021-02-11
Aluminum	endOfLife	recyclingGeneric	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	-2267.13376	2020-11-06	2021-02-11
Aluminum	endOfLifeTransport	incinerationNoER	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01883	2020-11-06	2021-02-11
Aluminum	endOfLifeTransport	landfilling	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01883	2020-11-06	2021-02-11
Aluminum	endOfLifeTransport	recyclingGeneric	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01883	2020-11-06	2021-02-11
Aluminum	production	production	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	4724.99869	2020-11-06	2021-02-11
AsepticContainers	endOfLife	incinerationER	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	210.11534	2020-11-06	2021-02-11
AsepticContainers	endOfLife	landfilling	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	388.83016	2020-11-06	2021-02-11
AsepticContainers	endOfLife	recyclingGeneric	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	-578.46351	2020-11-06	2021-02-11
AsepticContainers	endOfLifeTransport	incinerationER	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01006	2020-11-06	2021-02-11
AsepticContainers	endOfLifeTransport	landfilling	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01006	2020-11-06	2021-02-11
AsepticContainers	endOfLifeTransport	recyclingGeneric	IPCC AR5	GWP 100	kg CO2 eq.	180	GWP100, excl biogenic carbon	41.01006	2020-11-06	2021-02-11

In this table, *impactFactor* is the field with the most essential information. This number expresses a potential environmental impact per short ton of waste of a particular material in a particular life cycle stage. All the other variables in each record identify or qualify the impact factor somehow – e.g. name the material, label its units, etc. (Note: the number of significant digits displayed for the *impactFactor* field is merely what is stored in the table – it is not an assertion of the precision of the results.)

material is the material name, and is defined identically to *material* in ***massProfiles***.

LCstage means life cycle stage. Entries here express the three life cycle stages used by WIC to characterize the materials life cycle: production, end-of-life transport, and end-of-life treatment itself.

disposition is defined the same as it is in ***massProfiles***. Observe that in the ***impactFactors*** table, every end-of-life disposition is associated with two *LCstages*: endOfLife, and endOfLifeTransport.

impactCategory is a short descriptive name for the environmental impact being calculated, for example "Acidification" or "Eutrophication". Note that the field *impactCategory* actually contains several kinds of quantities – "LCIA profiles" like global warming potentials, and "inventory metrics" such as water use. For a more details on *impactCategory* meanings, see *corporateSource* and *impactCategoryLong*.

impactUnits is the technical reference unit applicable to the *impactFactor*, for example "MJ" (megajoules) for energy use. <u>KEY POINT: all impact units are PER SHORT TON of the solid waste *material*.</u> So if *impactUnits* are entered as "MJ", the real impact units are "MJ/short ton". However the "short ton" part is omitted here for convenience in later processing.

impactFactor is the datum that actually relates impact to mass. So if *impactFactor* is 100000, *material* is "material A", *LCstage* is production, *disposition* is production, *impactCategory* is Energy Use, and *impactUnits* are MJ, that means it takes 100000 MJ of energy to produce 1 short ton of "material A".

impliedMiles is relevant only to the endOfLifeTransport *LCstage*, and ignored elsewhere. This expresses the number of transport miles assumed to be involved in end-of-life transport for the material in question. Once ***impactFactors*** has been merged with ***massProfiles***, *impliedMiles* will be compared to any custom mileages that have been entered in ***massProfiles*** by the user, so that end-of-life transport impacts can be scaled up or down.

corporateSource is the LCIA method associated with the *impactCategory*, for example IPCC AR5 or ReCiPe. If this field is blank, the associated *impactFactor* represents a life cycle inventory metric taken from GaBi software and databases.

impactCategoryLong is the full-length impact category name provided by GaBi software, which may be more explicit in detail than the shorter *impactCategory* used elsewhere in WIC.

gabiExportDate is the date DEQ staff exported impact factor information from their GaBi software.

wicImportDate is the date DEQ staff took the GaBi export files and imported them into WIC.

Merging the two tables and calculating impacts

The fundamental work of WIC is done when ***massProfiles*** information is merged with the ***impactFactors***, on the basis of their common fields: *material* and *disposition*. Spellings of entries in these fields must match exactly between the two tables. This merge allows impacts to be calculated.

