LIFE CYCLE ASSESSMENT OF CORRUGATED CONTAINERS AND REUSABLE PLASTIC CONTAINERS FOR PRODUCE TRANSPORT AND DISPLAY

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For:

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THE Natural CHOICE

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Executive Summary

The relative environmental profiles of single-use corrugated fiberboard shipping containers and reusable plastic shipping containers have been investigated in recent years using a life cycle approach. Most of these studies evaluate the containers in the context of European markets, and further research is needed to better understand the relative environmental profiles of single-use corrugated fiberboard containers and reusable plastic containers for produce transport, storage and display in the U.S.

The Corrugated Packaging Alliance (CPA) has commissioned Quantis to perform an ISO 14044 compliant comparative LCA of corrugated containers (CC) and reusable plastic containers (RPC) used to transport and display fresh produce (e.g., apples) in the U.S. This investigation aims to identify the relative environmental performance of these two container systems. More specifically, the objectives of the study are to:

I. Establish credible and transparent profiles of the life cycle potential environmental impacts of corrugated containers and reusable plastic containers utilizing appropriate and accepted databases and LCIA characterization factors according to ISO 14040 and 14044:2006;
II. Identify the magnitude and confidence of comparative environmental advantages of either system; and
III. Ensure compliance of results with ISO 14044 (clause 6) and ISO 14040 (clause 7) to support a public comparative claim, including critical review by a panel of interested parties.

This study includes comparative statements regarding the environmental performance of the two products. It evaluates the relative environmental performance of single-use corrugated fiberboard containers and reusable plastic containers in the context of the U.S. produce market through an ISO 14044 compliant LCA.

The CC and RPC under evaluation are utilized for transporting produce from produce grower to a retail market. The reusable container studied is a standard footprint RPC that is available in the U.S. as a produce packaging solution. The CCs evaluated for comparison are the most prevalent size used for each commodity and were selected based on data from member companies who combined provide more than 70% of the boxes to the produce sector.

The functional unit for this study is to provide containment during filling, transport and display of 907,185 kg (1,000 short tons) of grocery market produce in the United States in a manner that maintains the safety of the produce for human consumption and that is consistent with commercial supply chains. The container profiles investigated are specific to eight types of produce: apples, carrots, grapes, lettuce (head), oranges, onions, tomatoes and strawberries. As the intent of this study is to capture a snapshot of average U.S. industry operations, only U.S.-grown produce are considered, and seasonal variation is not discretely evaluated.

This study assesses the life cycle of CCs and RPCs from the extraction and processing of all raw materials through the end-of-life of the containers. The models are intended to represent the RPC and CC industries and associated processes in the United States at the time the study is conducted. As there is a lack of published studies evaluating the myriad parameters applicable to this assessment (e.g., recycled content, RPC number of uses, etc.), the work herein represents CPA's understanding of each industry based on its own research. Information from pre-existing, recent life cycle studies on CCs and RPCs are used as applicable in conjunction with information offered in confidence by both CC and RPC industry members. Available life cycle data for some elements of the systems represent industry operations as early as 2002 (NREL 2014).

TRACI 2.1 is chosen as the primary impact assessment method for this study, except in the case of the non-renewable energy indicator. TRACI's fossil fuel use indicator is substituted by the non-renewable energy indicator from IMPACT2002+ v2, as it is a direct assessment of energy use and does not require projections regarding the future state of resource availability and consumption. Environmental indicators for land use and land transformation are excluded. These are not able to be adequately quantified due to the lack of inventory data. Also excluded are indicators for ecotoxicity and human health (carcinogens and non-carcinogens) because the toxicity-related data used for the RPC and CC systems are not comparable. A total of seven (7) environmental metrics are evaluated with no normalization of results or weighting of impact categories: acidification, eutrophication, global warming, non-renewable energy, ozone depletion, respiratory effects and smog formation. Two (2) inventory flows are also presented: freshwater consumption and solid waste. GaBi 8 software is employed to perform the calculations.

Several additional evaluations are performed to understand the robustness of the study conclusions. These include numerous sensitivity tests around the CC and the RPC systems, calculation of results using a second impact assessment method (ReCiPe 2016), and a data quality assessment. The latter consists of a completeness and consistency check of the data, a contribution analysis, and an uncertainty analysis. An external panel has been commissioned to conduct a review in accordance with the ISO 14040 series.

Results

Figure ES-1, ES-2 and ES-3, following below, demonstrate some of the baseline results found in this study. Figure ES-1 depicts the market-weighted average results for each container system. Figure ES-2 shows the commodity-specific results for CC and RPC systems. Figure ES-3 depicts the potential ranges of impact for each container system carrying apples. Conclusions reached by this study are based on the baseline results for all commodities in combination with results of the sensitivity tests and uncertainty and data quality analyses performed.

Market-Weighted Results

The market-weighted average results in Figure ES-1 show that four of seven (4/7) impact categories are favorable for the RPC system, and three of seven (3/7) impact categories are favorable for the CC system. Specifically, acidification, ozone depletion, respiratory effects and smog formation show lesser environmental impact for RPCs. Eutrophication, global warming and non-renewable energy use demonstrate better environmental performance for CCs.

These observations of the market-weighted average results do not consider uncertainty. While the uncertainty analysis was carried out only for the commodity-specific results, it is reasonable to apply those outcomes here in a broad way. In doing so, the list of indicators that favor RPCs is narrowed to acidification, ozone depletion and respiratory effects, and the list of indicators that show an advantage for CCs reduces to global warming and non-renewable energy use. **From a market-weighted average perspective, tradeoffs exist in the environmental profiles of CCs and RPCs.**

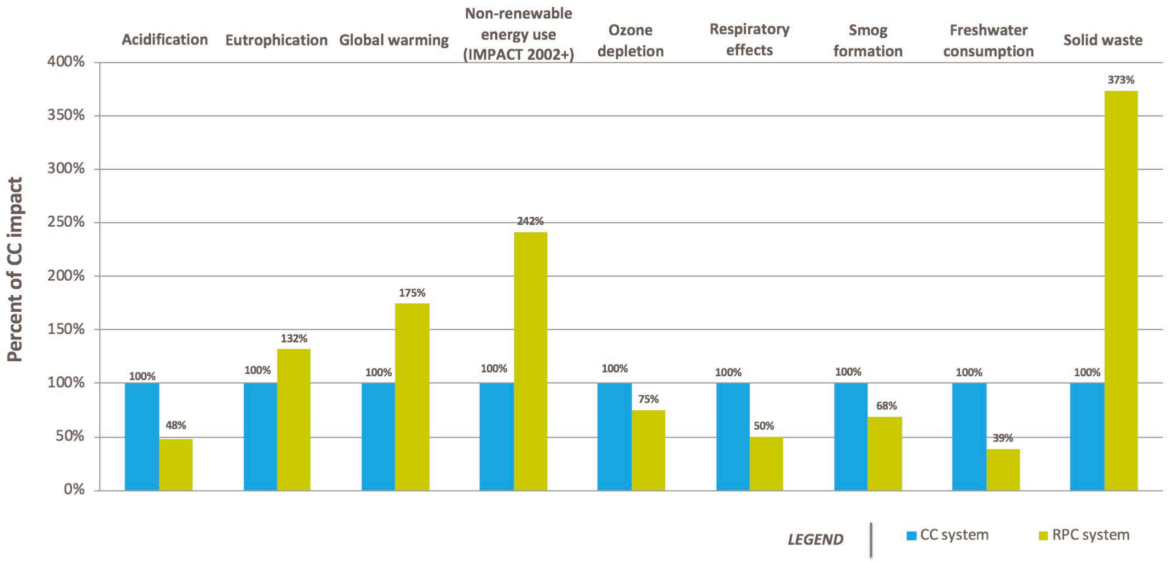
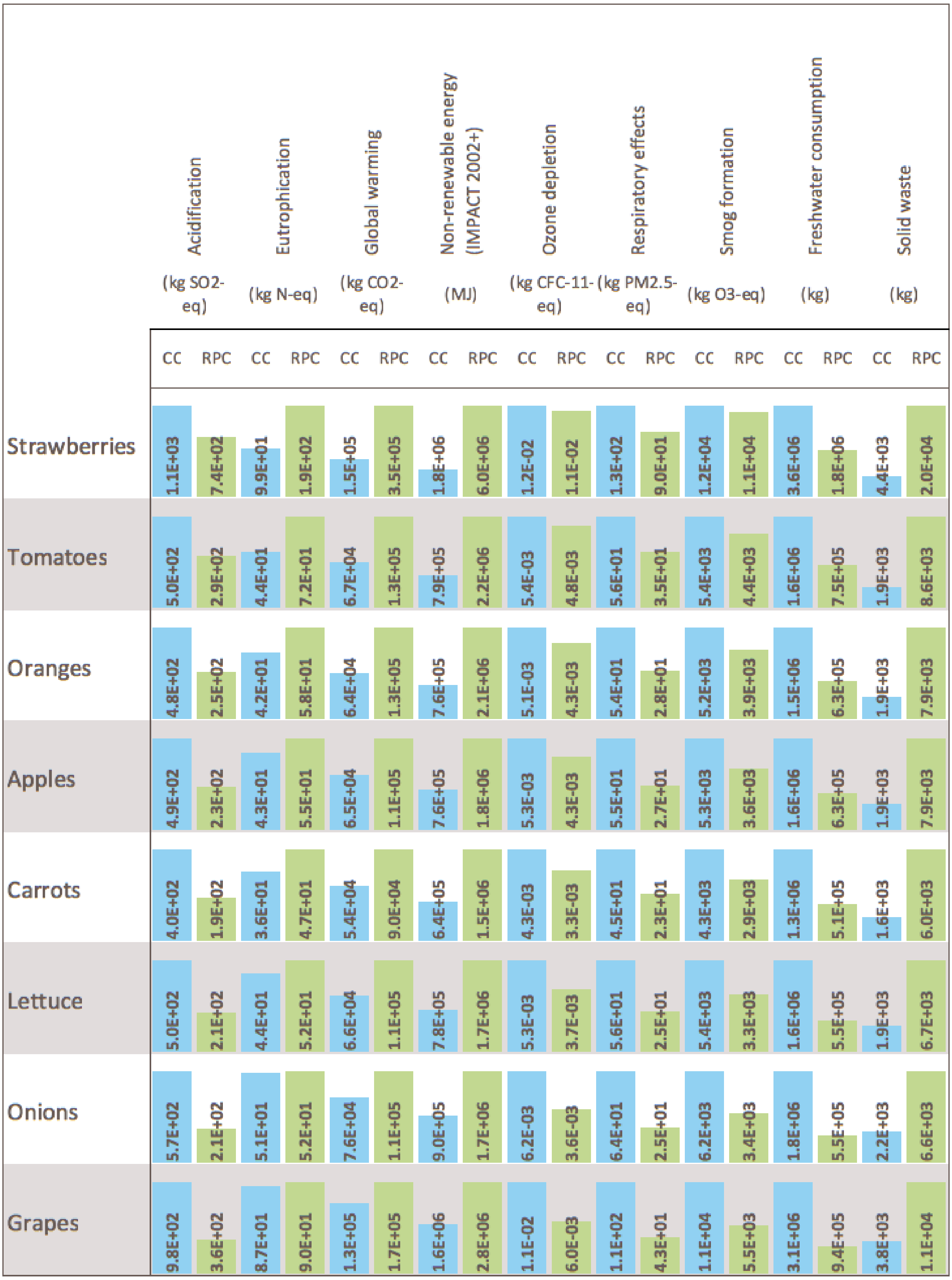


Figure ES-1. Market-weighted average results for the baseline analysis.

Commodity-Specific Results

Commodity-specific results show similar trade-offs between the container systems. Digging deeper, across the commodity-specific results shown in Figure ES-2, four of seven (4/7) impact categories are favorable for the RPC system, and two of seven (2/7) impact categories are favorable for the CC system. For the remaining indicator (eutrophication), the direction of the advantage is not consistent across commodities, as no discernible difference can be made for grapes and onions. Thus, a conclusion for eutrophication regarding the directional results cannot not be made with confidence.

The RPC system has an advantage in acidification, respiratory effects, ozone depletion and smog formation while global warming and non-renewable energy use shows an advantage for CCs. However, **after considering the uncertainty assessment of the results, (see section 5.5.2) three (3) impact categories show an advantage for RPCs (acidification, respiratory effects, and ozone depletion), and two (2) impact categories show an advantage for CCs (global warming and non-renewable energy use).** No difference between the systems can be concluded for



	Acidification (kg SO2-eq)		Eutrophication (kg N-eq)		Global warming (kg CO2-eq)		Non-renewable energy (IMPACT 2002+) (MJ)		Ozone depletion (kg CFC-11-eq)		Respiratory effects (kg PM2.5-eq)		Smog formation (kg O3-eq)		Freshwater consumption (kg)		Solid waste (kg)	
	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC
Strawberries	1.1E+03	7.4E+02	9.9E+01	1.9E+02	1.5E+05	3.5E+05	1.8E+06	6.0E+06	1.2E-02	1.1E-02	1.3E+02	9.0E+01	1.2E+04	1.1E+04	3.6E+06	1.8E+06	4.4E+03	2.0E+04
Tomatoes	5.0E+02	2.9E+02	4.4E+01	7.2E+01	6.7E+04	1.3E+05	7.9E+05	2.2E+06	5.4E-03	4.8E-03	5.6E+01	3.5E+01	5.4E+03	4.4E+03	1.6E+06	7.5E+05	1.9E+03	8.6E+03
Oranges	4.8E+02	2.5E+02	4.2E+01	5.8E+01	6.4E+04	1.3E+05	7.6E+05	2.1E+06	5.1E-03	4.3E-03	5.4E+01	2.8E+01	5.2E+03	3.9E+03	1.5E+06	6.3E+05	1.9E+03	7.9E+03
Apples	4.9E+02	2.3E+02	4.3E+01	5.5E+01	6.5E+04	1.1E+05	7.6E+05	1.8E+06	5.3E-03	4.3E-03	5.5E+01	2.7E+01	5.3E+03	3.6E+03	1.6E+06	6.3E+05	1.9E+03	7.9E+03
Carrots	4.0E+02	1.9E+02	3.6E+01	4.7E+01	5.4E+04	9.0E+04	6.4E+05	1.5E+06	4.3E-03	3.3E-03	4.5E+01	2.3E+01	4.3E+03	2.9E+03	1.3E+06	5.1E+05	1.6E+03	6.0E+03
Lettuce	5.0E+02	2.1E+02	4.4E+01	5.2E+01	6.6E+04	1.1E+05	7.8E+05	1.7E+06	5.3E-03	3.7E-03	5.6E+01	2.5E+01	5.4E+03	3.3E+03	1.6E+06	5.5E+05	1.9E+03	6.7E+03
Onions	5.7E+02	2.1E+02	5.1E+01	5.2E+01	7.6E+04	1.1E+05	9.0E+05	1.7E+06	6.2E-03	3.6E-03	6.4E+01	2.5E+01	6.2E+03	3.4E+03	1.8E+06	5.5E+05	2.2E+03	6.6E+03
Grapes	9.8E+02	3.6E+02	8.7E+01	9.0E+01	1.3E+05	1.7E+05	1.6E+06	2.8E+06	1.1E-02	6.0E-03	1.1E+02	4.3E+01	1.1E+04	5.5E+03	3.1E+06	9.4E+05	3.8E+03	1.1E+04

Figure ES-2. Baseline results (impact per functional unit) for the 8 commodities evaluated in this study. Commodities are ordered from greatest to least functional unit mass ratio. Each bar is shown relative to the system of greatest impact for that impact category and commodity.

smog formation and eutrophication given the level of uncertainty in those results. Further, the data quality assessment reveals that the CC inventory data used to calculate eutrophication is characterized by high uncertainty, and due to its important influence on the results, it is not possible to conclude whether one container system is more than or equally impacting as the other. This observation reinforces the conclusion made earlier regarding the inability to judge the relative performance of the container systems in terms of eutrophication. **Thus, without prioritizing types of impact, it is not possible to say from the present assessment that one of these systems is an overall better environmental performer than the other on the US market,**

and it does not appear that further refinements in data or methodology would be likely to find a fully consistent directional finding.

Best and Worst Case Results

The best and worst case scenarios support these conclusions. Taking the apple system as an example (Figure ES-3), the RPC system range of results for non-renewable energy use sits completely above the CC system range of results for the same indicator. This lack of overlap confirms the deduction made from the baseline and uncertainty analyses: the CC system uses less non-renewable energy than the RPC system across all market

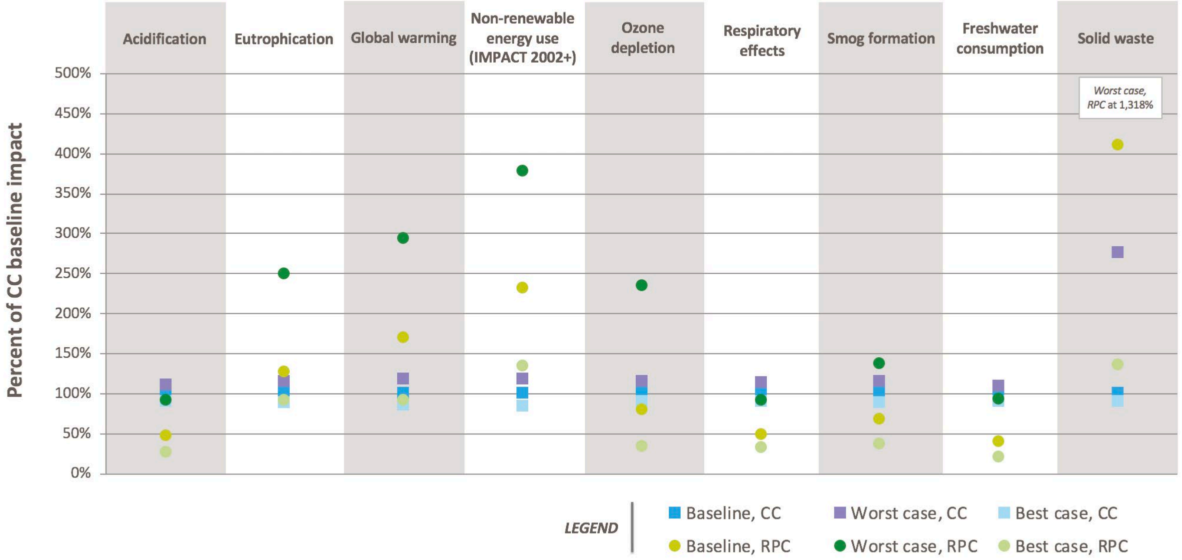


Figure ES-3. Baseline, best and worst case scenarios for RPCs and CCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

conditions. A similar and opposite conclusion can be drawn when comparing the best and worst case results for apples in acidification and respiratory effects. The ranges of RPC results are almost entirely below the range of the CC results, meaning that in most market conditions, RPCs are less impacting for these two indicators. For all other indicators, there is notable overlap between the span of best and worst case results for the two systems. This means that neither container system has a clear advantage for these metrics.

The strawberry and grape systems show similar outcomes. However, the overlap between the best and worst case results occurs in somewhat different indicators. This means that **within the range of industry variability captured by the sensitivity analyses, the directional conclusions can change for all but a small number of indicators, specific to each commodity.**

Conclusions

While tempting, it is not appropriate to determine the comparative advantage between container types by counting the number of indicators in which a container system shows less impact. Counting the number of categories supporting a container system requires the assumption that each category of impact is equally important. While it is possible to have views or values that define the importance of each category, it is not possible for the authors to defend these values as more correct than the values that might lead another party to a different decision. It is therefore not possible here to draw a definitive conclusion of environmental superiority in cases where there are conflicting indicators that require a trade-off that is primarily value-based. In such cases, including the current one, the only overall conclusion that can be drawn is that trade-offs exist between the systems. Users of this study may apply values systems to arrive at conclusions that may assist in making selections between the container systems under different market conditions.

The inventory flows, freshwater consumption and solid waste, are not considered when comparing the environmental performance of the CC and RPC systems because they are inventory flows only and not impact indicators. They are included to provide a sense for the amounts of these flows required/generated by the system, which allows for some reflection on how results of this study may differ from those of comparable past and future assessments.

The environmental performance of each system is influenced by variation within their life cycles, and the combination of assumptions made for a single system causes the total impact to vary. The ranges observed for this study's context demonstrate that **the assumptions about the RPC life cycle coupled with the assumptions for the CC life cycle can affect the directional**

findings of the study in certain indicators. This is true for all indicators.

CC weight and RPC transportation distances are the most influential factors in determining the relative results between the two container systems. However, it appears that even in those conditions within the market variability that would seem to favor one system more so than the other, a clear environmental advantage for either system is not likely to exist for most commodity systems.

The results, on balance, show that variation exists in the comparative findings among the categories of impact assessed, and**, for a given commodity, the environmental trade-offs between container systems can be predicted based on the ratio of the masses of containers required to achieve the functional unit for each container system.** The difference in container mass needed to ship a specified quantity of produce determines which indicators show an advantage for each container system.

Both systems have opportunities to improve and lessen their impact on the environment. For the CC system, this includes minimizing container weight and maximizing container recovery. The RPC system can achieve environmental performance improvement through increasing reuse and recycled content along with reducing breakage/loss as well as transport distances.

For most of the environmental indicators considered, the impacts associated with produce production far outweigh most or all of the processes in the life cycle of a container, and differences of even a few percent in produce loss between the two container types would likely dictate the relative environmental performance for those indicators. Data describing product protection of the containers (i.e., perishability differences) are not available but could potentially push the advantage in one direction or the other if a significant difference exists.

While this study considers a steady-state market in which the containers evaluated are not changing in the middle of providing the functional unit, it is important to note that container weights and/or dimensions can change over time. Additionally, custom container designs for specific retailers, though not evaluated here, can result in inventories of containers with useful service life remaining when the designs are no longer needed. When a system stops operating before the containers meet their useful service life, a larger portion of the production and disposal impacts of the containers are allocated to that system. In other words, the impact per container is higher because there are fewer lives over which those impacts are distributed.

An important knowledge gap is around the number of RPCs in float[1]. This study takes a conservative approach, assuming float makes up a very small portion (<1%) of the total mass of crates in the system. The effect of this approach is that environmental impact associated with float is negligible. If float is a much larger portion of total mass, its contribution to impact can be important and therefore should be included in a study such as this one.

Considering the conclusions of this study with those of other LCAs comparing CCs and RPCs, the overall deduction is that **environmental trade-offs indeed exist between the RPC and CC systems, and the market characteristics, which vary by geography, have an important influence on these trade-offs**. Given the closeness of results between the two systems in certain impact categories and the sensitivity of the results to certain factors, it is clearly important to model in detail the specific market in question.

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[1] Float refers to the quantity of excess RPCs that exist in the total system. These excess RPCs are required to assure the flexibility to respond to surges in system demand or extended time in the return loop.

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Abbreviations and Acronyms

AF&PA	The American Forest and Paper Association
BTU	British Thermal Unit = 1,060 joules (j)
CC	Corrugated container
CH_4	Methane
CO_2	Carbon dioxide
CPA	Corrugated Packaging Alliance
EOL	End-of-life
FBA	Fibre Box Association
GHG	Greenhouse gas
GMA	Grocery Manufacturer's Association
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Control
ISO	International Organization for Standardization
kg	Kilogram = 1,000 grams (g) = 2.2 pounds (lbs.)
kWh	Kilowatt-Hour = 3,600,000 joules (j)
lb	Pounds = 0.45 kilograms (kg)
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MJ	Mega joules = 1,000,000 joules (j)
NCASI	National Council for Air and Stream Improvement, Inc.
PP	Polypropylene
ReCiPe	Impact assessment method developed by: RIVM, CML , PRé Consultants, Radboud Universiteit Nijmegen and CE Delft
RPC	Reusable plastic container
Tonne-km	Tonne-kilometer; 1 metric ton traveling 1 kilometer
Ton-mi	Ton-mile; 1 short ton traveling 1 mile
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts

1. Introduction

The increasing awareness of the importance of environmental consequences associated with products and services has placed a focus on developing methods to better understand and proactively manage such impacts. Since as early as the 1970's, it has been recognized that approaches to characterizing environmental burdens must be comprehensive, a concept which has come to be known as life cycle thinking. A leading method for performing such an extensive evaluation, characterized by an attempt to account for all sources and types of impact, is life cycle assessment (LCA), a framework defined by the International Organization for Standardization (ISO) 14040-14044 standards (ISO 2006a; ISO 2006b).

LCA is an internationally recognized method that evaluates the relative, potential environmental and human health impact associated with products and services throughout their life cycles, beginning with raw material extraction and including transportation, production, use, and end-of-life treatment. Among other applications, LCA can identify the relative contribution of life cycle stages, thus providing opportunities to improve the environmental performance of products at various points in their life cycles, inform decision-making, and support marketing and communication efforts. It is important to note that the impacts described by LCA are estimates of relative and potential impacts, rather than direct measurements of real impacts, with limitations as described in the ISO international standards series 14040. Despite these limitations, the concept and the need for LCA are so powerful that for decades the tool has been contributing to decision-making regarding environmental sustainability, fostering knowledge and communication rather than avoiding or externalizing the difficult questions.

The relative environmental profiles of single-use corrugated fiberboard containers and reusable plastic containers have been investigated in recent years using a life cycle approach (Franklin Associates 2004; Rizo 2005; University of Stuttgart 2007; WRAP 2010; Levi et al. 2011; Franklin Associates 2013; Franklin Associates 2017). Most of these studies evaluate the containers in the context of European markets; only Franklin Associates (2004), Franklin Associates (2013), and Franklin Associates (2017) address the North American market. However, Franklin Associates (2004) is a life cycle inventory, not an LCA and not ISO-compliant for providing the basis for comparing the environmental performance of the container systems. Further, it is not adequately transparent in the data and assumptions used. Franklin Associates (2017) is the most comparable study to-date, however some data inventory gaps with important implications to the final results have been identified (see Appendix E: Comparison to previous studies for additional information). Considering these observations, further research was needed to better understand the relative environmental profiles of single-use corrugated fiberboard containers and reusable plastic containers for produce transport, storage and display in the U.S. The study here evaluates the relative environmental performance of single-use corrugated fiberboard containers and reusable plastic containers in the context of the U.S. produce market through an ISO 14044 compliant LCA.

The Corrugated Packaging Alliance (CPA) has commissioned Quantis to perform an ISO 14044 compliant, comparative LCA of Corrugated Containers (CC) and Reusable Plastic Containers (RPC) used to transport and display produce. The intent of this study is to bring a scientifically robust and transparent environmental assessment of the two alternatives to the industry and the public. The CPA is aware of the difficulties in performing a comparative LCA study and follows expert review procedures in accordance with the provisions of the ISO standard for comparative assertions made public.

2. Goal and scope of the study

This chapter describes the goal and scope of the study, along with the methodological framework of the LCA. It includes the objectives of the study, a description of the product function and product system, the system boundaries, data sources, methodological framework, and outlines the requirements for data quality as well as review of the analysis.

2.1 Objectives

This investigation aims to identify the relative environmental performance of CCs and RPCs used to transport and display produce. More specifically, the objectives of the study are as follows:

1. Establish **credible and transparent profiles** of the life cycle potential environmental impacts of corrugated containers and reusable plastic containers utilizing appropriate and accepted databases and LCIA characterization factors according to ISO 14040 and ISO 14044: 2006;
2. Identify the magnitude and confidence of **comparative environmental advantages** of either system; and
3. **Ensure compliance of results with ISO 14044** (clause 6) **and ISO 14040** (clause 7) to support a public comparative claim, including critical review by a panel of interested parties.

This study includes comparative statements regarding the environmental performance of the two products. According to the ISO standards, a critical review of an LCA is mandatory if the results are to be communicated publicly. The intent of the third-party review is to enhance quality and credibility, thereby improving public acceptance of the study. This report has been through critical review in compliance with the ISO criteria.

2.2 Intended audiences

The intended audience of this study includes the stakeholders of the RPC and CC industries including raw material producers, container manufacturers, transport providers, farms, produce retailers and produce consumers. The report is intended to support public disclosure of the comparative findings. This report may also be used by the CPA, AF&PA, the Independent Packaging Association (AICC), the Fibre Box Association (FBA), the Technical Association of the Pulp and Paper Industry (TAPPI) and their members to improve understanding of their products and identify opportunities for environmental improvement.

2.3 General description of the products studied

The CC and RPC under evaluation are utilized for transporting produce from produce grower to a retail market (e.g., a grocery store) and can be used to store and display the produce at the point of sale. While these products fulfill the same service, they differ in material composition and end-of-life management, specifically the rate at which the containers are recovered or reused. The following sections provide further description of the two products.

2.3.1 Corrugated containers

This study evaluates corrugated containers with a typical container design for each produce type. In other words, the most prevalent size, style [e.g., regular slotted container (RSC), telescoping] and packing configuration used for each commodity are applied. Containers are assumed to exhibit sufficient strength to hold the amount of produce indicated, although mass capacity (for a given size) does vary throughout the industry. Each pallet has 5-10 cases per layer (also referred to as, for instance, “5-down”[2]). The pallet considered in this study is the standard Grocery Manufacturer’s Association (GMA) 40”x48” pallet. Additional information is provided in section 2.4.

While a CC is not reusable for the shipment of produce, it is recyclable. This means it can be used as feedstock for a variety of wood fiber-based products, such as additional corrugated boxes. Discarded CCs are therefore usually collected for recycling but may also be sent to landfill or incineration. It is assumed no wax or other contaminants are used during the production or use of CCs that would prevent normal recycling.

Figure 2-1 illustrates the life cycle of CCs. The virgin fiber production includes seedling production, reforestation and fertilization, harvesting, sawmill processing and transport. Containerboard production includes pulping of both virgin and recovered fibers and the production of containerboard.

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[2] “5-down” implies five (5) containers per layer of containers on a pallet.

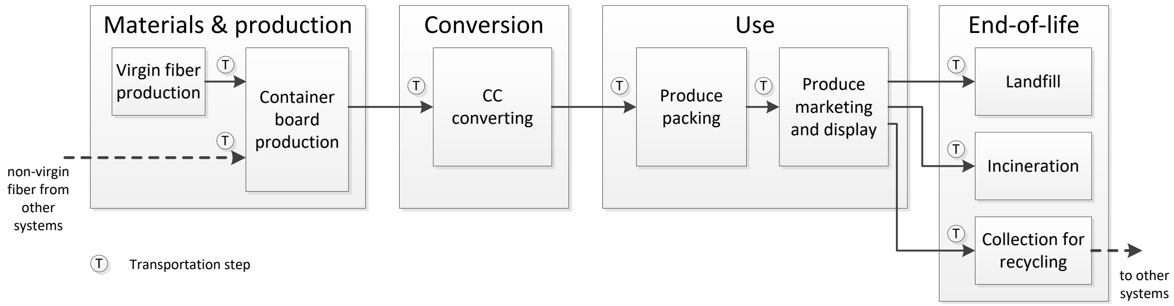

Figure 2-1: Life cycle stages of corrugated containers (CCs).

Containerboard converting and box assembly are aggregated as conversion in Figure 2 1. Converting includes containerboard corrugation, laying, gluing and drying. Box assembly includes seam construction (folding and gluing) as well as printing, as described in PE Americas (2009). The use stage includes container erection, produce packing and display of produce at retailer. End-of-life includes collection and waste processing steps including landfill, incineration and recycling. Transport between processes is included in the life cycle stages as depicted.

2.3.2 Reusable plastic containers

This study considers a standard footprint (16” x 24”, 5-down) RPC that is widely available in the United States as a produce packaging solution. Like the CC, the RPC is designed to optimize stacking, loading and display and is transported on standard GMA 40”x48” pallets. The RPC is constructed of a blend of virgin and recycled polypropylene and formed through injection molding. RPCs are both reusable and recyclable. After use at the produce retailer, most RPCs are washed and reused. The RPC can be managed by produce growers, retailers, pooling agencies or a collection of stakeholders. RPCs unfit for reuse may be used as raw material for new RPCs or exit the system as lost or discarded RPCs, which would eventually be landfilled, incinerated or recycled.

