CATRA 2021 Scrap Tire Life Cycle Assessment

LCA Study

Final Version - Reviewed

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Table of Contents

1 Background

Scrap tires represent one of the largest post-consumer waste streams in developed economies (OECD, 2006). In Canada, nearly half a million tonnes of tires reach end of life every year, corresponding to around 40 million tires, or roughly one tire per capita. Because of the large magnitude of the scrap tire flow, the challenges posed by scrap tires in landfills, the potential for fire danger from tire stockpiles, and the wide range of potentially valuable products and industrial materials that can be made from tires, this material is an exceptionally good candidate for mandatory product stewardship and/or producer responsibility programs.

Tires were among the first major products to be targeted by extended producer responsibility programs in Canada (Sheehan & Spiegelman, 2017) and at present, every province has a program in place. Under the most common structure, new tires are assessed an environmental handling fee at the time of purchase, which is then used to provide incentive payments to collectors and processors that handle tires at the end of life. Programs of this nature are centrally administered by a product stewardship organization that is responsible for managing the fees and tracking program performance.

Among Canadian provinces, Ontario is exceptional in having what is known as an individual producer responsibility (IPR) program. Instead of being centrally managed, the program is designed to be competitive, in which privately-run producer responsibility organizations compete for a share of the scrap tire management market.

As a result of widespread stewardship, there is a robust industry for scrap tire recycling in Canada, producing a wide range of products including crumb rubber and molded rubber goods, blasting mats, landscaping mulch, athletic fields, playground surfaces, rubber aggregates for civil engineering applications, and industrial fuels, as well as scrap steel and synthetic fibers. Tires can also be retreaded or remanufactured by removing worn treads and replacing them with new tread stock.

Because of the wide range of potential uses for scrap tires, it can be valuable to assess the relative merits of the different processing routes from an ecological perspective. Life cycle assessment (LCA) is a scientific framework for computing quantitative metrics of sustainability for industrial activities. Here, we report the results of an LCA study of scrap tire collection and recycling in Canada.

1.1 About Scope 3

Scope 3 Consulting specializes in transparent and responsive sustainability assessment tools and case studies. We provide consulting services to clients who need to understand the environmental impacts of their actions and decisions. Our goal is to provide actionable sustainability intelligence.

1.2 About Life Cycle Assessment

Life cycle assessment (LCA) is an analytic approach to estimate the potential environmental impacts of a product or service. LCA must take into account both the direct impacts of the product and the upstream / downstream impacts associated with producing, distributing, and disposing of it. Performing an LCA requires developing a model of the different processes or stages the product goes through during its life cycle, and then estimating the environmental implications of each stage.

This model includes a foreground, which describes the system that has been directly modeled, and a background, which includes the industrial ecosystem that provides electricity, fuels, and other materials. Both the foreground and background may use proxy data to describe systems whose actual properties are not known.

The quantitative result of an LCA is a set of numerical impact scores that describe the total potential impacts in terms of an equivalency factor that helps interpret the significance of the impact. For instance, global warming potential of many different gases is expressed in terms of an equivalent amount of carbon dioxide.

1.3 Participants

- Study Commissioner: Canadian Association of Tire Recycling Agencies (CATRA), on behalf of its members
- Study Practitioner: Scope 3 Consulting LLC; Brandon Kuczenski and Kyle Meisterling, directors
- Participating member organizations:
    - Tire Stewardship British Columbia
    - Alberta Recycling Management Authority
    - Tire Stewardship Saskatchewan
    - Tire Stewardship Manitoba
    - eTracks, Ontario
    - Recyc-Quebec
    - Multi-materials Stewardship Board, Newfoundland and Labrador
- Target Audience: This LCA Study report is intended for all provincial staff and boards of directors, CATRA staff and board, and the Critical Review. The report may also form the basis for comparative assertions made to third parties (e.g. regulators, the public, associated industry associations).

2 Goal and Scope

2.1 Goal of the Study

The goal of this study is to evaluate the environmental performance of scrap tire management in Canada, and participating provinces thereof. These study results are meant to provide information to CATRA member organizations, their boards of directors, and program participants The study will also be used in communication with third parties. The study has been conducted according to the requirements of ISO 14044 and established best practices in LCA.

- Intended Application: The intended application is to inform the target audience about the environmental significance of program activities, and to describe the relative impacts and benefits of alternative fates of scrap tires. The ultimate motivation is to provide advice and support for policy decisions by CATRA and its member organizations.

- Comparative Assertions: The report includes comparative assertions regarding:
  - The relative significance of impacts from recycling activities compared with the respective impacts of avoided activities (displaced production)
  - The relative impacts of different displaced material systems (wood chips, mined aggregate; molded rubber; etc.) in comparison to one another. This is valuable to the study participants in order to determine the highest or best uses of scrap tires.

ISO 14044 requires that LCA results be critically reviewed before they are used to support comparative assertions disclosed to the general public or to third parties. The present report was critically reviewed (see Section 2.2.10). The critical review report is attached as Appendix F.

2.2 Scope of the Study

The focus of the study is the impacts incurred from activities related to **the management of scrap tires generated in Canada**. We have prepared a *gate-to-gate* study, meaning that material flows cross the system boundary as both inputs and outputs. At the input end, scrap tires enter the system *burden-free*. This means that the impacts associated with resource extraction, manufacturing, distribution, and use *of the tires*, are all assigned to the tire life-cycle, and none of them are assigned to the recycled products. This is also known as the *cut-off* approach because the life cycle is cut-off at the point of recycling.

At the output end of the recycling system, the products of scrap tire management exit the system when they are marketed. The study reports impacts incurred within the system boundary, and compares these impacts to the potentially-avoided impacts of displaced production.

The scope is constrained by geographic, temporal and material factors. Geographically, the scope includes scrap tires generated in participating provinces, which include British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, and Newfoundland and Labrador. Due to differences in Ontario's regulatory system for scrap tires, the inclusion of Ontario is incomplete (See Section 3.2).

The time period for the study includes the years 2017-2020. Saskatchewan joined the study after the initial phase was completed, and the study period for that province begins January 1, 2018. For Alberta, Quebec, and Newfoundland and Labrador, the study period begins April 1, 2017; for the other provinces the study period begins January 1, 2017. These differences are due to the different fiscal years of the member organizations. For all provinces except Ontario the study period ends on December 31, 2020; for Ontario, 2019 was the most recent year for which data were available at the time of reporting.

The material scope of the system is also constrained by the regulatory systems established by the member organizations. Our study *includes* scrap tires whose disposal is governed by scrap tire management programs participating in the study (known as "program tires"), and *excludes* tires that are not governed by those same programs ("non-program tires"). Per-province differences are discussed in Section 3.1.

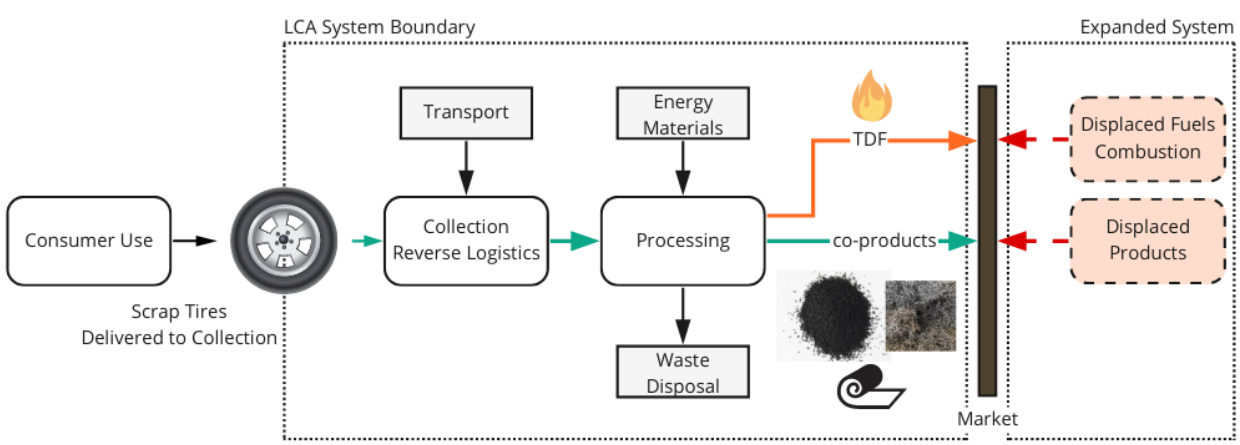

Figure 1 - Basic system boundary diagram. The LCA system boundary includes activities related to scrap tire management, while the expanded system boundary includes activities displaced by the products of scrap tire management.

2.2.1 Function of the System

The primary function of the system under consideration is to provide responsible management of scrap tires generated within participating provinces during the study period. This function can be broadly described as having two main elements: disposal of wastes; and production of raw materials, products, and/or fuels that can be delivered to market.

Only management measures that are sanctioned by program operators are included in the study. Neither stockpiling of tires nor discarding tires into the environment is considered. However, in all jurisdictions considered in the report, neither stockpiling nor direct discard are thought to occur in significant amounts because of the existence of effective stewardship programs. Eliminating stockpiling and improper disposal of scrap tires are primary objectives of all CATRA member organizations.

2.2.2 Functional Units

Our study considers the two different functional elements separately. The primary function concerns the management of the scrap tire waste flow. The functional unit for this function includes “management of all scrap tires included within the geographic scope over a specified period of time.” The reference flows for this study can be selected for any time interval during the study period. In the present report, the results for the calendar year 2019 are used as the reference flow.

A second function, production of tire-derived products, is used to evaluate the relative merits of different processing routes. In this case, the exact functional unit being evaluated depends on the end-product. In order to achieve a consistent comparison, the reference flow for each processing route is one tonne of tires processed to an end product, and each functional unit is selected according to the products that can be generated from one tonne of tires. The functional unit is defined for each processing route in Section 3.5.

2.2.3 System Boundary

Scrap tires enter the Recycling system when they are received by a registered scrap tire collector. The basic system boundary is illustrated in Figure 1. The study boundary includes two distinct systems, the Recycling system, and the Displacement (Expanded) system. The system boundary includes scrap tire transport from point of receipt to a processing facility. Transportation of tires to a collection facility, both by consumers and by informal haulers who are not registered with stewardship organizations, is not included.

In this study, scrap tires arrive at end of life “burden free” (see Section 2.2 above). The Recycling system includes processing of the tires into products or raw materials, the manufacturing of products from scrap tire derived material, as well as disposal of unmarketed recycling byproducts. Tire-derived products then enter the market with the assumption that they are displacing other products or fuels.

Transport of the recycled product from the manufacturing facility to point-of-use is included for most recycling routes, as shown in Table 3.18. Where transport is omitted, it is because both the tire-derived product and the displaced product are assumed to have the same mass and transportation distance, and thus they cancel each other out. Use-phase impacts are excluded; however, differing service lifetimes between tire-derived products and displaced products are accounted for by assuming a displacement rate that accounts for the amount of displaced product required to equal the longevity of the tire-derived product.

Because scrap tires are not sent to landfill in significant quantities in any jurisdiction in the study, no avoided burdens from landfill are assigned to any system. Tire-derived waste disposed of to landfill is included in the study; however, disposal of tire-derived products at the end of their lives is excluded from the scope.

Impacts that result from direct dissipation of tire-derived materials into the environment (including deposit of tire-derived aggregate, dissipation of crumb rubber, mulch, road particles, tire wear particles, etc.) are beyond the scope of our expertise and are excluded from the study. Maintenance, repair, office/shop supplies, and manufacture and decommissioning of capital equipment, are also excluded from the scope of the study.

2.2.4 Co-products and Displacement

In order to avoid allocating the burdens of scrap tire management between the two main functions of the system (waste management and production of marketable products), we accounted for the effects of supplying tire-derived products using *consequential system expansion*. This means that we expand the scope of the study to include the production of products judged to compete with tire-derived products in the marketplace, and we calculate "avoided burdens" that result from the displacement of those competing production activities. Avoided burdens (or credits) have negative impact scores and are always reported separately from incurred burdens.

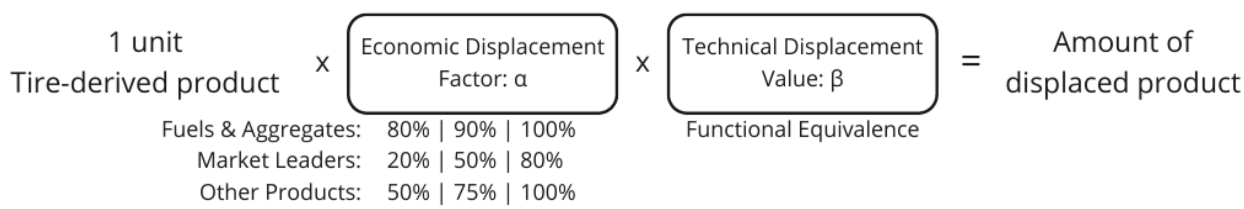

Figure 2 - Modeling displacement relationships.

In general, we assume that tire-derived products and services provide the same function as the non-tire-derived products and services. However, this does not mean that a tonne of tire-derived product necessarily displaces an equivalent mass of the competing product. Displacement of primary production is more likely when demand for a particular product is inelastic- meaning that the increased supply of a commodity will not necessarily lead to increased consumption. In these cases, a consumer who purchases a product made from recycled tires is likely to do so *instead* of purchasing a non-tire-derived product, thus leading to displacement of primary production.