There are many ways the merge and calculation of impacts could be executed. One implementation of this process can be found in the R Markdown document in *Example Applications of the Waste Impact Calculator*. In that example, ***massProfiles*** has been expanded into a new table called ***massProfilesPlus***, which includes records representing tonnages in the production phase. Mass records are still missing for the end-of-life-transport stage, but these are created in the next step, the merge itself.

The merging command (in this case, left_join() from R's dplyr package) is configured to create one record every time a *material-disposition* pair in ***massProfilesPlus*** matches an available *material-disposition* pair in ***impactFactors***. No fields from either table are dropped.

The merge command and subsequent code creates a new data table, called in this example ***impactsInDetail***. This table has useful properties. Within each *impactCategory*:

- There are *two* records for every record from ***massProfilesPlus*** that represents an end-of-life tonnage. The tonnage in each record will be the same, but one of these two cases will have the *LCstage* "endOfLife", while the other's *LCstage* is "endOfLifeTransport". (That is, merging the two files creates records that represent the *tons* associated with end-of-life-transport.)
- There is one record for every record from ***massProfilesPlus*** that represents production tonnage. The *LCstage* for these records will be "production".
- Every record has both *tons* (based on original entries in the ***massProfiles*** table) and *impactFactor* (from the ***impactFactors*** table).
- Records with the *LCstage* "endOfLifeTransport" also have any custom *miles* values entered.
- Impacts have been calculated by multiplication and added as a new column. *impact* = *tons* * *impactFactor*, except when *LCstage* is "endOfLifeTransport," where *impact*=*tons**impactFactor**(*miles*/*impliedMiles*).

Note that ***impactsInDetail*** has records representing tons handled in 3 life cycle stages (production, end-of-life-transport, and end-of-life treatment), associated with and identified by values of *scenario*, *wasteshed*, *material*, *LCstage*, *disposition*, and *impactCategory*. In addition, each line is labeled with the *umbDisp* from ***massProfilesPlus***, so distinctions can be made between recovery and disposal impacts or tonnages if desired.

An ***impactsInDetail*** table drawn from the previous examples of ***massProfiles*** and ***impactFactors*** is shown below. Since this table is very long, results are shown for only a single impact category.

impactsInDetail table (example)

scenario	wasteshed	material	disposition	umbDisp	tons	miles	LCstage	impactCategory	impactUnits	impliedMiles	impactFactor	impact
baseline	Anytown	FoodWaste	landfilling	disposal	7669	178	endOfLife	Acidification	kg SO2 eq.	180	3.0183015	23147.35415
baseline	Anytown	FoodWaste	landfilling	disposal	7669	178	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	668.36960
baseline	Anytown	FoodWaste	production	production	7669	180	production	Acidification	kg SO2 eq.	180	15.8027864	121191.56916
baseline	Anytown	YardDebris	composting	recovery	9000	4	endOfLife	Acidification	kg SO2 eq.	180	0.9002805	8102.52432
baseline	Anytown	YardDebris	composting	recovery	9000	4	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	17.62627
baseline	Anytown	YardDebris	production	production	9000	180	production	Acidification	kg SO2 eq.	180	0.0629918	566.92620
compostFW1000	Anytown	FoodWaste	composting	recovery	1000	77	endOfLife	Acidification	kg SO2 eq.	180	0.9002805	900.28048
compostFW1000	Anytown	FoodWaste	landfilling	disposal	6669	178	endOfLife	Acidification	kg SO2 eq.	180	3.0183015	20129.05266
compostFW1000	Anytown	FoodWaste	composting	recovery	1000	77	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	37.70064
compostFW1000	Anytown	FoodWaste	landfilling	disposal	6669	178	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	581.21748
compostFW1000	Anytown	FoodWaste	production	production	1000	180	production	Acidification	kg SO2 eq.	180	15.8027864	15802.78643
compostFW1000	Anytown	FoodWaste	production	production	6669	180	production	Acidification	kg SO2 eq.	180	15.8027864	105388.78272
compostFW1000	Anytown	YardDebris	composting	recovery	9000	77	endOfLife	Acidification	kg SO2 eq.	180	0.9002805	8102.52432
compostFW1000	Anytown	YardDebris	composting	recovery	9000	77	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	339.30572
compostFW1000	Anytown	YardDebris	production	production	9000	180	production	Acidification	kg SO2 eq.	180	0.0629918	566.92620
compostFW585	Anytown	FoodWaste	composting	recovery	585	77	endOfLife	Acidification	kg SO2 eq.	180	0.9002805	526.66408
compostFW585	Anytown	FoodWaste	landfilling	disposal	7084	77	endOfLife	Acidification	kg SO2 eq.	180	3.0183015	21381.64778
compostFW585	Anytown	FoodWaste	composting	recovery	585	77	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	22.05487
compostFW585	Anytown	FoodWaste	landfilling	disposal	7084	77	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	267.07130
compostFW585	Anytown	FoodWaste	production	production	585	180	production	Acidification	kg SO2 eq.	180	15.8027864	9244.63006
compostFW585	Anytown	FoodWaste	production	production	7084	180	production	Acidification	kg SO2 eq.	180	15.8027864	111946.93909
compostFW585	Anytown	YardDebris	composting	recovery	9000	77	endOfLife	Acidification	kg SO2 eq.	180	0.9002805	8102.52432
compostFW585	Anytown	YardDebris	composting	recovery	9000	77	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	339.30572
compostFW585	Anytown	YardDebris	production	production	9000	180	production	Acidification	kg SO2 eq.	180	0.0629918	566.92620
reduceFW03	Anytown	FoodWaste	landfilling	disposal	7439	178	endOfLife	Acidification	kg SO2 eq.	180	3.0183015	22453.14481
reduceFW03	Anytown	FoodWaste	landfilling	disposal	7439	178	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	648.32461
reduceFW03	Anytown	FoodWaste	production	production	7439	180	production	Acidification	kg SO2 eq.	180	15.8027864	117556.92828
reduceFW03	Anytown	YardDebris	composting	recovery	9000	4	endOfLife	Acidification	kg SO2 eq.	180	0.9002805	8102.52432