To be reused, RPCs must be collected for sorting at distribution centers after use in the market and then transported to cleaning/sanitation. These containers are then transported back to the produce grower to again be filled with produce and sent to the market. The empty containers are commonly kept in storage directly after use at the retail store, chain store distribution facility and again after sanitation.

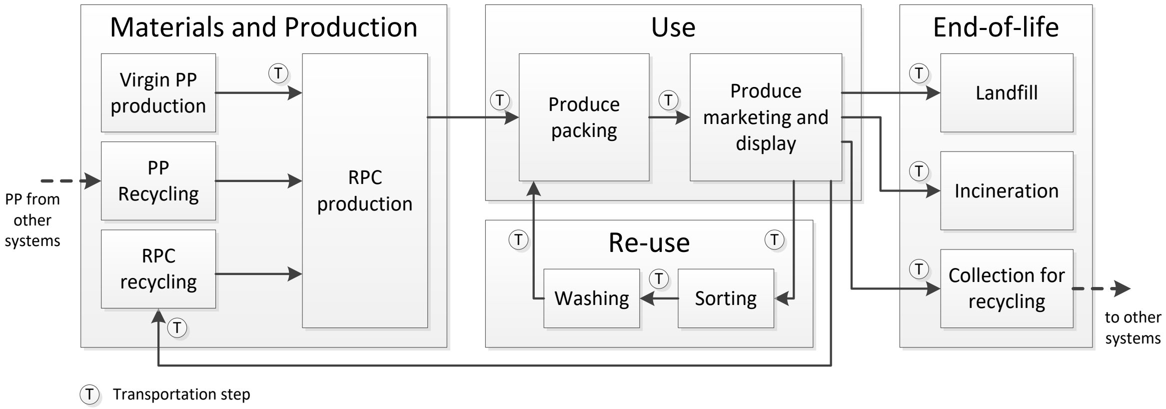

Figure 2-2: Life cycle stages of reusable plastic containers (RPCs).

It is important to note that reusable containers require a float inventory due to the inherent existence of holding points throughout the distribution system (e.g., on a shelf at a retailer, at a washing facility). Float also enables an RPC supplier to meet the dynamic nature of the demand cycle. This stock of containers ensures containers are available as needed.

Figure 2-2 illustrates the life cycle stages of RPCs. The aggregated materials and production stage includes virgin polypropylene (PP) production, PP recycling (i.e., PP sourced from products other than RPCs), RPC recycling and RPC production (injection molding). The use stage includes produce packing and display of produce at retailer. The re-use stage consists of washing and sorting of RPCs as well as temporary storage of RPCs. The end-of-life includes waste management steps: landfill, incineration and collection for recycling. Transport between processes is included in the life cycle stages as depicted.

2.4 System function and functional unit

LCA relies on a 'functional unit' as a reference for evaluating the components within a single system and or among multiple systems on a common basis. It is therefore critical that this parameter is clearly defined and measurable.

> The functional unit for this study is to provide containment during filling, transport and display of 907,185 kg (1,000 short tons) of grocery market produce in the United States in a manner that maintains the safety of the produce for human consumption and that is consistent with commercial supply chains.

Produce damage or perishability is excluded from the functional unit due to a lack of data describing loss rates for the containers. A sensitivity analysis is conducted to better understand the importance of this aspect and is described in section 4.2.3.1.

Both the CC and the RPC assessed in this study can fulfill the functional unit. While there may be other containers which fulfill this functional unit, this report is limited to the CC and RPC, which are produce packaging solutions widely available in the U.S. market.

Within the system function, there is an opportunity to compare the CC and RPC under various container profiles. A container profile is a combination of characteristics, such as container volume and produce density, which relate to different types of produce shipped with these containers. The container profiles investigated in this analysis are specific to eight types of produce: apples, carrots, grapes, lettuce (head), oranges, onions, tomatoes and strawberries. These commodities are selected because they are the top eight fresh market produce commodities transported and displayed by both CCs and RPCs (USDA 2017). Table 2-1, Table 2-2 and Table 2-3 provide the distinguishing characteristics of these containers. Other produce commodities having similar pack size and density characteristics could be assumed to have similar results. Only the aspects listed in this table differ in the representation of the various profiles; the remainder of the model framework is the same.

The outer dimensions of each container are presented in Table 2-1 and are used in this study only as a qualitative description of the containers. The mass and capacity of each container are presented in Table 2-2. These values are the basis for calculating the number of container shipments required to fulfill the functional unit. All RPC containers evaluated are 5-down, while CCs have 7-10 containers to a layer, depending on commodity. Table 2-3 presents the knock-down ratios for RPCs. Knock down containers are ones that can fold flat when not in use in order to increase shipping efficiency. The knock down ratio impacts the number of truck trips needed to fulfill the functional unit. This specifically pertains to the leg from the washing center to the packer and from the retailer back to the washing center, legs where the containers are empty and therefore collapsed.

The RPC information in Table 2-1 and Table 2-2 is sourced from Franklin Associates (2017)[3], and the CC information is sourced from industry experts[4]. The CC values used in this study are averages of the numbers shared with the CPA. All parties submitting the numbers have agreed that the averages may be used in this study as they mask any individual number provided by one party. It should be noted that not all parties provided capacity data. In these instances, the individual mass is used in combination with the average mass-to-capacity ratio from data provided by the remaining parties to calculate the capacity. The industry experts consulted are large corrugated box manufacturers for the produce industry who work in conjunction with growers and shippers that also purchase RPCs.

While the containers provide additional functions such as display aesthetics, handling ease and secondary uses, these functions are considered equivalent and/or irrelevant in this report and therefore the containers are compared only on the basis of the functional unit listed above.

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[3] In the present study, RPCs are assumed to have a common footprint of 60cm x 40cm (23.62in x 15.75in). Data provided by Franklin Associates (2017) agree with these.

[4] It is not clear what resource(s) was used to derive the CC characteristics applied in Franklin Associates (2017); the report simply lists (in Table 1-1) Franklin Associates as the source of the data. The document later mentions CPA (2014) as a source for other information. However, this report does not provide the CC characteristics.

The containers are also required to protect the produce they are transporting; while this function is excluded from the baseline assessment, produce perishability is investigated in a sensitivity analysis. In particular, container strength is implied through the capacity of the containers, as listed in Table 2-1. It is recognized that performance metrics for a given container (e.g., RPCs carrying apples) can somewhat vary between manufacturers, but the variation is assumed to be within a very narrow range.

*Table 2-1: CC and RPC outer dimensions for each commodity. **

	Length, cm (in)		**Width, cm (in)**		**Height, cm (in)**	
	RPC	**CC**	**RPC**	**CC**	**RPC**	**CC**
Apples	60 (23.62)	49.54 (19.50)	40 (15.75)	30.75 (12.04)	27 (10.60)	28.9 (11.4)
Carrots	60 (23.62)	43.36 (17.07)	40 (15.75)	30.56 (12.03)	19 (7.30)	28.2 (11.1)
Grapes	60 (23.62)	49.00 (19.29)	40 (15.75)	40.64 (16.00)	15 (5.90)	12.7 (5.00)
Lettuce – head	60 (23.62)	59.52 (23.44)	40 (15.75)	39.20 (15.44)	29 (11.5)	27.9 (11.0)
Onions	60 (23.62)	48.80 (19.21)	40 (15.75)	38.10 (15.00)	21 (8.31)	23.6 (9.29)
Oranges	60 (23.62)	43.36 (17.07)	40 (15.75)	28.68 (11.29)	27 (10.60)	27.9 (11.0)
Strawberries	60 (23.62)	49.36 (19.44)	40 (15.75)	33.20 (15.44)	10 (4.1)	8.91 (3.51)
Tomatoes	60 (23.62)	43.36 (17.07)	40 (15.75)	33.20 (13.07)	15 (5.9)	17.8 (7.00)

*Values are rounded to an appropriate number of significant figures here for reporting purposes.

Table 2-2: Key container and container system properties for 10 commodities.[1]

	Average weight per empty container, kg (lb)		Amount of produce per container, kg (lb)		Thousand container movements required per FU[1]		Number of containers in each layer on a pallet		Functional unit mass ratio
	RPC	**CC**	**RPC**	**CC**	**RPC**	**CC**	**RPC**	**CC**	**CC:RPC[3]**
Apples	2.27 (5.01)	0.82 (1.8)	18.18 (40.08)	18.0 (39.6)	50	50	5	7	0.37
Carrots	1.73 (3.81)	0.71 (1.6)	18.18 (40.08)	19.0 (41.7)	50	48	5	10	0.39
Grapes	1.55 (3.41)	0.76 (1.7)	9.09 (20.04)	8.32 (18.3)	100	109	5	6	0.54
Lettuce-head	2.38 (5.25)	1.1 (2.4)	22.59 (49.8)	23.6 (51.9)	40	38	5	5	0.44
Onions	1.91 (4.21)	0.89 (2.0)	18.18 (40.08)	16.7 (36.8)	50	54	5	6	0.51
Oranges	2.27 (5.01)	0.90 (2.0)	18.18 (40.08)	20.3 (44.7)	50	45	5	9	0.36
Strawberries	1.27 (2.81)	0.39 (0.86)	4.09 (9.02)	3.78 (8.33)	222	240	5	6	0.33
Tomatoes	1.55 (3.41)	0.60 (1.3)	11.36 (25.05)	13.0 (28.6)	80	70	5	8	0.34

[1] Values are rounded to an appropriate number of significant figures here for reporting purposes.

[2] Functional Unit (FU) = 907,185 kg of produce delivered.

[3] Calculated as (CC mass per functional unit) / (RPC mass per functional unit).

Table 2-3. Knock-down ratios of RPCs.

Commodity	Knock-down ratio*
Apples	0.30
Carrots	0.36
Grapes	0.45
Lettuce – head	0.33
Onions	0.38
Oranges	0.38
Strawberries	0.56
Tomatoes	0.64

*Computed as the number of erected containers per pallet divided by the number of knocked-down containers per pallet.

2.5 System boundaries

The system boundaries identify the life cycle stages, processes and flows considered in the LCA and include all activities relevant to attaining the above-mentioned report objectives and therefore necessary to provide the specified function. The following paragraphs present a general description of the system, temporal and geographical boundaries of this report, as well as exclusions.

2.5.1 General system description

This study assesses the life cycle of CCs and RPCs from the extraction and processing of all raw materials through the end-of-life of the containers. Within each of these stages, the LCA considers all identifiable "upstream" inputs to provide as comprehensive a view as is practical of the product system. In this way, the production chains of all inputs are traced back to the original extraction of raw materials.

2.5.2 Temporal and geographic boundaries

This LCA is intended to represent the RPC and CC industries and associated processes in the United States at the time the study is conducted (2017-2018). Data and assumptions are intended to reflect current equipment, processes, and market conditions. However, the data available—and most temporally comparable data—for CCs and RPCs describe the industries during earlier timeframes. In particular, the RPC information represents 2003 North American polypropylene resin [USLCI (2010)] and 2007-2008 European injection molding [Plastics Europe (2010)]. The latter is modified as possible to adapt the data to the North American context. For

CCs, data describing 2002 North American forestry practices and 2014 U.S. CC industry operations are used. Section 2.6 offers further details on the data that are used in this analysis.

As the intent of this study is to capture a snapshot of average U.S. industry operations, only U.S.-grown produce are considered, and seasonal variation isn't discretely evaluated. For produce grown in multiple locations within the U.S., composite values for transport distances (to and from growers) are computed as a weighted average based on the percentage of produce sourced from each area in a given year. The data for these distances are provided by the U.S. Census Bureau and U.S. Department of Agriculture (USDA) (U.S. Census Bureau 2012, USDA 2017). The calculations and resulting distances from these data are provided in Appendix A. Produce transport is modeled as refrigerated transport.

Similarly, only U.S.-produced and managed containers are considered. The RPC system evaluated is considered a closed loop, and RPC manufacturing, use, servicing and disposal occur in the U.S. In the case of the CC system, a portion of the recovered containers leave the geographical boundary. This is because the domestic supply of recovered materials exceeds the domestic demand. The excess containers are exported for use as raw material input in other markets, and the dynamics of these markets are outside the boundaries of this study. It is not possible to expand these boundaries without substantial investigation of the fate of CCs on the global market.

All processes used in the foregrounds of the models reflect North American processes in terms of electricity grids and transportation, as appropriate. Whenever possible, generic datasets used in this report are adapted to increase their representativeness to the geographical context of the systems. Processes located in the background of the model are not adjusted to use North American electricity grids and transportation as products within the supply chain may be manufactured in locations across the globe. Because the supply chains of each system are not obvious, it is unclear in many cases that this would result in greater representativeness of the true source of electricity used within the supply chains.

It should be noted that some processes within the system(s) boundaries might take place anywhere or anytime. For example, the processes associated with the supply chain and with waste management can take place in North America or elsewhere in the world. In addition, certain processes may generate emissions over a longer period of time than the reference year. This applies to landfilling, which causes emissions (biogas and leachate) over a period of time whose length (several decades to over a century/millennium) depends on the design and operation parameters of the burial cells and how the emissions are modeled in the environment. Long-term effects of carbon storage at landfill are discussed in greater detail in section 3.1.2.

2.5.3 Treatment of recycled material

Allocation for recycling and reuse is an important element of analysis. ISO 14044:2006 (ISO

2006b), in section 4.3.4.3.2, describes the need for considering sharing of resources and processing loads between the original product and subsequent product cycles. The “number of uses” is one such allocation approach and can be applied for recycling of paper products. ISO 14049:2012 (ISO 2012a), provides different examples of this approach consisting in full formulation if there are available industry statistics (Galeano et al. 2011) or number of uses based on laboratory experimentation. For the RPC system, the model is a closed-loop, meaning all flows of recovered material (RPCs) remain in the system and there is therefore nothing to allocate. The number of uses approach could have been applied and would have provided the same results mathematically. For the CC system, a portion of the model is treated as closed-loop, and it is therefore treatment of the exported, recovered old CCs (OCC), which are cut off after the point of recovery, that could influence the outcome of the study. A sensitivity test on the treatment of exported OCC is not performed as the end-of-life fate is unknown, and it is not possible to distribute the impacts of these activities across product systems.

2.5.4 Exclusions and cut-off criteria

Processes may be excluded if they (1) are identical for the systems being compared and/or (2) are considered negligible (flows contributing less than 1% by mass or energy). It should be noted that when processes are excluded due to equivalence, the relative (percent, %) differences between the products may be affected. Mass and/or energy are used as proxies for environmental relevance as it is not possible to determine the environmental relevance without having first computed the LCA results. The following are excluded from this LCA:

- **Wholesale distribution** of produce is not investigated since it is not an option offered by both systems; RPCs are not available on the wholesale market. The study considers only applications for which there is a choice between CCs and RPCs.

- **Infrastructure and capital goods** are excluded from the analysis, except in cases where inventory data provide this information as part of an aggregated dataset. Specifically, temporary storage of CCs (between manufacture and use) and RPCs (after retail and after washing is not included). Duration of storage may approach one year.

- **Container loss between production and use** due to structural damage incurred during container manufacturing, transport or use (e.g., defective manufacturing, influence of humid environment) is excluded. These losses are considered to be negligible (<1%) for both containers.

- **Container erection and produce packing at the grower as well as display of produce at the retailer** are excluded based on a lack of information on infrastructure and energy requirements. However, it is likely that these processes are negligible (<1%) contributors to total requirements as they are in-part manual processes.

- **Secondary packaging**, such as clamshell container for strawberries, is excluded from the analysis. The type and quantity of such packaging for each commodity is the same between CCs and RPCs.

- **Storage of produce** between the grower and retailer, as well as at the retailer, is excluded. While this step may be important due to refrigeration, it is assumed that the storage processes are the same for the two systems and therefore contribute the same amount of environmental impact to the CC and RPC life cycles.
- **Backhaul** has not been included in the analysis. For produce transport, there is no reason to assume that backhaul schemes would differ between the container types; trucks drive a certain route and with a set payload capacity from grower to distributor/retailer and back regardless of container type. Although the number of backhaul trips differs between the container systems and by produce type because the number of trucks required to fulfill the functional unit differs, contribution of this transportation to total life cycle impacts is expected to be minor.
- **Sorting of RPCs** in the reuse stage is excluded from the LCA due to a lack of information on infrastructure and energy requirements. However, these are assumed to be negligible (<1% of total requirements).
- **For RPCs, the float inventory** is excluded from the baseline analysis. A sensitivity test is conducted to assess the importance of float to the footprint of RPCs. Please see Appendix B for further explanation.
- **Transport from RPC collection at end-of-life to PP recycling** is excluded from the RPC system; this step is considered negligible given the small quantity of material transported (<1% of total requirements).
- **Exported, recovered OCC** is excluded from the analysis after the point of recovery because it is not possible to credibly characterize the fate of these containers without further investigation. Assuming these materials are treated similarly to recovered OCC that remain in the U.S. is considered an inaccurate representation of system dynamics. It is not realistic to assume the excess OCC is sent to municipal solid waste. Looping the materials back in to the CC production process requires an increase in the recycled content of the average CC, which would not align with industry statistics for recycled content. Using this cut-off approach for managing exporting recovered OCC means that burdens associated with the CC system are retained within the current system and not shared with future product systems, as would be done if the number of uses allocation method had been applied. This cut-off approach is therefore conservative.
- **Produce production** is excluded from the baseline assessment due to a lack of data describing produce loss while in transit. A sensitivity analysis is included which explores the impact of produce production and the effect of damage during transit.
- All transport of produce is modeled as refrigerated transport; however, **thermal**

properties of the containers are excluded from the report due to a lack of data. If the container is cooled during transport, differences in these characteristics will influence energy used to bring the container to a specified (cool) temperature. Considering the total transit distance, this difference in initial cooling is considered negligible (<1% of total requirements).

- **Land use and land transformation** is excluded from the study due to a lack of inventory data. See section 6 for further discussion.
- **Toxicity indicators** are excluded from the study because data describing toxicity-related emissions are not comparable between the two container systems. This disparity in data quality precludes a reliable comparison of impacts. See section 6 for additional information.
- **Social and economic impacts** are beyond the scope of this report and therefore excluded. However, differences do exist in human resource aspects (e.g., labor requirements) and cost between the two container systems.

2.6 Data sources and assumptions

The quality of LCA results is dependent on the quality of data used in the evaluation. Every effort is made here to implement the most credible and representative information available. The data collection process has been conducted iteratively between Quantis and CPA. When no source is available, assumptions are based on professional judgment, and sensitivity analyses are conducted to understand the influence of the parameter on reported results.

Data and assumptions made throughout this report are based on previous work, publicly available data and expert knowledge which characterize industry operations and quantify the data necessary to compile the life cycle inventory of each system. This chapter describes the data sources and assumptions which comprise the life cycle inventory for each system.

Although every effort is made to establish the best available information and to consider key influential factors, such as geography, temporal relevance, scientific credibility, and internal report consistency, and while the results to be presented by this report are intended to be considered reliable, they should be used only within the context of the boundaries and limitations identified. In cases where important information is unknown, uncertain or highly variable, sensitivity analyses are performed to evaluate the potential significance of the data gap.

This report utilizes pre-existing, recent life cycle studies on CCs and RPCs as sources of primary data describing current industry operations. Relevant prior life cycle studies are listed in Table 2-4. An assessment of the 2010 fiberboard container industry contracted by the CPA and AF&PA and performed by NCASI (2014) serves as an initial basis for the CC model in this LCA and is updated to reflect industry operations in 2014 according to NCASI (2017). The RPC system model is constructed from the information provided in a number of publications describing the RPC life cycle with the priority of using U.S. (or North American) data where possible (e.g., Franklin Associates 2017), augmented with input from RPC industry experts[5]. The framework, assumptions, and data are iteratively reviewed by the project team and enhanced where appropriate and possible. Where the quality or relevance of data is inappropriate or unclear, Quantis and client expert judgment are used to determine the most appropriate information to apply in the report.

Table 2-4: Sample recent life cycle studies on CCs and RPCs

Reference	Description	
Franklin Associates, 2004	Title	*LCI of reusable plastic containers and display-ready corrugated containers used for fresh produce applications*
	Scope and Transparency	Study is a life cycle inventory of containers in U.S. produce market and does not include impact assessment; It is therefore not a life cycle assessment; Systems' primary data and key assumptions are not reported.
Rizo SC, 2005	Title	A Comparative Study of the Environmental and Economic Characteristics of Corrugated Board Boxes and Reusable Plastic Crates in the Long-distance Transport of Fruit and Vegetables: Executive Summary.
	Scope and Transparency	Study is an LCA of one type of corrugated box and one type of reusable plastic container for tomatoes exported from Spain and delivered to Germany; Some foreground data reported in Executive summary, and remaining data may be available in the main report.
University of Stuttgart, 2007	Title	*The Sustainability of Packaging Systems for Fruit and Vegetable Transport in Europe based on Life-Cycle-Analysis*
	Scope and Transparency	Study is an LCA of corrugated common footprint containers and reusable plastic containers in Europe; Foreground and background data are comprehensively reported.
PE Americas and Five Winds International, 2009	Title	*LCA of US Industry-average Corrugated Product*
	Scope and Transparency	Study utilizes primary data from fiber and corrugated box industries; Data describes 2006 industry operations
Levi et al., 2011	Title	*A comparative life cycle assessment of disposable and reusable packaging for the distribution of Italian fruit and vegetables*

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[5] The names of the consulted parties are not listed in this report to protect their interests. Please inquire for more information.

Reference	Description	
	Scope and Transparency	Study is specific to Italian packaging for distribution; Foreground and background data are comprehensively reported.
Franklin Associates, 2013	Title	*Comparative life cycle assessment of reusable containers and display- and non-display-ready corrugated containers used for fresh produce applications*
	Scope and Transparency	Study is an LCA of corrugated common footprint containers and reusable plastic containers in North America; Foreground and background data are comprehensively reported.
NCASI, 2014	Title	*Life Cycle Assessment of U.S. Average Corrugated Product –Final Report*
	Scope and Transparency	Study utilizes primary data from fiber and corrugated box industries; Data describes 2010 industry operations; Foreground and background data are comprehensively reported.
Franklin Associates, 2017	Title	*Comparative life cycle assessment of reusable containers and display- and non-display-ready corrugated containers used for fresh produce applications*
	Scope and Transparency	Study is an update of Franklin Associates 2013 including more recent data and corrections to prior study.
NCASI, 2017	Title	*Life Cycle Assessment of U.S. Average Corrugated Product –Final Report*
	Scope and Transparency	Study is an update of NCASI 2014 including more recent data. Data describes 2014 industry operations; Foreground and background data are comprehensively reported.

3. Life cycle inventory

It is intended by this study to use the most current and relevant life cycle inventory (LCI) data describing the CC and RPC life cycles. Background processes are modeled using Ecoinvent 3.3 as provided by GaBi 8; no adjustments (to grid mixes or otherwise) are made, unless noted in this report. Data used to represent foreground processes for CCs and RPCs are described in sections 3.1 and 3.2, respectively. A summary of the parameter values used for the baseline analysis (and sensitivity tests) are presented in Table 4-1.

3.1 CC system model

The life cycle of CC is modeled based on the data and assumptions of prior work. Specifically, construction of the model began with the NCASI (2017) system model, and life cycle stages were added and/or modified to reflect the full CC life cycle. Within this model, the LCI for fiber production and upstream (forest) operations (for the prior report and thus this study) is sourced from the Consortium for Research on Renewable Industrial Materials (CORRIM) which describes 2002 practices, as provided in the USLCI Database (NREL 2014). Containerboard production data and CC conversion data are provided by an NCASI survey which studied industry operations in 2014.

3.1.1 Recycled content

As determined by a CPA survey of members providing boxes to the produce industry, the utilization rate of recycled fiber for average containerboard is 38.4%: 0.384 kg/kg containerboard or 0.42 kg/kg of corrugated product. (Approximately 1.1 kg of containerboard is required to produce 1.0 kg of corrugated product.)

3.1.2 Biogenic carbon accounting

For products comprised of little to no bio-based materials, it can generally be assumed that the net flow of biogenic carbon is zero and the issue has little effect on the outcomes of the assessment. On the other hand, when a product contains a substantial amount of bio-based materials—such as in the case of corrugated board—attention must be paid to carbon accounting in order to accurately characterize the flow of greenhouse gases.

In producing a forest or agricultural product, such as virgin fiber for CCs, carbon dioxide (CO_2) is removed from the atmosphere and incorporated into the material that is harvested from the forest or field. This ("biogenic") carbon is stored in the material throughout the life of the product until that product is used as fuel or begins to degrade, at which point the carbon is released back into the environment. The release is predominantly in the form of CO_2 and methane (CH_4).

This study assumes a net zero impact for biogenic carbon in the form of CO_2 emissions, whereas it is assumed there is a net impact associated with the emission of biogenic carbon in the form of CH_4, and this is counted. This approach is justified by the assertion that if the removed carbon is replaced within a short timeframe (<100 years), the overall flow of carbon to and from the atmosphere is net of zero (and thus the net impact on climate is zero). As a precedent, PAS 2050 (section 5.1.1) allows for the exclusion of biogenic carbon that becomes part of human food or animal feed because they generally do not persist beyond 100 years. CCs also fall into this category of having a lifetime that is less than 100 years.

Methane, which has a GWP many times that of CO_2, is not removed from the atmosphere during the production of a forest or agricultural product, and its net impact is therefore not zero. ISO 14067 describes this net zero phenomenon (except for CH_4) in section 6.4.9.2. This study applies the net zero biogenic carbon approach to simplify the modeling and ensure that the net result is correct. NCASI (2017) offers an in-depth explanation of the carbon flows in the cradle-to-gate CC production process, which was used in this analysis.

Considering the gate-to-EOL stages, biogenic carbon emissions occur only at EOL. These emissions may be released shortly after the end of the product's life or trapped in a landfill for a reasonably long time (e.g., hundreds or thousands of years). An exception to the net zero approach mentioned above is made in cases where carbon will be stored away from the atmosphere for long periods of time as it is reasonable to assume that over an extended period (e.g., many decades or centuries), carbon stored away from the atmosphere is a significant influence on the environment. Carbon still within the landfill after 100 years is included in the inventory as stored carbon. The value of this is assumed to be 55% of the carbon in the CCs (as reported by NCASI 2017 and originally sourced from Wang 2011); there is approximately 0.491 kg carbon per 1 kg containerboard (NCASI 2017). One hundred (100) years is the same period used to calculate the global warming potentials (GWPs) applied here.

To make clear how each type of carbon flow is treated, Table 3-1 describes the inventory of greenhouse gas (GHG) flows used in the assessment. The first column lists the possible ways in which the GHGs (predominantly CO_2 and CH_4) may be taken up or released. The second column offers a variable to represent the numeric value of the flow, and the third column indicates whether the flow is included in this analysis and if so, the direction of the flow. A positive value indicates an emission, while a negative sign indicates a GHG is being taken up (i.e., removed from the atmosphere).

The fourth column notes the GWP for the specified GHG. The final column provides the resulting calculation in the model to arrive at climate change impact for each GHG flow. This is a multiplication of the amount of GHG (kg) emitted or taken up times the GWP of that GHG. The sum of this column arrives at the total climate impact assigned to the biogenic carbon flows in the life cycle of a container.

Sensitivity tests are used to explore the influence this methodological decision has on the study outcomes. See sections 4.2.1.4 and 4.2.1.5 for details.

Table 3-1: Biogenic carbon accounting approach implemented in this report for each greenhouse gas flow.

Type of greenhouse gas flow	Amount	Representation in the life cycle inventory (kg to or from air)	Global warming potential ($kg\ CO_2$-eq / kg emitted to air)	Result ($kg\ CO_2$-eq)
Removal of CO_2 from atmosphere by forest or agricultural product, to be stored for less than 100 years	A	-A	0	-A*0
Removal of CO_2 by forest or agricultural product, to be stored for more than 100 years	B	-B	1	-B*1
Uptake or release of CO_2 by forest soils	C	Not included	N/A	N/A
Other indirect uptake or release of CO_2 by forestry and land use	D	Not included	N/A	N/A
Emission of CO_2 from fossil sources (e.g., oil combustion) pre 100 year threshold	E	E	1	E*1
Emission of methane from fossil sources (e.g., oil combustion) pre 100 year threshold	F	F	30[1]	F*30
Emission of CO_2 from biotic sources (e.g., biomass combustion) pre 100 year threshold	G	G	0	G*0
Emission of methane from biotic sources (e.g., biomass combustion) pre 100 year threshold	H	H	28[1]	H*28
Emission of GHG beyond threshold of 100 years	I	Not included	N/A	N/A

[1] The global warming potential for CH_4 used by TRACI 2.1 is based on IPCC (2007). This value was manually updated to reflect the latest IPCC (2013) recommendations. It does not include the impact of CO_2 produced by the degradation of CH_4 because, as described in (IPCC 2007) section 2.10.3 by Solomon et al. (2007), the degradation product is included in national carbon inventories and would result in double counting should the characterization factor also include it. Since this study is using LCIs, rather than national inventories, to compute climate change, the additional impact is included here. It is included only for *fossil* methane as biotic CO_2 is ignored in this study.

3.1.3 End-of-life

After use, CCs are sent to end-of-life. According to NCASI (2017), 89.5% of corrugated containers are recovered for recycling. This number is an average for all corrugated products and is considered somewhat low by the CC industry as recycling offers economic savings to produce retailers by avoiding traditional waste management fees (i.e., trash disposal) and by offering a potential source of revenue in markets where containerboard is in-demand. Indeed, Franklin Associates (2004), Franklin Associates (2013), and Franklin Associates (2017) assume a recovery rate of 95%. The baseline assessment for this report also uses a value of 95%, and a sensitivity analysis is conducted to evaluate a value of 85% (See section 4.2.1.2). The remaining material is assumed landfilled or incinerated; the distribution of CCs between landfill and incineration is based on U.S. EPA data (U.S. EPA 2010) for corrugated containers in the municipal solid waste stream. Approximately 82% is landfilled and 18% is incinerated.

3.1.4 Transportation

Transportation data within the first two stages of the CC system (Raw materials & production, Conversion) are provided by NCASI (2017). These data, as well as the End-of-life transportation data, are sourced from the 2012 Commodity Flow Survey from the U.S. Dept. of Commerce. The use stage data is described in section 3.3. Appendix A includes the transport modes, distances and data sources used for each transport step identified in Figure 2-1, as well as utilization rates and sample calculations.

3.2 RPC system model

Similar to the CC model, the life cycle model of RPCs is intended to represent the U.S. RPC market for the produce industry. Due to a lack of publicly available information, the system is based heavily on data describing IFCO RPCs, as provided by Franklin Associates (2017).[6] This includes recycled content of new RPCs, RPC dimensions and weights and details of the RPC production and washing processes. The data used for the baseline analysis are considered practical for the U.S. context, although the Franklin Associates (2017) study does consider the greater North American RPC market. Additional information, where available, is included to better represent the industry at-large and is described in the ensuing sections of this report. Sensitivity analyses are performed to better understand the importance of these parameters on study outcomes. See section 4.2 for details. The unit process LCIs are provided in Appendix A: Model inputs.

LCI data for polypropylene resin production is sourced from the American Chemistry Council's 2010 report detailing practices in 2003, as provided by the USLCI database (NREL 2012).

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[6] The IFCO data are considered representative of a large portion of RPC production in the U.S. given IFCO's relatively large market share in North America. IFCO's 2010 Annual Report states that it constitutes "an estimated 75% market share in the United States" based on total number of RPC trips per annum and "…the produce market has been, historically, the [primary] focus of IFCO's RPC Management Services segment" (IFCO 2010).

3.2.1 Number of uses, loss rate and breakage rate

The number of uses, also referred to by the RPC industry as the number of cycles or turns, is the number of times a container may be employed for produce containment and protection before being removed from service due to adequate wear. An RPC is also removed from use if it is broken or lost. The number of times an RPC is used can vary widely.