For each displacement relationship, the overall displacement rate is calculated as the product of an *economic displacement factor*, known as α, with a *technical displacement value*, known as β (Figure 2). The economic factor represents the likelihood that the competing product will be avoided *because of* the production of the tire-derived product. Meanwhile, the technical value represents the functional equivalency of the two products, and is determined from physical properties. As an example, the use of tire-derived aggregate (TDA) is highly likely to displace gravel, because the number of projects requiring aggregate is not dependent on the quantity of TDA available (high likelihood of economic displacement). However, because TDA is less dense than gravel, a given mass of TDA displaces a larger mass of gravel (technical displacement = 1.7 tonnes gravel per tonne of TDA).

Because of fundamental uncertainty in the displacement relationship, we apply sensitivity cases to the economic displacement rate according to the type of product being displaced (Figure 2). For fuels and aggregate, we assume there is a high likelihood of displacement, so we consider the range of 80-100% economic displacement, with 90% as the median (reported) case. On the other hand, some tire-derived products (namely, crumb rubber infill and tire-derived blasting mats) are "market leaders," meaning the tire-derived product is the default choice in the market. These products are less likely to cause displacement of alternative products, so we assign an economic displacement rate of 20-80%, with 50% as the median. For all other products, we assume a range of 50-100% displacement, with 75% median as the reported amount.

Table 2.1 - Displacement relations considered in the model

Tire-derived product	**Displaced product**
Shred, tire-derived	Aggregate, gravel, displaced
Mulch, tire-derived	Wood Chips, displaced
Mulch, tire-derived	Sand, displaced
Blast Mat, Tire derived	Blast Mat, steel cord, displaced
Crumb rubber, tire-derived	Acrylic coated sand, displaced
Crumb rubber, tire-derived	Primary rubber, polybutadiene
Crumb rubber, in asphalt	Roadway mix and service lifetime
Molded Product	Concrete product, displaced
Molded Product	Primary rubber, in product, displaced

Surface replacement, tire derived	Wood Chips, displaced
Surface replacement, tire derived	Sand, displaced
Sidewalls, Tubes, other	Silage weight, displaced
Processing waste	Heat, coal, in cement kiln, displaced
steel scrap, tire-derived	Steel, displaced
steel scrap, tire-derived, in cement kiln	Iron ore, in cement kiln, displaced
Heat from combustion, tire-derived fuel	Heat, natural gas, in cement kiln, displaced
Heat from combustion, tire-derived fuel	Heat, coal, in cement kiln, displaced
Scrap tires, to reuse	New tire, displaced
Retreaded tire	New tire, displaced
Devulcanized rubber, tire-derived	Primary rubber, polybutadiene
Pyrolysis fuel	Fuel oil, displaced
Pyrolysis char	Carbon Black, displaced
Heat from combustion, tire-derived fuel	Heat, fuel oil, displaced

Table 2.1 shows a list of the products and/or services that are provided using scrap tires and are considered in this study. The table also shows (non-tire-derived) products and services that compete in the market with products of the tire recycling system, and thus could be displaced by tire-derived products. The displacement factors used in the study are shown in Table 3.18 and each system's functional unit and other details is discussed in Section 3.5.

2.2.5 Co-product Transport

Transportation of the tire-derived product to the point of use is included within the system boundary. Table 3.18 shows transport distances modeled for most displacement routes. In cases where transportation is omitted, this is because both the tire-derived products and displaced products are assumed to have identical mass and transport distance, and so this transport is omitted. Transportation modeling for each displacement route is discussed in Section 3.5.

2.2.6 Types and Sources of Inventory Data

Material Flows
The mass flows of tire-derived material into and out of the recycling systems were reported directly by each participating province. These reports form the underlying empirical basis for the study.

Primary data were also collected from processors (and provincial organizations) about material flow inputs and outputs from recycling facilities. This data provides the basis for recycling product yields and waste flows to disposal for most of the unit processes in the Recycling system. For unit processes for which no primary data were collected, we estimated process inventories and product mass flows using literature values and mass and energy balance constraints.

Life Cycle Inventory Foreground
The inventories for processing and recycling activities were primarily based on primary data collected from scrap tire processors in Canada. Using a confidential survey, processors were asked about material flows (inputs, product outputs, and waste outputs), fuel and electricity use, and about ancillary material use, including water, lubricants, and other supplies. The data collected from recycling and processing facilities have been validated using published inventories of similar processes (see Section 3.4).

Background Systems: Data and Models
Our project makes principal use of the ecoinvent database, version 3.7.1 (2020), cut-off system model, and supplements that with selected data sets from the US Federal LCA Commons and the World Steel Association. The ecoinvent database includes process models for most high-volume products and materials in the global economy and is primarily drawn from industry and government research reports, as well as academic literature. It is updated routinely, but many datasets remain unaltered since their version 2.2 release in 2006.

USLCI (2021) is a minimal LCI database originally developed under contract for the US EPA, which now includes a database on refining and plastics production prepared by the American Chemistry Council (2010). Our study uses the USLCI for diesel and LP gas combustion in equipment and light truck transport, and the associated fuel supply, which were judged to be more representative than the available ecoinvent datasets. A USLCI process for polybutadiene rubber (PBR) is also considered.

A listing of background data sets used is provided in Appendix B.

Steel Recycling: World Steel Association
The treatment of steel scrap was modeled using the World Steel Association's most recent reference data (2021). Their methodology includes a survey-derived model of global steel production, allocated amongst different uses. They also publish a “value of scrap” activity which is a reverse allocation (an induced burden) on the steelmaking process based on their measurement of global scrap consumption. Generating scrap input to this process produces an avoided burden (WorldSteel 2017), which we use to represent the environmental benefit of scrap steel. A WorldSteel model was also used to model the displaced production of new wire steel for blast mats.

Environmentally Extended Input-output Model
Due to a lack of suitable quality life cycle inventory data for new tire production, we elected to use an environmentally-extended input output LCA model to represent the impacts of new tire production. This figure is relevant in comparison to the modeled impacts of reuse (culls) and remanufacturing. We utilize version 2.0.1 of the (USEEIO, 2021) database for this purpose. The USEEIO database can be regarded as having a cradle-to-gate system boundary design (Yang et al., 2017), making it appropriate to the task of modeling displaced new tire production and compatible with the cut-off methodology. EEIO models have an inherently broader scope than process-based LCA models, so the impact results from this category may be overstated in comparison to ecoinvent. Both databases have comparable sets of elementary flows (see Section 4.4)

2.2.7 Allocation

We apply the “cut-off” system modeling methodology throughout our inventory model. In the cut-off approach, the flows of scrap materials are assigned zero burdens (the products’ prior life cycles are “cut off” at the point that they are made available for recycling). The inventory requirements and impacts of multi-output processes exclusive of scrap flows are allocated to the various products according to quantitative parameters of a physical or economic nature. This is consistent with the methodology of both the cut-off system model of ecoinvent 3.7.1 and the USLCI database.

In the foreground for this study, the principal process being modeled is scrap tire processing. We described all production activities in terms of a single operation: acceptance of scrap tires or tire-derived scrap as an input. Although several of these processes have multiple outputs (e.g. steel, crumb, and fiber), the outputs remain within the study boundary and no allocation of the foreground activity is required. The output material flows are followed until they reach final disposal or displacement. The only exception is the tire sidewalls route, which reflects only a part of the tire. This route is treated using mass-based allocation, with the remainder of the tire assumed treated as TDA.

2.2.8 LCIA Methodology and Types of Impacts

We use the TRACI 2.1 impact characterization method, produced by the US EPA (Bare, 2012), as the most suitable methodology for conditions in North America. The TRACI methodology includes 10 indicators: climate change, acidification, smog formation, particulates, ozone depletion, two measures of eutrophication (air and water emissions), and three toxicity indicators (human cancer and non-cancer, and freshwater ecotoxicity). We report the non-toxicity indicators primarily, and we also review and discuss the toxicity impacts in Section 4.4.2. We utilize the reference implementation of TRACI, published in 2012. There is also an implementation distributed with USEEIO 1.1, but its flow list is less complete. As a benchmark, we compare our scores with the results from ReCiPe 2016 Midpoint, Hierarchical.

The elementary flows in the study were checked against USEEIO, ecoinvent, and WorldSteel and found to have relatively good comparability, omitting the resource use categories. This review is discussed in detail in Section 4.4.

We report the following midpoint impact category indicators from TRACI 2.1:

- Global Warming (kg CO2 eq)
- Photochemical Smog Formation (kg O3 equivalent)
- Particulate Matter Formation (kg PM2.5 equivalent)
- Acidification of Air (moles H+ equivalent)
- Ozone Depletion (kg CFC-11 equivalent),
- Eutrophication (kg N equivalent)

A brief summary of the impact categories reported is found in Section 4.1.

Toxicity impacts are difficult to assess accurately using LCIA indicator scores. Single emissions, such as specific metals or compounds, can dominate category results by 90% or more. We perform a screening review of a range of toxicity indicators and identify these dominating emissions as signals identifying activities of potential concern. We report the results in Section 4.4.2.

Due to limitations in project budget and timeline, The TRACI 2.1 Fossil Resource Depletion indicator was not assessed nor reviewed for this project. This indicator, or a related resource depletion indicator, may be assessed in a future revision.

2.2.9 Data Quality, Assumptions, and Limitations

In general, numerical results of LCA studies are unverifiable. There is no way to directly measure the life cycle emissions associated with a particular industrial activity. The use of standard background databases to represent industrial processes includes an implicit assumption that the operation of these processes is approximately consistent around the world and does not vary widely with the passage of time. Many of the most important contributors to environmental impacts, including fuel production and combustion, electricity generation, and transportation, are well-understood and well-represented in reference databases. However, specific situations invariably differ from generic cases. LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

Primary data, study core:

- Because of the incentive systems in place for scrap tire management, the records of scrap tire collection and processing used as the basis for the study, including total amounts of tires collected and products produced, can be regarded as very high quality.

- Transportation distances during reverse logistics were estimated from actual information about the origin, destinations, and modes of transport wherever possible. Logistics data are considered to be high quality.
- Transport requirements for getting scrap tires from collection points to recycling locations are modeled specifically for each participating province (not shown) The transport requirements in the national model (shown in this report) are derived from the aggregated flows.
- The processing activities in the model are described based on survey information provided confidentially to Scope 3 Consulting by scrap tire processors operating throughout Canada. The resulting models are judged to be highly representative and of high quality.
- The mix of tire-derived products sent to market, including the use of crumb rubber in molded products versus other crumb applications, and the use of molded products are estimated according to available publications, as well as records of international trade between Canada, the US, and the rest of the world (Section 3.2.4). Market data used to support the disposition of waste flows is discussed in Section 3.2.6.

Proxy data, model foreground:

- No direct information on emissions resulting from combustion of tires in industrial furnaces was available. We adapted combustion datasets for comparable fuels found in the ecoinvent database (see Section 3.5.15). These models were adjusted to account for the biogenic carbon content found in typical tires (see Table 3.1).
- Impacts for sidewall-cutting are modeled as ½ of shred as a place-holder process.
- Transportation vehicle emissions were modeled using EURO-6 emission standards as implemented by ecoinvent, and in some cases representing US conditions in USLCI. The background models were judged to be comparable to emissions standards in Canada. No Canada-specific modeling of vehicle or equipment emissions was performed.
- Scrap tire facility infrastructure was described using a simple automobile shredding facility model found in ecoinvent as a proxy.
- For pyrolysis:
    - Heat content of pyrolysis oil and pyrolysis gas were adjusted (downward) to achieve energy balance (within 1%)
    - Carbon content of pyrolysis liquid was calculated by difference (to achieve Carbon mass balance
- Limited inventory data for rubber production were available in the background data. The only two data sources were extruded EPDM rubber (ambiguous provenance, found in ecoinvent), unspecified polybutadiene (a PlasticsEurope eco-profile from 2005, via ecoinvent) and non-vulcanized polybutadiene (found in USLCI). We utilize the ecoinvent process. In particular, no inventory data for natural rubber or for any styrene-based rubber compounds were available.

Background data:

- In all cases, the use of proxy data from life cycle inventory databases is subject to the constraints and limitations of the background data source.
- ecoinvent 3.7.1 is the primary source for inventory data. Although ecoinvent is widely regarded as state-of-the-art for commercial LCI databases, it contains substantial data gaps and inaccuracies.
  - Its data are primarily derived from European facilities, and the ecoinvent Association uses analytic methods to adapt these datasets to use in other geographic scopes.
  - Many data sets have not been updated since version 2.2 of ecoinvent was released in 2008 or even earlier.

- USLCI is a much sparser data set than ecoinvent. However, its central refinery model is one of its strengths, and the fuel supply chain was considered to be more suitable than the alternatives available in ecoinvent. Though the database contains notably fewer elementary flows overall, the 2021 release has been harmonized with the reference elementary flow list that was used for LCIA. For the systems studied, the representation of impact-generating flows is largely comparable, although ecoinvent does include more toxic substances, particularly pesticides.
- For electricity use, province-specific data were selected from ecoinvent.