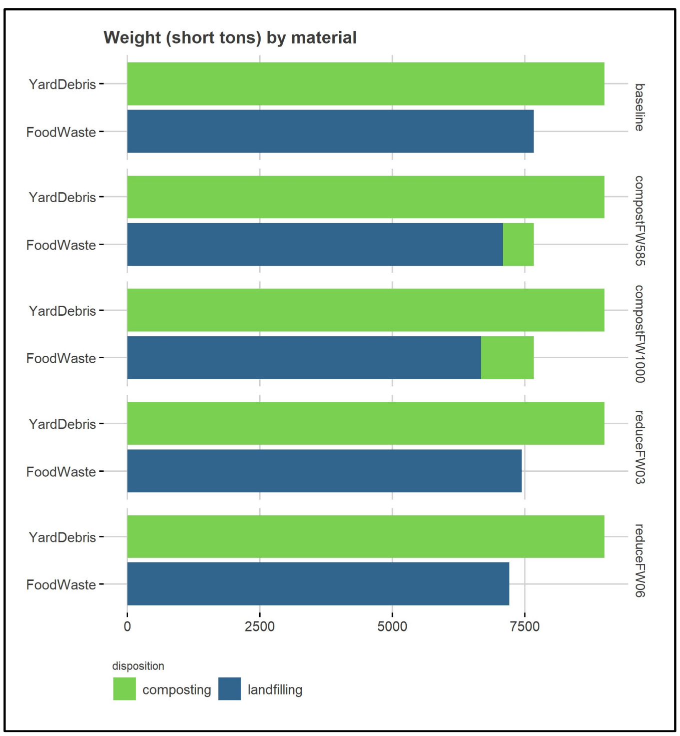
reduceFW03	Anytown	YardDebris	composting	recovery	9000	4	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	17.62627
reduceFW03	Anytown	YardDebris	production	production	9000	180	production	Acidification	kg SO2 eq.	180	0.0629918	566.92620
reduceFW06	Anytown	FoodWaste	landfilling	disposal	7209	178	endOfLife	Acidification	kg SO2 eq.	180	3.0183015	21758.93547
reduceFW06	Anytown	FoodWaste	landfilling	disposal	7209	178	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	628.27962
reduceFW06	Anytown	FoodWaste	production	production	7209	180	production	Acidification	kg SO2 eq.	180	15.8027864	113922.28740
reduceFW06	Anytown	YardDebris	composting	recovery	9000	4	endOfLife	Acidification	kg SO2 eq.	180	0.9002805	8102.52432
reduceFW06	Anytown	YardDebris	composting	recovery	9000	4	endOfLifeTransport	Acidification	kg SO2 eq.	180	0.0881314	17.62627
reduceFW06	Anytown	YardDebris	production	production	9000	180	production	Acidification	kg SO2 eq.	180	0.0629918	566.92620