Franklin Associates (2017) assumes 39.3 uses and a 1.78% break and loss rate. A European LCA of RPCs (University of Stuttgart 2007) assumes 50 cycles as a baseline and as many as 100 cycles in a sensitivity analysis. The report also notes a breakage rate of 0.4%. These turn values are considered relatively high and the break and loss rates low, for the U.S. context.

The baseline evaluation here assumes 24 uses and a combined 5% break and loss rate. These values are based on inputs shared by RPC industry experts.[7] These industry experts commented that RPCs turn every 3-4 months and last for 5-6 years. Conservatively assuming a turn rate of four (4) times per year (once every 3 months) and a lifetime of six (6) years, the result is 24 uses (4 x 6). These assumptions reflect the U.S. context and may differ notably from the logistics in other markets. Sensitivity tests are conducted to better understand the influence of these parameters on the study conclusions.

These values are used to calculate the reference flow quantities into and out of the Use stage. To illustrate this computation, consider that the reference flow quantity (mass of RPCs) associated with the functional unit is X for a given commodity. Using the life cycle stages depicted in Figure 2-2, the flow from Materials and Production into the Use stage is (5% + 1/24)X. The same equation applies to the flow from the Use phase into the End-of-life stage. This is balanced by the flow into and out of the Re-use stage: (100%-5%-1/24)X. The value of 5% represents the flow out of the Use/Re-use loop with every cycle due to break and loss, and the fraction 1/24 is the "average" amount of RPC material that leaves this loop every turn.

3.2.2 Recycled content

The baseline RPC recycled content is estimated to be 25%, as gleaned from insights provided directly by RPC experts.[8] In comparison, the Franklin Associates (2017) study applies a value of 50%. A sensitivity analysis, described in section 4.2.2.2, is conducted to assess higher and lower amounts of recycled content to understand this value's importance on study outcomes.

3.2.3 Cleaning process

It is assumed that all (100%) of reused RPCs are washed and sanitized. The detergent, water and electricity inputs to the cleaning process are modeled using a composite inventory based on data provided by the University of Stuttgart (2007) and Franklin Associates (2017). The data provided by Franklin Associates (2017) characterize the cleaning and sanitizing process specifically implemented by IFCO and is representative of all of their service centers in 2016.

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[7] Please inquire with CPA if you are interested in the names of the parties consulted.

[8] Please inquire with CPA if you are interested in the names of the parties consulted.

The cleaning chemicals represent usage from a single facility in 2015. IFCO is one of the major RPC manufacturers and distributors in the U.S., and the information is considered representative of a cleaning process applied to a large portion of RPCs currently in circulation. An inventory describing less efficient technology, as inferred from University of Stuttgart (2007), is applied in the model to represent the remaining portion of the industry. The composite dataset is computed by weighting Franklins Associates (2013) data at 70% (based on the approximate amount of IFCO's market share[9]) and the University of Stuttgart (2007) data at 30%. This composite inventory is intended to more closely model the "average" cleaning process across the U.S. RPC market, assuming the remainder of the industry uses an older technology than that implemented by IFCO facilities. All other inputs and outputs are taken from Franklin Associates (2017). The data are provided in Appendix A: Model inputs.

A sensitivity test is conducted using only the data from Franklin Associates (2017) to understand the potential results should the entire U.S. RPC industry implement the new cleaning technology (see section 4.2.2.4).

It should be noted that the water emissions data provided in Franklin (2013) is limited in that it does not include emissions that are typical in wastewater from industrial processes using detergents, such as sulfates. These substances can have important impacts on receiving water bodies. Such impacts are not captured by this study, and their magnitude relative to other aspects of the life cycle of RPCs is unclear.

3.2.4 End-of-life

Given the economic value of RPCs, it is assumed that the far majority of these containers are recovered by RPC providers and subsequently sent to re-grinding for use in new RPC manufacturing. A portion of the lost RPCs that end up in the municipal solid waste stream are very likely recycled, and the PP is put on the recycled materials market. The total amount of RPCs recovered for recycling is defined as the product of (1) the mass of RPCs used, (2) the percent recycled content of an RPC and (3) the sum of the break and loss rate and the inverse of the number of uses. The model is built as a closed loop for the combined PP that comes from the recycled materials market and PP from spent RPCs. A 98% efficiency in the recycling process is applied for both recycling processes, as per Franklin (2017). Reference flows are depicted in Appendix A1.

The RPCs that are not recycled are sent to end-of-life. The distribution of RPCs at their end-of-life is based on U.S. EPA municipal waste figures (U.S. EPA 2011). Of all municipal solid waste which is discarded and not recycled, 17.8% is combusted for energy recovery; the remaining 82.2% is landfilled.

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[9] IFCO's 2010 Annual Report estimates the company holds 75% of the RPC market across all industries in the U.S. (IFCO 2010). A value of 70% of the market share in the produce industry is applied for the current study based on insight from RPC industry experts.

3.2.5 Transportation

Transportation throughout the RPC life cycle is modeled based on data from several sources, including the U.S. Department of Transportation and U.S. Department of Commerce as well as Franklin Associates (2017). Appendix A includes the transport modes, distances and data sources used for each transport step identified in Figure 2-2, as well as truck utilization rates and sample calculations. Transport in the use and reuse stages is further described in section 3.3.

3.3 Transportation from grower to retailer

The two container systems share a common transport step between the produce grower and the retailer. These distances are specific to commodity type and may change over the course of the seasons as one location becomes more or less suitable for commodity production.

In the baseline analysis, a composite transportation profile is calculated using statistics sourced from the Economic Research Service, U.S. Census Bureau and USDA National Agricultural Statistics Service. Seasonal variations are aggregated as a weighted average based on the portion of produce sourced from each agriculture center over a given year, as appropriate. The calculations and resulting distances from these data are provided in Appendix A. Transportation of produce is modeled as refrigerated transport.

While in practice pallets and trucks can carry mixed loads (i.e., different types of commodities at once), this study makes the simplifying assumption that a single commodity is being transported.

Transportation of the full containers going to the retailer for all commodities is modeled as volume-limited or mass-limited, depending on the commodity. Most combinations of container and commodity exceed the payload limitations of the truck, assumed to be approximately 18,143 kg (40,000 lb), implying that most commodities travel by truck in a mass-limited situation. Trailers are assumed to be 16 m (53 ft) in length and carry a maximum of 24 pallets. Backhaul is excluded from the model, as described in section 2.5.3. Additional details, including truck utilization rates and sample calculations, are provided in Appendix A.

3.4 Product end-of-life

Whenever a material is shared across multiple product systems, a question arises regarding how the impacts of producing, recycling and managing this material over its life cycle should be shared among those multiple product systems. The need to address the issue of sharing resources and other burdens in the original product with subsequent uses has been addressed by ISO LCA standards since 2000 in ISO 14041 and more recently is described in ISO 14044:2006 (ISO 2006b), section 4.3.4.3.2. In addition, ISO 14049:2012 provides examples in estimating the number of uses as well as the allocation of burdens between the original product and subsequent uses, which are well suited for products such as paper where the reclaimed

Table 3-2: Summary of end-of-life modeling for CCs and RPCs sent to incineration or landfill.

	CC		RPC	
	Impact	*Credit*	*Impact*	*Credit*
Incineration (with energy recovery)	Corrugated board incineration process	Heat & electricity generation	Polypropylene incineration process	Heat & electricity generation
Landfill	Corrugated board landfill process (including methane flaring as well as fugitive emissions)	Heat generation from captured methane combustion	Polypropylene landfill process	(none)

material retains essential useful properties of the original product.

A variety of approaches for handling this allocation issue has been proposed in the literature and elsewhere. Although not all approaches are ISO compliant, these approaches provide several options both from a computational standpoint as well as in regard to the basis identified for determining how impact should be divided among product systems. The allocation approaches used for recycling in this study are presented and discussed further in section 2.5.3 and Appendix B.

In addition to the amount recycled, a portion of both CC and RPC material is sent to waste. The flow to end-of-life for CCs and RPCs includes landfill and incineration. In the case of waste-to-energy conversion, a flow of energy exists between the CC or RPC life cycle to a second (receiving) life cycle, which may be one of many industrial processes. The flow of energy must be allocated (shared) between the emitting and receiving product systems. Such flows for each system will be modeled under the system expansion approach. Details of this approach are described in Table 3-2. This is represented as the net values of the inventory flows associated with the treatment (i.e., landfill or incineration) process and credited (negative) inventory flows associated with the production of conventionally-generated energy (heat and electricity). The same approach is applied to methane captured from landfills, and the methane collected is assumed to be combusted for heat generation at the landfill. These processes occur within the end-of-life boxes illustrated in Figure 2-1 and Figure 2-2. This model is based on the update to that study (NCASI 2017), which uses industry data characterizing 2014 operations.

4. Life cycle impact assessment

TRACI 2.1 (Bare 2012) is chosen as the primary impact assessment method for this study. TRACI 2.1 is a peer reviewed and internationally recognized life cycle impact assessment (LCIA) method. One exception to using the TRACI method is in the case of the non-renewable energy indicator. TRACI's calculation of this impact—termed Fossil fuel use—estimates an additional amount of energy needed in the future to extract a non-renewable energy resource. This additional or surplus energy is the difference between the energy currently required to extract a given resource (e.g., coal) and the energy that is required to extract the same amount of that resource in the future. It is assumed that future extraction is more energy intensive due to decreasing availability of resources over time. This LCA report instead uses the non-renewable energy use indicator offered by IMPACT2002+ v2 (Jolliet et al. 2003) as it measures the primary energy (energy content) of the resources consumed. This is a direct assessment of energy use and does not require projections regarding the future state of resource availability and consumption.

The following are the indicators (potential impacts) that are evaluated in this report. These are as provided by TRACI 2.1, unless otherwise noted.

- Acidification (to air and water, kg SO_2-eq)
- Global warming (kg CO_2-eq)[10]
- Non-renewable energy (IMPACT2002+) (MJ primary)[11]
- Eutrophication (to air and water, kg N-eq)
- Smog formation (kg O_3-eq)
- Respiratory effects (kg $PM_{2.5}$-eq)
- Ozone depletion (kg CFC-11-eq)

All of these metrics are midpoint indicators, meaning that each describes a physicochemical process that occurs in the environment due to release of a substance into the environment. A second type of indicators is known as endpoint or damage categories. Examples include measures of ecosystem quality, human health and resource depletion. This study does not evaluate endpoints as they are not available in the TRACI methodology.

A sensitivity analysis using the ReCiPe 2016 (hierarchist approach) impact assessment method is conducted to further evaluate the assessment using TRACI. Further description of this analysis is offered in section 4.2.3.2.

No normalization of the results is carried out. In some cases, results are presented on a relative basis (%) and compared to the reference for each system. No weighting of the impact categories is done; they are presented individually and not as a single score. ISO explicitly forbids combining indicators for comparative assertions as there is no objective method by which to achieve this.

In addition to evaluating impact indicators, two inventory flows are considered: freshwater consumption and solid waste generation. The latter is calculated by summing the solid waste outputs characterized by the inventory (unit process) datasets. Freshwater consumption is

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[10] The global warming potential for CH_4 used by TRACI 2.1 is based on IPCC (2007). This value was manually updated to reflect the latest IPCC (2013) recommendations.

[11] IMPACT2002+ applies the higher heating value (i.e., gross calorific value) in the calculation of Non-renewable energy (Joliet et al. 2003).

defined in this study as the volume of freshwater that is either incorporated into the product or evaporated. It also includes ground or surface water withdrawn and not returned to the same catchment. Here it is calculated as the summation of cooling water, process water and turbined water, each multiplied by an evaporation factor. The factors are 0.388 (Scown et al. 2011), 0.15[12] and 0.01[13], respectively. It is important to note that freshwater consumption and solid waste are inventory flows and do not quantify impact on the environment or human health. It is therefore inappropriate to draw conclusions on the relative environmental performance of the two systems in these categories. They are included in the present study for informational purposes and to better compare the results of the present study with those of previous LCAs on CCs and RPCs.

4.1 Calculation tools and model

GaBi 8 is used to assist the LCA modeling, link the reference flows with the life cycle inventory database, and compute the complete life cycle inventory for each product system. The final life cycle inventory result is calculated combining foreground data (intermediate products and elementary flows) with generic datasets providing cradle-to-gate background elementary flows to create a complete inventory of the two systems. GaBi 8 is also used to apply the impact assessment method and compute the results of the analysis. The information is then exported to Microsoft Excel® where it is organized in tables and applied to create the graphs provided in this report.

4.2 Sensitivity analyses

The parameters, methodological choices and assumptions used when modeling the systems present a certain degree of uncertainty and variability. It is important to evaluate whether the choice of parameters, methods and assumptions significantly influences the report's conclusions and to what extent the findings are dependent upon certain sets of conditions. A series of sensitivity analyses is used here to report the influence of the possible variability of modeling assumptions and data on the results and conclusions, thereby evaluating their robustness. Sensitivity analyses have been made on a limited number of commodities. The strawberry, apple and grape systems have been selected due to their respective functional unit mass ratios. The apple system functional unit mass ratio is nearest the average of the range of commodity functional unit mass ratios. Strawberries and grapes have the lowest and highest ratios, respectively.

A summary of the sensitivity analyses parameters, along with the baseline values, are provided in Table 4-1.

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[12] Stephan Pfister, Senior Research Associate, ETH Zurich, ESD (water footprint expert), personal communication, 2012.

[13] Stephan Pfister, Senior Research Associate, ETH Zurich, ESD (water footprint expert), personal communication, 15 August 2011.

Table 4-1. Parameter values used in the baseline and sensitivity tests for this study.

Sensitivity test	CC system			RPC system		
	Worst case	*Baseline*	*Best case*	*Worst case*	*Baseline*	*Best case*
Container mass	110% of Baseline	Average mass of CC for each commodity	90% of Baseline	----------(Not applicable)----------		
Recovery rate (OCC)	85%	95%	95%	----------(Not applicable)----------		
Number of uses	1	1	1	7	24	40
Break and loss rates	----------(Not applicable)----------			8%	5%	2%
Recycled content	(Not applicable)	38.4%	52%[1]	0%	25%	50%
Cleaning process	----------(Not applicable)----------			(Not evaluated)	Composite technology (weighted average)	IFCO technology (Franklin Associates, 2017)
Transportation[2]	Max distance from grower to retailer	Average distance from grower to retailer	Min distance from grower to retailer	Max distances from grower to distributor/ retailer to servicing/ distributor and back to the grower	Average distances from grower to distributor/ retailer to servicing/ distributor and back to the grower	Min distances from grower to distributor/ retailer to servicing/ distributor and back to the grower

[1] While a sensitivity test is performed on the CC recycled content, it is not included in the best and worst analysis due to the fact that there are tradeoffs in the results. Global warming and non-renewable energy use impacts increase with increased recycled content, while the remaining indicators' impacts decrease. Thus, the recycled content contributes both positively and negatively to the extreme cases.

[2] See Appendix A for distances.

4.2.1 CC system model

There is sufficient reliable information describing the CC system such that few sensitivity analyses are warranted. Nevertheless, some parameters must be tested to understand their influence on study outcomes. In addition, a sensitivity analysis around the approach to biogenic carbon is conducted in order to assess the importance of the proportion of storage. These evaluations are described in the following sections.

4.2.1.1 CC unit mass

A sensitivity analysis is performed on the weight of the CC. In this analysis, the container weight is varied between 90% and 110% of the baseline container weight. This test is included to account for some variation in container dimensions. Size differences are due to variation between manufacturers as well as variation in produce size over the course of a year.

4.2.1.2 OCC recovery rate

The recovery rate sensitivity in this report utilizes an average recovery rate of OCC produced in the U.S. of 85% (EPA 2011). Results are compared to the baseline assumption of 95% (see section 3.1.3). Details are provided in section 3.1.3.

4.2.1.3 CC Recycled content

The recycled content sensitivity is based on the average recycled content for container board that is produced and used in the U.S. of 52% as per NCASI (2017). This is compared to a baseline assumption of 38.4% which represents the average recycled content specific to containerboard going in to produce containers.

4.2.1.4 Biogenic carbon accounting

The approach to counting biogenic carbon used in this study is the typical method employed in LCA and is sometimes referred to as the *flows approach*. Under this technique, the exchanges of carbon to and from the atmosphere are tracked when they occur. An alternative approach, which is often used in national inventories of carbon, is referred to as *stock change accounting*. In this method, biogenic carbon is tallied as changes to carbon stocks occur. Stock change accounting is applied in a sensitivity test.

Carbon stocks exist within forests, products and landfills, and it is therefore the flux of carbon to and from these things that are counted. As per NCASI (2017), it is assumed here that harvesting wood for the production of containerboard does not cause a change in forest carbon stocks. It is also assumed that there is no increase in product carbon stocks as CCs are not intended to last a relatively long period of time (e.g., >100 years). Landfill carbon stocks are, however, increased when CCs are disposed of in this way. This study counts the portion of CC carbon that does not degrade in a landfill within 100 years as an increase in carbon stocks. NCASI (2017) offers additional explanation of stock change accounting.

4.2.1.5 Biogenic carbon stored in landfill[14]

Any approach to biogenic carbon accounting requires an assumption of the time over which storage of carbon away from the atmosphere is considered important. Several approaches have been developed for accounting for carbon storage in products during their useful life and other approaches have been developed for accounting for carbon storage in products that enter landfills, where their carbon would eventually be released but perhaps not for hundreds

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[14] The carbon contained in the RPC is assumed to be from fossil sources and so there is no need to consider the effect of carbon taken from the atmosphere being stored during its use or disposal. The discussion of carbon storage is therefore presented only in regard to the CC system.

or thousands of years.

Regarding carbon stored in products during their use, calculations and models are provided in ISO/TR 14047:2012, example 3. With regard to paperboard and wood products, an Excel model, GPCARB© (Georgia Pacific 2005) is available as a basis to calculate the carbon storage of a specific product using a discount method based on a calculation of the half-life of products in use. It is assumed that the service life of the paperboard products assessed here are short (less than one year to as many as a few years at most, excepting archival storage). CCs are not intended to be used for long-term storage purposes, and thus this study does not include any representation of carbon storage during the use of the CC container.

Once the product life is considered to be over, there is also a question of its disposal and whether the carbon is released (e.g., in product incineration) or further stored (e.g., in a landfill). For carbon storage in landfills, approaches are available from US EPA technical reports based on information from US landfill monitoring for methane generation, capture and different biomass materials factors.

This study evaluates the range of potential carbon storage in the landfill over time through a sensitivity test of the extreme cases. No (0%) storage and 100% storage conditions are assessed as alternatives to the 55% baseline assumption.

4.2.2 RPC system model

The RPC system model includes assumptions regarding number of uses, filling rate, washing and transportation; the baseline assumptions are described in section 3.2. As indicated by previous studies (Franklin Associates 2004, Franklin Associates 2013, Franklin Associates 2017), these parameters can vary in important ways and may affect the environmental performance of the RPC system. Thus, the number of fillings (or uses) of the RPC, recycled content and transport distances are manipulated individually to determine the influence of each. These parameters are modeled such that they are independent of each other yet meet the constraints required for system mass balance. All values evaluated are within a feasible and likely range for the U.S. market.

4.2.2.1 Number of uses

In this sensitivity test, the number of uses is altered from the 24 cycles assumed in the baseline analysis to 7 and 40. The values chosen are based on feedback from RPC industry experts on their actual usage, as well as Franklin Associates (2017) which applies 40 as the baseline value.

4.2.2.2 Break and loss rates

The amount of RPC breakage and loss is varied to understand the influence of this parameter on study outcomes. A minimal value of 2% and a maximal value of 8% are applied in the sensitivity test. These figures are based on feedback from RPC industry experts on their actual breakage rate.

4.2.2.3 Recycled content

The average recycled content of an RPC is assumed to be 25%. A worst-case scenario of 0% and best-case of 50% are evaluated through a sensitivity test to determine the importance of this parameter. All recycled content values are based on input from RPC experts.[15] A description of how recycled material is accounted for in the present study's model is provided in Appendix B: Model approach and assumptions.

4.2.2.4 Cleaning process

Different technologies can be implemented in the RPC cleaning process, each with its own operating specifications and efficacy. The baseline analysis applies a composite cleaning process that combines process inputs from technologies of different efficiencies based on estimated market penetration, as described in section 3.2.3. A sensitivity test is performed to understand the effect of the entire U.S. RPC industry implementing the IFCO-applied technology—which is less intensive than the composite values used in the baseline analysis—on the study outcomes. The cleaning process datasets are provided in Appendix A: Model inputs.

4.2.2.5 Transportation

Transportation distances between the grower, retailer and cleaning facility vary depending on produce type and population center. As found by the University of Stuttgart (2007) and Levi et al. (2011), these steps can contribute a substantial portion (over 30% in the 2007 study) of the total life cycle impact of RPCs, rendering transportation an important component of the system and potentially the comparison between RPCs and CCs. Franklin Associates (2017) report that transport (from retailer to service center) is somewhat influential to the overall study results, even though Franklin Associates (2013) state that it is inconsequential. Evaluation of this parameter is thus warranted.

In the sensitivity analysis presented here, minimum and maximum distances for transport in the use (grower to retailer) and reuse stages (retailer to sorting and cleaning and back to produce grower) are applied. These transport steps and their minimum and maximum values are detailed in Appendix A. Distances between retail, servicing and back to the growers were calculated based on data from the U.S. Department of Agriculture (USDA 2017) and U.S. Census bureau (2012) data. Distances are selected to align with published values and to maintain the logic that inbound distances (from grower to retailer) must be less than or equal to outbound distances (from retailer to servicing and back to the grower).

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[15] Please inquire with CPA if you are interested in the names of the parties consulted.

Transportation in the use stage (between produce grower and retailer) itself does not warrant a sensitivity test as this would change in the same way for both RPCs and CCs and is well characterized for each produce type based on data from the U.S. Department of Agriculture (USDA 2017) and the U.S. Census Bureau (2012). However, because of its connection to the return leg distance, it is included; when the return leg is at its minimum or maximum, the inbound distance is also at its minimum or maximum, respectively. Additionally, because the inbound distance is the same regardless of container, the CC transport distances are modified in the same way.

4.2.3 Global parameters and assumptions

By testing parameters and assumptions that are common to all systems under evaluation, it can be determined whether results are dependent on the approach to the report. Two global components of this LCA are explored: the inclusion of produce and produce loss (perishability) and the choice of impact assessment method. The approach to model allocation is not included as other methods are expected to yield the same results. See section 2.5 for additional explanation.

4.2.3.1 Perishability

Perishability is excluded from the baseline analysis because of a lack of data describing loss rates for the containers. However, because in many cases impacts due to the production of agricultural products significantly outweigh those contributed by the produce packaging, the protective function of the two containers plays a major role in their relative life cycle impacts. To assess the importance of product protection for CCs and RPCs, sensitivity analysis is carried out, which adds to the baseline analysis the impact associated with the production of produce as well as the effect of produce loss.

Publicly available LCI data describing crop production are available throughout the world are currently sparse. Onions are chosen for evaluation because it is the commodity with the highest functional unit mass ratio, and thus a conservative choice for CCs, for which a dataset describing its production is available in Ecoinvent 3.3 (Described in GaBi as “GLO | Onion production | aggregated LCI”).

This analysis investigates three produce loss rates: 0% (baseline analysis), 2% and 30%. These values are based on a study that evaluates peach bruising rates caused by vibration in a simulated cross-country shipment (Thompson et al. 2001). While peach bruising may not be representative of onion losses, the perishability rates provide at least a sense of potential impact. Additionally, the United Nation’s FAO SAVE FOOD program found that nearly 35% of North American produce is wasted or lost from production through distribution (FAO 2011), further confirming that such high loss is the reality.

4.2.3.2 Impact assessment methodology choice

TRACI 2.1 is implemented for the baseline analysis. ReCiPe 2016 hierarchist approach (Goedkoop et al. 2008) is used in the sensitivity analysis. Like TRACI, ReCiPe is an internationally well recognized impact assessment method. Table 4-2 presents the TRACI and ReCiPe indicators in which directional results are compared. ReCiPe offers several indicators that are not available in TRACI, specifically Ionizing radiation, impacts related to land use and transformation, as well as damage categories (endpoints). Since there is no TRACI indicator to compare to the ReCiPe result, these results are not presented. It is recognized that land use may be an important issue for CC or RPC production. However, land use inventory data are not available as part of many of the key datasets used here, including for forestry, and presenting results of this indicator using significantly incomplete data would be misleading. Please see section 6 Limitations for additional reflection on this topic.

Table 4-2. Environmental indicators offered by TRACI 2.1 and ReCiPe 2016 included in the sensitivity analysis.

TRACI indicator	ReCiPe indicator
Acidification (to air and water, kg SO2 eq)	Terrestrial acidification (kg SO_2 eq)
Global warming (kg CO_2 eq)	Climate change (kg CO_2 eq)
Non-renewable energy (IMPACT2002+) (MJ primary)*	Fossil depletion (kg oil eq)
	Metal depletion (kg Fe eq)
Eutrophication (to air and water, kg N eq)	Freshwater eutrophication (kg P eq)
Smog formation (kg O_3 eq)	Photochemical ozone formation (kg NO_x eq)
Respiratory effects (kg $PM_{2.5}$ eq)	Fine particulate matter formation (kg $PM_{2.5}$ eq)
Ozone depletion (kg CFC-11 eq)	Stratospheric ozone depletion (kg CFC-11 eq)

*The TRACI indicator for this impact category is Fossil fuel use, which is exchanged for the IMPACT2002+ non-renewable energy use indicator.

4.3 Data quality assessment

The reliability of the results and conclusions of the LCA depend on the quality of the data used in the report. It is therefore important to ensure that the information is adequate to meet the objectives of the report. Data sources are assessed on the basis of time-related coverage, geographical coverage, technology coverage, precision, completeness, representativeness, consistency, reproducibility, source description and uncertainty of the information as prescribed in ISO 14044.

The methodology for the completeness and consistency check, contribution analysis and uncertainty analysis for this report are described in the following paragraphs.

4.3.1 Completeness and consistency check

The completeness check ensures that data used are applicable and sufficiently comprehensive to meet the objectives of the goal and scope. The consistency check ensures that assumptions, methods and data are consistent with the goal and scope of the report.

All data used are (1) checked regarding their temporal, geographical and technological representativeness, (2) collected at the highest level of detail possible, and (3) documented according to the best practices available. In particular, differences in the quality of data for each system are noted.

4.3.2 Contribution analysis

The contribution analysis illustrates the extent to which each process modeled contributes to the overall impact of the systems. Probing into the systems in this manner allows for a better understanding of the sources of environmental impacts as well as where the greatest opportunities for improvement exist. Further, identification of the most important aspects of the life cycle indicates where it is important to focus on data quality. Processes with a substantial influence on results should be characterized by high-quality information. Similarly, lower quality data may be suitable in the case of a process whose contribution is minimal. In this study, the contribution analysis identifies the processes with highest impact for each system and environmental indicator. Datasets which represent greater than three percent (3%) of impact in any indicator for either system are reported in the contribution analysis.

4.3.3 Uncertainty analysis

Several uncertainties are introduced during the preparation of an LCA, including parameter uncertainty, model uncertainty, uncertainty due to choices in modeling, spatial variability, temporal variability, and variability between sources/objects (Huijbregts 2001). The uncertainty analysis for this study focuses on the total propagated uncertainty (total uncertainty based on the relationships between parameters) resulting from individual parameter uncertainty (empirical inaccuracy, poor representativeness and lack of data). Parameter and propagated uncertainty exist in both the inventory and impact characterization phases of LCA.

In this study, the uncertainty analysis focuses on the key processes of each container life cycle as identified through the contribution analysis. Processes must be important contributors to total life cycle impact and be represented by data of poor or unknown quality to be included in the uncertainty assessment. For these processes, the quantity (flow) of each process is assessed for uncertainty based on an updated pedigree matrix based on Weidema (1996). A description and characterization of the pedigree matrix is available in Appendix D. A sampling approach is taken for each system using the Monte Carlo function in the GaBi software. Results of the uncertainty assessment are presented in section 5.5.

4.4 Interpretation and requirements for comparative assertion

Conclusions from this study will be made in consideration of the baseline analysis, sensitivity tests, study limitations, data quality and uncertainty assessment results. ISO 14044 (clause 5.3) requires for comparative assertions that the scope is equivalent and data are of comparable quality and resolution for the two systems. Additionally, conclusions, limitations and recommendations are required to be consistent with the scope of the report. These requirements are met here through the implementation of the consistency check, completeness check, contribution analysis and uncertainty analysis. A critical review, also mandated by ISO 14044 for comparative assertions, is conducted as described in the following section.

4.5 Critical review

A critical review is conducted by a panel of experts who are independent of this LCA. This process ensures that the report follows the stipulations set forth in the ISO 14040 and 14044 standards (ISO 2006a, b).

For this study, the panel consists of three qualified individuals considered experts in their fields. Mr. François Charron-Doucet, Scientific Director of the Groupe AGECO, has over a decade experience in LCA and is the chair of the critical review committee. Richard Venditti, Ph.D. is an Elis and Signe Olsson Professor in the Department of Forest Biomaterials at North Carolina State University and is an expert in the pulp and paper industry. Adam Gendell is the Associate Director of the Sustainable Packaging Coalition. He brings knowledge of the packaging industry, including both RPCs and corrugated packaging.

The critical review process is carried out in several steps.

1. Report review by all panelists;
2. Clarification of and response to points raised by the reviewers; and
3. Review of responses and final comments by all panelists.

The external critical review reports, practitioner comments and practitioner responses to the review comments are available in Appendix E.

5. Results

This section provides results for the baseline analysis, sensitivity analyses and data quality assessments as described in the previous sections of this document.

5.1 Baseline results

The following are the results of the baseline analysis. The first two sections provide an overview of all eight produce types in all indicators evaluated. Outcomes are shown in two ways—as a market-weighted average across all commodities and by individual commodity—to offer an interpretation of results that are useful for different audiences. The market-weighted average perspective combines results for all commodities by using the share each commodity holds of the produce market, based on USDA data. This view of the results is intended to meet the needs of container purchasers that use only one container type, such as produce retailers. The commodity-specific view of the study outcomes is helpful to parties who purchase containers for a specific commodity, or those who could purchase different containers for different commodities, such as produce growers.

Section 5.1.3 dives one level deeper to better understand the importance of each life cycle stage for each container type.

Appendix A1 summarizes the major reference flows in the modeling, and Appendix C offers an example of the method used for carrying out impact assessment (i.e., translating the life cycle inventories to environmental impacts). Specifically, the demonstration uses the global warming baseline results for each commodity system.

5.1.1 Market-weighted average results

Figure 5-1 presents the market-weighted average results. The produce-market weights are shown in Table 5-1 and are based on the top eight commodities (by production) transported and displayed commonly in both RPCs and CCs. The apple and onion systems have the greatest influence on the average results as they comprise the largest individual portions (approximately 20% each) of fresh market production. The remaining commodities hold a share between 7-15% each.

The market-weighted average results reflect the directional trends observed at the commodity level (see section 5.1.2). Similar to the commodity-specific results, the four (4) indicators that favor RPC in every commodity—acidification, respiratory effects, ozone depletion and smog formation—show a 25-52% advantage over the CC system in the market-average results (relative to the CC system results). Global warming, non-renewable energy use, and eutrophication which show an advantage for the CC system in each commodity, show an advantage of 24%-59% over the RPC system when applying the market weights.

When applying commodity specific uncertainty results, eutrophication and smog formation are the only indicators where the results for the container systems overlap within their range of uncertainty. Thus, no conclusion can be drawn about the relative performance in eutrophication or smog formation. See sections 5.5.2 and 5.5.1, respectively, for more information.