Displacement:

- The nominal assumption in this study is that tire-derived products compete effectively with non-tire-derived products in the marketplace, and that the two systems being compared can be made functionally equivalent.
- If the displacement assumption is weakened, the magnitude of the negative-valued scores in the results will be attenuated, while the magnitude of the positive-valued scores will not be affected. Thus the potential “net benefit” of scrap tire recycling could be reduced or eliminated.
- Comparisons between the impact indicator scores of recycling systems and their corresponding displacement systems should be made with an understanding of the importance of scale: If a large fraction of tire rubber is to displace virgin rubber production, then the recycled rubber will likely have to be used in tires, since tires dominate the global market for rubber.

Life cycle impact assessment:

- TRACI 2.1 uses a US-based geographical context to compute average characterization values, which are then applied universally to all flows in the study.No regionally-differentiated impacts are discerned.
- In our Human and Ecotoxicity screening, we do not consider near-field toxicity or direct exposure to rubber, in occupational and consumer settings.

- Human health and Ecotoxicity due to plastic leakage (including microplastic as rubber dust) are not yet accounted for in LCA. Although research in this topic is ongoing, addressing this is outside the scope of the current study.

Cutoff criteria:

- We did not employ an arbitrary cut-off criterion. All known flows are included in the construction of inventories and the calculation of impact scores.

2.2.10 Critical Review

This study underwent critical panel review in accordance with ISO 14044 and ISO 14071. The panel was chaired by Jean-François Ménard, a senior analyst at CIRAIG- École Polytechnique de Montréal and an expert in life cycle assessment. The panel also included two subject matter experts, Glenn Maidment, former President of the Tire and Rubber Association of Canada (TRAC), and William Heung, formerly a senior waste management engineer specializing in tires at the California Department of Resource Recycling and Recovery (CalRecycle).

The first version of the report was delivered to the study commissioner in the Spring of 2020. This report was reviewed for methodology by Mr. Ménard, but the results were not reviewed.

The present report is the outcome of the second phase of the study. The initial revision (known as version 2.0) was delivered to the panel for review on October 14, 2021, and the panel's comments were received November 11, 2021. The next revision (version 2.1) was prepared and delivered with the practitioners' responses on March 15, 2022. A second round of comments followed, and the final revision (2.2) was completed on June 30, 2022. This version was accepted by the panel. The critical review report is attached to this document as Appendix F. Detailed review comments and practitioner responses are available from CATRA and from Scope 3 Consulting.

3 Life Cycle Inventory Modeling

3.1 The Scrap Tire Material Flow

3.1.1 Types of Tires

The scrap tires considered in the present LCA study are primarily Passenger and Light truck tires (PLT), Medium Truck tires, as with tractor-trailer trucks and trailers (MT) with a smaller amount of Off the Road tires, as with construction, agricultural, and mining equipment (OTR). Very large OTR tires are sometimes referred to as “OTR II” tires.

All provinces include essentially all PLT and MT tires in the program. Because different provinces have different regulations, the inclusion or exclusion of OTR tires is not consistent throughout the study region. The province-specific treatment of OTR tires is as follows:

- BC: includes agricultural tires, forklift, logger and skid steer tires of all sizes
- AB: includes all tires having a diameter of 99 cm and smaller
- SK: includes all OTR tires
- MB: includes all OTR tires
- ON: includes all tires
- QC: excludes all OTR tires aside from forklift tires
- NL: excludes all OTR tires

We did not attempt to estimate the magnitude of OTR tires reaching end-of-life outside the scope of the provincial programs.

3.1.2 Tire Characterization

Tires are composed of a wide variety of specialized products, but most tires are made up of rubber, steel, polymer-derived fiber materials, fillers such as carbon black, and additives to enhance performance. The rubber in tires consists of a mix of natural and synthetic rubbers depending on the application: PLT tires are predominantly synthetic rubber, whereas larger-dimension tires include a higher proportion of natural rubber because it has better durability and mechanical performance. Table 3.1 shows typical characteristics of different types of tires seen in the study.

Table 3.1 - Typical Tire Composition (Feraldi et al., 2013; Pehlken & Essadiqi, 2006; US TMA, 2019).

Property	unit	PLT	MT	OTR	OTRII
Typical New Weight	kg	10.2	52.0	100-250kg	>500 kg
Typical Scrap Weight	kg	9.1	45.4		
Synthetic Rubber	% of scrap tire mass	21%	10%	0%	0%
Natural Rubber		17%	30%	40%	40%
Steel		20%	31%	20%	20%
Fiber		7%	0%	5%	5%
Carbon black		20%	18%	21%	21%
Mineral fillers		4%	3%	4%	4%
Chemicals[1]		12%	9%	10%	10%
Energy content[2]	MJ (LHV) / kg tire	24.17	20.46	23.71	23.71

1 Chemicals includes oil and wax, curing systems, antioxidants, and antiozonants

2 Values in literature range from 23-28 MJ (LHV) / kg scrap tire

3.2 Material Flow Analysis

The study design is based on a comprehensive material flow analysis (MFA) of scrap tire collection and processing within each provincial program. Records of collection, transport, processing, and tire-derived products were obtained and used to construct a database of material transfers. These transfers were then aggregated over different time periods and used to drive an LCA model composed of a collection of processing and disposition routes, terminating in displaced production activities.

3.2.1 Collections by Province

Table 3.2 shows the total mass of tires reported collected by each province for each year. “Phase 1” represents the 12-month fiscal year for each program that includes December 31, 2017. For AB, QC, NL this is April 1- March 30; for the other included provinces it is the 2017 calendar year. Note the significant omission of Ontario data for 2020 causes total freight requirements to be reduced.

Table 3.2 - Total scrap tire collections per year by province (tonnes).

	Phase 1	2018	2019	2020
Ontario	141,738	163,503	145,924	NA
Alberta	64,459	66,432	69,283	69,655
Quebec	92,504	94,485	102,976	93,980
BC	49,650	51,419	52,622	51,738
Manitoba	19,186	18,838	17,662	18,638
Newfoundland	5,996	6,255	6,366	6,382
Saskatchewan	NA	18,014	20,608	22,346
Total (t)	373,533	418,946	415,441	262,739

3.2.2 Transportation Modeling

Freight transport in life cycle assessment is modeled using the composite unit of mass*distance, e.g. the tonne*kilometer. A truck carrying a load of 15 t a distance of 100 km will provide a 1,500 t*km of freight services.

- Truck transportation. The model includes transport activity for trucks of various net weight capacities including 1.5 t (light truck), 5 t (small truck), 8 t, 13 t, and 20 t (53' Trailer). All trucks are modeled as diesel-fueled. The mix of truck sizes used in each provincial model is dependent on hauling data for that province. All transport processes are scaled up by a factor of 1.3 to account for the lower utilization rate afforded by bulky scrap tires. The scale-up represents the difference between the estimated utilization rate of 65% and the nominal rate of 85% taken from the data sources. Data sources: (ecoinvent [v3.7.1], 2020; US LCI, 2021)
- Transport, light truck, diesel. Data source: US LCI, 2021.
- Transport, train, diesel. Data source: (ecoinvent [v3.7.1], 2020)
- Ocean freight transportation, diesel-fueled, is used for open ocean transport. Data source: (ecoinvent [v3.7.1], 2020)
- Barge transportation, diesel-fueled, is used for transport on inland waterways. Data source: (ecoinvent [v3.7.1], 2020)

Barge transport is used in British Columbia between Vancouver Island and the mainland. Ocean freight is used principally to transport tires from Newfoundland to Quebec. No train transport is included for scrap tires; however, train transport is used to represent displaced transport of coal fuel.

The logistics requirements of scrap tire collection was determined from the material flow analysis. For most provinces, material flow data were provided at the level of individual truckloads. These shipments were assigned to transport modes based on size, since the size of the actual truck was almost never systematically available. For Ontario, no freight records were available. Tires in Ontario were assumed to have the same freight requirements as tires in neighboring Quebec. Total freight requirements are shown in Table 3.3. The average shipment distance can be determined by dividing total freight requirements by total collections. The resulting value ranged from 260-290 km and is also shown in Table 3.3.

Table 3.3 - Reverse logistics by freight mode (million tonne*km)

	Phase 1	2018	2019	2020†
Transport truck_20t	56.891	69.734	63.201	45.533
Transport truck_13t	19.147	16.893	14.809	10.019
Transport ocean_freight	10.265	10.024	12.673	2.078
Transport truck_5t	10.988	11.353	11.826	11.660
Transport truck_8t	4.311	4.172	4.709	4.474
Transport light_truck_1.5t	0.657	0.711	0.835	0.811
Transport barge	0.357	0.469	0.411	0.482
Total	102.616	113.356	108.463	75.057
Average Distance (km)	271	269	261	285

† - 2020 excludes Ontario processing.

3.2.3 Products Reported by Provincial Organizations

Tables 3.4a and 3.4b show the total quantity of tire-derived products reported by provincial organizations and/or processors for each year of the study period, as well as changes to tire stockpiles under management by provincial organizations. These tables includes directly-reported products only, and therefore do not accurately reflect the ultimate fate of tire-derived crumb, which is not directly reported anywhere. Differences between product outflows and collections are reported as a net addition (positive) or withdrawal (negative) from stock on-hand at processors.

Table 3.4a reports totals for all provinces in the study except Ontario, and Table 3.4b reports results for Ontario. The results were split in this fashion because of inconsistencies and irregularities observed in the Ontario statistics. In particular, in 2017-2018 the quantities of recovered steel scrap and tire-derived waste are both very high in comparison to the other provinces, both of which contribute to a very large mass balance discrepancy. Also, due to changes in administration between 2018 and 2019, Ontario stopped reporting waste altogether, and also stopped reporting the fate of tire-derived crumb. Finally, as mentioned, 2020 data for Ontario were not available.

Table 3.4a - Tire-derived products reported by stewardship organizations for each study year for (includes BC, AB, SK, MB, QC, NL) (tonnes)

	Phase 1	2018	2019	2020
Molded Product (product)	43,359	51,140	55,089	48,729
Crumb (product)	45,059	52,028	50,551	53,481
Steel for recycling	28,334	30,024	32,226	31,773
TDF whole tires (product)	30,141	19,703	27,998	27,554
Aggregate (product)	36,263	58,162	25,194	70,931
TDF fibre (product)	18,529	19,051	20,391	17,476
Mulch (product)	16,430	10,921	15,709	17,295
Cut / Fabricated (product)	8,877	11,298	9,471	10,461
Tire-derived waste	2,702	3,190	2,022	5,375
Retread / Remolding	462	338	534	350
Tire Fiber, Recovered	110.13	201	239	295
Pour in Place (product)	NA	78	175	373
Reuse / Culls	514	284	14	130
Tubes / other	192	33	NA	NA
Total Products	230,972	256,451	239,612	284,224
Net Stock Change	823	1,290	32,338	-12,857
Stockpile	NA	-2,299	-2,435	-8,628
Total Collections	231,795	255,442	269,516	262,740

Table 3.4b - Tire-derived products reported by Ontario Tire Stewardship (2017-2018) and RPRA (2019) (tonnes).

	Phase 1	2018	2019	2020
Crumb (product)	30,614	17,398	78,958	NA
Steel for recycling	32,211	53,082	21,188	NA
Retread / Remolding	3,605	3,535	17,215	NA
Cut / Fabricated (product)	6,717	7,951	6,111	NA
Reuse / Culls	797	611	1,753	NA
Tire Fiber, Recovered	1,149	2,058	722	NA
Mulch (product)	NA	NA	126	NA
Aggregate (product)	3,864	7,509	42	NA
Molded Product (product)	54,099	61,353	NA	NA
Tire-derived waste	25,040	38,338	NA	NA
Total Products	158,096	191,835	126,115	0
Net Stock Change	-16,358	-28,332	19,809	NA
Total Collections	141,738	163,503	145,924	NA

The apparent additions to stock for the reference year of 2019 are large, amounting to almost 60,000 tonnes of material across all seven provinces considered. Of this amount, roughly 19 kt was reported in Ontario, 17.5 kt in Alberta, 8 kt in Saskatchewan, and the rest from the other provinces. Some of this is explained as year-over-year stockpiling (for instance, Saskatchewan reported a net withdrawal from stock of 31 kt in 2020), but it is possible that some portion of this amount was either converted into products or disposed of as waste. In this study, we do not apply any assumptions to the fate of this “missing mass”, other than to assume it was an addition to processor stock.

3.2.4 Trade in Tire-derived Products

In order to approximate the end-use fate of tire-derived crumb, we reviewed available information about the international trade in rubber products. We identified several Harmonized System (HS) trade categories with relevance to the study, shown in Table 3.5 below. Based on a review of the Harmonized System Chapter 40, as well as customs court findings and trade records, HS heading **4003 Reclaimed rubber in primary forms or in plates, sheets or strip** is most commonly used to describe finished tire-derived products, whereas HS heading **4004 Waste, parings and scrap of rubber (other than hard rubber) and powders and granules obtained therefrom** is most commonly used to indicate crumb rubber.

Table 3.5 - Trade in tire-derived and related products according to Canadian statistics.