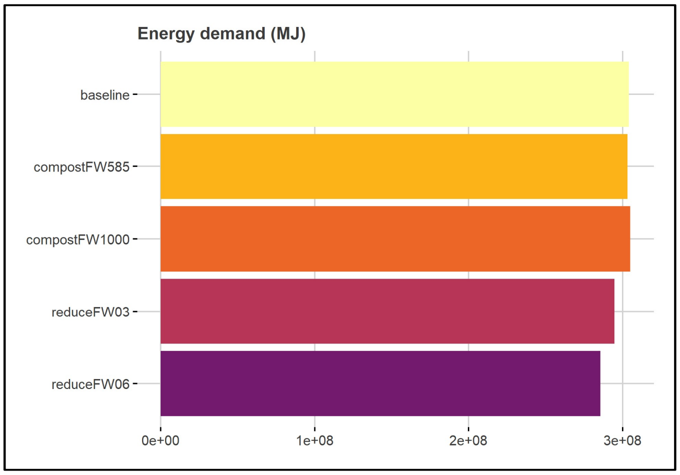
Reporting results: examples and guidelines

The table resulting from the merge of ***massProfiles*** and ***impactFactors***, called ***impactsInDetail*** in the example above, can be very large. However ***impactsInDetail*** is also very convenient, serving as a single data source for all future output from WIC. Most results of interest – for example, the total waste tonnages and total impacts linked to each scenario – are the output of simple filtering, grouping, and summation operations on the *tons* or *impacts* in *impactsInDetail*.

The example analysis in *Example Applications of the Waste Impact Calculator* contains multiple demonstrations of such operations. That analysis explores five management scenarios related to a wastestream composed of only food waste and yard debris. The management question is, how would life cycle impacts change if some food waste, usually destined for landfill, is added to yard debris collections destined for composting? One of the five scenarios represents a baseline of current activity (“baseline”), two represent increases in food waste composting (“compostFW585” and “compostFW1000”), and two more represent reducing food waste generation modestly as an alternative to additional composting (“reduceFW03” and “reduceFW06”).

The results of such an analysis may be presented in simple or complex displays. A simple summary of the results would provide one chart summarizing weight-based management for each scenario with one chart summarizing total impact by some metric. For example see the following two charts:





The second chart suggests the five management scenarios differ very little in their impact, as measured by energy demand. Reasons for this particular result will be examined below. But first – as when confronting any result, expected or unexpected – the user is advised to make quality checks to assure the data is internally consistent and reflects the intended waste management scenarios. For example:

- Within each scenario, are the tonnages applied to each *LCstage* the same? They should be, because the WIC framework assumes that within each scenario, the same number of tons have been produced, moved to an end-of-life treatment, and received an end-of-life treatment. (See earlier discussion under "Addition of production and end-of-life-transport tonnages.")
- Does every record have a value in every field? (With the exception of the *miles* field, which may be missing when *LCstage* is not "endOfLifeTransport"?) The answer should be yes, because WIC assumes that every record has an *impactFactor* and an *impact*. That is, no *impactFactors* or *impacts* should be missing, and any *impactFactor*s that are exactly zero should be examined for correctness. The latter are unlikely, and may represent a computation error either on the user's part or within WIC's databases.