The results of the market-weighted average depend on the market shares of each commodity at a given time. If apples and/or onions comprise a substantially smaller portion of the market, the outcomes of the market-weighted average could shift both in terms of the magnitude of difference between the container systems' environmental performance and the directional results. However, where an indicator shows an advantage for one system across all commodities, the directional results cannot change for that indicator if the market share across commodities changes.

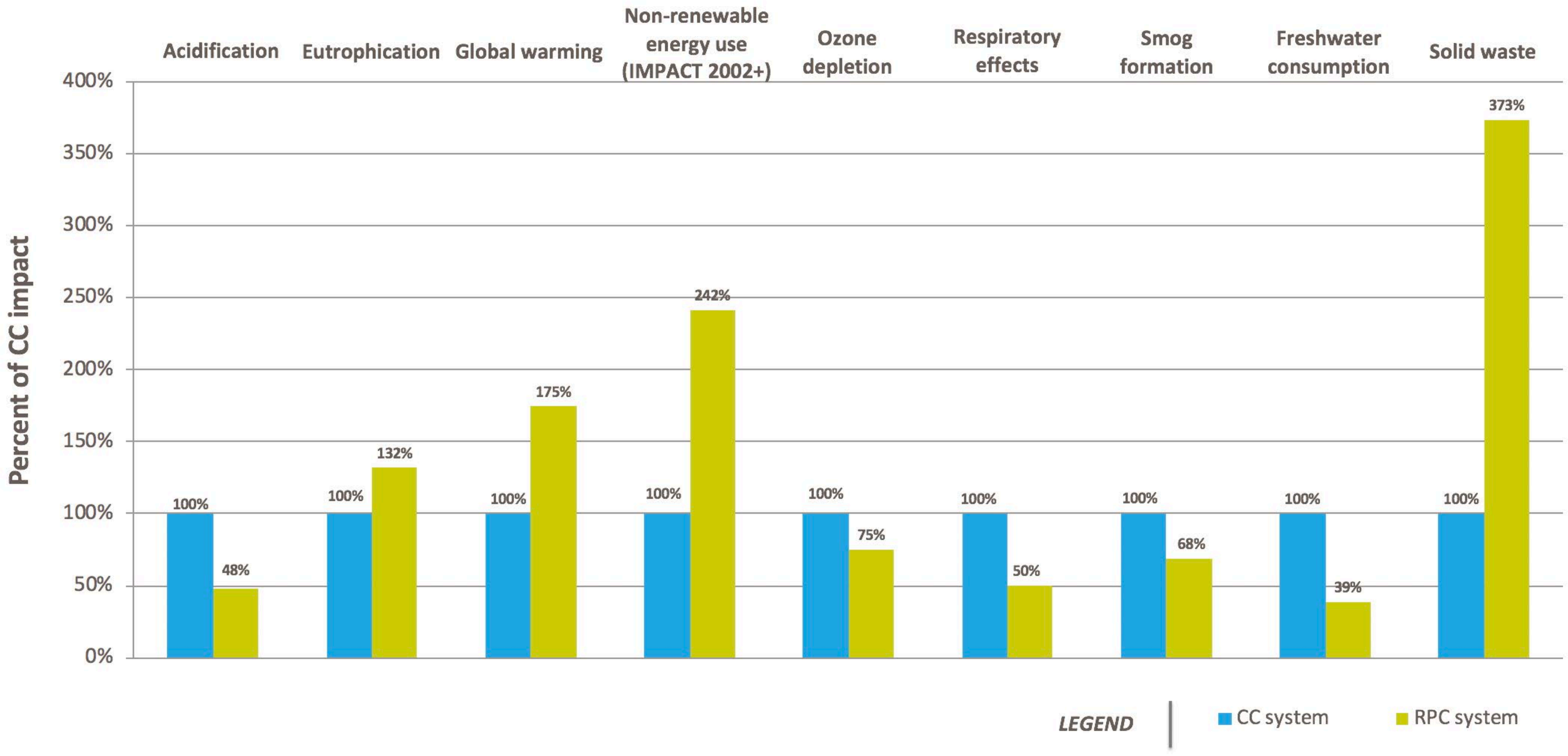

Figure 5-1. Market-weighted average results for the baseline analysis.

Table 5-1. Commodity market shares used to calculate the market-weighted average results.

Commodity	Market share*
Apples	23%
Carrots	7%
Grapes	7%
Lettuce – head	15%
Onions	19%
Oranges	11%
Strawberries	8%
Tomatoes	10%

*Based on top eight commodities (by fresh market production) commonly transported and displayed in both RPCs and CCs (USDA 2017).

5.1.2 Commodity-specific results

Figure 5-2 and Table 5-2 summarize the baseline results for all commodities and environmental indicators evaluated. Each commodity demonstrates trade-offs in types of environmental impact; neither CCs nor RPCs is less impacting across all indicators evaluated.

Four (4) indicators show an environmental advantage for RPCs regardless of commodity: acidification, respiratory effects, ozone depletion and smog formation. In these indicators, the RPC system demonstrates 6-63% less impact (relative to CC results) than the CC system.

Two (2) indicators, global warming, and non-renewable energy use show an environmental advantage for CCs regardless of the commodity.

The final indicator, eutrophication, is favorable for CCs in 6 out of the 8 commodities. However, for the remaining two (grapes and onions), no difference in the results is observed.

However, as explained in section 5.5.2, uncertainty assessment shows that eutrophication and smog formation show no difference between the two systems. Thus, after considering uncertainty, three (3) impact categories show an advantage for RPCs (acidification, respiratory effects, and ozone depletion), and two (2) impact categories show an advantage for CCs (global warming and non-renewable energy use). Section 5.5 provides further analysis of which differences within the comparative results should be viewed as meaningful.

It is not possible to conclude that either system is clearly a superior overall environmental performer as **the number of categories supporting a particular container system is not a good measure of environmental superiority.** Counting the number of midpoint categories to determine relative environmental performance requires the assumption that each category of impact is equally important. Evaluating the relative importance of these categories requires not only an evaluation of the contribution each has in effecting the things we are concerned about (often assumed within an LCA to be protection of human health, ecosystem quality and resource availability), but also the relative importance of these concerns (e.g., what amount of human health should be equivalent to what amount of ecosystem quality). While it is possible to have views or values that define a position on such matters, it is not possible for the authors to defend these values as more correct than the values that might lead another party to a different decision. It is therefore not possible here to draw a definitive conclusion of environmental superiority in cases where there are conflicting indicators that require a trade-off that is primarily value-based. In such cases, including the current one, the only overall conclusion that can be drawn is that trade-offs exist between the systems. Users of this study may apply values systems to arrive at conclusions that may assist in making selections between the container systems under different market conditions.

The observation that the directional results (i.e., whether CCs or RPCs are preferable) are not the same across impact categories indicates that there are different processes in the life cycles of each container type that are the primary drivers of impact among different indicators. In other words, it is not a common process between the systems that is the primary cause of environmental impact. This is explored in the section 5.5.

Three variables principally affect the trends between the different commodity profiles: mass-to-capacity ratio, the functional unit mass ratio and grower-to-retailer transport distances.

Regarding the first, each commodity requires a different mass of containers (for a given container type) to fulfill the functional unit. These quantities are listed in Table 5-2 and are calculated based on the data presented in Table 2-2. The total mass affects the scale of the impact for each system; as the total mass increases, the magnitude of impacts increases. For instance, as shown in Table 5-2, the strawberry container requires the greatest amount of container weight as compared to any other commodity. This is true for both the CC and RPC systems. Consequentially, the absolute results for this system are higher than for other commodities. A similar observation can be made for the carrots system: for both containers, carrots require the least amount of container mass to fulfill the functional unit and therefore show the lowest impact for every indicator compared to other commodities.

The functional unit container mass is dictated by the ratio of container mass to produce mass (per container) for a given commodity. These “mass-to-capacity ratios” are used to calculate the total mass required to fulfill the functional unit for each container system. It is therefore possible to predict, for a given container system, the relative magnitude of impact for each commodity system using the mass-to-capacity ratios. Thus, the mass-to-capacity ratio is the most important variable in the relative results across commodities for a given container system.

The second variable affecting trends between commodity profiles is the ratio of these container masses, referred to herein as the “functional unit mass ratio” and depicted in Figure 5-3. The ratio influences the relative results for each commodity. In other words, comparing the mass required by CCs to that required by RPCs for a given commodity provides an indication of the relative environmental performance of the two container systems.[16] A high CC/RPC functional unit mass ratio favors the RPC system, while a low ratio favors the CC system. For instance, the containers carrying strawberries have the lowest CC/RPC mass ratio than any other commodity. This results in a greater degree of environmental advantage for the CC system in global warming, an advantage for the CC system in non-renewable energy use and a lesser degree of environmental advantage for the RPC system in the remaining indicators.

In one indicator (eutrophication), the differences in functional unit mass ratios across produce types are sufficient to cause some commodities to favor one container system and other commodities to show no difference between the two systems. Specifically, eutrophication shows an environmental advantage for CCs for most commodities, but as the functional unit mass ratio of the commodity increases, the difference between the container systems becomes negligible. When considering uncertainty, however, neither container has a clear advantage.

The strong dependence on functional unit mass ratio indicates that it is possible to predict with a fair amount of accuracy the comparative results for commodities not evaluated in this study. Conclusions reached by this study may be applicable to other produce types if they are packaged, transported and displayed in CCs and RPCs in a manner similar to that described herein.

The third variable that causes some difference between the environmental performances of commodity profiles is the grower-to-retailer transport distance, which varies between commodities. Like container mass required per functional unit, grower-to-retailer transport distance affects the scale of impact for a given commodity. However, since these distances vary less across commodities than do mass-to-capacity ratios, the distances contribute less to the differences in the magnitude of results seen between commodities. Transport distances are listed in Appendix A: Model inputs.

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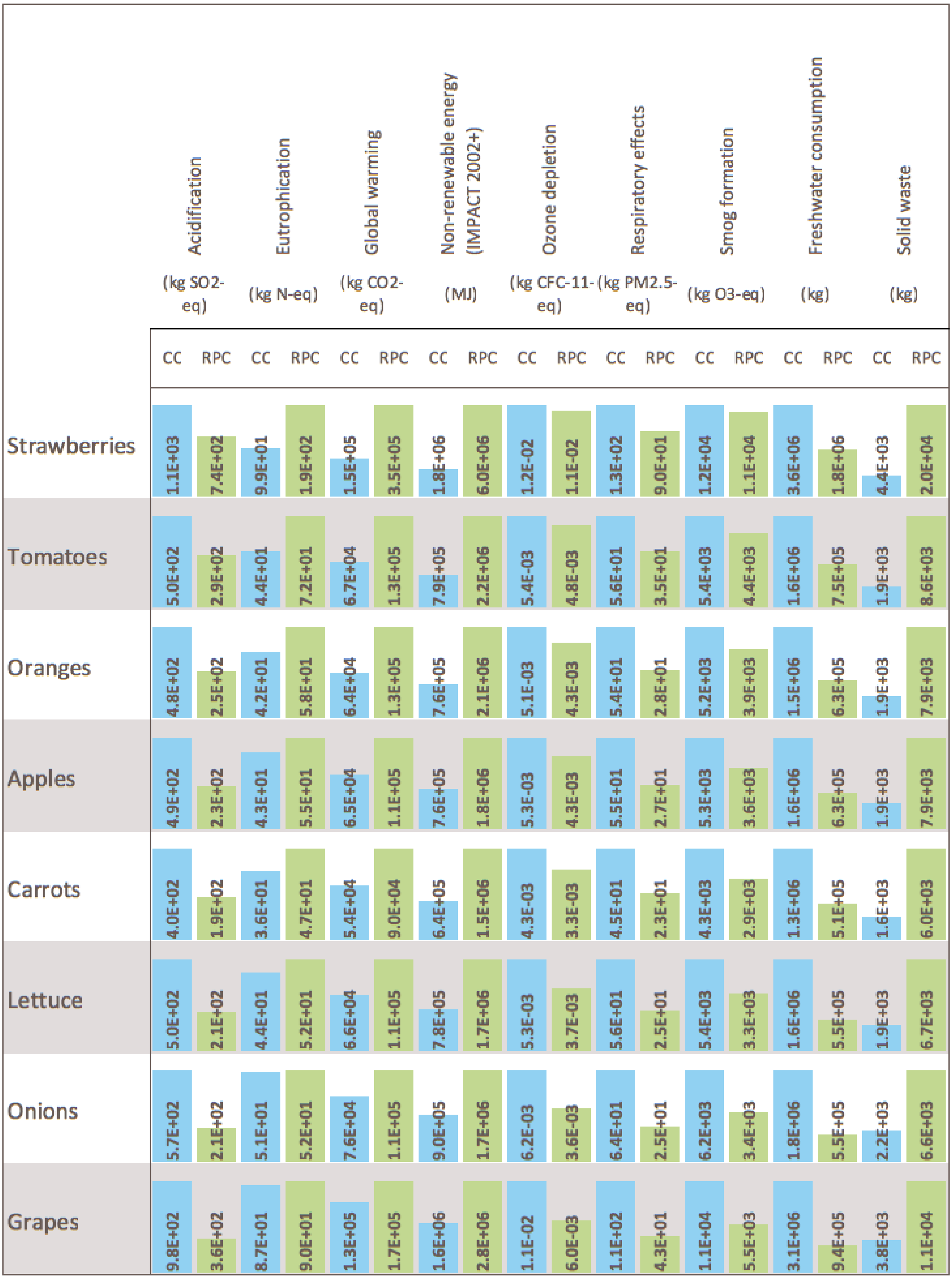
[16] Note that it is generally not possible to predict the relative environmental performance of two different materials (e.g., containerboard and polypropylene) or the products in which they are used by considering—with no other information—the masses of the two materials. One product may have a higher impact despite a lower mass to fulfill the functional unit. The ability to use the functional unit mass ratio as an indication of relative environmental performance is a phenomenon of the results of this study.



	Acidification (kg SO2-eq)		Eutrophication (kg N-eq)		Global warming (kg CO2-eq)		Non-renewable energy (IMPACT 2002+) (MJ)		Ozone depletion (kg CFC-11-eq)		Respiratory effects (kg PM2.5-eq)		Smog formation (kg O3-eq)		Freshwater consumption (kg)		Solid waste (kg)	
	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC	CC	RPC
Strawberries	1.1E+03	7.4E+02	9.9E+01	1.9E+02	1.5E+05	3.5E+05	1.8E+06	6.0E+06	1.2E-02	1.1E-02	1.3E+02	9.0E+01	1.2E+04	1.1E+04	3.6E+06	1.8E+06	4.4E+03	2.0E+04
Tomatoes	5.0E+02	2.9E+02	4.4E+01	7.2E+01	6.7E+04	1.3E+05	7.9E+05	2.2E+06	5.4E-03	4.8E-03	5.6E+01	3.5E+01	5.4E+03	4.4E+03	1.6E+06	7.5E+05	1.9E+03	8.6E+03
Oranges	4.8E+02	2.5E+02	4.2E+01	5.8E+01	6.4E+04	1.3E+05	7.6E+05	2.1E+06	5.1E-03	4.3E-03	5.4E+01	2.8E+01	5.2E+03	3.9E+03	1.5E+06	6.3E+05	1.9E+03	7.9E+03
Apples	4.9E+02	2.3E+02	4.3E+01	5.5E+01	6.5E+04	1.1E+05	7.6E+05	1.8E+06	5.3E-03	4.3E-03	5.5E+01	2.7E+01	5.3E+03	3.6E+03	1.6E+06	6.3E+05	1.9E+03	7.9E+03
Carrots	4.0E+02	1.9E+02	3.6E+01	4.7E+01	5.4E+04	9.0E+04	6.4E+05	1.5E+06	4.3E-03	3.3E-03	4.5E+01	2.3E+01	4.3E+03	2.9E+03	1.3E+06	5.1E+05	1.6E+03	6.0E+03
Lettuce	5.0E+02	2.1E+02	4.4E+01	5.2E+01	6.6E+04	1.1E+05	7.8E+05	1.7E+06	5.3E-03	3.7E-03	5.6E+01	2.5E+01	5.4E+03	3.3E+03	1.6E+06	5.5E+05	1.9E+03	6.7E+03
Onions	5.7E+02	2.1E+02	5.1E+01	5.2E+01	7.6E+04	1.1E+05	9.0E+05	1.7E+06	6.2E-03	3.6E-03	6.4E+01	2.5E+01	6.2E+03	3.4E+03	1.8E+06	5.5E+05	2.2E+03	6.6E+03
Grapes	9.8E+02	3.6E+02	8.7E+01	9.0E+01	1.3E+05	1.7E+05	1.6E+06	2.8E+06	1.1E-02	6.0E-03	1.1E+02	4.3E+01	1.1E+04	5.5E+03	3.1E+06	9.4E+05	3.8E+03	1.1E+04

Figure 5-2. Baseline results (impact per functional unit) for the 8 commodities evaluated in this study. Commodities are ordered from greatest to least functional unit mass ratio. Each bar is shown relative to the system of greatest impact for that impact category and commodity.

Table 5-2. Baseline results (impact per functional unit) for the 8 commodities evaluated in this study.

	System	Strawberries	Tomatoes	Oranges	Apples	Carrots	Lettuce	Onions	Grapes
Functional unit mass ratio	n/a	0.33	0.34	0.36	0.37	0.39	0.44	0.51	0.54
Acidification (kg SO2-eq)	CC	1,100	500	480	490	400	490	570	970
	RPC	740	290	250	230	190	210	210	360
Eutrophication (kg N-eq)	CC	99	44	42	43	36	40	46	79
	RPC	190	72	58	55	47	52	52	90
Global Warming (kg CO2-eq)	CC	150,000	67,000	64,000	65,000	54,000	67,000	78,000	130,000
	RPC	350,000	130,000	130,000	110,000	90,000	110,000	110,000	170,000
Non-renewable energy (IMPACT 2002+) (MJ)	CC	1,800,000	790,000	760,000	760,000	640,000	790,000	910,000	1,600,000
	RPC	6,000,000	2,200,000	2,100,000	1,800,000	1,500,000	1,700,000	1,700,000	2,800,000
Ozone depletion (kg CFC-11-eq)	CC	0.012	0.005	0.005	0.005	0.004	0.005	0.005	0.009
	RPC	0.011	0.005	0.004	0.004	0.003	0.004	0.004	0.006
Respiratory effects (kg PM2.5-eq)	CC	130	56	54	55	45	52	60	100
	RPC	90	35	28	27	23	25	25	43
Smog formation (kg O3-eq)	CC	12,000	5,400	5,200	5,300	4,300	5,100	5,900	10,000
	RPC	11,000	4,400	3,900	3,600	2,900	3,300	3,400	5,500
Freshwater consumption (m3)	CC	3,600,000	1,600,000	1,500,000	1,600,000	1,300,000	1,500,000	1,700,000	2,900,000
	RPC	1,800,000	750,000	630,000	630,000	510,000	550,000	550,000	940,000
Solid waste (kg)	CC	4,400	1,900	1,900	1,900	1,600	2,000	2,300	3,900
	RPC	20,000	8,600	7,900	7,900	6,000	6,700	6,600	11,000

Table 5-3. Key container mass ratios for CCs and RPCs.

	Container mass required to fulfill the functional unit, kg[1]		Container mass-to-capacity ratio[2]	
	RPC	**CC**	**RPC**	**CC**
Apples	110,000	42,000	0.13	0.046
Carrots	86,000	34,000	0.10	0.037
Grapes	150,000	83,000	0.17	0.091
Lettuce – head	96,000	42,000	0.11	0.046
Onions	95,000	49,000	0.11	0.054
Oranges	110,000	40,000	0.13	0.045
Strawberries	280,000	94,000	0.31	0.10
Tomatoes	120,000	42,000	0.14	0.046

[1] Calculated as [(907,185 kg produce) * (Container mass, kg)] / (Produce mass per container, kg). Values have been rounded to two significant figures. Does not subtract the amount of RPCs reused.

[2] Calculated as (Container mass, kg) / (Produce mass per container, kg)

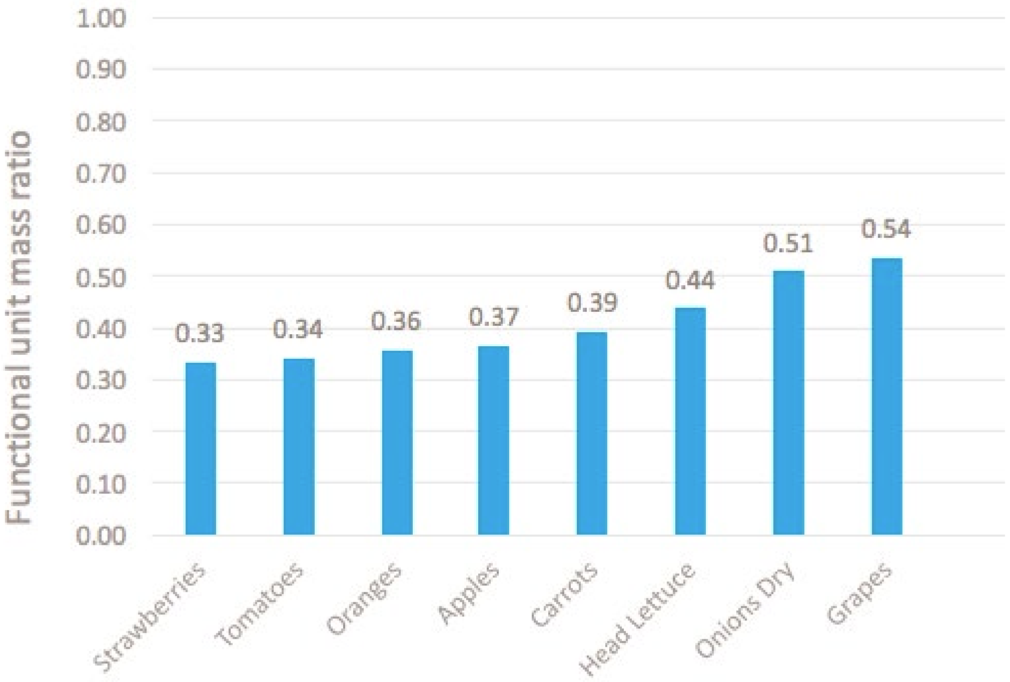


Figure 5-3. Functional unit container mass ratios (CC mass per functional unit/RPC mass per functional unit).

5.1.3 Life cycle stage contribution

In this section, the impact for each container system is presented by life cycle stage. (The scope of each life cycle stage is described in section 2.3.) For brevity, only the apple scenario is depicted here as the overall trends for this commodity are consistent for all other commodities. Tabulated results for all commodities are presented in Appendix C.

Figure 5-4 provides the baseline results by life cycle stage for the CC carrying apples. As shown in this diagram, raw materials and production is the greatest contributor to each indicator result. The conversion and/or use stages are the second-greatest contributors to all indicators. Contribution from the end-of-life stage is relatively small for most indicators, even negligible in some indicators compared to other life cycle stages. This includes the credit given to CCs sent to the municipal solid waste stream that are disposed of via waste-to-energy (WTE) incineration and methane capture at landfills. End-of-life is the main contributor to solid waste due to the disposed CCs, which are the greatest flow of solid waste from the system. Section 5.5.1 provides additional details regarding the sources of impacts within these stages.

As shown in Appendix C, these trends are similar for the seven remaining commodities. The exact contribution of each stage is slightly different across produce types primarily due to differences in the container mass-to-capacity ratio, although transportation distances (to and from the grower) play a (very minor) role.

The RPC baseline results by life cycle stage for the apple system are shown in Figure 5-5. As depicted by this diagram, the reuse stage is the greatest contributor to most indicators, except for ozone depletion. For this indicator, the raw materials and RPC production stage is the largest contributor. Section 5.5.1 offers further insight to the processes that contribute to these stages.

The second greatest contributor to all indicators is the raw materials and production stage or reuse stage. Contribution from the end-of-life stage is relatively negligible for most indicators. This is in part due to the credit given to RPCs sent to the municipal solid waste stream that are disposed of via waste-to-energy (WTE) incineration, which reduce the magnitude of burden associated with these processes. Section 5.5.1 provides additional details regarding the processes that contribute to these stages.

The substantial contribution of the end-of-life stage to the solid waste tally reflects the fact that all RPCs sent to disposal are tracked in the end-of-life stage, no matter where in the life cycle they are lost, broken or otherwise deemed unfit for reuse. The strong dependence of the solid waste metric on the end-of-life stage (and the quantity of disposed RPCs) may also indicate that this inventory flow (for other waste materials) is not well-tracked in datasets throughout the model.

As shown in Appendix C, these trends are similar for the seven remaining commodities. The exact contribution of each stage is slightly different across produce types mainly due to differences in the container mass-to-capacity ratio, although transportation distance between the grower and retailer also cause some (slight) differences.

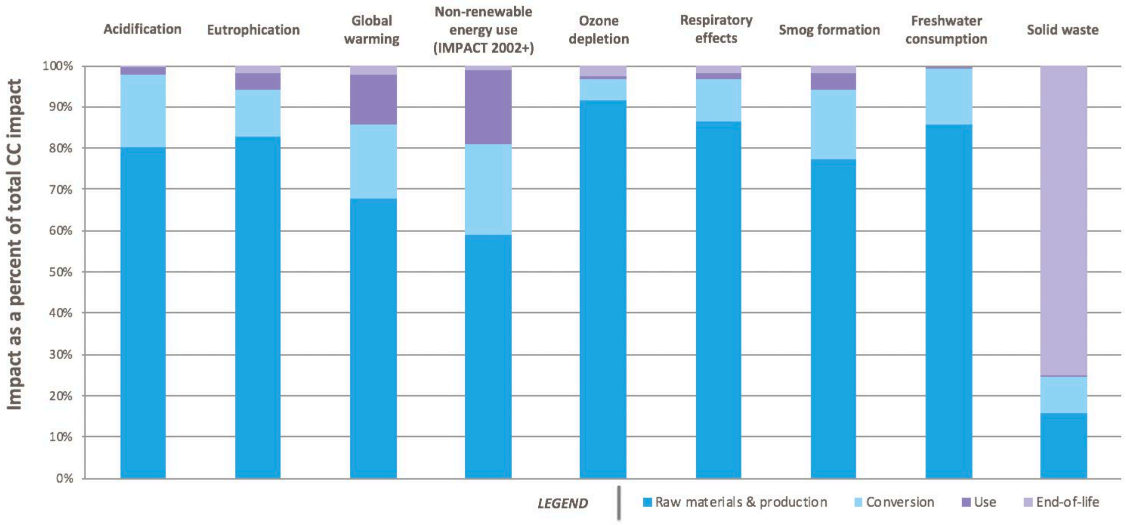


Figure 5-4: Baseline results by life cycle stage for CCs containing apples.

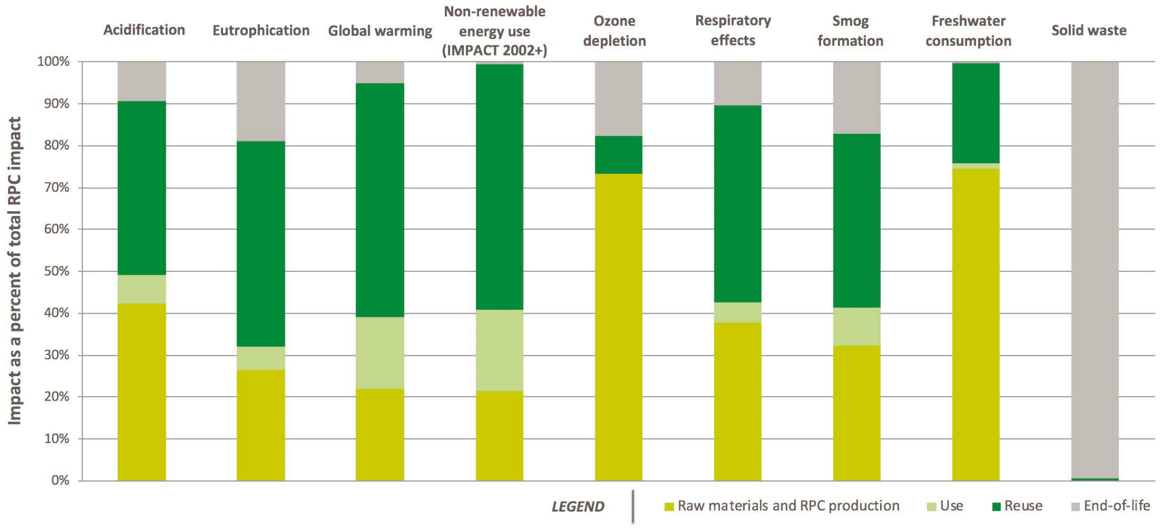


Figure 5-5: Baseline results by life cycle stage for RPCs containing apples.

5.2 Sensitivity analyses

This section presents the results for each sensitivity analysis. The parameters value evaluated are presented in Table 4-1. For brevity, only the apple scenario is depicted here as the overall trends for this commodity are consistent for all other commodities. Complete results for two exemplar commodities' (i.e., strawberries and grapes) sensitivity analyses are available in Appendix C.

The figures throughout this section illustrate results relative to the results for the CC system. Unless otherwise indicated, results are shown as a difference between CC and RPC impact relative to CC impact (i.e., ($Impact_{RPC}$ – $Impact_{CC}$)/$Impact_{CC}$). The effect is that positive (>0) values indicate impact is less for the CC system, while negative (<0) values indicate the RPC system is less impacting. This relative approach to displaying results addresses the ultimate objective of assessing whether the study conclusions change under the different parameter values tested.

5.2.1 RPC number of uses

The sensitivity of the RPC system to the number of times an RPC is used is presented in Figure 5-6. All impact categories show at least some reduction in total impact with increasing uses of the RPC. This is because as the number of uses increases, the number of new RPCs that must be manufactured and disposed of is reduced, eliminating some of the life cycle impacts during these stages. However, because the use and reuse stages are greater contributors than manufacturing to most indicators, the number of times an RPC is used does not substantially influence the RPC system results.

In all but two indicators—ozone depletion and smog formation—the use rates typical to the U.S. market, as evaluated here, are not adequate to shift the outcomes of the study. Ozone depletion has a break-even point[17] at 23 uses, meaning that RPCs are favorable in the case of the baseline (24 uses) and 40 uses, but not in the 7-use case. The break-even point for smog is ten (10) turns. As an illustration of magnitude, consider that RPCs are not advantageous to CCs in the case of global warming until the use rate is beyond approximately 77, a value atypical for the US market. These estimates are based on linear extrapolation of the results in Figure 5-6 and are not depicted by the diagram.

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[17] The break-even point is the point at which there is no discernable difference between the two systems, as calculated by simple linear extrapolation of the results depicted.