Sector		Quantity	2016	2017	2018	2019	2020
	Imports – from World						
4002	Synthetic Rubber in Primary Forms	kt	228.91	211.60	218.10	202.65	174.22
4003	Reclaimed Rubber	kt	6.75	16.00	21.41	25.85	15.75
4004	Reclaimed Crumb Rubber	kt	12.92	14.18	14.05	16.34	14.13
4012.1x	Retreaded Tires	thousands	18.63	21.08	22.82	106.55	87.58
4012.2x	Used Tires	thousands	116.64	156.82	141.65	162.38	109.26
4016.91	Rubber Mats, Floor Coverings	$MM CAD	97.01	101.41	100.74	93.65	77.24
	estimate $15 CAD/kg	kt – est.	6.47	6.76	6.72	6.24	5.15
	Exports – to World						
4002	Synthetic Rubber in Primary Forms	kt	105.67	101.75	100.53	88.54	53.27
4003	Reclaimed Rubber	kt	37.93	50.61	48.86	61.09	64.16
4004	Reclaimed Crumb Rubber	kt	59.72	65.69	76.83	77.31	74.94
4012.1x	Retreaded Tires	thousands	23.42	26.08	13.82	18.07	25.61
4012.2x	Used Tires	thousands	578.05	520.02	428.48	441.79	430.86
4016.91	Rubber Mats, Floor Coverings	$MM CAD	89.11	89.93	101.66	89.40	77.62
	estimate $15 CAD/kg	kt – est.	5.94	6.00	6.78	5.96	5.17

4016.91 Articles of vulcanized rubber - Floor coverings and mats appears to represent trade in rubber mats made from non-reclaimed rubber. The category is only reported in units of currency, except for the years 2019-2020 in which the US trade statistics reported mass in kilograms. These reported values produced an average price of $11.90 USD/kg. We applied a price estimate of $15 CAD/kg to estimate mass from reported currency values.

Trade figures were obtained from the (Statistics Canada, 2022) and (US Census Bureau, 2022) web applications. Please refer to the supplemental tables for US-specific trade data. The data support a number of findings:

- Canada is a net importer of primary rubber (net imports roughly 120 kt/year) but still produces significant primary rubber domestically.
- Canada is a net exporter of reclaimed rubber (net exports roughly 70-110 kt/year). This accounts for roughly 40-45% of tire-derived crumb, molded products, mulch, and cut/fabricated products observed in this study.

- Crumb rubber (4004) net exports have climbed from 45-60 kt/year over the 2016-2020 period, while other reclaimed rubber (4003) has climbed from 31-48 kt/year.
- Over 95% of exported rubber in 4003 and 4004 go to the US.
- Canada's trade in 4016.91 is roughly balanced, and apparently small compared to the trade in reclaimed rubber.
- Canada is a net supplier of used tires, which we take as equivalent to culled tires.

3.2.5 The US Tire-Derived Rubber Market

The US market is prominent in disposition of tire-derived products. We reviewed a publication from the Rubber Manufacturers Association that provided summary statistics on US scrap tire utilization in 2015 (RMA, 2016). Though the summary did not make any statements regarding imports, it did report disposition trends. Approximately 4.04 million short tons (3.66 million tonnes) of scrap tires were managed in 2015, with 48% used as fuel; 25% as "ground rubber," 15% to other uses or export, and 12% to landfill. The crumb rubber market itself consumed 680 kt of tire-derived crumb according to the uses shown in Figure 3. We used this information to construct the disposition markets for Canadian crumb rubber.

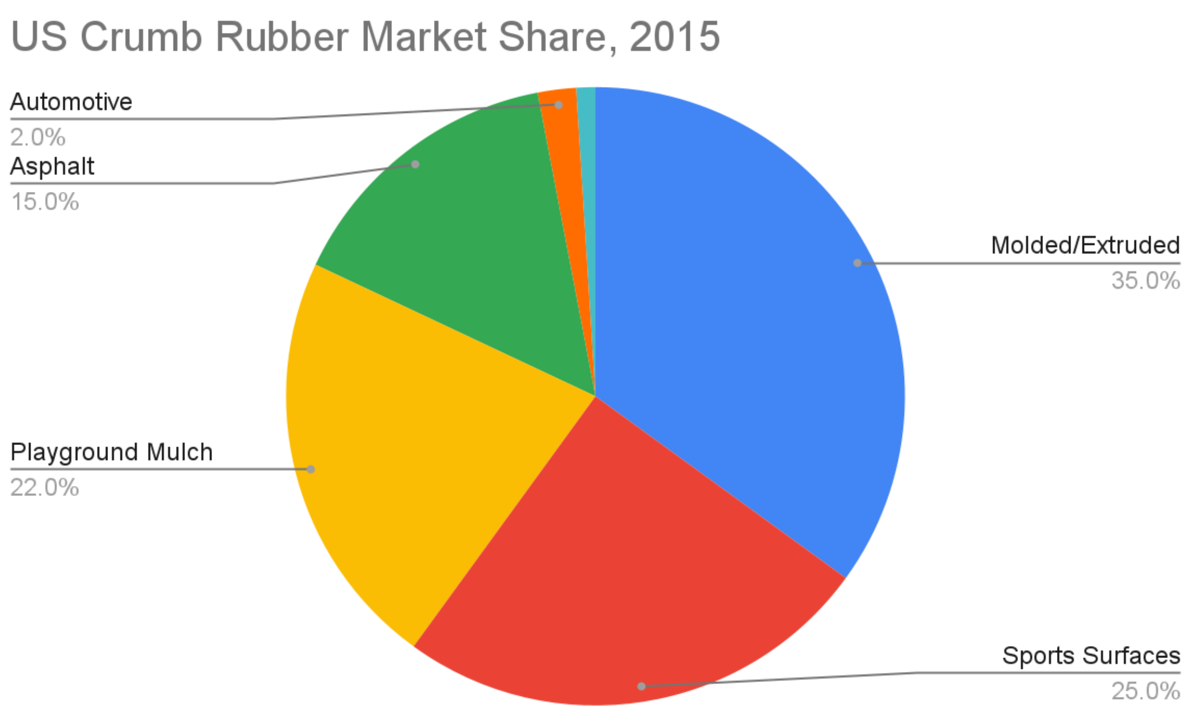

Figure 3 - US Crumb Rubber Market share, 2015 (source: RMA, 2016).

3.2.6 Tire-derived product mix

Figure 4 shows the mix of tire-derived products for the study period, 2019. The figure reports the average freight distance, breakdown of freight modes, and total amount of material handling estimated for the study period. Note that the “material handling” figure includes all tires that passed through a processing facility. Tires that went through multiple facilities will be counted multiple times in this total. The flow magnitudes reported on this chart represent our assumption that about 67% of crumb rubber with unspecified fate is used for poured and molded products, and thus the totals do not equal the values reported in Tables 3.4a and 3.4b.

Our tire-derived product mix parameters are reported in Table 3.6. The use of crumb rubber to make molded products was based on information provided by manufacturers to Ontario Tire Stewardship for the year 2017, indicating that approximately 90% of molded products displaced rubber products (such as floor mats); the remaining 10% displaced stone or cement products (such as pavers). The remaining crumb was distributed amongst turf infill, asphalt modification, and primary rubber replacement based on available information, including US crumb rubber statistics (Section 3.2.5). Note that these market parameters do not alter the fate of tires known to enter specific disposition routes. The parameters below only apply to material for which the end disposition is not known.

For surface coverings (mulch and pour-in-place), there was no information on the relative popularity of tire-derived products versus wood chips or sand, so each route was split 50/50 between the two choices.

Table 3.6 - Disposition assumptions for tire-derived materials.

Market	Share to:	Amount
Mulch versus wood chips or sand	wood chips	0.5
Crumb	pour-in-place	0.06
Crumb	to molded vs rubber	0.57
Crumb	to molded vs concrete	0.04
Crumb	rubberized asphalt	0.07
Crumb	vs acrylic infill	0.15
Crumb	primary rubber (incl. infill vs new crumb)	balance = 0.11
Pour-in-place versus wood chips or sand	wood chips	0.5
Molded products vs rubber or concrete	concrete	0.095

CATRA, 2019

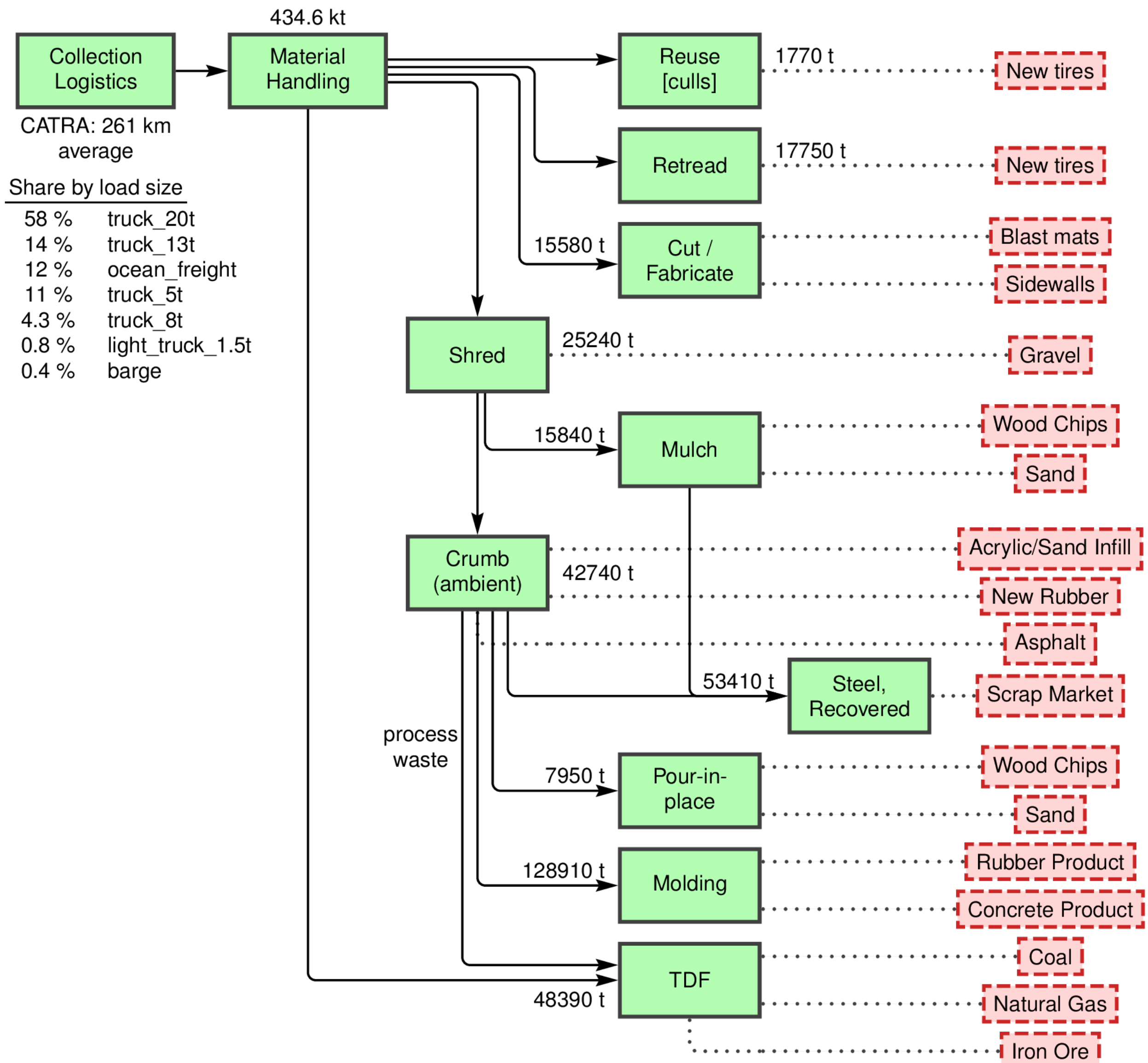

Figure 4 - Material processing of scrap tires throughout the study area, for the year 2019. Green boxes indicate processing stages and tire-derived products; red boxes indicate potentially displaced production activities. The fate of tire-derived material in this figure differs from the data shown in Table 3.4(a,b) because those tables include intermediate fates as reported directly by processors or product stewardship organizations, whereas this figure shows our best estimates for final disposition of scrap-tire derived materials. The "material handling" quantity includes double-counting of tires that were handled in multiple facilities. The steel scrap market is modeled using the World Steel Association "value of scrap" activity (see Section 3.5.16).

3.3 Scrap Tire Processing

This section describes the inventory requirements of the industrial activities involved in converting scrap tires into marketable products. These data were collected via a survey administered to scrap tire processors throughout Canada. A total of 20 facilities were solicited; 19 responded and generated 17 usable facility inventories. The two discarded survey results included a very low outlier and a mobile shred facility that could not dis-aggregate on-site from off-site fuel use. A copy of the survey instrument is included as Appendix C.

Survey responses were interpreted through follow-up communications and technical review. All survey results were expressed as unit inventories, normalized to the total inflow of scrap tires handled by the facility. Of the 17 facilities, 13 operated in the shred / crumb / molding route, 3 were retreading facilities, and one performed cut-and-binding operations to produce blasting mats. The total processing throughput of surveyed facilities amounted to 387,000 tonnes, which we estimate is at least 75% of total scrap tire processing in Canada.