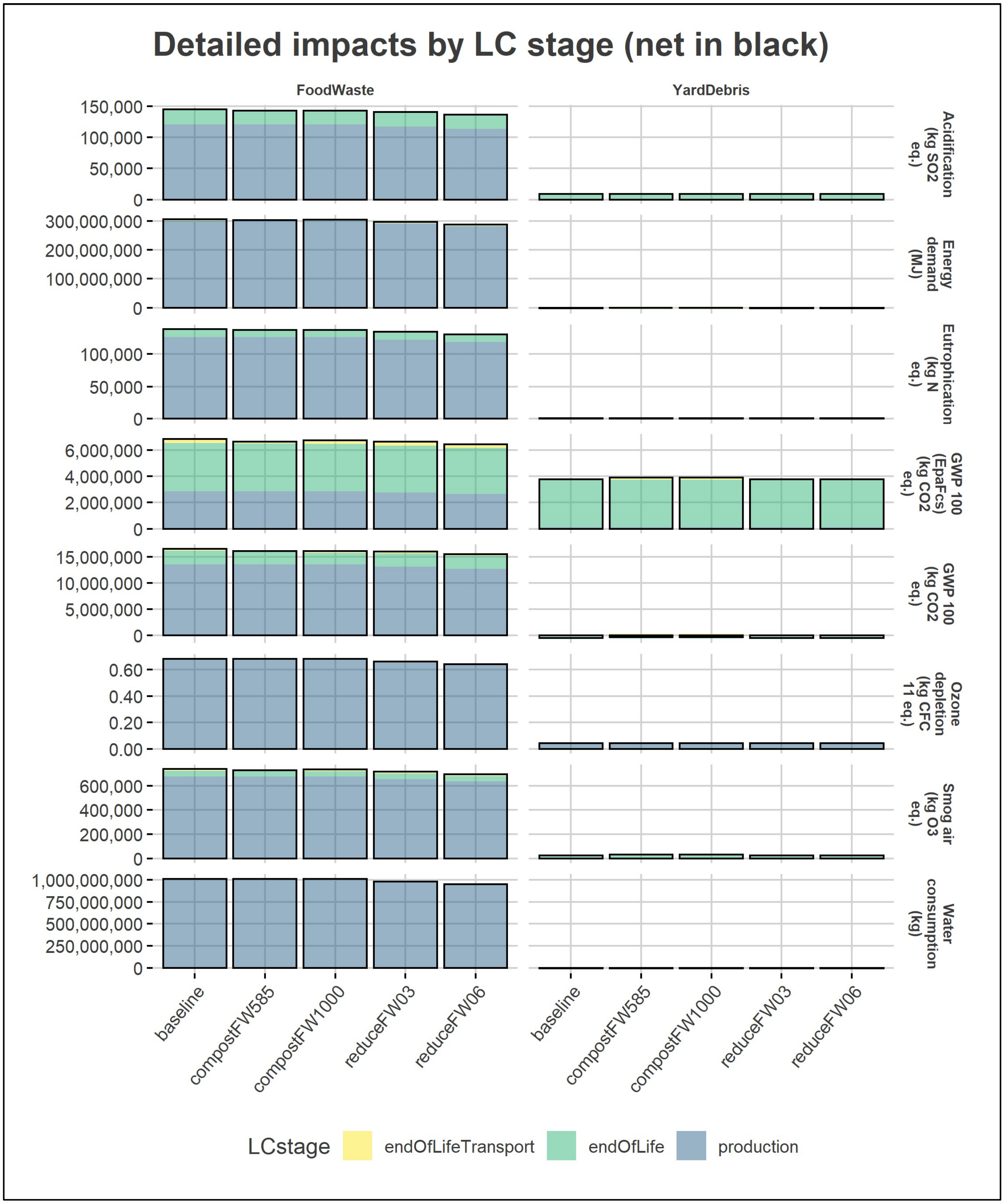
When simple checks of this type fail, it often because the ***massProfiles*** table provided by the user somehow does not match the ***impactFactors*** table – perhaps in the spelling of *material* names or *dispositions*. The *material* and *disposition* names available as of this writing are tabled in the next section, "Available materials and dispositions".

When creating results from an internally consistent ***impactsInDetail***, recall that there is much redundancy in this data table – there are one or more lines for every combination of *scenario, wasteshed, material, LCstage, disposition, umbDisp,* and *impactCategory*. Data must be filtered and grouped conscientiously for each piece of output produced.

- In particular, when *tons* are summed, they should be restricted to tons linked to the "endOfLife" *LCstage*. The *tons* that appear in other *LCstages* are redundant and only serve for the calculation of the impacts of those stages.
- Likewise, when *tons* are summed, records should be restricted to a single *impactCategory* (the tons have appeared only once; they are simply duplicated within *impactsInDetail* for convenience).
- It is expected that *impacts* will only be summed within the context of a single *impactCategory*. If the user has a desire to combine or normalize results from multiple impact categories, it is their responsibility to create and defend a method of doing so.