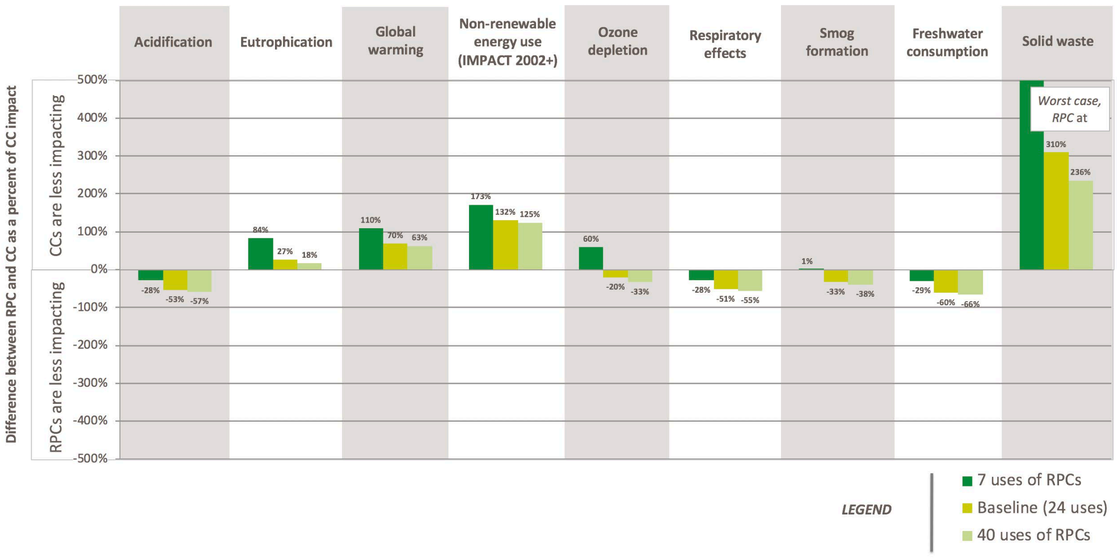

Figure 5-6. Sensitivity of RPC results to number of uses for RPCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable

As shown in Appendix C, the grape and strawberry systems have a similar sensitivity to this parameter, and the general trend of decreasing RPC impact with increasing number of uses holds true. These differences in trends between the commodities reflect differences in container mass-to-capacity ratios and—to a much lesser extent—transport distances between the grower and retailer for the different commodities, as shown in Table 5-1 and explained in section 5.1.2. To illustrate the strong dependence on functional unit mass ratio, consider the trends for global warming. The number of uses break-even point for the systems decreases with increasing functional unit mass ratio. The grape, apple, and strawberry systems have functional unit mass ratios of 0.54, 0.37, and 0.33 respectively. Mathematically speaking, the break-even points for these commodities are approximately 64, 87, and 144 uses, respectively.

5.2.2 RPC break and loss rates

The influence of break and loss rates is illustrated in Figure 5-7. An increase in RPC breakage and loss causes additional RPCs to be produced and additional spent RPCs to be sent to end-of-life, thereby increasing the total impact of the RPC system. The magnitude of this change in environmental impact is a function of the dependence of an indicator on these life cycle stages (i.e., raw materials and production and end-of-life). Indicators to which these stages contribute only small portions of total life cycle impact, such as global warming and non-renewable energy use, are not as affected as those in which these stages play important roles, such as ozone depletion.

The directional results do not change within the range of total break and loss rates evaluated here. For ozone depletion, the highest combined break and loss rate shows a negligible difference between RPCs and CCs. Mathematically the break-even point is 7%.

The strawberry and grape systems each demonstrate changes in directional trends from the baseline commodity for at least one indicator. For strawberries, CCs are favorable in ozone depletion at both the baseline (5%) and 8% break and loss rate. They are also less impacting in smog formation at the 2% and baseline (5%) break and loss rate, although show a negligible difference at the 8% break and loss rate. For grapes, RPCs are advantageous for eutrophication at the 2% break and loss rate and also favorable in ozone depletion at all break and loss rates.

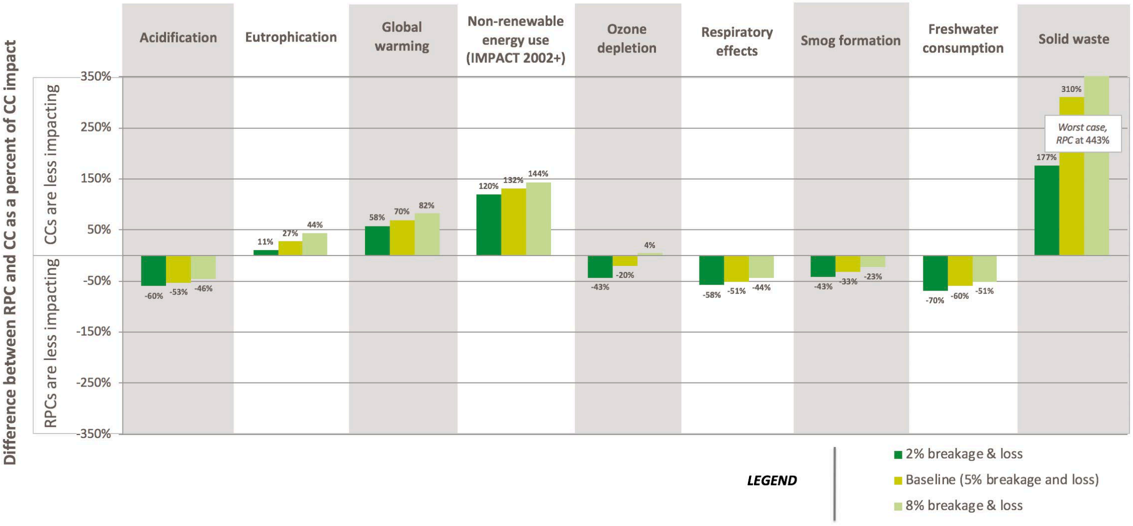

Figure 5-7. Sensitivity of RPC results to break and loss rate for RPCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

5.2.3 RPC recycled content

Figure 5-8 shows the effect of increasing or reducing the recycled content of RPCs. When the recycled content of the RPCs increases, the use of virgin polypropylene is reduced. Therefore, a trend of reduced impact occurs as recycled content increases. Additionally, since virgin PP production is a major contributor to the raw materials and production stage, for indicators where a relatively large portion of impact sources from the raw materials and production stage, the relative results shift more substantially in favor of the RPC system.

This phenomenon is particularly the case for ozone depletion, as shown in Figure 5-5. For the apple system, RPC is favorable when 25% or 50% recycled content is used in the case of ozone depletion, which has a breakeven point of 15%. As shown in Appendix C, the strawberry and grape systems show similar sensitivity to this parameter. In the strawberry system, CCs are favorable for ozone depletion in the case of 0% recycled content. For the grapes system, CCs show an advantage in eutrophication when 0% or the baseline (25%) recycled content is used, and a negligible difference when 50% recycled content is used.

Figure 5-8. Sensitivity of RPC results to recycled content for RPCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

5.2.4 RPC cleaning process

The influence of the cleaning process on study outcomes is depicted in Figure 5-10. As indicated by the results for the apple system, the amount of detergent, electricity and water used during cleaning do not notably influence the relative results of the study. While implementing a more efficient cleaning process offers some environmental savings for the RPC system, the process is not a driver of total environmental impact, nor is the process modified (i.e., environmental performance improved) to a sufficient extent, to alter directional outcomes.

It should be noted that the cleaning process data used here do not include emissions typically found in wastewater from industrial processes that use detergents and chloro-sanitizers. These substances can have important impacts on receiving water bodies or air emissions. While adding these emissions to this study would only result in an increase in impacts for the RPC system, it is unknown whether the magnitude of these impacts relative to other aspects of the life cycle of RPCs is important.

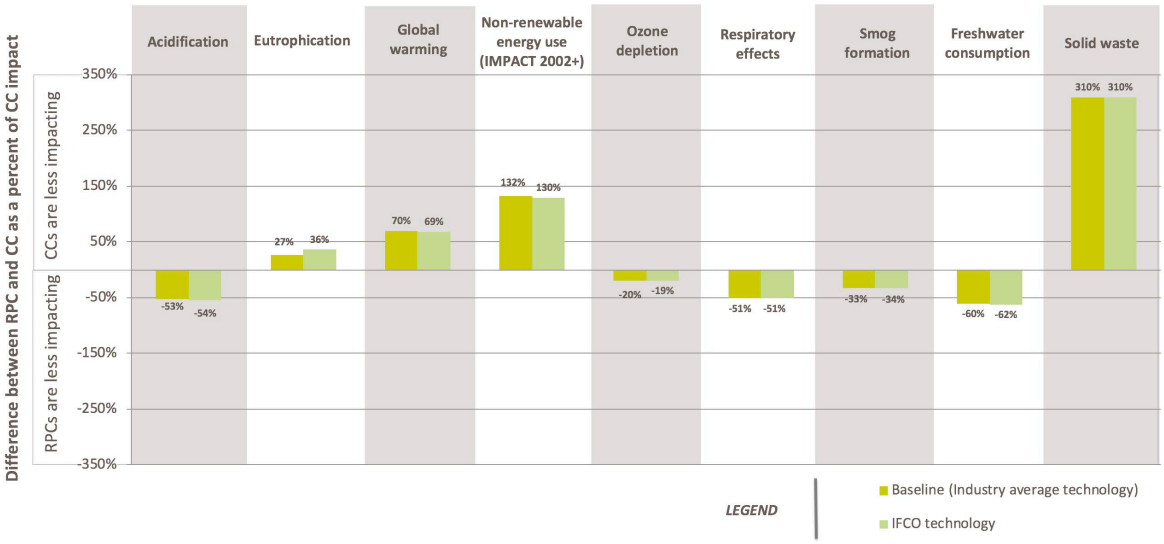

Figure 5-9. Sensitivity of RPC results to the RPC cleaning process for RPCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

Eutrophication is the only indicator whose results worsen with the switch to the more efficient cleaning process. This is because IFCO technology, while using less water and energy than the industry average technology, uses more soap, which drives that indicator.

Results for the strawberry and grape systems show the same outcome. The baseline relative results are unaffected by an improvement in cleaning efficiency.

5.2.5 RPC transport

Figure 5-10 provides results of the sensitivity analysis around RPC transportation distances during the use and reuse stages (growers to retailer, retailer to sorting and cleaning, cleaning to growers) for the apple system. The minimum, baseline and maximum distances applied are 1,420 km, 2,498 km and 3,408 km from growers to retailers (for CCs and RPCs), 1,345 km, 2,472 km, and 3,766 km from the retailer to servicing, and 405 km, 1,121 km and 1,833 km from servicing to growers. See Appendix A3 for additional information on transportation assumptions and distances.

Results for the apples system indicate that transportation can play an important role in the relative results for global warming and non-renewable energy use but does not affect the directional outcomes of any indicator. Under the shortest transport distances, the CC system retains its environmental advantage, although further reductions could eliminate this benefit in the case of global warming and—with additional reduction—non-renewable energy use. However, increasing the distances offers an opportunity for CCs to multiply its advantage.

Results are susceptible to change where transportation in the use and reuse stages is a key player. This is reflected in the magnitude of the shifts in results within each indicator; where transportation is the key contributor, a larger difference in results is observed between the three scenarios (i.e., transport distances). As shown in Figure 5-5, this is the case for most of the indicators evaluated, particularly global warming and non-renewable energy use which predominantly source from these two stages. Ozone depletion is more influenced by other life cycle stages, as discussed in section 5.1.3 and as shown in section 5.5, and are minimally affected by the transportation distances. In all indicators, the RPC system's environmental performance improves as the distances that RPCs are transported from the grower to the retailer to the cleaning facility and back to the grower are reduced.

As shown in Appendix C, the strawberry and grape systems show similar sensitivity to this parameter. For the grape system, the range of transportation distances evaluated is adequate to alter the directional results of the study in global warming and eutrophication. For global warming, the minimal transport scenario results in an advantage for the RPC system, while the baseline and the maximal transport scenario results in an advantage for the CC system. For eutrophication, the minimal transport scenario results in no difference between the systems. For the strawberries system, the maximal transport scenario results in an advantage for CCs in the smog formation indicator, and no difference is seen between the systems in the baseline scenario. The environmental advantage of RPCs can be eroded when transport distances are relatively long. Transportation of RPCs throughout the RPC system collectively is an important factor in the directional outcomes for global warming.

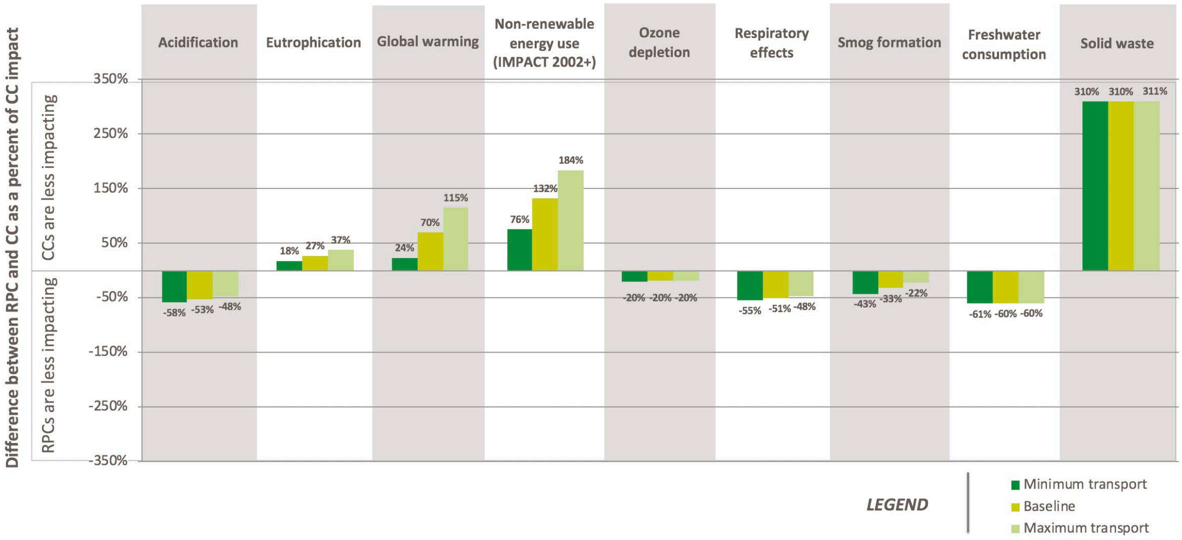

Figure 5-10. Sensitivity of RPC results to transport distances during use and reuse for RPCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

5.2.6 CC container weight

Figure 5-11 presents the results of modifying the CC weight by plus and minus ten percent (+/-10%). Due to the fact that this adjustment to the model directly manipulates the amount of container required for the functional unit, total impact of the CC system simply changes by a magnitude of ten percent (10%) for each indicator. Note that Figure 5-11 depicts the relative results, which do not necessarily shift to the same degree.

The strawberry and grape systems show a similar trend of reduced environmental impact with reduced container weight for the CC system, as presented in Appendix C. Directional changes are observed in both the strawberry and grape systems. For grapes a directional change occurs in the case of eutrophication, showing no difference between CCs and RPCs with a 10% increase in CC weight. For strawberries, CCs show a negligible difference in the 10% decrease in CC weight for both ozone depletion and smog formation.

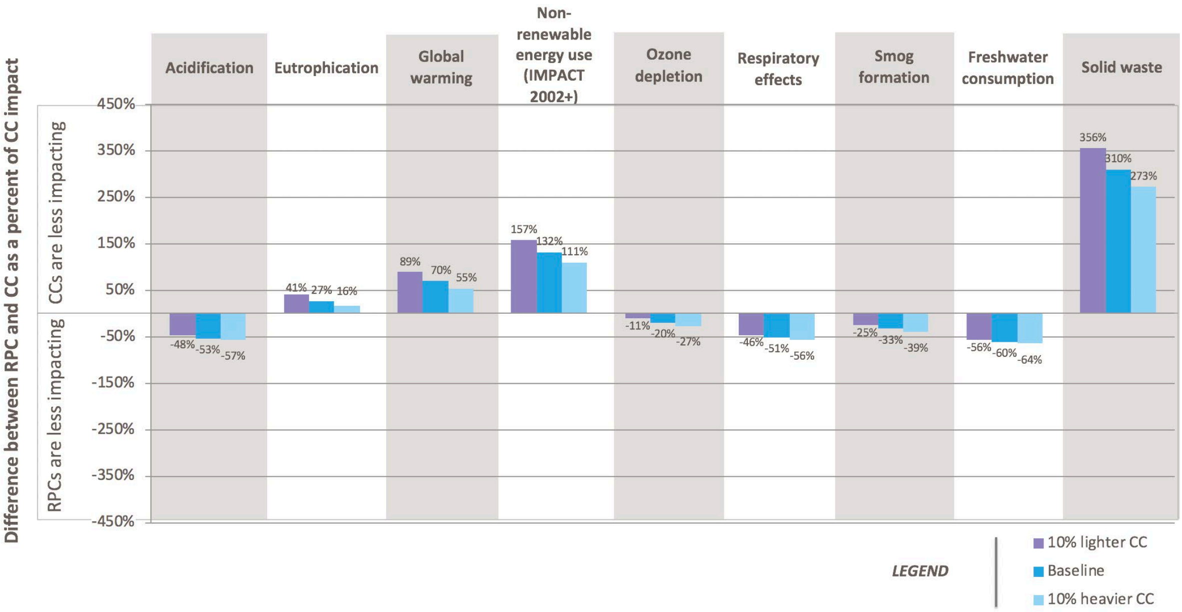

Figure 5-11. Sensitivity of CC results to container weight for CCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

5.2.7 OCC recovery rate

Figure 5-12 presents the results of the CC recovery rate sensitivity analysis. As shown in the diagram, the directional results are not sensitive to the amount of CC recovered after use within the range of values assessed.

Recovery rate determines the amount of material being disposed (via landfill or incineration) and the amount of material exported. It does not affect the average recycled content of CCs as that would require assumptions about the dynamics of the global fiber market. Results of changing the recovery is thereby a balance between increased impact for additional waste treatment (i.e., landfilling and incineration) and the credits earned for the energy generated by these waste management processes.The impact outweighs the credits, as evidenced by the fact that the results for each indicator are positive values.

Theoretically, the amount of virgin materials needed to produce CCs could also be affected by the recovery rate. However, because the amount of recycled fiber in CCs is held constant here in order to reflect the average recycled content for produce containers, the amount of recovered containerboard does not affect the quantity of virgin fiber used to produce CCs. Recovering more CCs results in lesser environmental impact, and the magnitude of the savings depends on the importance of the end-of-life stage to the total CC system results as well as the difference between the CC system and RPC system results. For all indicators, end-of-life is a very small or negligible contributor. Thus, the effect of recovery on total impact is also very small or negligible.

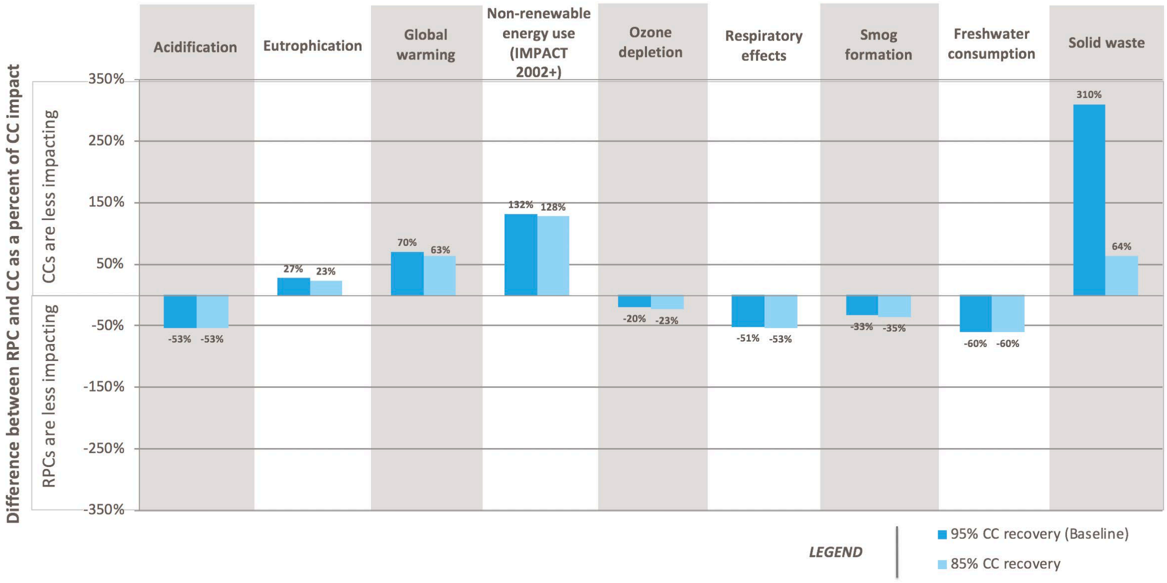

Figure 5-12. Sensitivity of CC results to recovery rate for CCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

The grape and strawberry systems show the same trend of lessened environmental impact with increased recovery. Directional results do not change under differing recovery rates for both the grape and strawberry system. Appendix C contains the results for these two additional container profiles.

5.2.8 CC Recycled Content

Figure 5-13 presents the results of the CC recycled content sensitivity analysis for the apple system. While the directional results do not change within the recycled contents evaluated, the results show that tradeoffs exist between indicators in response to increasing the recycled content. Counterintuitively, increasing the amount of recycled content increases the global warming and non-renewable energy impacts for the CC system. This is because there is a higher electricity usage for recycled liner production than for virgin liner production. Mills can use excess biomass from virgin liner production as a fuel, which results in a lesser electricity need. The remainder of the indicators, however, show a benefit when increasing the recycled content since they are less driven by electricity usage within the raw materials life cycle stage [See

NCASI (2017) for details].

The grape and strawberry systems show the same tradeoffs between the indicators as seen in the apple system. While no changes in directional trends are seen for the grape system, the strawberry system shows a directional change for ozone depletion.

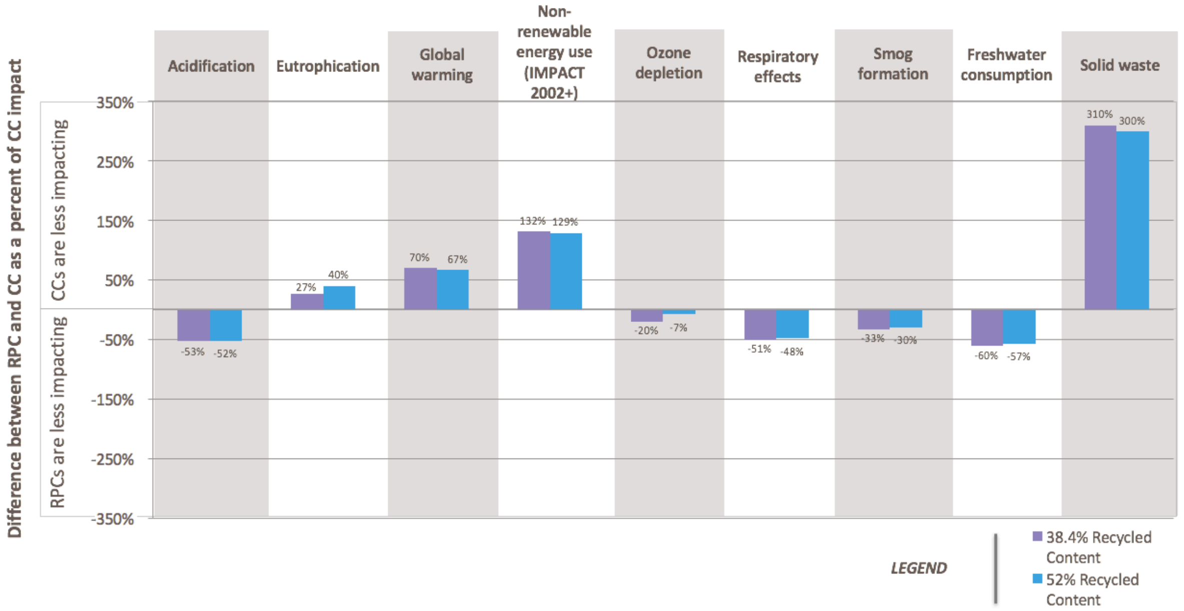

Figure 5-13. Sensitivity of CC results to recycled content for CCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

5.2.9 Biogenic carbon accounting

Figure 5-14 presents the comparative results using the flows approach (baseline analysis) and stock change accounting. While the choice in biogenic carbon accounting does influence the results for the CC system, it does not affect the comparative results. This is because the impact of CCs is already lower than that of RPCs for every indicator under the flows accounting method (excluding biogenic carbon), and the impact of CCs under the stocks accounting method is less. The RPC system has a negligible amount of biogenic carbon flows and is therefore negligibly influenced by the change in biogenic carbon accounting. Refer to Appendix B3. Carbon balance.

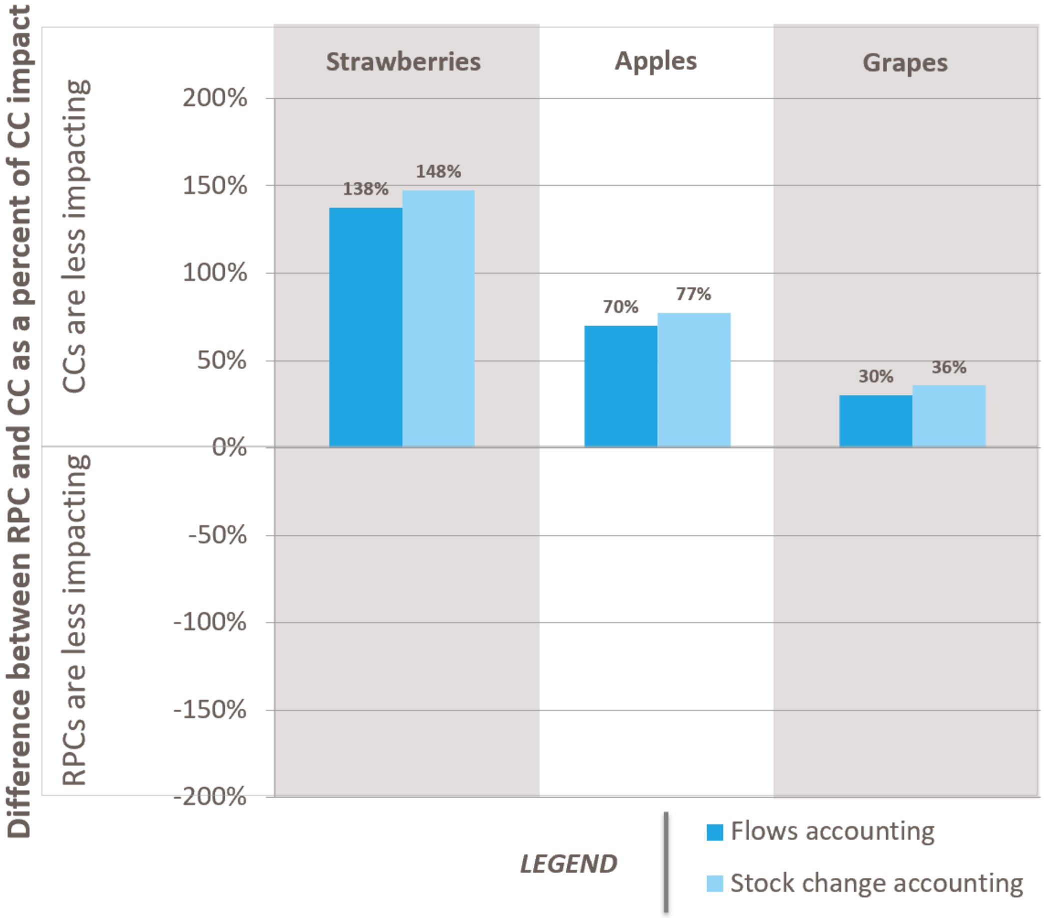

Figure 5-14. Sensitivity of CC results to biogenic carbon accounting method for CCs containing apples. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

5.2.10 Biogenic carbon stored in landfill

Section 4.2.1.4 explains the reasons and approaches for considering the amount and timing of biologically-fixed carbon being stored away from the atmosphere. Figure 5-15 presents the results for the sensitivity of this parameter in which the extreme conditions of considering no storage or complete storage of carbon in landfills is tested. Only the global warming indicator is shown as it is the only indicator affected by carbon storage. Appendix C contains the results for the other impact categories.

For all three commodities evaluated, increasing the amount of carbon stored improves the environmental performance of the CC system. This owes to the fact that storage of sequestered carbon avoids emissions to the atmosphere, thereby avoiding impact on the environment. In no commodity system does carbon storage affect the directional results of the analysis.

The magnitude of change in the relative result (i.e., from 55% storage to 0% or 100%) increases with decreasing functional unit mass ratio. In other words, the range of the strawberry system results is greater than the range of the apple system results, which is greater than the range of the grape system results. This is because the difference in impact between the container systems decreases with increasing functional unit mass ratio.

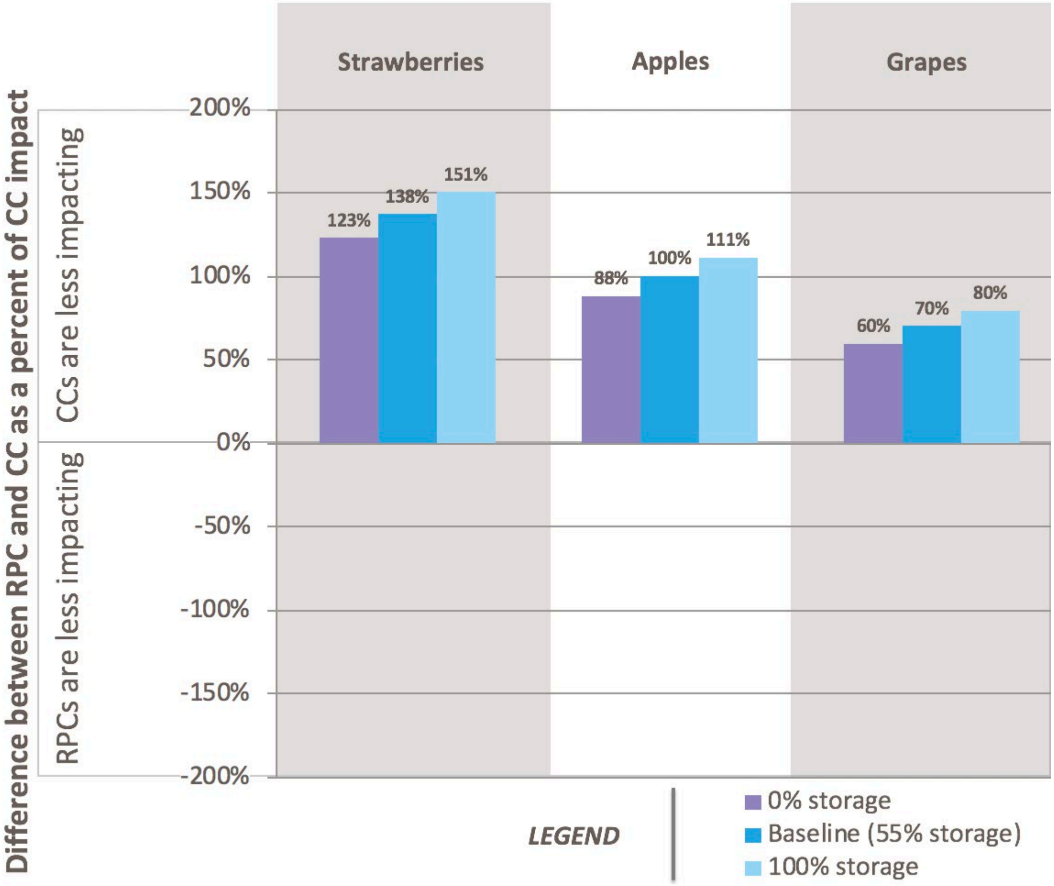

Figure 5-15. Sensitivity of CC global warming results to biogenic carbon storage for CCs. Values indicate the difference between RPC and CC as a percentage of the RPC impact. A positive value indicates CCs are preferable, while a negative value indicates RPCs are preferable.

5.2.11 Best and worst case scenarios

In addition to the sensitivity analyses in sections 5.2.1 through 5.2.10, best and worst case scenarios are evaluated for both systems. These scenarios implement the most favorable (best) and least favorable (worst) values from each sensitivity analysis. The only exception is the CC recycled content, which was not varied for the best and worst case scenarios since the sensitivity test revealed that tradeoffs exist between indicators depending on the recycled content value used. Parameter values are summarized in Table 4-1.

The best- case scenario for the RPC system includes the highest reuse rate, lowest break/loss rate, greatest amount of recycled content, shortest transport distances (from growers to retailers, retailers to servicing and servicing back to growers) and state-of-the-art cleaning technology. The worst case for RPCs applies the opposite ends of these values (e.g., lowest reuse rate), except for the cleaning technology, for which the baseline assumption (composite technology) is used. This is a conservative (favorable) assumption for RPCs.