One facility provided information for a cryogenic crumbing process using liquid nitrogen. Our methodological approach was to develop a single average facility model for the nationwide study. We reviewed the model changes that would be required to reconcile the inventories between the synthesis model and the lone cryogenic facility, including differences in product yields. We concluded that it was not appropriate to include the cryogenic facility in the synthesis model. However, directionally, it appears that the cryogenic facility has lower overall energy intensity, comparable crumb rubber yields, and notably lower scrap steel recovery.

3.3.1 Material Handling

Material handling includes diesel use, propane use, hydraulic oil (primary data), and capital equipment (proxy). All facilities that provided data on material handling were included in this inventory, based on the assumption that the requirements of handling tires are consistent. The combustion of diesel and propane are modeled with US LCI; hydraulic oil and equipment are linked to ecoinvent.

Table 3.7 - Material Handling inventory.

direction	flow	amount	unit	source
output	material_handling	1	tonne	facility surveys
input	propane	0.88	l	Weighted average of 12 facilities, 0.2--1.6
input	diesel	1.88	l	Weighted average of 13 facilities, 0.4--3.9
input	hydraulic_oil	0.38	l	Weighted average of 2 facilities, approx 0.3-0.6
input	shred_facility	8.00E-07	unit	based on ecoinvent automobile shredding facility

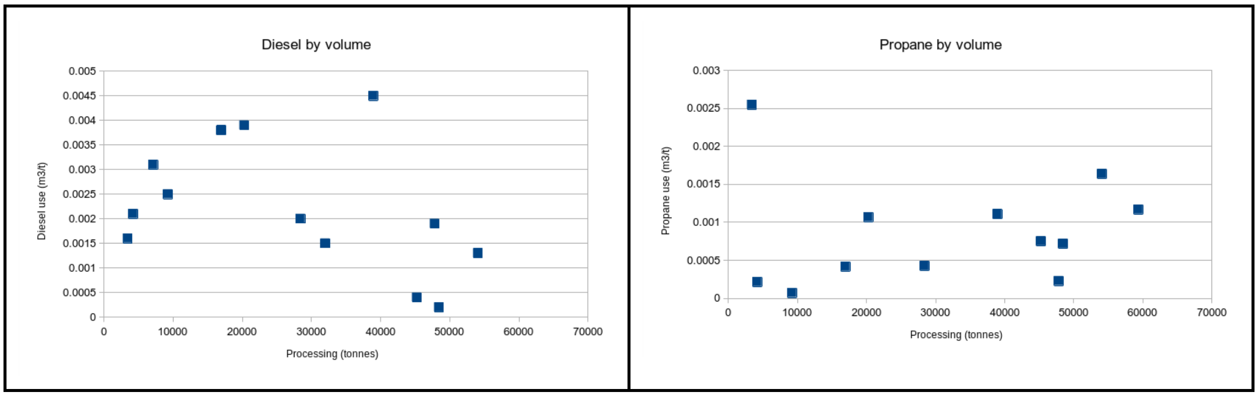

Figure 5 - Diesel and propane use reported by surveyed facilities. Horizontal axis indicates the total quantity of scrap tires reported processed by the facility, while the vertical axis indicates the reported amount of the inventory item per tonne of tires.

3.3.2 Primary Shred

Whole tires can be shredded into several-inch size pieces and used in place of mined aggregate materials in civil engineering projects such as road construction, embankment infill, and landfill leachate systems. The resulting tire-derived aggregate (TDA) includes the steel, fiber, and other components and has negligible yield losses. Shredding is typically the first processing step in the production of other tire derived materials.

Of the 13 facilities in the shred-crumb-molding operational model, three were strictly shredding facilities and were used to develop the electricity requirements for shredding.

Table 3.8 - Inventory for producing primary shred from whole scrap tires

direction	flow	amount	unit	source
input	whole_tires	1	tonne	
input	elec	43	kWh	Unit average of 3 facilities
output	t_shred	1	tonne	

3.3.3 Cut & Bind

A number of products are derived from the materials produced by cutting apart tire sidewalls and treads. Sidewalls are used as weights for tarps and traffic barrels; Materials can be baled to produce civil engineering blocks. Scrap tires cut into large chunks can be bound together using steel cables. The resulting mats are used for containing debris during excavation.

One major blast mat production facility provided data; the inventory is not disclosed to protect their proprietary information.

Table 3.9 - Cut and Bind product inventory. (one facility; not disclosed)

direction	flow	unit
Input	whole_tires	t
Output	t_blast_mat	m2
Input	elec	kWh
Input	ng_m3	m3
Input	water_at_user	kg
Input	steel_element	t

3.3.4 Mulch and Crumb Rubber

Shredded tire pieces with steel removed can be used as a mulch or surface cover for gardening applications. Ground further, fiber and steel are removed and rubber is ground to form crumb ranging from 0.5-5mm in size, depending on the application and process. Ambient temperature and cryogenic processes can be used. Uses include

- Infill for synthetic turf
- Feedstock for moulded rubber products, or used as a component of “pour-in-place” playground surfaces.
- As a component of engineered composite materials, such as synthetic lumber and shingles
- Ingredient in asphalt and sealants

Seven facilities primarily produced crumb rubber. One of them used a cryogenic process and was excluded from the average model. Of the other 6, the average inventory for shred was subtracted and the remainder was allocated to the crumbing process. There was insufficient information to isolate mulching from crumb production, so the same inventory is applied for mulching.

Table 3.10 - Crumb rubber production inventory.

direction	flow	value	unit	source
input	t_shred	1	tonne	
input	elec	186	kwh	Weighted average of 5 facilities
input	ng_m3	5.74	m3	Weighted average of 3 facilities
input	water_at_user	144	kg	Weighted average of 3 facilities
output	t_crumb	0.658	tonne	Weighted average of 6 facilities
output	t_steel	0.144	tonne	Weighted average of 5 facilities
output	t_fibre	0.101	tonne	Weighted average of 4 facilities
output	t_waste	0.097	tonne	balance

The pour-in-place inventory was adapted from the Pembina study (Haines et al., 2010) and manufacturer specifications. The binder glue is a urethane adhesive from ecoinvent. No energy of mixing is assumed.

Table 3.11 - Pour-in-Place surface production inventory.

direction	flow	value	unit
input	t_crumb	0.86	t
input	binder_glue	0.14	t
output	t_molded_surface	1.00	t

3.3.5 Molded Product

Four facilities reported molded products, however two were in very small quantities and among other products. Two large facilities primarily produced molded rubber mats, pavers, and similar items. Binder is a mix of 95% polyurethane and 5% latex.

Table 3.12 - Molded rubber product inventory.

direction	flow	value	unit	Comment
input	t_crumb	1	t	
input	elec	*3##*	kWh	average of 2 facilities
input	ng_m3	*2#*	m3	average of 2 facilities
input	binder_mix	38.5	kg	average of 4 facilities
input	water_at_user	*4###*	kg	average of 2 facilities

output	t_molded	1.0385	t	

Note: italicized data are obfuscated to prevent disclosure of proprietary information.

3.3.6 Tire Reuse

Reuse involves the separation of still-useful tires during the collection or pre-processing phase. These tires are sold into a reuse market. Sorting out useful tires is often called “culling”; these tires are often exported for use in other countries. Reuse was not assigned any impacts beyond collection and material handling.

3.3.7 Retread

Retreading involves removing the worn-out treads from a tire casing and adding a new layer using adhesive or another remolding process. Retreading is most common for high-value MT and OTR tires. However, the facilities represented in our survey processed PLT, MT, and OTR tires. One facility reported abnormally high electricity usage on a per-tire basis, which we suspect may be erroneous. However, we included it in the weighted average. We modeled the new tread stock as EPDM rubber.

The retreading process also produces steel-free rubber shavings, which are treated in the model as additional crumb rubber supply and assigned disposition according to the crumb rubber market mix.

Table 3.13 - Retread inventory.

direction	flow	value	unit	Comment
input	whole_tires	1	t	
input	elec	875	kWh	average of 3 facilities, one v high
input	ng_m3	13.50	m3	average of 2 facilities
input	binder_heptane	2.4	kg	average of 2 facilities
input	retread_sole	314	kg	average of 3 facilities
output	t_retread	1.18	t	
output	t_crumb	0.145	t	average of 3 facilities

3.3.8 Devulcanization

The devulcanization recycling route involves mixing crumbed tire rubber with devulcanization agents and applying mechanical shear stress. The inventory is an average of the inventories in (Farina et al., 2020) and (Li et al., 2014). The ecoinvent activity “petroleum slack wax production, petroleum refinery operation” for the RoW / rest-of-world locale is used as a proxy for rosin. Infrastructure requirements for devulcanization were described using petroleum refining facilities as a proxy on a mass-input basis. The process apparent yield is 90%.

Devulcanized rubber can be used as a raw material in molded rubber products. The fraction of virgin (unvulcanized) rubber that can be replaced by recycled devulcanized rubber in a product varies with the application, but is typically less than 20% by mass. Micronized rubber powder produced from devulcanization can be used in new tire production. Use of devulcanized rubber is assumed to displace some production of virgin, fossil-based synthetic unvulcanized rubber.

Table 3.14 - Devulcanization inventory.

direction	flow_ref	value	unit
input	t_crumb	1	t
input	devulc_facility	5.45E-12	units
input	rosin	0.015	t
input	dimethyl_disulfide	0.1	t
input	water_at_user	0.01	t
input	elec	230	kWh
input	heat_ng_mj	2250	MJ
output	t_devulc	1	t
output	t_waste	0.115	t

* - dimethyl sulfide was used as a proxy.

3.3.9 Pyrolysis

Pyrolysis is a thermo-chemical conversion (TCC) process that occurs in an oxygen-free reactor. Heat is added to the pyrolysis reactor, but the feedstock - in this case scrap tires - does not combust because of the lack of oxygen. The high temperatures of pyrolysis cause some of the feedstock (including rubber, polymers, and some chemicals) to break-up and volatilize. Products include liquid pyrolysis fuel oil and syngas. In addition to these liquid and gaseous products, the third product of pyrolysis is the solid char, which does not volatilize during the process, and is collected from the reactor. The gaseous fuel product is used by the pyrolysis process to heat the reactor, and thus no syngas is marketed.

Table 3.15 - Pyrolysis inventory

direction	flow_ref	value	OTR_val	PLT_val	MT_val	unit
input	whole_tires	1	1	1	1	kg
input	elec	0.0543	0.0543	0.0543	0.0543	kWh
input	pyrol_facility	5.45E-12	5.45E-12	5.45E-12	5.45E-12	units
input	heat_ng_mj	0.0183	0.0183	0.0183	0.0183	MJ
input	water_at_user	2	2	2	2	kg
input	water_treatment	1.5	1.5	1.5	1.5	kg
output	pyrol_gas_to_self_use	0.080172	0.0792	0.081957	0.06897	kg
output	pyrol_char	0.223224	0.2448	0.226587	0.2055306	kg
output	pyrol_liq	0.466884	0.46	0.478886	0.4014054	kg
output	t_waste	0.02	0.02	0.02	0.02	kg
output	t_steel	0.20972	0.196	0.19257	0.304094	kg

The feedstock for the pyrolysis route is whole tires -- 85% from PLT, and 15% from MT (mass basis). The composition of PLT and MT rubber is shown in Table 3.1, and the properties of these components are shown in Table 3.16. The yield of pyrolysis products (mass basis) are based on yields from (Williams, 2013), assuming a 2% mass loss from the process, with the following assumptions made to maintain mass and energy balance:

- The mass ratio of liquid:gaseous products is 5.8 : 1 (Williams, 2013)
- The yield of pyrolysis liquid is calculated by difference, to maintain mass balance
- The char contains all black carbon and ash in the feedstock (minus 2% loss), and the heat value and carbon content of the char are based on the properties of the black carbon and ash in the feedstock (Table 3.1)
- The carbon content and heat value of loss is the same as the tire rubber feedstock
- The carbon content of the pyrolysis gas is 0.815 (mass basis), from (Lopez et al., 2017)
- The heat value of pyrolysis gas is 81% of the average value from (Akkouche et al., 2017; Lopez et al., 2017; Undri et al., 2013), to maintain energy balance
- The heat value of pyrolysis liquid is 81% of the value from (Williams, 2013) to maintain energy balance

The products from pyrolysis oil are char and pyrolysis liquid. Water use and natural gas use for the pyrolysis inventory are from (Khoo, 2019); the electricity use is the average of (Altayeb, 2015; Iribarren et al., 2012; Khoo, 2019). Combustion of pyrolysis gas during the process was modeled using the ecoinvent activity “refinery gas, burned in a furnace” as a proxy, with the carbon content and bio-carbon content adjusted to conform to the properties in Tables 3.16 and

3.17. The capital equipment for pyrolysis was modeled using a petroleum refinery as a proxy (mass input basis).

Table 3.16 - Carbon content, bio carbon content, and heating value of tire components.