The R Markdown document in *Example applications of the Waste Impact Calculator* suggests quality checks that should prevent the most likely pitfalls in data processing.

Assuming the data is internally consistent, what do the impact results suggest about yard debris, food waste, and their management? In particular, why are the total impacts of all the scenarios so similar? A more complex chart makes the reasons understandable:



This chart gives separate results for the two materials (yard debris and food waste), and distinguishes among life cycle stages (end-of-life transport, end-of-life treatment, and production). It also shows multiple impact metrics (acidification, energy demand, etc).

Even without an understanding of the details of each scenario (which can be found in the *Example Applications* document), this chart illustrates some themes typical of WIC results.

- Materials can differ dramatically in their impact characteristics. Though food waste and yard debris have similar weights (as shown earlier, on the simpler charts), total impacts are dominated by just one material (food waste), as the complex chart shows. (One implication of this finding is that weight-based summaries which mix materials -- common in government waste statistics, for example diversion rates -- will be unreliable proxies for impacts.)
- Life cycle impacts can be dominated by the production stage – as is the case for food waste in the complex chart. End-of-life adjustments such as composting do provide some net change in impact, but not on the magnitude that changes in weight-based recovery rates might suggest.
- Changes in the generation of waste are more likely to change total impacts substantially.

These are the kind of relationships and contrasts WIC is designed to let you investigate. WIC's authors welcome your feedback on, experiences with, and contributions to the model.

Available materials and dispositions

The following impact factors have been defined for WIC as of this writing. For more information about the meaning of material and disposition names, see *Impact Modelling for the Waste Impact Calculator*.

This list may be updated at any time – see the project's github site for the most recent release.

material	incinerationNoER	landfilling	recyclingGeneric	production	incinerationER	anaerobicDigestion	composting	recyclingPozzolan	recyclingToAggregate	recyclingToContainer	recyclingToFiberglass
AcceptedOtherSteel	TRUE	TRUE	TRUE	TRUE							
Aluminum	TRUE	TRUE	TRUE	TRUE							
AsepticContainers		TRUE	TRUE	TRUE	TRUE						
AsphaltRoofing	TRUE	TRUE	TRUE	TRUE	TRUE						
Cardboard	TRUE	TRUE	TRUE	TRUE	TRUE						
Carpeting	TRUE	TRUE	TRUE	TRUE	TRUE						
Electronics		TRUE	TRUE	TRUE							
EPS		TRUE	TRUE	TRUE	TRUE						
FoodWaste	TRUE	TRUE		TRUE	TRUE	TRUE	TRUE				
FreezerBoxes		TRUE	TRUE	TRUE	TRUE						
GableTopCartons		TRUE	TRUE	TRUE	TRUE						
Glass	TRUE	TRUE		TRUE				TRUE	TRUE	TRUE	TRUE
GypsumWallboard	TRUE	TRUE	TRUE	TRUE							
HDPE		TRUE	TRUE	TRUE	TRUE						
LDPE		TRUE	TRUE	TRUE	TRUE						
Newsprint		TRUE	TRUE	TRUE	TRUE						
Nonrecyclables	TRUE	TRUE		TRUE	TRUE						
Paperboard		TRUE	TRUE	TRUE	TRUE						
PaperFiber	TRUE	TRUE	TRUE	TRUE	TRUE						
PET		TRUE	TRUE	TRUE	TRUE						
PlasticFilm	TRUE	TRUE	TRUE	TRUE	TRUE						
PlasticOther	TRUE	TRUE	TRUE	TRUE	TRUE						
PP		TRUE	TRUE	TRUE	TRUE						
PrintingWritingPaper		TRUE	TRUE	TRUE	TRUE						
PS		TRUE	TRUE	TRUE	TRUE						
RigidPlastic	TRUE	TRUE	TRUE	TRUE	TRUE						
ScrapMetal	TRUE	TRUE	TRUE	TRUE							
Textiles	TRUE	TRUE	TRUE	TRUE	TRUE						
TinnedCan	TRUE	TRUE	TRUE	TRUE							
Wood		TRUE		TRUE	TRUE		TRUE				
YardDebris	TRUE	TRUE		TRUE	TRUE	TRUE	TRUE				