The best case for the CC system includes the least container weight and highest recovery rate; the worst case evaluates the heaviest container and least amount of recovery. The biogenic carbon accounting scheme and the biogenic carbon storage parameter are excluded from the best and worst case scenarios because the purpose of the test is to understand the relative results of RPCs and CCs under varying industry conditions, and the biogenic carbon topics are methodological choices, rather than industry variables.

The results offer a sense for the range of results that could be obtained under various combinations of the different assumptions. One system's worst case scenario doesn't necessarily have to be preferable to the others' best case scenario for conclusions to be drawn. The best and worst case scenarios are presented here for the apple system in Figure 5-16.

It should be noted that there is no basis for assuming that the best or worst parameter values will exist in tandem. The analysis is theoretical and offers a sense for the potential range of results.

As shown by the spread of results for each indicator in Figure 5-16, the RPC system results show wider variability in most indicators compared to the CC system for the best and worst case scenarios. This span can be attributed to the relatively wide range of parameter values as well as their influence on the system comparison. The different ranges of RPC results for each indicator (in terms of percentage points) indicates that parameters affect indicators in different ways, and some impact categories are affected by the parameters to a greater extent than are others. In order of most to least influenced, non-renewable energy use, ozone depletion, global warming, and eutrophication are more sensitive to the RPC parameter values than acidification respiratory effects, and smog formation. The parameters that are varied affect the amount of raw materials produced, the distances RPCs travel, the servicing process inputs, as well as the amount of RPC sent to end-of-life. This implies that indicators most sensitive to changes in

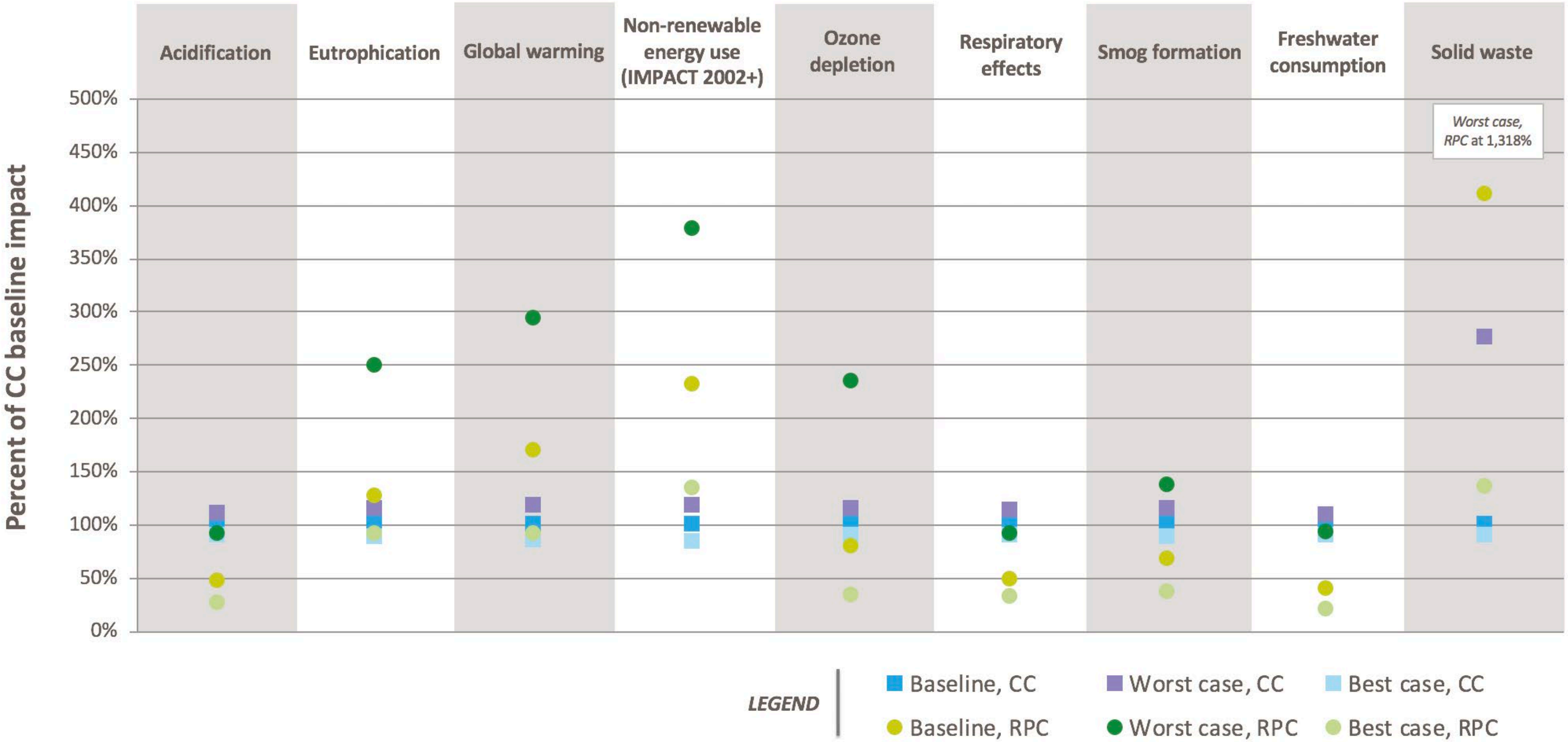

Figure 5-16. Baseline, best and worst case scenarios for RPCs and CCs containing apples. For each indicator, a score higher than 100% indicates greater impact than the CC baseline results.

these parameters are materially contributed to by one or more of these processes. Additional exploration of process contribution is provided in section 5.5.1.

Overlap between the ranges of results for the two container systems carrying apples exists in all indicators, except non-renewable energy use. However, if we consider that a higher CC recycled content would push the worst case higher, it is likely there would be overlap. This means that within the range of industry variability captured by the sensitivity analyses, the directional conclusions can change for all indicators.

The strawberry and grape systems show similar outcomes. However, the overlap occurs in somewhat different indicators. For the strawberry system, overlap exists in all cases except eutrophication and non-renewable energy use. This means that those two indicators will be favorable to CC no matter the combination of parameter values. For the grape system, overlap exists in all cases except acidification, and respiratory effects. Acidification and respiratory effects favor RPCs no matter the combination of parameter values.

The trends illustrated in this sensitivity test indicate that the functional unit mass ratio can be used to predict the degree of overlap between results of the two container systems. For commodities with lower ratios, more indicators will favor CCs, while for commodities with higher ratios, more indicators will favor RPCs, but across the board there will always be trade-offs. The functional unit mass ratio in combination with parameter values plays a defining role in the directional outcomes between the systems.

5.2.12 Perishability

The perishability sensitivity test evaluates the importance of produce loss on the study results. This evaluation is conducted for one commodity only (onions[18]) and assumes equal rates of perishability for the two containers, as described in section 4.2.3.1. When produce is lost, additional containers are required to fulfill the functional unit. This analysis includes the life cycle of the additional containers as well as the production of the additional (lost) produce needed to fulfill the functional unit, represented here by onion production. The remaining produce (i.e., 907,185 kg) is excluded from the analysis since the associated impact is the same between the two containers; only the amount of lost produce may differ between the containers in the case that the containers have different protection performance.

Figure 5-17 presents the results of the analysis. In the diagram, each bar represents the life cycle impact for a given container under the indicated perishability rate. The bars are divided into three sections. The grey section shows the baseline results, which do not change with change in perishability rate. The blue sections represent the impact associated with the life cycles of the additional containers required (to move the additional amount of produce needed

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[18] Given the significance of onion production in the life cycle results presented in this section, and the known relatively large environmental impact of agriculture, it is expected that the high-level conclusions of this example are applicable to other commodities.

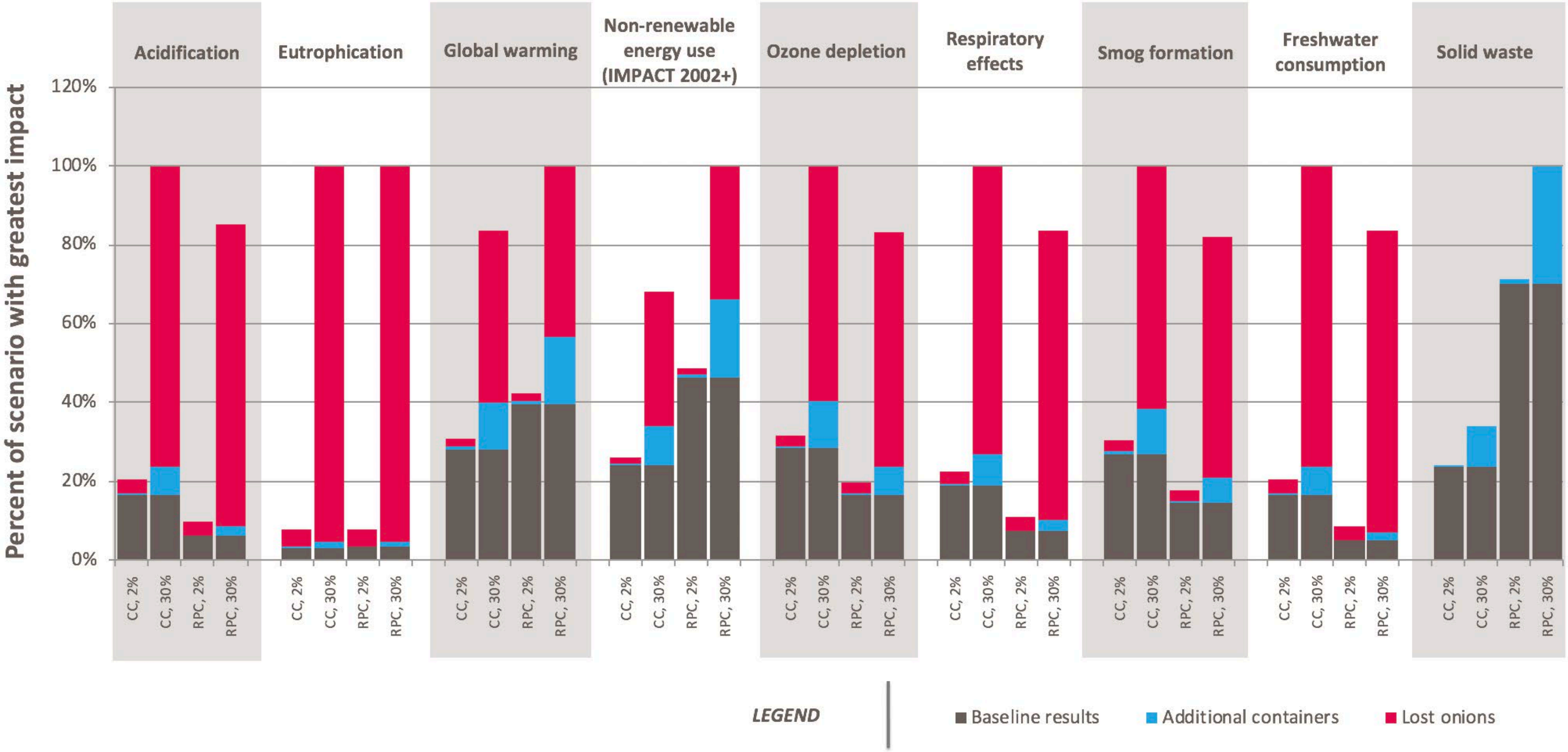

Figure 5-17. Sensitivity analysis of produce perishability. Produce perishability rates of 2% and 30% are shown for each container system.

to fulfill the functional unit). The red sections show the impact associated with the lost produce. Appendix C provides the tabulated results.

It is clear from Figure 5-16 that the production of lost onions may be the greatest contributor to impact for many indicators. In the scenario of 30% perishability, the lost produce contributes at minimum about 34% to all indicators and in some cases much more. In addition, the impact from additional containers contributes between about 1% and 20% to total impact. Combined, at this loss rate, the produce-related (i.e., lost produce plus additional containers) impacts contribute 34%-95% of total system impact. Where RPCs and CCs have equal perishability rates, there is no change in the directional results of the study because both systems increase by the same factor.

Although the inventory values are not being interpreted in this analysis, it is worthwhile to note that agricultural water use is not characterized in the onion production process as provided by Ecoinvent and used here. It is expected that this indicator is dominated by onion production.

These trends indicate that produce production plays an important role in the environmental performance of both container life cycles. While the present study has assumed no difference in the rate of produce damage among the systems compared, it is clear that a modest difference in perishability between RPCs and CCs can affect the relative impact of the systems and ultimately dictate the environmental advantage of either container.

5.2.13 Impact assessment methodology choice

This section presents the results of the primary and secondary impact assessment methods for the strawberry, apple, and grape systems.

Figure 5-18 depicts the data for the apple system as an example, and the results for the remaining commodities are provided in Appendix C.

Across the three commodities, the directional results between TRACI and ReCiPe are largely the same. However, grapes show a small directional shift in metal depletion and eutrophication.

While the directional results are quite similar, the relative differences are somewhat different, such as for ozone depletion. The agreement of the TRACI and ReCiPe directional results indicate that the conclusions of the study are not dependent on the impact assessment method chosen. ReCiPe provides some additional resolution in certain impact categories by offering multiple indicators (i.e., eutrophication and resources), and viewing the results of both methods allows for a more comprehensive perspective of environmental performance.

With regard to ozone depletion, the strawberry, apple, and grape systems show a notable difference in the magnitude of relative results produced by the two methods. In reviewing the characterization factors within GaBi, the list of substances included in the calculations appears to be more comprehensive for ReCiPe. Further, where TRACI and ReCiPe include the same

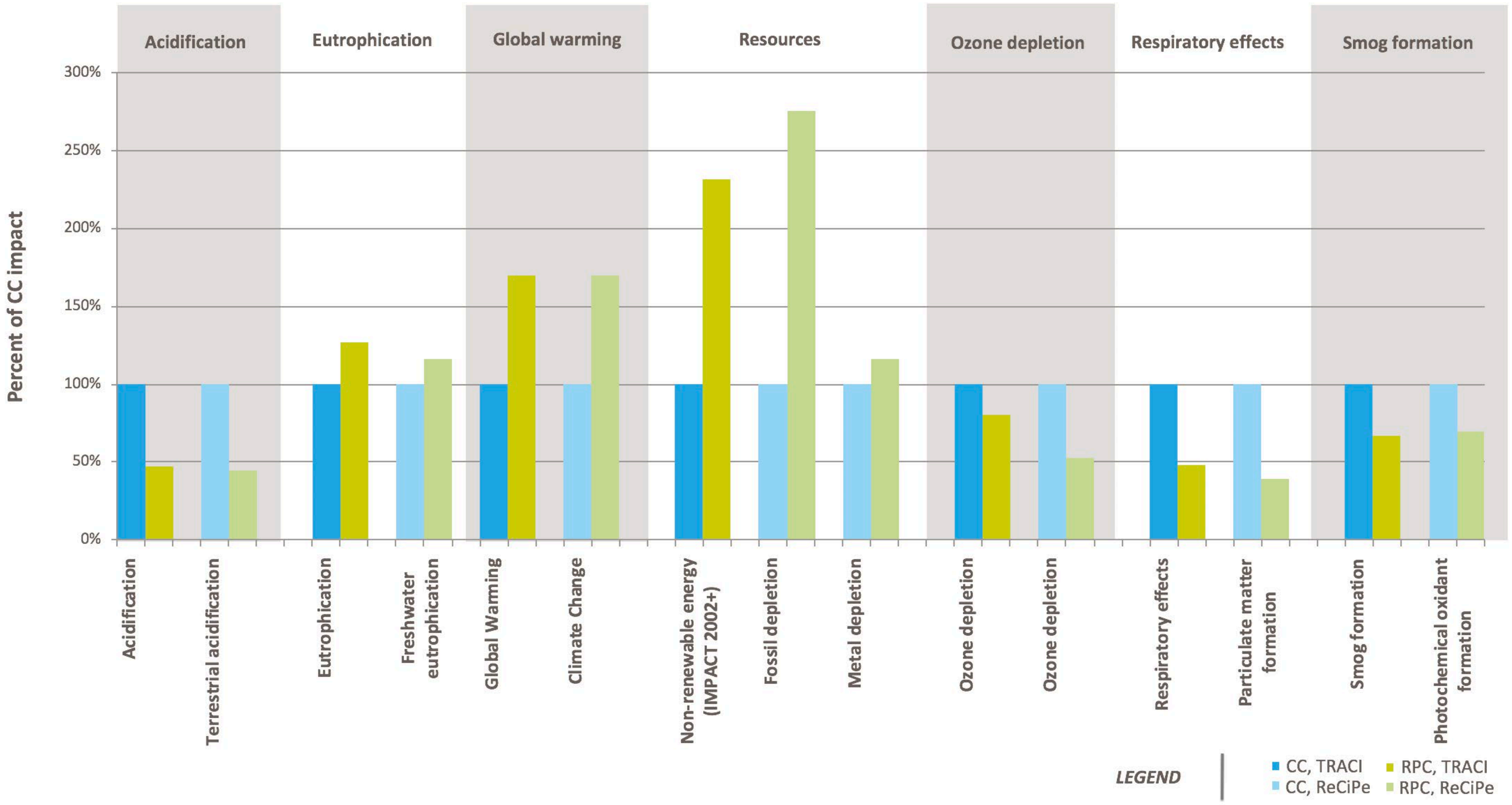

Figure 5-18. Baseline results using TRACI and ReCiPe for RPCs and CCs containing apples. Results are shown as a percent of CC impact for each indicator.

substances, in some cases the characterization factors are not equal and show as much as a factor of 10 different. It is not clear whether the source of these disparities is at the level of the method developers or during implementation of the methods within GaBi. Additional exploration is warranted to better understand the differences observed here. Nevertheless, the directional results are the same using either method.

Certain differences between the LCIA results of the two methods exist because of the differences in structure and nature of the characterization factors. When directional results differ due to the structure and/or nature of impact characterization, it does not necessarily imply that the outcomes of the study are questionable; impact is simply being measured in different ways. This occurs in the case of resources.

Resources are measured in different ways between the two methods. In this study, the IMPACT 2002+ metric non-renewable energy is implemented, which sums the amount of energy used that is derived from non-renewable sources (e.g., fossil fuels). ReCiPe also measures depletion of (fossil) energy sources but computes this as the amount of additional energy required in the future to obtain the same amount of energy (source) used today; the additional energy is an estimate representing the extra effort required to extract less available resources. Results for the three (3) exemplar commodity systems evaluated in this sensitivity test agree directionally between the IMPACT2002+ indicator and the ReCiPe fossil depletion indicator. ReCiPe also measures metal depletion as the surplus energy that will be required in the future to obtain the same amount of a metal ore. This metric is not comparable to the IMPACT 2002+ metric or a TRACI metric.

5.3 Data quality assessment

This section provides an evaluation of the quality of the information used in this study as well as the implications of using the data.

5.4 Completeness and consistency check

The information used to construct the CC system and RPC system models is provided throughout this report. While the data used for either model are considered to be of high quality, their completeness and consistency warrant more investigation.

The container systems, as modeled, are sufficiently comparable to draw comparative conclusions across the indicators evaluated. Data used to describe the RPC system are primarily sourced from a single RPC provider (IFCO)[19], whereas the CC system model primarily sources

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[19] The RPC modeled in this study does not intend to represent an RPC provided by IFCO. The LCI for RPC production and cleaning, as well as some transport steps, are sourced from a publication [Franklin Associates (2017)] describing the IFCO RPC

from studies that consider the greater U.S. containerboard industry. However, since IFCO provides the majority of RPCs on the market and because the data is modified to incorporate other potential RPC providers' practices (as discussed in section 3.2), it is reasonable to assume that the data used here adequately characterize a typical RPC life cycle in the U.S. market. Industry-level information and/or data describing additional players in the U.S. RPC market would facilitate validation of this assumption.

To further assess the importance of the data used to model either container, key parameters are identified for each system based on contribution to each impact category. Results are provided in section 5.5.

5.5 Contribution and uncertainty analyses

The key parameters for each container are identified using the method described in section 4.3.2. Table 5-4 and Table 5-6 show these for the CC system and RPC system carrying apples, respectively. Standard deviations are calculated and provided in Table 5-5 and Table 5-7. Each key parameter is evaluated based on a qualitative assessment of the reliability, completeness, temporal correlation, geographical correlation, technological correlation and sample size of the dataset to which it corresponds; this is referred to as the *pedigree matrix*[20]. Descriptions of the pedigree matrix categories and ratings are provided in Appendix D. The rating for a given parameter (process) is used to calculate a geometric standard deviation for the quantity of flow for the output of that process.

The geometric standard deviations found for each process (shown in Table 5-5 and Table 5-7) are applied to each system in an uncertainty analysis using the Monte Carlo analysis feature within the GaBi 8 software. The resulting standard deviations of the indicator outcomes for CCs and RPCs carrying apples are provided in Table 5-5 and Table 5-7 and depicted with the baseline results in Figure 5-19.

5.5.1 Contribution analysis

Listed in Table 5-4 are processes in the CC system that contribute greater than two percent (>2%) to any indicator. These include two (2) processes in raw materials and production (i.e., containerboard production), two (2) processes in conversion, two (2) processes in the use stage and three (3) processes in the end-of-life stage. These processes in sum contribute to roughly 100% of impact in each impact category. Notable processes include linerboard and medium production, which are important contributors to all environmental metrics evaluated. The former contributes at least 38% to all impact and as much as 75%, while the latter provides

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system due to a lack of available data describing the greater U.S. RPC industry. The model is developed in the present study with the objective of reflecting this broader context.

[20] A pedigree matrix is a framework for characterizing uncertainty of a dataset to assess data quality.

between 16-25% of the impact to each indicator to which it contributes.

Table 5-5 shows for the CC system the uncertainty assessment of each parameter using the pedigree matrix classification and the resulting geometric standard deviation of the pedigree matrix classification. Several processes in the CC system are well described by previous literature and utilize primary data. The result is that most processes have a low geometric standard deviation. These processes (linerboard production, medium production and CC converting) are excluded from the uncertainty analysis, the results of which are described later in section 5.5.2.

In Table 5-6, processes in the RPC system which contribute greater than two percent (>2%) to any indicator are listed. These include four (4) processes in the raw materials and production stage, one (1) process in the use stage, seven (7) processes in the reuse stage and one (1) process in the end-of-life stage. These processes in sum contribute to at least 98.8% of impact in each impact category.

While no single process or life cycle stage dominates the impacts, three types of processes stand out in this contribution analysis, namely transportation of RPCs, electricity use and production of plastics. Transportation of RPCs from the grower to the retailer, from the retailer to servicing and from servicing back to the grower are important contributors to most indicators. Electricity use during RPC production and RPC cleaning are important to acidification, respiratory effects and, to a smaller extent, smog formation. Plastics production is also a notable contributor, specifically the production of PP used in RPCs and LLDPE used for packaging sanitized RPCs.

Table 5-7 shows for the RPC system the results for the uncertainty assessment of each parameter using the pedigree matrix classification and the resulting geometric standard deviation of the environmental flows of these processes. More information on the pedigree matrix classification can be found in Table D-1. The RPC data are characterized by various literature sources and databases, and while the geometric standard deviations of the processes are similar to those for CCs, a greater number of processes are considered uncertain. All processes are included in the uncertainty assessment.

Table 5-4. Key contributors to each impact category for CCs containing apples.

LEGEND

Process rank within impact category: High value ↕ Low value

Impact category	Contribution of life cycle stage to total life cycle impact									Total contribution to life cycle accounted for[1]
	Raw materials & production		Conversion		Use		End-of-life			
	Linerboard production	Medium production	Transport of containerboard to converting	Converting	Transport from CC production to grower	Transport from grower to retailer	Transport from retailer to end-of-life	Incineration of CCs	Landfill of CCs	
Acidification	55%	25%	2.1%	15%	0.67%	1.2%	0.66%	-0.35%	0.061%	**100%**
Eutrophication	62%	21%	1.6%	10%	1.5%	2.6%	1.0%	-0.067%	0.74%	**100%**
Global warming	43%	24%	2.0%	16%	1.7%	10%	0.89%	-0.30%	1.6%	**100%**
Non-renewable energy use	38%	21%	2.3%	19%	2.0%	16%	1.1%	-0.12%	-0.019%	**100%**
Ozone depletion	75%	16%	0.41%	4.4%	1.0%	0.0%	2.5%	-0.050%	-0.0069%	**100%**
Respiratory effects	66%	20%	0.82%	9%	0.78%	0.83%	0.90%	-0.20%	0.9%	**100%**
Smog formation	57%	21%	6.6%	10%	1.7%	2.2%	1.9%	-0.23%	0.23%	**100%**
Freshwater consumption	51%	28%	0.22%	22%	0.52%	0.0%	0.22%	-0.92%	-0.14%	**100%**
Solid waste	9%	6.4%	0.0%	8.9%	0.020%	0.21%	0.00%	3.8%	71%	**100%**

[1] Values may equal or exceed 100% due to rounding.

Table 5-5. Pedigree matrix classification and standard deviation of CC system processes that contribute to at least three percent (3%) of total impact of the CC life cycle for CCs containing apples. Processes are color coded to life cycle stages in Table 5-4.

CC system processes		Pedigree matrix classification*	Geometric standard deviation
🟦	**Linerboard production**	1, 1, 1, 1, 1	1.02
	Medium production	1, 1, 1, 1, 1	1.02
🟦	**Transport of containerboard to converting**	1, 1, 1, 1, 1	1.41
	Converting	1, 1, 1, 1, 1	1.02
🟪	**Transport from producer to grower**	2, 2, 2, 1, 1	1.42
	Transport from grower to retailer	2, 2, 2, 1, 1	1.42
🟪	**Transport from retailer to end-of-life**	4, 1, 2, 2, 1	1.42
	Incineration of CCs	4, 1, 2, 2, 1	1.10
	Landfill of CCs	4, 1, 2, 2, 1	1.10

*Matrix ratings {a, b, c, d, e} refer to the following attributes: reliability (a), completeness (b), temporal correlation (c), geographical correlation (d), further technological correlation (e).

Table 5-6. Key contributors to each impact category for RPCs containing apples.

LEGEND

Process rank within impact category: ↑ High value ↓ Low value

Impact category	**Contribution of life cycle stage to total life cycle impact**													**Total contribution to life cycle accounted for[3]**
	Raw materials & RPC production				**Use**	**Reuse**							**End-of-life**	
	PP resin production	Solvent production[1]	Electricity use during RPC production	Transport of materials to RPC production	Transport from grower to retailer	Transport of dirty RPCs to cleaning	Electricity use during cleaning	Natural gas use during cleaning	Transport of materials to cleaning	Detergent production	LLDPE production[2]	Transport of cleaned RPCs to growers	Disposed RPCs (to landfill and incineration)	
Acidification	13%	0.68%	25%	3.3%	6.9%	11.4%	9.7%	0.96%	0.86%	5.2%	7.5%	5.1%	9.4%	**98.8%**
Eutrophication	20%	1.3%	1.8%	3.4%	5.6%	8.4%	0.71%	0.32%	0.80%	33%	1.6%	3.8%	19%	**100%**
Global warming	13%	0.35%	5.9%	1.7%	17%	31%	2.3%	2.6%	0.40%	1.2%	5.3%	14%	5.1%	**100%**
Non-renewable energy use	16%	0.63%	1.7%	2.9%	20%	28%	0.68%	2.7%	0.43%	0.76%	12%	13%	0.45%	**98.8%**
Ozone depletion	60%	0.73%	2.1%	10%	0.16%	0.0%	0.81%	0.00%	2.7%	5.3%	0.077%	0.0%	18%	**100%**
Respiratory effects	14%	1.5%	13%	9.5%	4.7%	7.8%	5.1%	0.40%	2.4%	14%	13%	3.5%	10%	**99.1%**
Smog formation	14%	0.50%	12%	5.6%	9.1%	16%	4.6%	1.7%	1.4%	3.0%	7.0%	7%	17%	**99.1%**
Freshwater consumption	21%	1.0%	47%	3.7%	0.10%	0.15%	19%	0.0020%	0.97%	8.0%	0.080%	0.066%	-0.41%	**100%**
Solid waste	0.0%	0.0%	0.0%	0.0%	0.15%	0.21%	0.0%	0.11%	0.00%	0.0%	0.0%	0.095%	99%	**100%**

[1] Solvent used in RPC production.

[2] LLDPE used for packaging cleaned RPCs for transport to growers.

[3] Values may equal or exceed 100% due to rounding.

Table 5-7. Pedigree matrix classification and standard deviation of RPC system processes that contribute to at least three percent (3%) of total impact of the life cycle of RPCs containing apples. Processes are color coded to life cycle stages in Table 5-6.

RPC system processes		Pedigree matrix classification*	Geometric standard deviation
🟨	PP resin production	2, 2, 1, 2, 1	1.04
	Solvent production	2, 2, 1, 2, 1	1.04
	Electricity use during RPC production	2, 2, 1, 2, 1	1.04
	Transport of materials to RPC production	2, 2, 1, 2, 1	1.42
🟩	Transport from grower to retailer	2, 2, 2, 1, 1	1.42
🟩	Transport of dirty RPCs to cleaning	3, 2, 1, 1, 1	1.42
	Electricity use during cleaning	2, 2.9, 1.6, 2.9, 1.6	1.05
	Natural gas use during cleaning	2, 2.9, 1.6, 2.9, 1.6	1.05
	Transport of materials to cleaning	2, 2, 1, 2, 1	1.42
	Detergent production	2, 2.9, 1.6, 2.9, 1.6	1.05
	LLDPE production	2, 2.9, 1.6, 2.9, 1.6	1.05
	Transport of cleaned RPCs to growers	3, 2, 1, 1, 1	1.42
⬜	Disposed RPCs (to landfill and incineration)	4, 1, 2, 2, 1	1.10

*Matrix ratings {a, b, c, d, e} refer to the following attributes: reliability (a), completeness (b), temporal correlation (c), geographical correlation (d), further technological correlation (e).

5.5.2 Uncertainty assessment

Presented in Table 5-8 are the standard deviations of each indicator result for the CC and RPC systems. The calculated standard deviation of the CC system is low for all indicators, not exceeding one percent (1%) in any category. The minimum deviation of the RPC system is higher, at five percent (5%), with a maximum of 13% in global warming. This indicates that a wider range of results exists for the RPC system than for the CC system. Such an outcome is expected given the high number of and large span in the values of variables (e.g., number of uses, recycled content) characterizing the RPC system. The variation in the parameters reflects the wide variation in the dynamics of the RPC market.

Figure 5-19 presents the findings of the Monte Carlo uncertainty analysis for the apple commodity. The error bars do not influence the directional conclusions, indicating that the results of the baseline analysis can be considered robust.

The results for the grapes system are similar to the apple results, showing that eutrophication is the only indicator with the potential for directional results to change. The results for the strawberry system, show that smog formation is the only indicator with the potential for directional results to change once uncertainty is considered. Appendix C contains the uncertainty analysis results for these three commodity profiles.

The uncertainty for the RPC system global warming and non-renewable energy use results is notably greater than the uncertainty for other indicators. This is because these two indicators are dominated by processes with relatively high uncertainty, specifically transportation of RPCs throughout its life cycle. The uncertainty here is with the distances traveled. Outcomes are consistent with those of the RPC transport sensitivity test in section 0. While global warming and non-renewable energy use are the two indicators in which the CC system is advantageous, the advantage is not due to the relatively high RPC uncertainty but simply due to substantial differences in the absolute results of the systems.

The uncertainty of a given system and the comparative uncertainty (i.e., the relative uncertainty of the results of the two systems) are affected by several factors. **The total uncertainty shown here for each system is very likely an underestimate.** Factors leading to a bias toward a low estimate of uncertainty include the inability to characterize the inventory uncertainty for all processes in the database and, perhaps more importantly, an inability to consider the uncertainty in the characterization factors used to predict the environmental impact of the inventory flows. While the latter issue is a limitation in the current state of science within LCA, the former is a limitation of the implementation of the Ecoinvent database within the GaBi software.