Tire component	C content [mass fraction]	Heating Value (LHV) [MJ / kg]	bioC fraction of C [fraction of C mass]
Synthetic Rubber	0.88	30.8	0
Natural Rubber	0.88	30.8	1
Carbon Black	0.97	28.0	0
Steel	0	0	0
Fiber	0.64	31.7	0
Oil and Chemicals	0.86	39.0	0
Mineral fillers	0	0	0

Table 3.17 - Energy content and carbon content of pyrolysis products. Mix is 85% PLT and 15% MT.

	Energy Content [MJ / kg]				Carbon Content [kg C / kg]			
	char	liquid	gas	loss	char	liquid	gas	loss
Mixed Tires	23.63	31.50	35.07	30.03	0.819	0.858	0.815	0.842
PLT	23.63	31.50	35.07	30.08	0.819	0.854	0.815	0.840
MT	23.63	31.50	35.07	29.66	0.819	0.887	0.815	0.859

3.4 Validating Crumb Rubber Inventory

Requirements of tire shredding, crumbing, molding, and inventory management are from primary data collected via surveys. We corroborate these estimates with other estimates from the literature.

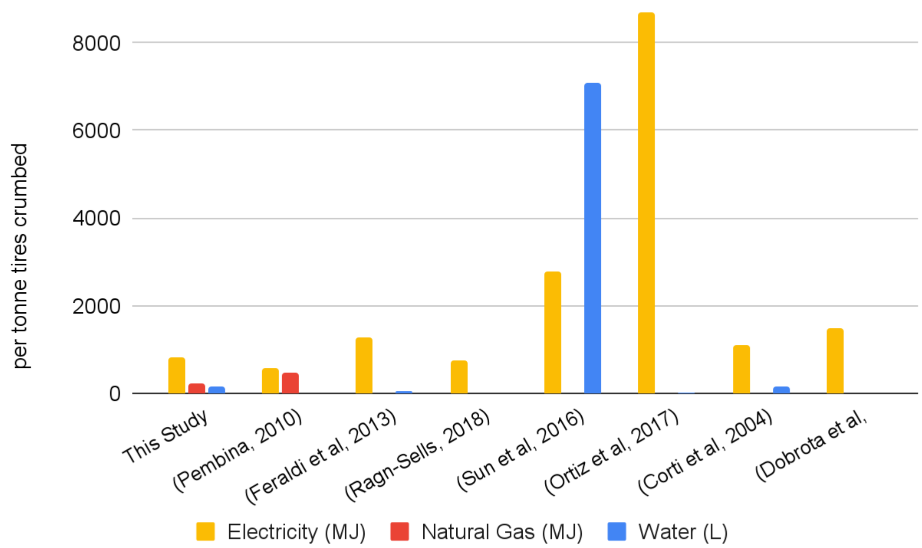

Figure 6 - Comparison of inventory requirements for scrap tire crumbing from literature sources.

Estimates used in this report of energy requirements during scrap tire processing are from Pembina (Haines et al., 2010). Other estimates: (Corti & Lombardi, 2004; Dobrotă et al., 2019; Feraldi et al., 2013; Ortíz-Rodríguez et al., 2017; Ragn-Sells & Johansson, 2018; Sun et al., 2016). Ortiz et al. (electricity) and Sun et al. (water use) are extreme outliers compared to the other sources. We conclude our crumbing inventory derived from survey results to be representative.

3.5 Tire-Derived Products and Displacement Relationships

Displaced production routes fall into two categories: routes that are in widespread use in Canada, and routes that were included in the study for informational purposes. Routes are presented in order of “circularity”, i.e. preservation of the original value and utility of the tire product. Routes in widespread use include:

- Reuse of culled tires
- Retreading or remolding of tires
- Tire-derived crumb used in molded products to displace synthetic rubber products
- Tire-derived crumb used in molded products to displace concrete products
- Tire sidewalls displacing silage weights as woven synthetic fabric bags filled with gravel
- Tire-derived fabricated products displacing steel blast mats
- Tire-derived mulch displacing wood chips or sand
- Tire-derived crumb displacing primary rubber
- Tire-derived crumb displacing synthetic infill
- Tire-derived crumb used in pour-in-place surface coverings replacing woodchips or sand
- Tire-derived crumb used in rubberized asphalt production
- Tire-derived aggregate displacing gravel
- Tire-derived fuels (whole tires, shred, and fibres) displacing conventional fuels
- Tire-derived scrap steel, recycled

Informational routes include:

- Tire-derived crumb, devulcanized, displacing primary rubber
- Tire-derived crumb, used in pyrolysis, displacing carbon black and heavy fuel oil

The quantity of each displaced product that is equivalent to a tonne of tires is determined on a basis of functional equivalency. The product of these equivalency parameters with the economic displacement factors reported in Figure 2 are shown in Table 3.18. Note that the physical displacement value (beta) is combined with (multiplied by) the market displacement rate (alpha) to determine the estimated displacement of primary production. We perform sensitivity analysis on the displacement rate, by default considering 75% displacement, with 50% and 100% as outer bounds for most products (see Section 2.2.4).

Table 3.18 - Displacement relationships modeled in the report. The rates shown here are the product of an economic displacement factor and a technical displacement factor, and include three values used for sensitivity analysis in Section 4.

Tire-derived Product	units	Displaces	low | rate | hi	unit	distance
Culls to Reuse	kg	Tire purchase	0.8 | 1.33 | 1.75	USD*	
Retreaded tire	kg	Tire purchase	2.39 | 3.5 | 4.77	USD*	
Devulcanized Rubber	kg	Primary rubber	0.5 | 0.75 | 1	kg	
Molded	tonne	Rubber	0.5 | 0.75 | 1	tonne	1200 km / 500 km
Molded	tonne	Concrete	1.42 | 2.13 | 2.84	tonne	500 km
Sidewalls	tonne	Bag of Gravel	0.8 | 0.9 | 1	tonne	1000 km / 100 km
Blast Mat	m2	Steel blast mat	0.3 | 0.75 | 1.2	m2	500 km / none
Mulch	tonne	Wood Chips	1.2 | 1.8 | 2.4	tonne	500 km
Mulch	tonne	Sand	2.6 | 3.8 | 5.1	tonne	500 km
Crumb	tonne	Rubber	0.5 | 0.75 | 1	tonne	none / 3500 km**
Crumb	tonne	Plastic Infill	0.2 | 0.5 | 0.8	tonne	1200 km / none
Pour-in-Place	tonne	Wood Chips	2.13 | 3.2 | 4.26	tonne	500 km
Pour-in-Place	tonne	Sand	4.54 | 6.81 | 9.08	tonne	500 km
Crumb	tonne	in Roadway	55 | 82.5 | 110	m	650 km / none
TDA	tonne	Gravel	1.36 | 1.53 | 1.7	tonne	100 km
TDF	MJ	Coal / NG	0.8 | 0.9 | 1	MJ	
Steel in Kiln	tonne	Iron Ore	0.7 | 1.05 | 1.4	tonne	
TDF (Fiber)	MJ	Coal / NG	0.8 | 0.9 | 1	MJ	550 km / 200 km
Pyrolysis fuel	kg	Fuel oil	0.5 | 0.75 | 1	kg	
Pyrolysis char	kg	Carbon black	0.25 | 0.38 | 0.5	kg	
Pyrolysis fuel	MJ	Fuel oil, combusted	0.8 | 0.9 | 1	MJ	
Steel	tonne	to Scrap	0.5 | 0.75 | 1	tonne	500 km / none

* USD/kg in 2013 producer prices

** 10 000 km transport by ocean freight displaced for 35% rest-of-world (non-US) market share

† 200 km displaced transport by train; applies only to coal production

3.5.1 Culled (reused) Tires Displacing New Tires

Tires culled from recycling are assumed to be sold into a reuse market and thereby to displace some activity in new tire production. The production of new tires is modeled using USEEIO 2.0.1 economic input/output database prepared by the US EPA. The sale of one culled scrap tire is assumed to displace 1/3 of the production of a new tire (i.e. three culled tires replace the production of one new tire). The production of a new tire is assigned a wholesale value of US$5.30 / kg. This value is based on a 10.2 kg tire that costs $90 USD new, and a producer price which is 60.2% of the retail price (BEA, 2019). Thus the culling and reuse of 1 tonne of scrap tires results in the displacement of $1,750 of economic activity in new tire production.

3.5.2 Retreaded Tires Displacing New Tires

Retreaded tires are assumed to be more likely to displace a new tire and are assigned a displacement rate of 90%. At the same producer price for tires, this amounts to $4,770 of economic activity in new tire production displaced per tonne of retreaded tires.

3.5.3 Tire-Derived Molded Product Displacing New Rubber Molded Product

Here, a molded tire-derived product is assumed to replace an extruded product made from new synthetic rubber on the global market. The primary rubber is modeled as an extruded piece of EPDM elastomer because that is the only model for a synthetic rubber product available in ecoinvent. Extrusion can only be applied to unvulcanized rubber, which is vulcanized later and retains its shape. In contrast, molding can be performed with either crumb rubber or unvulcanized rubber, which is vulcanized in the procedure. The products of these processes are regarded as functionally equivalent for this study.

Because Canada is a net exporter of molded recycled rubber and is roughly at a trade balance for new rubber floor mats, we assume the displaced product is produced domestically and may be exported. Thus we add an asymmetric transport burden to the displacement route.

3.5.4 Tire-Derived Molded Product Displacing Concrete Product

Tire crumb is assumed to be formed into a molded curb that is used to replace a concrete curb. The functional equivalence is based on volume. The displacement factor is based on the densities of the two materials being 845 kg/m3 for molded rubber and 2400 kg/m3 for concrete. Both the rubber and concrete products are assumed to have a similar lifespan (in the Pembina study, the rubber curbs were assumed to last 4 times as long as the concrete curbs).

3.5.5 Tire-Derived Sidewalls Displacing Gravel-in-Bag Weights

Sidewalls used as weights are assumed to displace gravel-in-bags on an equivalent mass basis. These weights are typically used to secure tarps. Electricity requirements for cutting sidewalls are assumed to be half of the requirements for shredding. The bags are assumed to be made of woven polyethylene and to weigh 8 oz empty and 50 lb full. In this case we assume that sidewalls are shipped a relatively long distance to the point of use (1000 km), but that gravel to fill the bags would be locally sourced and travel at most 100 km.

3.5.6 Tire-Derived Blast Mats Displacing Steel Blast Mats

Blasting mats are laid down over terrain being blasted with explosives in engineering and mining applications to suppress debris. The tire-derived mats appear to be more common and are made by stitching together large chunks of tire with steel connectors. The alternative blasting mats are made of coiled steel wire; these are lighter in weight but have reduced durability.

Tire-derived blast mats are assumed to weigh 195.3 kg per square meter (40 lb/sq. ft); steel blast mats are assumed to weigh 80.6 kg per sq. m (16.5 lb / sq. ft). The tire-derived blast mats displace steel blast mats on an equivalent area basis, and they are assumed to have the same lifetime. Because tire-derived mats appear to be the market leader, we discount the displacement potential of this route to 50%, with 80% and 20% considered in sensitivity.

3.5.7 Tire-Derived Rubber Mulch Displacing Wood Chips

Mulch is assumed to cover an area to a certain depth, resulting in a functional unit based on volume. We assume that wood chips last two years. Rubber mulch is completely replaced after 10 years, and it requires a 10% top-up every year. The density of rubber mulch is 0.42 tonne per m^3, based on a 1,000 lb bag of Vigoro rubber mulch having 38.5 cu ft. The density of wood chips is assumed to be 0.38 tonne per m^3. Thus, on an equivalent volumetric basis, one tonne of rubber mulch is equivalent to about 0.91 tonne of wood chips.

3.5.8 Tire-Derived Rubber Mulch Displacing Sand

Tire-derived rubber mulch can also displace sand for playground applications. We assume that the displacement is on a 9:6 volume basis, since a 9” layer of sand provides comparable performance to a 6” layer of rubber mulch (CPSC, 2015) (table 2). Sand has a density of 1.42 tonne per cubic meter, and rubber mulch has density 0.42 tonne per cubic meter. We assume the rubber mulch and sand must be topped-up at a rate of 10% per year.

3.5.9 Tire-Derived Crumb Displacing Primary Rubber

Tire-derived crumb could displace primary rubber in functional applications, including both molded products and infill. We consider this case to be among the most common displacement cases, largely because of Canada’s status as a large net importer of primary rubber (see Section 3.2.4). We apply a 3,500km ocean freight transport burden to the displaced rubber to account for the fact that approximately 35% of Canada's primary rubber is imported from overseas (the rest originates in the US).

We use non-vulcanized poly-butadiene rubber (PBR) as a proxy for the rubber product displaced, and assume a 1:1 displacement value. There are two available models for PBR production: one in USLCI, based on a study from the American Chemistry Council (2010); the other in ecoinvent, based on a study from Plastics Europe (data from 2005). We use the ecoinvent process for consistency..