Confidence in the comparative results is strengthened when the same uncertainties are found in both systems, such as with characterization factor uncertainty, as well as correlated processes between the two systems. With respect to the former, the magnitude of characterization factor uncertainty is equal between the two container systems (since the systems are being analyzed with the same impact assessment method, TRACI 2.1). While uncertainty in the characterization factors adds uncertainty to the results for a given system, it is the same degree of uncertainty for both systems. In other words, if a characterization factor should in fact be 10% higher, it should be 10% higher for both systems. Applying that revised characterization factor would result in somewhat higher impact for both systems. The relative results may or may not be affected, depending on the influence of that factor on the results for each individual system. Characterization factor uncertainty is not included in the assessment here.

The correlation of processes between the two systems also reduces the uncertainty in the comparative results. In other words, each system has important contributions from processes, such as electricity generation and truck transport, common to the two systems. Uncertainty in the inventory of these processes does not contribute to the uncertainty of the comparison. That is, an overestimate or underestimate of the impact of any of these processes will affect both systems in the same way. This consideration of correlated processes is not reflected in the depiction of error bars in Figure 5-19.

Even with imperfect representation of the uncertainty in the calculations, the assessment of uncertainty presented here is useful in understanding the size of the uncertainty relative to the size of the differences between systems. The conclusion can be reached that the comparative finding within each environmental impact category is large enough to be confident in the results, except for global warming and eutrophication in the case of the grape system as well as ozone depletion and smog formation for the strawberry system.[21]

Table 5-8. Standard deviation of results within each impact category for CCs and RPCs containing apples.

Standard deviation of indicators and inventory items	CC system	RPC system
Acidification	<0.01%	8%
Eutrophication	<0.01%	6%
Global warming	<0.01%	13%
Non-renewable energy (IMPACT 2002+)	<0.01%	13%
Ozone depletion	<0.01%	5%
Respiratory effects	<0.01%	5%
Smog formation	<0.01%	7%
Freshwater consumption	<0.01%	6%
Solid waste	<0.01%	10%

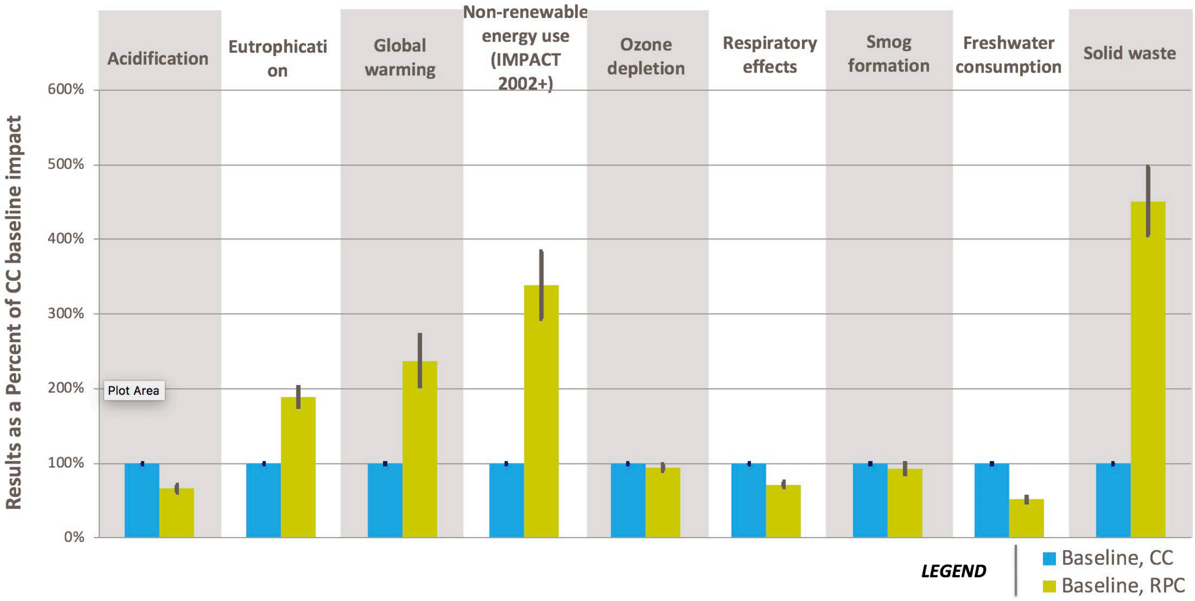

Figure 5-19. Uncertainty analysis for apple containers showing indicator standard deviation as error bars for each system.

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[21] This analysis considers only the uncertainty in reference flows, as described in Table 5-4 and Table 5-6. It does not consider process flow uncertainty, as described in section 5.5.1.

6. Limitations

The present study has limitations that should be understood when applying its results including some limitations inherent in LCA and others based on the current state of the science, as well as the methodological approaches taken here. The following limitations should be considered along with the context described in earlier sections of this report when interpreting the information presented in this report.

- LCIA results present relative and potential, not measured, environmental impacts. They are relative expressions (to the functional unit), which cannot be used to predict specific instances of adverse impacts or risk or whether standards or safety margins are exceeded. LCIA models generally attempt to represent the most probable case, rather than consideration of a worst case, safety margin or similar conservative approaches often taken in a regulatory context. Additionally, the categories evaluated here do not cover all the environmental impacts associated with human activities. For example, impacts such as noise, odors, electromagnetic fields and others are not included in the present assessment. The methodological developments regarding such impacts are not sufficient to allow for their consideration.
- LCIA methodologies cannot characterize the full array of emissions released to soil, air and water from processes. However, they do characterize the most well-known pollutants and, in doing so, provide the best estimate to evaluate environmental impact.
- In contrast to the CC systems, the RPC systems are primarily characterized by data that describe a single company's operations (due to a lack of available information). Thus, the quality of data used to model the two container types are not necessarily equivalent. Several sensitivity tests—particularly around parameters found by previous life cycle studies to be important drivers of impact—are performed to evaluate the effect of selecting a given value within the range of values considered practical for the U.S. market, as well as the cumulative effect of varying multiple parameters.
- Water emissions data for the RPC cleaning process is limited in that they do not include emissions typically found in wastewater from industrial processes using detergents and chloro-sanitizers. These substances can have important impacts on receiving water bodies or air emissions. It is unknown whether the magnitude of these impacts relative to other aspects of the life cycle of RPCs is important.
- While produce production and losses are included in a sensitivity analysis, the difference in loss between CCs and RPCs is excluded from the baseline assessment. It should be recognized that impacts associated with produce production far outweigh any of the processes in the life cycle of a container for most indicators, and differences of even a few percent in produce loss between the two container types could dictate the relative

environmental performance for those indicators. No evidence was identified in conducting this study suggesting a difference in produce loss rates between these two systems.

- The scope of the assessment excludes environmental indicators for land use and land transformation. This is due to a lack of such information in many of the datasets that are central to the assessment. It should be recognized that land use and transformation are complex issues, some with competing perspectives. Topics that may be considered when assessing impact include forestry economics, competing demands for land, and the value of ecosystem services offered by forest land, among others. Impact assessment methods currently are not capable of addressing these issues, nor are methods capable of distinguishing impacts of conventional versus sustainable forestry practices. Had data related to land use and transformation been available for this study, a thorough analysis of these issues would have been outside the scope of the LCA.
- The study omits environmental indicators for ecotoxicity and human health (carcinogens and non-carcinogens) due to a difference in inclusion of these flows within the LCIs used to model polypropylene and containerboard. Specifically, toxicity flows are not included in the polypropylene production inventory data (as provided by the USLCI database), whereas the NCASI containerboard production data detail the toxicity flows. Therefore, the authors do not have confidence that the data for this metric are comparable between systems.
- Social and economic impacts are beyond the scope of this report and therefore excluded. Evaluation of these impacts is necessary to provide a complete assessment of system sustainability.

7. Conclusions

This comparative LCA has assessed the relative performance of CCs and RPCs in transporting and displaying eight types of produce. In both the market-weighted and commodity specific results, neither container system is advantageous across all indicators or commodities. After considering uncertainty, three (3) impact categories show an advantage for RPCs (acidification, respiratory effects, and ozone depletion), and two (2) impact categories show an advantage for CCs (global warming and non-renewable energy use). No difference between the systems can be concluded for eutrophication and smog formation given the level of uncertainty in those results.

That said, the number of categories supporting a container system is not a good measure of environmental superiority (see section 5.1.1 for additional discussion). **The overall finding is that it is not possible to conclude from this assessment that either of these systems has a clear overall environmental advantage in comparison to the other in the baseline US market conditions**

represented here. It is not clear that further refinements in data or methodology would be likely to find a fully consistent directional finding.

Secondary findings reached by a detailed examination of the results and their variation under the scenarios examined are discussed in the remaining paragraphs of this section.

While neither container system shows an environmental advantage in most indicators for most commodities and under varying parameters, it is important to note that it is not possible for the authors to use a count of indicators to conclude that one system definitively performs better from an environmental perspective. Doing so requires the assumption that each category of impact is equally important. Evaluating the relative importance of these categories requires not only an evaluation of the contribution each has in effecting the things we are concerned about (often assumed within an LCA to be protection of human health, ecosystem quality and resource availability), but also the relative importance of these concerns (e.g., what amount of human health should be equivalent to what amount of ecosystem quality).

While it is possible to have views or values that define a position on such matters, it is not possible for the authors to defend these values as more correct than the values that might lead another party to a different decision. It is therefore not possible here to draw an objective, definitive conclusion of environmental superiority in cases where there are conflicting indicators that require a trade-off that is primarily value-based. In such cases, including the current one, the only overall conclusion that can be drawn is that trade-offs exist between the systems. Users of this study can apply weighting schemes to arrive at values-based conclusions.

Exploration of the variability and sensitivity of the results reveals the likelihood that the comparative performance is context dependent. That is, the combination of factors—such as the type of produce transported, the RPC transport distances, and the weight of CCs, among other factors—influence the outcomes. Individually, varying such assumptions within a reasonable range moves the results in the direction of one system or the other but only rarely reverses the directional findings. In most cases, varying these assumptions do not move the directional findings enough that a significant result for one system changes to a significant result for the other.

Consideration of a “best case” and “worst case” for each container system reveals that for certain indicators and commodity systems there is the potential for directional changes in results under certain market conditions. It is therefore concluded that it is unlikely that a clear and definitive advantage exists for either system for all scenarios or conditions.

The environmental trade-offs between container systems can be predicted based on the ratio of the mass of containers required to achieve the functional unit for each container system. The indicators which show an advantage for each container system and the magnitude of difference between the systems for each indicator are directly related to the difference in container masses needed to ship a specified quantity of produce.

The findings reveal potential opportunities for both systems to lessen their impact on the environment. For the CC system, this includes maximizing recovery and minimizing container weight (to the extent this can be done without increasing produce damage). The RPC system can find environmental performance improvement through maximum reuse (increased turns and lower damage/loss rates) and recycled content, along with optimization of logistics (i.e., transport distances).

Although no evidence was identified in conducting this study that a difference in produce damage rates exists between these systems, if such a difference were to exist this could potentially push the advantage in one direction or the other, as even relatively small differences (e.g., a few percent more produce lost) would be sufficient to provide a definitive advantage in most indicators for the system with lesser damage.

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8. Appendices

Appendix A: Model inputs

A1. Reference flow quantities

The main reference flow quantities for container material in the CC and RPC systems are listed in Table A-1 and Table A-2 along with the calculation of these quantities.

Table A-1. Summary of key reference flows for the RPC system.

From	To	Equation*	Calculation example: Apples
RPC production	Use	(B+1/N)X	(0.05+1/24)(110,000 kg RPC) = 10,083 kg RPC
Use	End-of-life	(B+1/N)X	(0.05+1/24)(110,000 kg) = 10,083 kg RPC
Use	Re-Use	[1-(B+1/N)]X	[1-(0.05+1/24)](110,000 kg) = 99,917 kg RPC
Re-Use	Use	[1-(B+1/N)]X	[1-(0.05+1/24)](110,000 kg) = 99,917 kg RPC
End-of-life	RPC production	(1/E)(B+1/N)XR	(1/0.98)(0.05+1/24)(110,000 kg)(0.25) =2,572.3 kg RPC

*B = Break and loss rate, N = Number of uses, X = Mass of containers per FU, E = Efficiency of recycling process, R = Recycled content

Table A-2. Summary of key reference flows for the CC system.

From	To	Equation*	Calculation example: Apples
Materials & production	Conversion	CX	(1.1 kg containerboard / kg CC)*(42,000 kg CC) = 46,200 kg containerboard
Conversion	Use	X	42,000 kg CC
Use	End-of-life	X	42,000 kg OCC
End-of-life	Materials & production	RX	(0.95)*(42,000 kg OCC) = 39,900 kg OCC

* X = Mass of containers per FU, C = Mass of containerboard per mass of CC, R = Recovery rate

A2. RPC production process

The RPC production process is taken from Franklin Associates (2017) and describes production of IFCO RPCs. As IFCO is one of the major RPC manufacturers in North America (and elsewhere), the data is considered to represent a large portion of RPCs currently in use in the U.S.

Table A-3. Life cycle inventory for RPC production (per 1,000 lbs RPCs manufactured) (Franklin Associates 2017).

INPUTS		
Materials	*Quantity*	*Units*
Cleaning solvent	0.025 (0.011)	lb (kg)
Colorant	17.9 (8.12)	lb (kg)
LLDPE stretch film	0.71 (0.32)	lb (kg)
Lubricant	0.047 (0.021)	lb (kg)
Polypropylene resin[1]	984 (446)	lb (kg)
Energy	*Quantity*	*Units*
Electricity (grid)	390 (4,013)	kWh (1,000 BTU)
LPG	0.15 (1.25)	gal (L)
Transportation (of material inputs)[2]	*Quantity*	*Units*
Combination truck	525 (1,863)	ton-mile (tonne-km)
Diesel	5.51 (46)	gal(L)
OUTPUTS		
Materials	*Quantity*	*Units*
RPCs, for use	1,000 (453.6)	lb (kg)
Solid waste, landfilled	2.98 (1.35)	lb (kg)
Solid waste, waste-to-energy	0.75 (0.34)	lb (kg)

[1] As per Franklin Associates (2017), this can be any ratio of virgin and recycled PP.

[2] As per Franklin Associates (2017), this transportation is mainly for delivery of PP resin to the manufacturing facility and is therefore used to model this transport step in the present study, as noted in Table A-7.

A2. RPC cleaning process

The baseline RPC cleaning process is a composite dataset based on information provided in University of Stuttgart (2007) and Franklin Associates (2017). The dataset weights the inputs for detergent, electricity, and water by the portion of the market estimated to be applying the new or older technology. All other inputs are characterized by the values provided in Franklin Associates (2017) and described in Table A-5. As the data provided by Franklin Associates (2017) represents all of IFCO's cleaning facilities, and as IFCO represents approximately 70%[22] of RPCs currently used in the U.S. produce industry, the Franklin Associates (2017) data is weighted at 70%. The University of Stuttgart (2007) data were chosen to represent the remainder of the industry, or 30% of the total composite dataset. Table A-4 presents this (composite) cleaning process. A sensitivity test assesses the effect of implementing the IFCO technology (i.e., Franklin Associates 2017 data) across the entire RPC industry in the U.S.

Table A-4. Calculation of detergent, electricity and water inputs for the life cycle inventory describing RPC cleaning used in the baseline analysis, weighting Franklin Associates (2017) data at 70% and University of Stuttgart (2007) data at 30%.

Item	Franklin Associates (2017)	University of Stuttgart (2007)	Value for composite cleaning process
Detergent (kg/RPC)	3.99E-03	8.88E-04	3.06E-03
Electricity (MJ/RPC)	1.86E-01	0.492	0.278
Water (kg/RPC)	7.21E-02	0.413	0.174

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[22] See section 3.2.2.

Table A-5. Life cycle inventory for RPC cleaning (per 1,000 washed & sanitized RPCs) provided by Franklin Associates (2017).

INPUTS		
Materials	*Quantity*	*Units*
RPCs, used (to be cleaned)	1,024	pieces
Chloro-sanitizer	0.54 (1.2)	kg (lb)
HDPE pallet cap	0.84 (1.86)	kg (lb)
Industrial detergent[1]	3.99 (8.80)	kg (lb)
LLDPE stretch film	9.79 (21.6)	kg (lb)
Water (consumed)[1]	72.1 (19)	L (gal)
Wood pallets	1.32 (2.90)	kg (lb)
Energy	*Quantity*	*Units*
Electricity (grid)[1]	51.7 (532)	kWh (1,000 BTU)
Natural gas	7.98 (282)	m^3 (ft^3)
LPG	1.8 (0.47)	L (gal)
Diesel	0.33 (0.086)	L (gal)
Transportation (of material inputs)[2]	*Quantity*	*Units*
Combination truck	16.3 (10.1)	tonne-km (ton-mi)
Diesel	0.40 (0.11)	L (gal)
OUTPUTS		
Materials	*Quantity*	*Units*
RPCs, cleaned & sanitized	1,000	pieces
Damaged RPCs[3]	24	pieces
LLDPE stretch film	9.79 (21.6)	kg (lb)
HDPE pallet cap	0.84 (1.86)	kg (lb)
Emissions	*Quantity*	*Units*
Chlorine, emission to air	1.6E-03 (3.6E-03)	kg (lb)
COD, emission to water	0.055 (0.12)	kg (lb)
Solid waste, landfilled	0.0031 (0.0069)	kg (lb)
TSS, emission to water	0.021 (0.045)	kg (lb)

[1] Input changed for the baseline analysis.

[2] As per Franklin Associates (2017), this transportation is primarily for materials used during the washing process. RPC transport is modeled with the information provided in Table A-.

[3] As per Franklin Associates (2017), this includes units that are repaired, and returned to service, as well as units scrapped for recycling

A3. Transport models

A full load is assumed for all container transportation from manufacturing to grower, from grower to retailer, and, for the RPC system, from retailer to servicing and then back to the grower. Determination of volume-limited or weight-limited transport (i.e., the truck's mass-based utilization rate) is based on (1) a truck payload capacity of 18,143 kg (40,000 lb), (2) the assumption that a maximum of 24 102-cm by 122-cm (40-in by 48-in) pallets each weighing 23 kg (50 lb) fit on a truck, and (3) a typical number of containers carried on a pallet.

For (full) containers traveling to the retailer, the total payload (i.e., weight of the containers, their produce and the pallets) exceeds the truck capacity for all commodities carried by CCs and RPCs, barring bell peppers and strawberries carried by CCs and RPCs, as well as apples and lettuce carried by RPCs, and are modeled as mass-limited transport. The four exceptions noted are modeled as volume-limited transport.

Computation of utilization rate for trucks hauling empty containers is performed somewhat differently between the two containers. For RPCs, the utilization rate of trucks carrying empty RPCs is performed with the same approach as for full RPCs, although the number of containers per pallet is different (as described in Table A-6), and the produce mass equals zero (0). For CCs, it is assumed that manufacturers send collapsed CCs to growers in consolidated stacks or bales. The utility rate of the trucks is based on a typical CC baling density of 535 kg/m^3 (900 lb/yd^3) (U.S. EPA 1993). The CC baling density is applied to a bale volume of 1.42 m^3 (50 ft^3) per bale (60 in x 30 in x 48 in). It is assumed that each pallet carries one bale.

The following equation is applied to determine the utilization rate of truck transport for CCs and RPCs regardless of commodity, transport step (i.e., to/from grower) or format (i.e., erected or knocked down). The exception is for empty CCs moving from the manufacturer to the grower, the calculation for which is provided directly following this first set of sample computations.

<u>Utilization rate for transport of containers, except for transport of CCs from the manufacturer to the grower.</u>

$$Utilization\ rate = \frac{N_{pa} * [N_c(M_c + M_{pr}) + M_{pa}]}{C_t}$$

Where

$N_{pa} = Number\ of\ pallets\ per\ truck$

$N_c = Number\ of\ containers\ per\ pallet$

$M_c = Mass\ of\ one\ container, kg$

$M_{pr} = Mass\ of\ produce\ per\ container, kg$

$M_{pa} = Mass\ of\ one\ pallet, kg$

$C_t = Mass\ capacity\ of\ truck, kg$

Sample calculations, Apple system:

$$Utilization\ rate, from\ grower\ to\ retailer, CCs$$
$$= \frac{\left(24\frac{pallets}{truck}\right)\left[\left(49\frac{containers}{pallet}\right)\left(0.82\frac{kg}{container} + 18.0\frac{kg}{container}\right) + 23\frac{kg}{pallet}\right]}{18{,}144kg/truck}$$
$$> 100\% \therefore 100\%$$

$$Utilization\ rate, from\ grower\ to\ retailer, RPCs$$
$$= \frac{\left(24\frac{pallets}{truck}\right)\left[\left(50\frac{containers}{pallet}\right)\left(2.27\frac{kg}{container} + 18.18\frac{kg}{container}\right) + 23\frac{kg}{pallet}\right]}{18{,}144kg/truck}$$
$$> 100\% \therefore 100\%$$

Utilization rate for transport of CCs from the manufacturer to the grower

$$Utilization\ rate, from\ manufacturer\ to\ grower, CCs = \frac{N_{pa}N_bV_b\rho_b}{C_t}$$

Where

$N_{pa} = Number\ of\ pallets\ per\ truck$

$N_b = Number\ of\ CC\ bales\ per\ pallet$

$V_b = Volume\ of\ one\ CC\ bale, m^3$

$\rho_b = Density\ of\ one\ CC\ bale, kg/m^3$

$C_t = Mass\ capacity\ of\ truck, kg$

Sample calculation, Apple system:

$$Utilization\ rate, from\ manufacturer\ to\ grower, CCs$$
$$= \frac{\left(24\frac{pallets}{truck}\right)\left(1\frac{bale}{pallet}\right)\left(1.43\frac{m^3}{bale}\right)\left(535\frac{kg}{m^3}\right)}{18{,}144kg/truck} > 100\% \therefore 100\%$$

Table A-6 summarizes key characteristics of truck transport in the CC and RPC systems. The ratio of container (plus produce) weight to maximum truck payload is shown as the utilization rate. In cases where the ratio exceeds 100%, it is shown as 100% utilization.

Table A-6. Pallet loads and truck utilization rates for container transport in the CC and RPC systems.

Container type	Produce type	Pallet load		Truck utilization rate (mass basis)	
		Number of containers when erected	*Number of bales/ containers when collapsed/knocked-down*	*Full containers*	*Empty containers*
CC	Apples	49	1 bale per pallet	100%	100%
CC	Carrots	60	1 bale per pallet	100%	100%
CC	Grapes	108	1 bale per pallet	100%	100%
CC	Head Lettuce	40	1 bale per pallet	100%	100%
CC	Onions	48	1 bale per pallet	100%	100%
CC	Oranges	63	1 bale per pallet	100%	100%
CC	Strawberries	108	1 bale per pallet	63%	100%
CC	Tomatoes	80	1 bale per pallet	100%	100%
RPC	Apples	50	165	100%	53%
RPC	Carrots	60	165	100%	41%
RPC	Grapes	75	165	100%	37%
RPC	Head Lettuce	35	105	100%	36%
RPC	Onions	40	105	100%	30%
RPC	Oranges	40	105	100%	35%
RPC	Strawberries	110	195	81%	36%
RPC	Tomatoes	105	165	100%	37%

Table A-7. Transport distances used in the baseline analysis for the CC system.

	Wood logs to pulp and paper mills[1] (km)		Wood chips to pulp and paper mills[1] (km)		Recovered fiber to pulp and paper mills[1] (km)			Chemicals[1] (km)				Purchased hogged fuel, other biomass[1] (km)	All other fuels[1] (km)
Commodity	*Truck*	*Train*	*Truck*	*Train*	*Truck*	*Train*	*Boat, barge*	*Truck*	*Train*	*Boat, barge*	*Boat, ocean*	*Truck*	*All*
Apples	159	1,580	299	1,670	241	505	822	217	1,300	674	2,990	145	See U.S. LCI database (NREL 2012)
Carrots	159	1,580	299	1,670	241	505	822	217	1,300	674	2,990	145	
Grapes	159	1,580	299	1,670	241	505	822	217	1,300	674	2,990	145	
Lettuce	159	1,580	299	1,670	241	505	822	217	1,300	674	2,990	145	
Onions	159	1,580	299	1,670	241	505	822	217	1,300	674	2,990	145	
Oranges	159	1,580	299	1,670	241	505	822	217	1,300	674	2,990	145	
Strawberries	159	1,580	299	1,670	241	505	822	217	1,300	674	2,990	145	
Tomatoes	159	1,580	299	1,670	241	505	822	217	1,300	674	2,990	145	

	Containerboard to converting[1] (km)		Corrugated sheets[1] (km)		Manufacturers to growers[1] (km)		Growers to retailers[2] (km)	Retailers to end-of-life[1] (km)		
Commodity	*Truck*	*Train*	*Truck*	*Train*	*Truck*	*Train*	*Truck*	*Truck*	*Train*	*Boat, barge*
Apples	262	1,510	283	2,450	283	2,446	2,498	241	505	2,256
Carrots	262	1,510	283	2,450	283	2,446	2,806	241	505	2,256
Grapes	262	1,510	283	2,450	283	2,446	2,827	241	505	2,256
Lettuce	262	1,510	283	2,450	283	2,446	2,721	241	505	2,256
Onions	262	1,510	283	2,450	283	2,446	2,599	241	505	2,256
Oranges	262	1,510	283	2,450	283	2,446	2,827	241	505	2,256
Strawberries	262	1,510	283	2,450	238	1,849	2,827	241	505	2,256
Tomatoes	262	1,510	283	2,450	238	1,849	2,827	241	505	2,256

[1] Sourced from NCASI (2017); Original source is USDOT and USDOC 2010.

[2] Calculated based on USDA 2017 and U.S. Census Bureau 2012.

Table A-8. Transport distances used in the minimum and maximum transport sensitivity analyses for the CC system.

	Growers to retailers[1] (km)	
Commodity	*Minimum*	*Maximum*
Apples	1,420	3,408
Carrots	589	4,435
Grapes	349	4,689
Lettuce	479	4,439
Onions	874	4,190
Oranges	349	4,689
Strawberries	349	4,689
Tomatoes	349	4,689

[1]Calculated based on USDA 2017 and U.S. Census Bureau 2012.

Table A-9. Transport distances used in the baseline analysis for the RPC system.

	PP resin to RPC production (tkm per 1 kg RPC)		RPC production to growers[1] (km)		Growers to (distributors and) retailer (km)		Collection (Retailer/Retailer & Distributor) to Washing center (km)		Washing Center to Growers (km)		Retailer to end-of-life (km)			
Commodity	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Train*	*Boat, barge*	*Source*
Apples	1.863	Franklin Associates (2017)	1,115	Franklin Associates (2017)	2,498	(multiple)[2]	2,472	(estimate)[3]	1,121	(estimate)[3]	241	505	2,256	USDOT and USDOC 2010
Carrots	1.863	Franklin Associates (2017)	1,115	Franklin Associates (2017)	2,806	(multiple)[2]	2,562	(estimate)[3]	505	(estimate)[3]	241	505	2,256	USDOT and USDOC 2010
Grapes	1.863	Franklin Associates (2017)	1,115	Franklin Associates (2017)	2,827	(multiple)[2]	2,554	(estimate)[3]	187	(estimate)[3]	241	505	2,256	USDOT and USDOC 2010
Lettuce	1.863	Franklin Associates (2017)	1,115	Franklin Associates (2017)	2,721	(multiple)[2]	2,554	(estimate)[3]	513	(estimate)[3]	241	505	2,256	USDOT and USDOC 2010
Onions	1.863	Franklin Associates (2017)	1,115	Franklin Associates (2017)	2,599	(multiple)[2]	2,001	(estimate)[3]	544	(estimate)[3]	241	505	2,256	USDOT and USDOC 2010
Oranges	1.863	Franklin Associates (2017)	1,115	Franklin Associates (2017)	2,827	(multiple)[2]	2,554	(estimate)[3]	468	(estimate)[3]	241	505	2,256	USDOT and USDOC 2010
Strawberries	1.863	Franklin Associates (2017)	1,115	Franklin Associates (2017)	2,827	(multiple)[2]	2,554	(estimate)[3]	468	(estimate)[3]	241	505	2,256	USDOT and USDOC 2010
Tomatoes	1.863	Franklin Associates (2017)	1,115	Franklin Associates (2017)	2,827	(multiple)[2]	2,554	(estimate)[3]	468	(estimate)[3]	241	505	2,256	USDOT and USDOC 2010

[1] Plastics and rubber manufacturing data used as a proxy.

[2] Calculated based on USDA 2017 and U.S. Census Bureau 2012.

[3] Estimated based on Franklin Associates (2017) and consultation with RPC industry experts.

Table A-10. Transport distances used in the minimum distance sensitivity analysis for the RPC system.

	PP resin to RPC production[1] (km)		RPC production to growers[1] (km)		Growers to retailers (km)		Collection (Retailer/Retailer & Distributor) to washing center (km)		Washing Center to Growers (km)		Retailer to end-of-life [3] (km)			
Commodity	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Train*	*Boat, barge*	*Source*
Apples	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	1,420	(multiple)[2]	1,345	(estimate)[4]	405	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Carrots	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	589	(multiple)[2]	972	(estimate)[4]	274	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Grapes	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	349	(multiple)[2]	1,036	(estimate)[4]	37	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Lettuce	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	479	(multiple)[2]	1,036	(estimate)[4]	350	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Onions	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	874	(multiple)[2]	1,473	(estimate)[4]	484	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Oranges	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	349	(multiple)[2]	1,036	(estimate)[4]	37	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Strawberries	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	349	(multiple)[2]	1,036	(estimate)[4]	37	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Tomatoes	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	349	(multiple)[2]	1,036	(estimate)[4]	37	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010

[1] Plastics and rubber manufacturing data used as a proxy.

[2] Calculated based on USDA 2017 and U.S. Census Bureau 2012.

[3] Waste and scrap data used as a proxy.

[4] Estimated based on consultation with industry experts.

Table A-11. Transport distances used in the maximum distance sensitivity analysis for the RPC system.

	PP resin to RPC production[1] (km)		RPC production to growers[1] (km)		Growers to retailers (km)		Collection (Retailer/Retailer & Distributor) to washing center (km)		Washing Center to growers (km)		Retailer to end-of-life [3] (km)			
Commodity	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Source*	*Truck*	*Train*	*Boat, barge*	*Source*
Apples	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	3,408	(multiple)[2]	3,766	(estimate)[4]	1,833	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Carrots	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	4,435	(multiple)[2]	4,244	(estimate)[4]	2,526	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Grapes	1.863	Franklin Associates (2017)	1,093	USDOT and USDOC 2010	4,689	(multiple)[2]	4,174	(estimate)[4]	1,244	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Lettuce	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	4,439	(multiple)[2]	4,174	(estimate)[4]	2,253	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Onions	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	4,190	(multiple)[2]	3,518	(estimate)[4]	2,568	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Oranges	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	4,689	(multiple)[2]	4,174	(estimate)[4]	2,526	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Strawberries	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	4,689	(multiple)[2]	4,174	(estimate)[4]	2,526	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010
Tomatoes	1.863	Franklin Associates (2017)	1,115	USDOT and USDOC 2010	4,689	(multiple)[2]	4,174	(estimate)[4]	2,526	(estimate)[4]	241	505	2,256	USDOT and USDOC 2010

[1] Plastics and rubber manufacturing data used as a proxy.

[2] Calculated based on USDA 2017 and U.S. Census Bureau 2012.

[3] Waste and scrap data used as a proxy.

[4] Estimated based on consultation with industry experts.

Appendix B: Model approach and assumptions

B1. RPC float

Float refers to the quantity of excess RPCs that exist in the total system. These excess RPCs are required to assure the flexibility to respond to surges in system demand or extended time in the return loop. Float can be considered as a type of infrastructure that needs to be constructed to enable the system to function. It can be thought of as what is needed to "prime" the system, similar to how a pipe system is primed. Take, for example, a toilet. The bowl contains the water that is used to carry out the system's function, while the tank contains the water that facilitates the function. When the toilet is first installed, both the bowl and the tank must be filled. The tank then replenishes the bowl over time. The bowl is analogous to the in-use RPCs, while the tank represents the float. The float must be produced only once, and new RPCs enter and leave the system as containers are worn out, broken or lost. Over time, as more containers are put through the system, the significance of providing that initial excess capacity or "float" diminishes with regard to the total impact of all containers that have been put through the system. Figure B-1 illustrates the flow of mass through the RPC industry over time.

As indicated by publications describing the container industry as well as other industries where float is required (e.g., the refillable bottle industry), float is indeed a non-negligible percentage of all containers within the system at any given time (Saphire 1994, Pira and ECOLAS 2004). However, it is important to remember that because float is produced only one time (at the onset of the industry in order to allow it to function), it is not the ratio of float to current in-use containers but the ratio of float to the entire container inventory over the lifetime of the RPC industry that must be considered. Assuming that the industry will exist many years, the mass of RPCs needed to create the float becomes negligible in comparison to the total mass of all containers ever manufactured.

Because the size of float within the industry is not well documented and because the number of RPCs ever to be manufactured is unknowable, it is not possible either add the float component into the system or to conduct a scenario around its inclusion based on good information. In the present study, it is assumed that the float required for the RPC system is less than one percent (1%) of all RPCs and therefore can be excluded. However, because the float is so poorly understood, it is important to explore a less conservative scenario to assess whether the float could have an important effect on the outcomes of this study.

Consider a hypothetical scenario in which for every RPC in use, one is in float. (This assumption is likely a worst-case approach, but no resources could be identified by the authors with which any assumption can be made.) This means that to fulfill the functional unit, two RPCs must be made for each RPC needed. The impact of this could be calculated by doubling the impacts at the RPC production stage.

Looking at the market weighted average, global warming would increase from 171% of the CC impact to 206%. Indicators where the raw materials phase is highly important are most influenced. For example, ozone depletion jumps from 87% of the CC impact to 149%. Thus, float can be a material contributor to impact in cases where the size of the float is significant. It is important to recognize that float is an aspect whose inclusion can only result in the impact of the RPC system being higher.

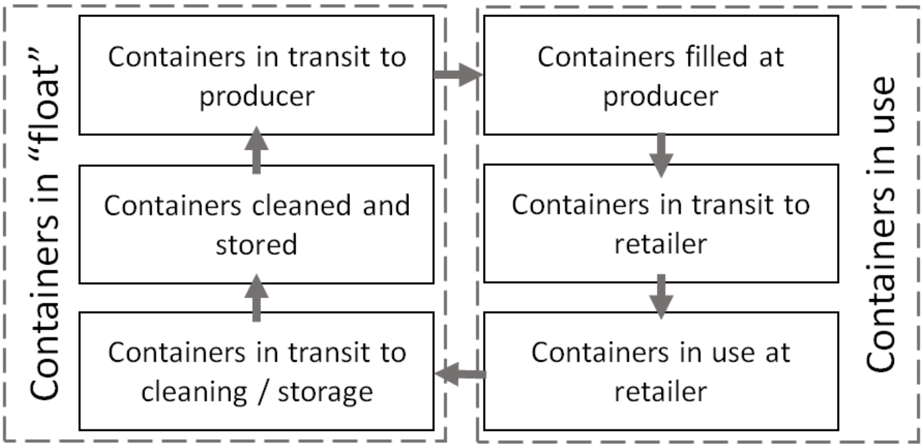

Figure B-1. Illustration of the movement of RPCs in use and in float over time.

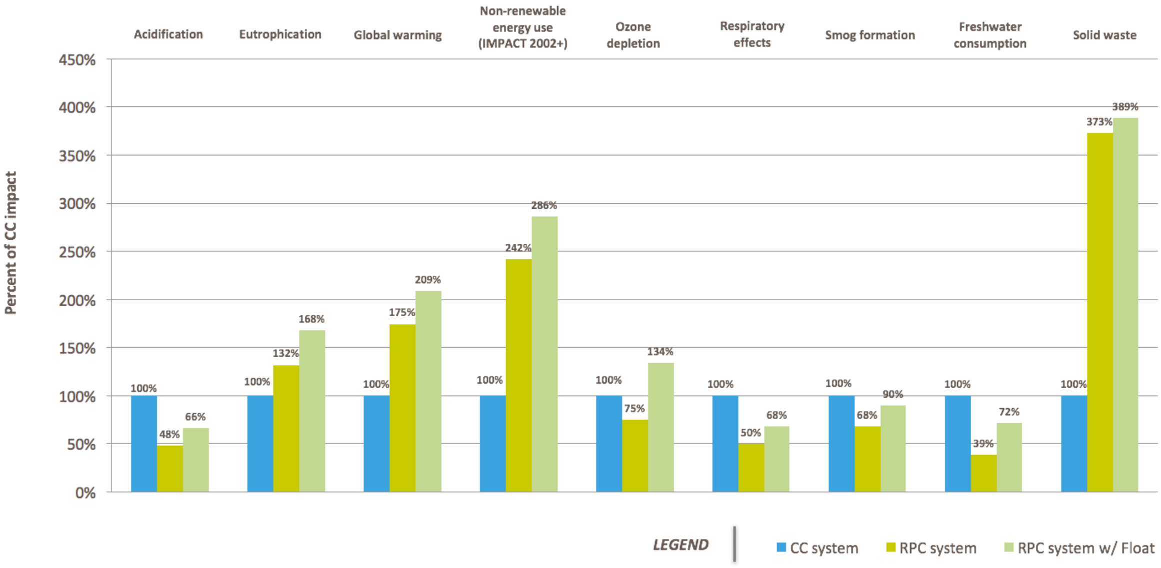

Figure B-2. Market-weighted average results for the baseline analysis including RPC Float

B2. Recycled material

This appendix provides further explanation and insight into the treatment of recycled materials in this study. As discussed in section 2.5.3, the main principle applied is a closed loop approach which is mathematically equivalent to the number of uses approach. One exception exists in the case of recovered OCC that are exported to other markets. This flow is modeled using a cut-off approach as it is not within the scope of the current study to assess the fate of the CCs once they leave the U.S. market.

Had these CCs been included in the model, the number of uses approach would be been employed in the baseline analysis. The concept of this approach is to evaluate the number of uses or lives (i.e., number of separate product systems) a material is likely to undergo before meeting a final disposal (e.g., landfill or incineration) and to distribute the material production impacts across these. A key assumption in applying the number of uses approach is identifying the number of uses of the material under evaluation. This can be done in different ways.

In the case of paper products such as CCs, methods for making such an evaluation have been presented in several places. Originally, in 1996, The International Working Group issued "Life Cycle Inventory Analysis. User's Guide," a TAPPI publication. In that publication, the "number of uses" formula was first described. Later, ISO/TR 14049 (ISO 2012a, 2^{nd} edition), and a specific treatment for containerboard by Galeano et al. (2011) reflected similar approaches. The latter of these references emphasizes the relevance of this approach for systems, such as paper, where desired physical properties of the material are retained in the recycling process.

The approach for calculating the number of uses may vary depending on the amount of data available on recycling rates and knowledge about how these materials flow in the economy. Examples on how to calculate the number of uses under different data availability circumstances is presented in ISO 14049, as are examples for handling the allocation (sharing) between the original and the subsequent uses In addition to estimating the number of uses from industry data on recycling rates, the referenced User's Guide and the ISO 14049 illustrates estimates of number of uses based on laboratory testing of materials indicating the limits in the number of times recycling can take place before essential material structure is altered in the successive recycling process. Allocation of the burdens among virgin (original) product and subsequent uses is described.

In the case of the plastics used for RPCs, no adequate industry average exists of the same reliability as in CC and neither is there laboratory or pilot experimental work. Therefore, a theoretical model alone is used to derive the number of lives (product systems) for the material, as explained below.

Figure B-3 presents a depiction of a material undergoing multiple product lives prior to its eventual disposal. If the material is used for N number of products, 1/Nth of the raw material and waste responsibilities would be attributable to each product life.

The number of lives that a material will undergo before its final disposal is determined by the rate of recovery of that material from each of the product systems it enters. If the same percent of material is recovered (C) from one product life and used in the next life over the lifetime of the material, the number of uses can be calculated as:

$$\text{Number of lives} = N = 1 / (1-C)$$

An alternate method for determining the allocation of material production across multiple lives is the “closed loop” representation, which is depicted in Figure B-4 and discussed further in ISO 14049 and Bauman and Tilman (2004), among other places. This is the approach taken in the present study for the RPC system and for the CCs that are not exported to other markets. In applying this approach, the amount of material recovered is represented as being re-used in the same product system, actually or virtually replacing the virgin production of that material. In this case, C in Figure B- represents the amount recovered and sent to recycling (also termed C in the above discussion of calculation of the number of lives).

We can see that if the collection rate is the same between all lives of the material, these two representations of the recycling system produce the same result. In the case of the number of lives calculation, the allocation of virgin material impact is equal to 1/N, which is shown in the equation above to be equal to (1-C). In the case of the closed loop recycling, the virgin material impact is equal to the flow of A in Figure B-4, which is also (1-C). Therefore, the results shown here could also be considered to be the results obtained through application of a closed loop recycling allocation method.

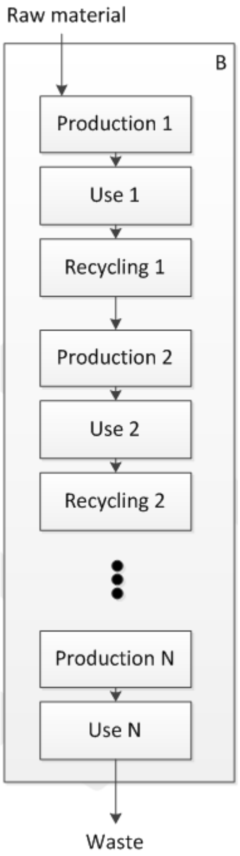

Figure B-3. Representation of a material undergoing several product lives prior to its disposal.

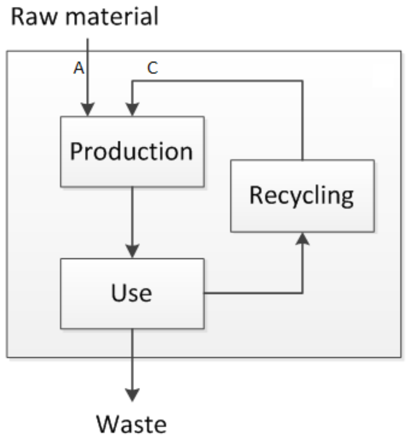

Figure B-4. Generic closed-loop product system diagram with recycling.

B3. Carbon balance

Figure B-5 depicts the flow of biogenic carbon through the CC system. Although these flows are ignored in impact assessment, except for carbon sequestered beyond 100 years, the balance is presented for transparency. The net total (inputs minus outputs) is not zero due to rounding errors. Additional details on carbon flows, including greater resolution in Materials & production, can be found in NCASI 2017.

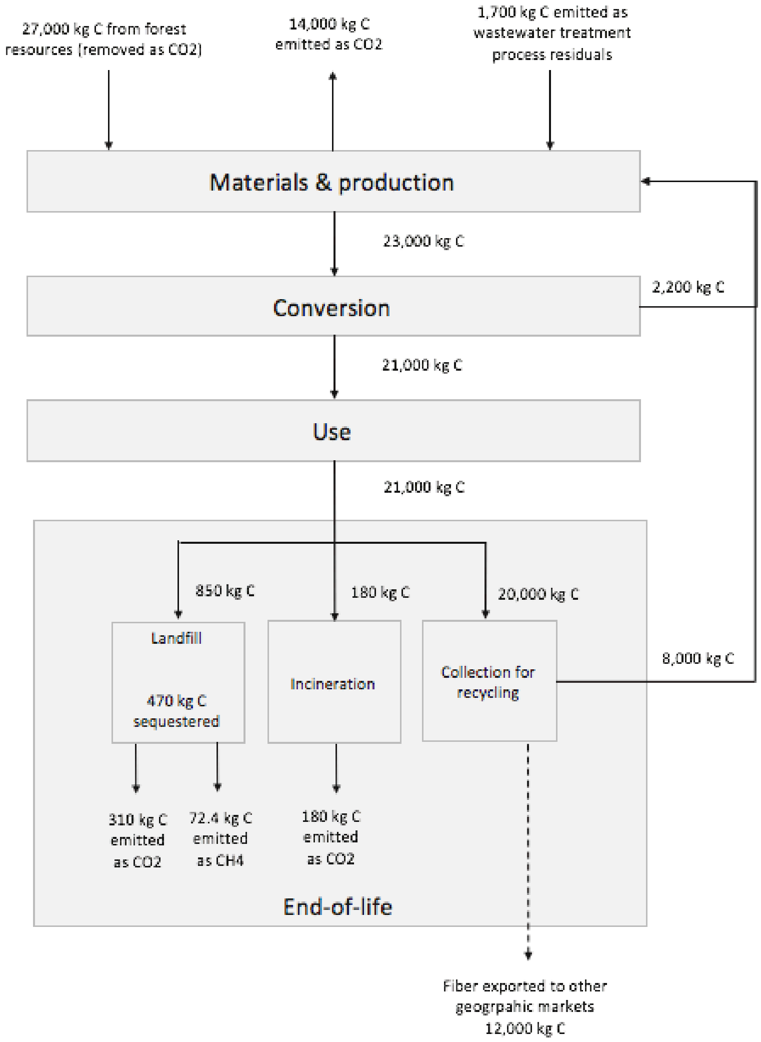

Figure B-5. Biogenic carbon balance for the CC system including only major flows of carbon.

Appendix C: Full results

Please refer to associated Excel file.

Appendix D: Data quality assessment

The data quality ratings in the pedigree matrix are defined in Table D-1. This approach to rating data quality and the content of Table D-1 has been taken from the guidance for the Ecoinvent database. (Frischknecht and Jungbluth 2007).

Table D-1. Description of scores for data quality assessment using the pedigree matrix.

	Score				
Data quality metric	1	2	3	4	5 (default)
Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimates (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<50%) relevant for the market considered OR >50% of the sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
Temporal correlation	Less than 3 yrs of difference to the time period of the dataset	Less than 6 yrs of difference to the time period of the dataset	Less than 10 yrs of difference to the time period of the dataset	Less than 15 yrs of difference to the time period of the dataset	Age of data unknown OR more than 15 yrs difference to the time period of the dataset
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown OR distinctly different area (e.g. Europe instead of North-America)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (e.g. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale OR from different technology

Appendix E: Comparison to previous studies

While it is not a goal of this study to conduct a literature review of comparable LCAs or to fully understand the potential reasons for similarities and differences between studies, it is worth considering findings from prior relevant work in order to understand the spectrum of conclusions drawn on the topic of the comparative environmental performance of CCs and RPCs. The following two paragraphs offer a very high level summary of some relevant literature in this space. Sections E1 and E2 provide a deeper dive into each study with a focus on Franklin

Associates (2017) as the study has a scope particularly similar to the present study.

This study differs from previous life cycle studies comparing RPCs and CCs in several key ways. Specifically, it focuses on the North American market and incorporates an internationally recognized impact assessment method (TRACI 2.1) together with an equally recognized alternate (ReCiPe 2016). Levi et al. (2011), the University of Stuttgart (2007) and Rizo (2005) focus on the Italian, Spanish and European markets, respectively. Three studies of the North American market, Franklin Associates (2004), Franklin Associates (2013), and Franklin Associates (2017) are useful references regarding the appropriate geographical context but are limited in scope. The 2004 study by Franklin Associates includes only the inventory stage of analysis and is therefore not a valid basis for comparisons. Franklin Associates (2017) is the most appropriate study which to compare the results found in the present LCA.

Except in the cases of Franklin Associates (2017) and the University of Stuttgart (2007), the consistent conclusion of each of these prior studies is that there are trade-offs between the container types. Franklin Associates (2017) and the University of Stuttgart (2007) show a very different result, concluding that in every metric evaluated, RPCs are environmental advantageous or no significant difference exists between CCs and RPCs. They are the only such studies that consequently do not find the existence of trade-offs between the systems.

E1. Comparison with Franklin Associates (2017)

The study offered by Franklin Associates (2017) is most similar to the present study with regard to context and approach. Additionally, the present study employs much of the data describing the RPC life cycle provided by Franklin Associates (2017), as cited throughout this report. It is thus the most comparable study to-date and can be compared at a more granular level than for other studies. Table E-1 summarizes the differences between the present study and the Franklin Associates (2017) study in terms of model inputs and offers some insight regarding how these disparities affect the conclusions reached by each study. Additional explanation is provided in the subsections that follow. It is recognized that a deeper comparison of the studies could be performed. This exercise is beyond the scope of the current analysis.

Table E-1. Summary of differences in data and assumptions between the Franklin Associates (2017) study and present study and the implications of these differences on study results.

Data/ Assumption	Franklin Associates 2017's approach	Present study's approach	Implications of difference
Inventory data: foreground processes	**CC system**: Based on 2010 industry operations **RPC system**: Based on data provided by IFCO	**CC system**: Based on 2014 industry operations **RPC system**: Same as Franklin Associates (2017)	As per NCASI (2017), containerboard industry operations were stable from 2010-2014, with the exception of significant reductions in respiratory effects and water use. Franklin Associate (2017) overestimates CC system impacts for these indicators.
Inventory data: background processes	Primarily the USLCI 2012 Database; Some data from Ecoinvent v2.2 for materials production, adjusted to align with the (less complete) USLCI Database	Primarily Ecoinvent v3.3; Some data from the USLCI 2012 Database for materials production, using Ecoinvent for upstream processes; thinkstep (GaBi 8) dataset for container transport by truck.	The impacts for both container systems are likely underestimated by Franklin Associates. The USLCI Database is not as comprehensive as Ecoinvent; See section E1.2 for an example.
CC recycled content (kg recycled fiber per kg containerboard)	38.4%	38.4%	No difference
RPC cleaning process	Based on technology used by IFCO facilities	Same as Franklin Associates (2017), except for amounts of electricity, detergent and water used. Present study uses composite values for these inputs based 70% on the Franklin Associates (2017) process and 30% on a less efficient process.	The present study will show a higher impact for the cleaning process if the background databases are the same. Since the composite process is based primarily on the Franklin Associates (2017) process, the difference is relatively small.
Interpretation approach	Concludes based on the market-weighted average. Arbitrarily assigns a flat amount (%) of difference required to conclude a significant difference exists between results of the two container systems; Does not consider statistical uncertainty or uncertainty of individual indicators.	Concludes based on all results for individual commodities. Considers statistical uncertainty and indicator uncertainty when drawing conclusions.	The Franklin Associates (2017) study loses some resolution and insight by concluding based on an aggregated level of results. The present study applies a more objective approach to interpreting results.

E1.1 Approach

Franklin Associates (2017) and the present study both compare RPCs to CCs used to transport and display produce[23], considering all life cycle stages: raw material production, use, re-use (for RPCs), and end-of-life. Franklin Associate (2017) considers delivery to Canada as well as the U.S., while the present study is limited to the U.S.

Both studies apply closed-loop modeling. Franklin Associates (2017) represents the system as an entirely closed loop, while the present study applies a closed loop only to the portion of recovered fiber that stays on the U.S. market. The present study cuts off the exported fiber once it is recovered from the US market.

With regard to modeling the end-of-life of materials, both studies apply a type of system expansion approach. Franklin Associates (2017) uses the *avoided burden* method, providing credits for producing recycled material and capturing energy during incineration. The present study employs the *number of uses* method for the closed loop portion of the system, also applying credits for recycling and waste-to-energy, and cuts off the exported fiber once it is recovered. Franklin Associates (2017) implements a second method, the *cut-off* method, as a sensitivity analysis, finding no difference in study conclusions. The present LCA does not conduct a sensitivity analysis regarding end-of-life modeling since, under closed-loop conditions, the number of lives method (plus credits) and avoided burden method should yield approximately equivalent results. This is true for the closed-loop portion of a system. It is not possible to test the cut-off approach regarding the exported fiber as the fate of that material is outside the scope of this study (see section 2.5 for further explanation).

Biogenic carbon is treated nearly the same in the two studies, both studies using the flows approach (see section 3.1.2). However, Franklin Associates (2017) treats the flow of biotic carbon dioxide as net zero. The present study also ignores biogenic carbon, except for long-term (>100 years) sequestration of carbon in a landfill. Both studies count the impact of other biotic carbon sources [i.e., methane that is a product of fiber (CC) degradation].

E1.2 Life cycle inventory data

The data used by the present study differs in important ways from that used by Franklin Associates (2017). The foreground processes for RPC production (e.g., RPC manufacturing and cleaning) are the same between the two studies. For the CC system, the foreground processes (e.g., containerboard production and converting) are modeled by Franklin Associates (2017) with containerboard industry data representing 2010 operations (NCASI 2014), which was the most recent data available at the time of that study. The present study implements the update to that report, characterizing industry operations in 2014 (NCASI 2017). Comparison of the inventories by NCASI (2017) indicates that all indicators show no difference or an improvement

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[23] Franklin Associate (2013) also evaluates non-display-ready (NDR) CCs, the results of which are not considered here.

in the environmental impacts from 2010 to 2014.

For upstream and background processes, such as electricity production, Franklin Associates (2013) uses the USLCI (NREL 2012) database to provide data on emissions and resource extraction. Although the USLCI database is geographically relevant for this study, it is known to be less complete than other available and geographically adaptable databases, such as Ecoinvent. Within the USLCI (and the aforementioned study's inventory), there are several "dummy" processes which act as placeholders, but contain no emissions or resource extraction data. Unless updated in a way not described in the project report, the inventories in Franklin Associates (2013) are therefore incomplete. The present study uses Ecoinvent, which the authors believe to be the most complete and transparent LCI database available, for background and upstream data. The two studies use similar or the same data for foreground processes.

For a few processes where the USLCI does not provide data, Franklin Associates (2017) uses Ecoinvent data. To maintain consistency with the rest of the USLCI data, which excludes certain emissions, Franklin Associates (2017) removes those specific emissions/elementary flows from Ecoinvent's inventory. For example, Halon 1301 and Halon 1211 were removed from Ecoinvent's crude oil production inventory. A contribution analysis is presented in Figure E-1 to better understand the importance of these emissions to the study results.

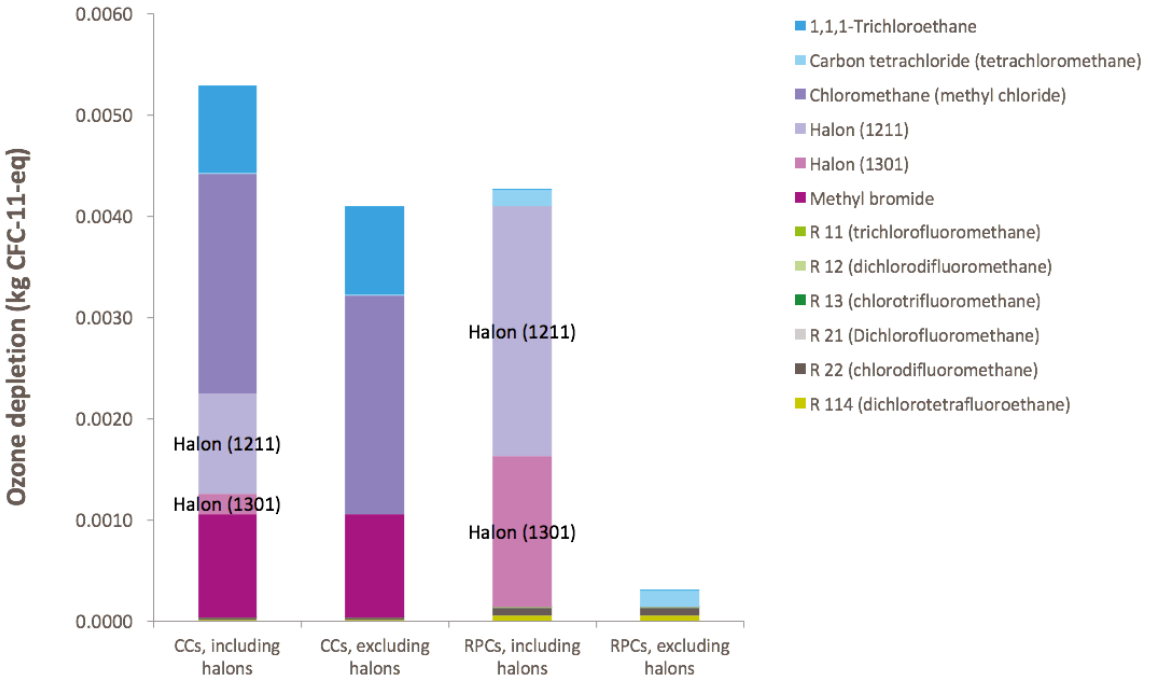

Figure E-1. Contribution analysis for CC and RPC ozone depletion results for the apple system, including and excluding halons.

As depicted in Figure E-1, the contribution analysis demonstrates that Halon 1211 and Halon 1301 are important contributors to ozone depletion. Franklin Associates (2017) removes these emissions not because they are inaccurate but to maintain consistency with the USLCI dataset, which is clearly incomplete compared to those within Ecoinvent. No sensitivity analysis was performed by Franklin Associates (2017) to assess the influence of these decisions. While the present study finds that omitting emissions does not have the potential to alter the directional outcomes of the results for the apple system, this is at least part of the reason the absolute results of the Franklin Associates (2017) study are notably lower than of those found by the present study for each container system.

E1.3 Impact assessment and conclusions

Franklin Associates (2017) aggregates the results across all commodities (by weighting the results for each commodity by its market share) and concludes that RPCs are overall the most environmentally responsible choice for produce display and transport in the North American context. This is based on the evaluation of five impact categories, plus three inventory items: acidification, eutrophication, global warming, ozone depletion, photochemical oxidation, plus cumulative energy demand, solid waste and water consumption. RPCs are found to be environmentally preferable for all metrics. A second impact assessment method is not applied to validate conclusions.

The present study analyzes the same five impact categories, as well as energy demand[24], freshwater consumption and solid waste. It also applies a second impact assessment method (ReCiPe 2016) to confirm study conclusions. The present study offers the results by commodity, drawing conclusions in light of the variation across the different types of produce. It also provides a market-weighted average of commodities.

Comparing these results to those of the prior study, some key differences are observed. Most notably, the present study finds that neither container system is advantageous across all impact categories; The present study finds that each container system has some impact categories in which it is advantageous (when uncertainty is considered). The present study also demonstrates that, for a given commodity, the directional results depend on several variables,

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[24] The energy metric used in the present study is an impact category (not an inventory item) and measures the energy content of the resources consumed. See section 4 for additional information.

including functional unit mass ratio, RPC transport distances and CC weight. Unlike Franklin Associates (2017), the present study concludes that because different containers have an advantage in different indicators, and because the advantage can change under different parameter values, there are trade-offs in types of environmental impacts between systems.

Table E-2. Comparison of results with those of Franklin Associates (2017). Values are shown as a percent (%) of the present study's results.

	CC		RPC		Impact assessment method	
Indicator	*Present study*	*Franklin Associates (2017)*	*Present study*	*Franklin Associates (2017)*	*Present study*	*Franklin Associates (2017)*
Acidification	100%	97%	100%	69%	TRACI 2.1	TRACI 2.1
Energy demand (MJ)	100%	0.3%	100%	0.04%	IMPACT2002+	(custom)*
Eutrophication (kg N-eq)	100%	116%	100%	13%	TRACI 2.1	TRACI 2.1
Global warming (kg CO2-eq)	100%	98%	100%	39%	TRACI 2.1 updated with IPCC (2013) GWPs	IPCC (2013)
Ozone depletion (kg CFC-11-eq)	100%	19%	100%	5%	TRACI 2.1	TRACI 2.1
Smog formation (kg O_3-eq)	100%	129%	100%	110%	TRACI 2.1	TRACI 2.1
Solid waste (kg)	100%	630%	100%	24%	n/a	n/a
Water consumption (m^3 H_2O)	100%	0.03%	100%	0.02%	n/a	n/a

*Franklin Associates (2017) applies a method developed by Franklin Associates that computes cumulative energy demand, including both fossil and non-fossil sources.

E2. Comparison with other studies

Some reflection on the outcomes of the present study in comparison with those from other studies can also be made.

Franklin Associates (2013) focuses on the North American market and includes the same commodity scenarios as reported here. Franklin Associates (2017) is an update of the Franklin Associates (2013) report and states that revision to both RPC and CC container weights and capacities, along with transport distances were made. The recycled content of the CC container was also updated to reflect more recent data. Franklin Associates (2013) concludes that RPCs are environmentally advantageous for 6 out of the 8 indicators, with an insignificant difference reported in the remaining 2 indicators, whereas Franklin Associates (2017) concludes that RPCs are preferable for all 8 indicators evaluated.

The study by Levi et al. (2011) includes six impact categories: global warming, ozone depletion, photochemical oxidation, acidification, eutrophication and non-renewable energy use and is tailored to the Italian market. The impact assessment method is not described. CCs are found by Levi et al. (2011) to be preferable in global warming, ozone depletion and photochemical oxidation categories. Levi et al. (2011) also finds RPCs to be preferable in the acidification category and the two containers comparable in eutrophication and non-renewable energy categories. Results of the present study agree with these conclusions for global warming and acidification. Also similar to this report, Levi et al. (2011) find that the mass of the container is critical for both systems and the raw materials phase is important for CCs. It also concludes that the cleaning process is important for RPCs, which is not consistent with the outcomes of the present study.

A study on tomato transport from Spain to Germany conducted by Rizo (2005) analyzed ten (10) environmental indicators as provided by Eco-indicator 99, which is the precursor to ReCiPe. Similar to the present study, Rizo (2005) found that trade-offs exist between the containers even when the RPC was used between 20 and 100 times, although the authors conclude that CCs are overall preferable because they are advantageous in a greater number of environmental metrics. The study also finds that once the RPC use rate is reduced to five (5) cycles, the CC becomes advantageous in every indicator. Conclusions did not change whether the RPC is constructed of high-density polyethylene (HDPE) or polypropylene (PP). Both Rizo (2005) and the present study demonstrate that the raw materials production stage of the CC life cycle is a major contributor to impact. Rizo (2005) concludes the same for the RPC system, while the present study shows that raw materials production is less important for the RPC system than use and/or reuse for five of seven (5/7) indicators.

A report by the University of Stuttgart (2007) is also focused on the European market and uses CML2001 impact indicators, but notably excludes human toxicity and ecotoxicity indicators. The report finds that CCs perform worse than RPCs in all impact categories; it is the only study that finds RPC advantageous in all the impact indicators considered and, similar to Franklin Associates (2017), does not find the existence of trade-offs between the systems. The study reports that twenty percent (20%) of the CC is recycled and eighty (80%) is incinerated, and the authors find that increasing the recycling rate shows very significant reductions in impact. It is possible that this choice, which is not representative of the North American system studied here, causes the overall poor scores of the CC system. In the present study, a default recovery rate of 95% is assumed, and a portion of the non-recycled CCs are landfilled. Both the University of Stuttgart (2007) and the present study find the raw materials production stage to be important for CCs. Similar to Levi et al (2011), the study concludes that the cleaning phase is important for the RPCs. The cleaning process applied by the University of Stuttgart (2007) is a notably less efficient process than the one applied in the present study (see section A2. RPC cleaning process), which is perhaps the reason for the different conclusions between these two studies. Similar to Rizo (2005), the University of Stuttgart (2007) also identifies raw materials production as an important contributor to the life cycle impact of RPCs, whereas the present study concludes that the reuse and/or use stages are more contributing for most indicators.

These studies, considered together, indicate that environmental trade-offs indeed exist between the RPC and CC systems, and the market geography has an influence on these trade-offs. Given the proximity of results between the two systems in certain impact categories, geographic-specific modeling choices and a full set of environmental indicators are warranted to provide a comprehensive and accurate comparison of RPCs and CCs within a given market.

Appendix F: Critical review report and comment log