3.5.10 Tire-Derived Crumb Displacing Plastic Infill

Synthetic turf infill appears to be dominated by crumb rubber based products. Other competing products include primary (i.e. non-recycled) crumb rubber, acrylic-coated sand (one specimen is marketed as "EnviroFill"), as well as natural products like coconut husk fibers or walnut shells (Synthetic Turf Council, 2022). Based on limited available information and almost no technical details, we elected to model two displacement cases for athletic field infill: tire-derived crumb rubber displacing primary rubber, and tire-derived crumb rubber displacing an acrylic-sand mixture containing 33.3% acrylic and 66.7% sand. We assume equivalent density, longevity, and maintenance requirement to all three infill materials. A consulting study for a synthetic turf athletic field at a high school in Massachusetts (Weston & Sampson, 2018) supports this assumption. We do introduce a transportation requirement of 1,200 km for this application, owing to its greater prevalence in the US.

The selection of natural versus synthetic turf was regarded as out of scope for this study, and potential displacement of natural turf induced by the availability of tire-derived crumb rubber was not considered. Because crumb rubber is regarded as the market leader, we discount its displacement potential to 50%, with displacements of 80% and 20% evaluated as sensitivity cases.

3.5.11 Tire-Derived Pour-in-Place Displacing Wood Chips

Tire-derived pour-in-place is modeled as a mix of 86% crumb rubber and 14% urethane binder (mass basis). There are negligible process impacts for mixing. This mix displaces wood chips on an equivalent volume basis (for example, a 6 inch layer of pour-in-place provides equivalent service as a 6 inch layer of wood chips). The density of the pour-in-place is 0.446 tonne per m^3 (converted from 14 lb/ft^2 for a 6-inch layer (Stutz et al., 2003)), and the density of wood chips is 0.38 tonne per m^3.

We assume that the pour-in-place surface lasts 10 years, while wood chip playground surfacing lasts two years. Thus, the pour-in-place surface displaces five uses of wood chips. The possibility of reclaiming the pour-in-place surface after 10 years by regrinding, remixing, and re-pouring would increase the amount of wood chips displaced.

3.5.12 Tire-Derived Pour-in-Place Displacing Sand

Tire-derived pour-in-place is modeled as described in §Tire-Derived Pour-in-Place Displacing Wood Chips. Sand is assumed to be 9” thick, with a density of 1.42 tonne / cu m. Sand is topped-up every year at a rate of 10%.

3.5.13 Tire-derived crumb, used as an Asphalt modifier

Tire-derived crumb rubber is increasingly used as an additive when preparing hot mix and warm mix asphalt because it provides improved durability, reduced maintenance, and lower road noise (Buttlar & Rath, 2021). However, the exact effect of adding crumb rubber to asphalt is difficult to quantify, and depends on the precise mix of materials used in laying the road. We created a representative model based on available literature, but the topic is worthy of study in greater depth. The model was developed to describe disposition of one tonne of crumb rubber.

Preparing the binder mix requires heating bitumen to a sufficient temperature to incorporate the rubber. This is modeled as requiring combustion of 18 l of diesel fuel on-site per ton of binder produced (Bartolozzi et al., 2015), with the modified binder including 20% crumb rubber by weight. This translates to 90 l of diesel combustion per tonne of crumb rubber consumed. This is a very high figure and can be considered as a pessimistic assumption. It is likely that some crumb-asphalt operations use cleaner energy sources, such as natural gas or electricity, and that their overall energy consumption is lower than the figure reported here. However, we have no specific information with which to correct this factor.

Thereafter, the binder is mixed with aggregates and spread out on the roadway. We used roadway construction parameters reported by (Farina et al., 2017) to characterize different roadway mixes. Their report suggested that crumb-rubber modification permitted the road design to use a thinner layer of asphalt than the unmodified case, as well as to utilize different mixtures of bitumen and aggregate. They also reported an estimated improvement of service life of approximately 10% (18 years to 20 years).

We used the data reported in Farina et al. to estimate that one tonne of crumb rubber was sufficient to modify 65-110 meters of roadway. We used this range to develop the sensitivity cases for rubber-modified asphalt. Table 3.19 shows the parameters included in the model. We modeled high, median, and low displacement cases, as well as an alternative case in which we used the median construction but did not consider increases in service life.

Table 3.19 - Roadway construction parameters used to describe the effect of introducing one tonne of crumb-rubber into modified asphalt production (developed from Farina et al, 2017 using the “Wet scenario *Wg*” and adjusting asphalt thickness).

Parameter	High	Median	Low	Alt	units
Asphalt Thickness	0.03	0.04	0.05	0.04	meter
Roadway Distance	**110**	**85**	**65**	85	meter/tonne
Change in Binder	-16.8	-3.4	+10	-3.4	kg/meter
Change in Aggregate	-461	-257	-52	-257	kg/meter
Change in service life	+2	+2	+2	+0	years

We modeled extended roadway service life as displaced road construction in ecoinvent, which is modeled in ecoinvent as a continuous distribution per meter*year of roadway use. We reasoned that an identical road construction that lasts an additional two years of service life could be described by an avoided burden of two meter*years of amortized road construction. This approach is sound because the ecoinvent road model is specified in order to allocate the road’s construction to an expected quantity of total freight load per meter*year over the service life. Thus, extending the life by two years will reduce this allocation by an amount that is cumulatively equivalent to 2 unit values of the “road construction” unit process.

3.5.14 TDA Displacing Gravel

Aggregate is used on a volume basis; therefore the functional utility of a tonne of tire-derived aggregate depends on its density relative to gravel. The displacement factor of 1.7 means that 1 tonne of TDA displaces 1.7 tonnes of gravel. This value is from the Pembina study (Haines et al., 2010). We include transport of 100 km (for both TDA and gravel)..

3.5.15 Combustion

Tires have a high heating value, which motivates their use as a low-cost replacement for purchased fuels in cement kilns, paper mills, and other industrial facilities. Tires can either be combusted whole or shred. Tire-derived fibers are also a high-energy fuel. Tires are often burned in facilities that use a variety of other fuels. Therefore, it is difficult to isolate emission factors for burning tires. We modeled TDF combustion in a cement kiln, which is the most abundant fate for TDF generated in Canada. When modeling TDF combustion, we consider each major component of the tire separately. The combustible portion of the tire is assigned a heating value of 29.9 MJ/kg and used to displace hard coal at 25 MJ/kg, and natural gas at a heating value of 38.4 MJ/m^3. Transport of the coal over a distance of 200 km by train is avoided as well. Displaced heat is modeled using coal in a 1-10MW industrial furnace from ecoinvent, including a correction to account for for ecoinvent’s 80% thermal efficiency assumption. Avoided natural gas production is modeled as heat from a condensing boiler >100kW, with a thermal efficiency of approximately 100%. Displaced processes include heat production and fuel supply, but exclude flows relating to the operation of the facility.

Biogenic carbon and the effect of natural rubber content on TDF
Since tires usually contain a mix of natural rubber and synthetic rubber, some of the carbon content of tires is considered “biogenic”. Following the methodology described in the Environmental Product Declaration Rules for tires (UL Environment & Quantis, 2017), this biogenic carbon is ignored in the life cycle inventory. This means that the tire production process does not receive a credit for the bio-C content of tires; it also means that the portion of CO_2 released during tire combustion that is biogenic does not contribute to the GHG emissions from combustion. The mass fraction of natural rubber in PLT, MT, and OTR tires are 0.14, 0.26, and 0.4, respectively (fraction of total scrap tire mass that is natural rubber). The carbon content of rubber is 0.88 (mass fraction, without compounding materials).

Tire-derived rubber in cement kiln
Tire combustion in a cement kiln is modeled as coal combustion in an industrial furnace 1-10MW, on a lower-heating-value-equivalent basis, with fossil and biogenic carbon dioxide emission adjusted according to the tire composition. We did not adjust the emission factors for other carbon-containing compounds because the tire parameters fell within the uncertainty reported in the ecoinvent dataset (75-94% carbon content). We neutralize several heavy metal emissions associated with coal combustion that are not expected to be found in tires, including antimony, arsenic, cadmium, chromium, lead, mercury, nickel, strontium, and others. We retain the zinc emission and amplify it to represent a 1% weight fraction of zinc in tires, of which 1% is emitted during combustion (for an emission factor of 1E-4 kg/kg or 100 mg/kg). This increased zinc emission is applied in the high-sensitivity case but not in the default case (see Table 4.2). Intermediate flows associated with the coal combustion are excluded from the model.

Tire-derived fiber in cement kiln displacing heat from fossil fuels
In some cases, fibers and other tire-derived wastes may be disposed as TDF, with recovered energy displacing fossil fuels. Tire-derived fiber was modeled as a mix of 40% crumb rubber (modeled as described above) and 60% fiber, modeled as a mixture of nylon and polyester having a lower heating value of 30.7 MJ/kg and a carbon content of 63% by mass. Incineration of polyethylene terephthalate was used to represent combustion emissions because the carbon fractions of polyester and nylon are nearly identical. The heat produced from the incineration was taken to be 30.7 MJ/kg for the purposes of displacement modeling. Intermediate flows relating to operation of the incineration facility were excluded from the model. An additional transport distance of 550 km is modeled to represent the delivery of the fiber waste to the cement kiln.

Steel in cement kiln displacing iron ore
When tire-derived steel is intentionally combusted in a cement kiln, the steel supplies iron that is necessary for the cement making process. The steel in tires displaces the use of other iron sources (e.g. requirement for iron like iron ore, pig iron, or slag). This relationship is modeled at a displacement ratio of 1:1.4 by mass, which is consistent with approximately 70% iron content in iron ore.

Whole tires in cement kiln displacing heat from fossil fuels
Combustion of tires in a cement kiln is modeled as the sum of its components: tire rubber with a biogenic carbon fraction; steel; and fiber. The components behave as described above. The approximate heating value of a whole tire is 25-26 MJ/kg, as reported in Table 3.1.

3.5.16 Tire-Derived Steel to Scrap Recycling

Steel is commonly recycled in a closed loop, and demand for scrap steel exceeds supply. The model utilizes a “value of scrap” dataset produced by the World Steel Association, which reports environmental benefits that arise from the inherent use of scrap steel in steelmaking worldwide (see Section 2.2.6). We also apply a transport burden of 500 km to steel scrap recovery.

4 Life Cycle Impact Assessment

In this section we present quantitative results of the life cycle impact assessment. Results have two types of contributions: positive-valued (incurred) contributions and negative-valued (displaced) contributions.

- Positive-valued contributions result from direct actions taken within the scrap tire management system that have environmental impacts. These include emissions from transportation of tires from collection centers to processors, direct emissions from facility operations, upstream emissions from materials used by processors, and emissions from electricity generation. In the TDA and fibre TDF end-use cases, incurred emissions are also estimated for transport of tire materials to the point of use.

- Negative-valued contributions represent emissions associated with the production of products that compete with tire-derived products in the marketplace, and so are potentially avoided by the use of scrap tires. These “displaced” products were listed in Table 2.1 and detailed in Section 3.5. For many uses, avoided transport is included with displacements as a negative contribution.

The sum of these positive and negative impact scores indicates the potential net environmental impacts that could occur if tire-derived products are fully displacing primary products.

4.1 Impact Category Indicators

Below, we present the TRACI 2.1 impact categories in brief. Interested readers should refer to the documentation for further details (Bare, 2012). Each indicator’s characterized flows were carefully reviewed for consistency with the emission inventories in ecoinvent, USEEIO, WorldSteel, and US LCI. Impact characterization factors were compared with ReCiPe 2016 to ensure consistency and completeness.

4.1.1 Global Climate Change (kg CO2 equivalent)

Global warming is an average increase in the temperature of the atmosphere near the Earth’s surface and in the troposphere, attributable to the release of carbon dioxide and other substances from industrial processes, including combustion of fuels. TRACI 2.1 utilizes global warming potentials (GWPs) for the calculation of the potency of greenhouse gases consistent with the guidance of the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC -The United Nations Framework Convention on Climate Change 2003). The indicator uses GWPs with 100-year time horizons.

4.1.2 Photochemical Smog Formation (kg O3 equivalent)

Ground level ozone is created by various chemical reactions, which occur between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in sunlight. Human health effects can result in a variety of respiratory issues including increasing symptoms of bronchitis, asthma, and emphysema. Smog creation potential is modeled using the Maximum Incremental Reactivity (MIR) method.

4.1.3 Particulate Matter Formation (kg PM2.5 equivalent)

Particulate matter is a collection of small particles in ambient air which have the ability to cause negative human health effects including respiratory illness and death. Particulate matter may be emitted as particulates, or may be the product of chemical reactions in the air (secondary particulates). The most common precursors to secondary particulates are sulfur dioxide (SO2) and nitrogen oxides (NOx). The method for calculation of human health impacts includes the modeling of the fate and exposure into intake fractions (i.e., that portion of the emitted substance, which is expected to be inhaled by a human being).

4.1.4 Acidification of Air (moles H+ equivalent)

Acidification is the increasing concentration of hydrogen ion (H+) within a local environment. This can be the result of the addition of acids (e.g., nitric acid and sulfuric acid) into the environment, or by the addition of other substances (e.g., ammonia) which increase the acidity of the environment. TRACI 2.1 uses an acidification model which incorporates the increasing hydrogen ion potential within the environment.

4.1.5 Eutrophication (kg N equivalent)

Eutrophication is the result of adding certain nutrients, mainly nitrogen and phosphorus, particularly to the aquatic environment, which can cause accelerated growth of algae, which can use up all the free oxygen in the water and also cause toxicity. Eutrophication emissions can arise from both direct emissions to water and also to air, where particles often enter freshwater eventually. In TRACI, the air and water emission routes are represented as separate categories, which include the same flows emitted to air and water compartments. We combined these two sets of factors into a single indicator.

4.1.6 Ozone Depletion (kg CFC-11 equivalent)

Ozone depletion describes the destabilizing effect of highly persistent halogenated chemicals in the stratosphere. Ozone-depleting compounds, predominantly refrigerants, act as catalysts for the conversion of ozone (O_3) into gaseous oxygen, which reduces the natural capacity of the atmosphere to block ultraviolet radiation from the sun. Ozone depletion was one of the first global-scale environmental crises to be addressed internationally through policy via the Montreal Protocol, which was established in 1987.

The TRACI 2.1 ozone depletion indicator does not include a characterization factor for nitrous oxide, which is emitted in large quantities in comparison to more trace ozone-depleting substances. Because nitrous oxide was found to be a major contributor to ozone depletion scores using the ReCiPe indicator, an equivalent characterization factor of 0.011 kg CFC-11 equivalent per kg of nitrous oxide was added to the TRACI 2.1 ozone depletion method.

4.1.7 Human and Ecological Toxicity (Comparative toxicity units)

Under the Life Cycle Initiative of the United Nations Environment Program (UNEP) / Society of Environmental Toxicology and Chemistry (SETAC) various international multimedia toxicity model developers created a global consensus model known as USEtox. The USEtox model adopted many of the best features of earlier models and was used to develop human health cancer and noncancer toxicity potentials and freshwater ecotoxicity potentials for over 3000 substances including organic and inorganic substances.

USEtox is implemented by many LCIA methodologies, but its implementations vary. The TRACI reference dataset includes several very high interim characterizations for metals. These factors are omitted from the USEEIO implementation of TRACI 2.1, and the factors from ReCiPe 2016 are different. Instead of reporting TRACI category scores for toxicity methods, we review the impact scores per tonne of tires processed for several different toxicity indicators in Section 4.4.2.

4.2 National Scale Scenario

The national scale scenario represents material flows for the 2019 calendar year. All processing facility's impact scores are estimated using the same synthesis facility model, but they each use the appropriate provincial electricity grid.

The tire-derived products were allocated to end-uses as best as possible according to information available from provincial organizations and processors, national trade statistics, and information about the US crumb rubber market (see Table 3.6).

When tire-derived material is used as fuel (TDF), the displaced product may be heat from a variety of fuels. In order to assess the impact of the displaced energy, the national scale scenario is calculated for two variants: a ‘base’ variant, and a ‘TDF’ variant. The main change in the TDF variant case is to assume 100% natural gas, rather than a mix of 90% coal and 10% gas, as the fuel being displaced by heat from TDF. This variant also routes all tire-derived waste to combustion for energy recovery rather than landfill, although the amount of material this applies to is very small (about 3 kt in the 2019 base year).

Table 4.1 - Baseline and TDF cases

Market	Share to:	2019 base	2019 TDF
TDF-derived Heat: natural gas vs coal	natural gas	0.1	1.0
TDW - TDF heat vs landfill	TDF heat	0.0	1.0
Fiber, recovered - TDF heat vs cutoff	TDF heat	0.0	1.0

4.2.1 Sensitivity Analysis

In addition to the displacement sensitivity analysis described in Section 2.2.4, tire processing parameters were also varied to evaluate the sensitivity of the results to the foreground model. These variations encompass 80% or more of the observed variation in reported facility data.

Table 4.2 - Foreground LCA parameters - sensitivity analysis.

Activity	Parameter	Low	Nominal	High
Material Handling	Diesel	80%	100%	125%
Material Handling	Propane	80%	100%	125%
Scrap Tire Processing	Electricity	65%	100%	150%
Transport	Distance	75%	100%	130%
TDF Combustion	Zinc emission (mg/kg)	0.12	0.12	100
PLT Combustion	Biogenic carbon fraction	0.45	0.23	0.15

4.2.2 National Scale Results

When reviewing results, variation in positive-valued bars reflects sensitivity interventions in foreground parameters (Table 4.2), while variation in negative-valued bars reflects interventions in displacement rates (Table 3.18).

2019 Base Case

The aggregated total results for national activity during 2019 are presented in Figure 6 and Table 4.3. In all, activities related to collecting and processing scrap tires are estimated to have resulted in emissions 219 kt (kilotonnes) of CO_2-equivalent of greenhouse gases, 13.8 kt O_3-equivalent of smog-creating compounds, and 126 tonnes PM2.5-equivalent particulates, among other indicators. At the same time, potentially avoided impacts from displaced production totaled 592 kt of CO_2 equivalent, 33 kt O_3-equivalent smog, and 385 t of PM2.5-equivalent.

In all six categories, the potentially avoided impact scores outweigh the incurred impact scores at the nominal sensitivity case. We can observe that the results are not sensitive to changes in foreground parameters (error marks on positive bars). This is primarily because emission from TDF combustion and the amount of ancillary materials (e.g. replacement treads and binder use) were not considered to be variable and were not included in the sensitivity analysis.

The magnitude of avoided impact scores, on the other hand, is strongly affected by the sensitivity cases. In four impact categories, the favorable result is robust to modeled variation in the displacement rate. In Ozone depletion and Eutrophication, however, the median shows only a marginal net benefit which vanishes in the low-displacement case.

The higher variability of the potentially avoided impacts is appropriate, since the degree of displacement is a variable that is fundamentally uncertain, as it is dependent on economic factors far outside the scope of this report. See Table 3.18 for the variability ranges assumed for the potentially displaced products.

Table 4.3 - Category Indicator results, national scale, 2019

		Incurred Impacts	Avoided Impacts	Net Result
Global Warming	kg CO2 eq	2.37E+08	-5.84E+08	-3.47E+08
Smog Air	kg O3 eq	1.50E+07	-3.25E+07	-1.75E+07
Particulates	PM2.5 eq	1.41E+05	-3.78E+05	-2.37E+05
Acidification	kg SO2 eq	1.30E+06	-2.73E+06	-1.43E+06
Ozone Depletion	kg CFC-11 eq	1.88E+02	-2.76E+02	-8.82E+01
Eutrophication	kg N eq	7.34E+04	-1.16E+05	-4.26E+04

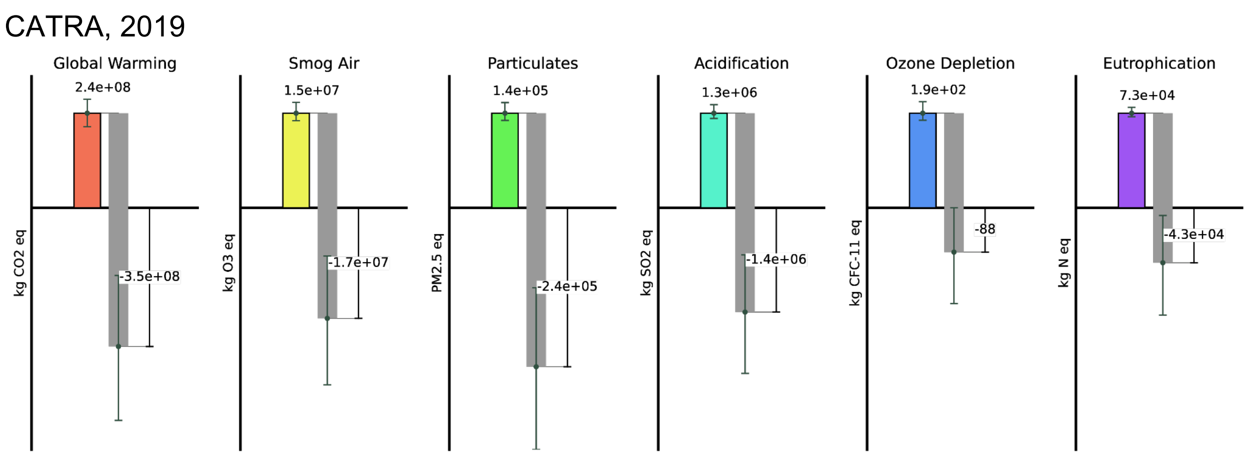

Figure 6 - National results in graphical form, each category normalized to incurred impacts.

Table 4.4 - Category Indicator results, TDF variant, 2019

		Incurred Impacts	Avoided Impacts	Net Result
Global Warming	kg CO2 eq	2.44E+08	-5.53E+08	-3.09E+08
Smog Air	kg O3 eq	1.52E+07	-2.67E+07	-1.14E+07
Particulates	PM2.5 eq	1.43E+05	-3.24E+05	-1.81E+05
Acidification	kg SO2 eq	1.33E+06	-2.02E+06	-6.95E+05
Ozone Depletion	kg CFC-11 eq	1.91E+02	-2.75E+02	-8.40E+01
Eutrophication	kg N eq	7.38E+04	-1.06E+05	-3.24E+04

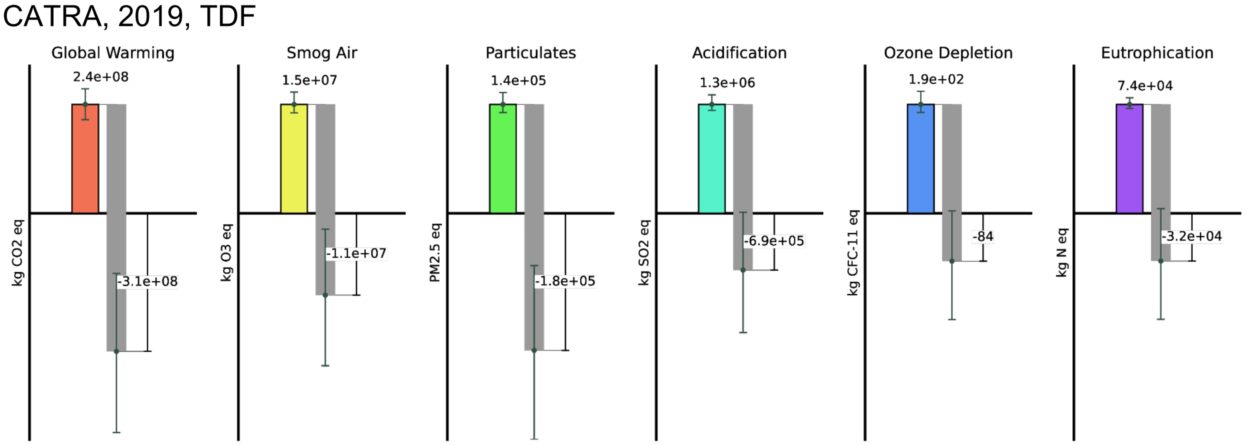

Figure 7 - National results in graphical form, each category normalized to incurred impacts; TDF variant.

2019 TDF Variant

The results for the TDF variant are presented in Table 4.4 and Figure 7. In the case where TDF is assumed to displace natural gas rather than predominantly coal, the change further reduces the difference between incurred and avoided impact scores in all categories. Moreover, in acidification, ozone, and eutrophication the system performance is now marginal.

4.2.3 Stage Contribution Analysis

The base case emission totals above are shown disaggregated into the contributions of different stages in Figure 8. Full details by disaggregated stage are available in Table A.1 and in the tabular annex.

Collection and material handling at processing facilities (including diesel and propane combustion) made generally small contributions to the impact indicator score, compared with processing activities. Likewise, transport of tire-derived products, and avoided transport of displaced products, were small in comparison to displaced production contributions. The largest impacts from collection and material handling were found in the smog indicator and can be traced to diesel combustion. Disposal of tire-derived waste made up a negligible share of impacts in all categories, although this activity did show up in the toxicity screen (Section 4.4.2).

The most significant impact contribution during the processing stage was the production of binder used in molding and pour-in-place product systems. The binder was modeled as a mix of 95% polyurethane adhesive and 5% latex, so the polyurethane production dominates. The selection of binder(s) is a key area for facilities producing molded or poured products to consider when evaluating their environmental impacts. Other processing impacts included facility natural gas combustion and new tread production (modeled as EPDM rubber).

Processing facility models each used the regionally-appropriate grid models drawn from ecoinvent for each processing facility. The largest contribution to electricity impact scores came from grid power in Alberta. However, since the largest quantities of materials were processed in provinces with low-carbon grids (ON, QC, BC), electricity production had a diminutive contribution to processing impact scores on the whole.

On the disposition of tire-derived products and fuels, the largest potential improvement came from displaced production of synthetic rubber from tire-derived crumb and molded products, which was the largest avoided burden in all six impact categories. Other large sources of avoided burden varied by impact category, but prominent contributors included primary rubber, followed by acrylic sand infill (both included in “Displaced: Other”). Avoided primary production of new tires, avoided road construction, and scrap steel recycling were also significant.

Impacts from burning tires (TDF combustion) are also significant, as are the avoided impacts associated with displaced fossil fuel combustion. It is assumed that TDF displaces a 90%/10% mix of coal/natural gas.

Impacts from disposal of tire-derived waste were almost undetectable in the results. Only 3 kt of waste was reported disposed to landfill across all 7 provinces. It is possible that some of the 57.0 kt of “missing mass” reported as a net addition to stock (Tables 3.4a and 3.4b) are actually waste to disposal.

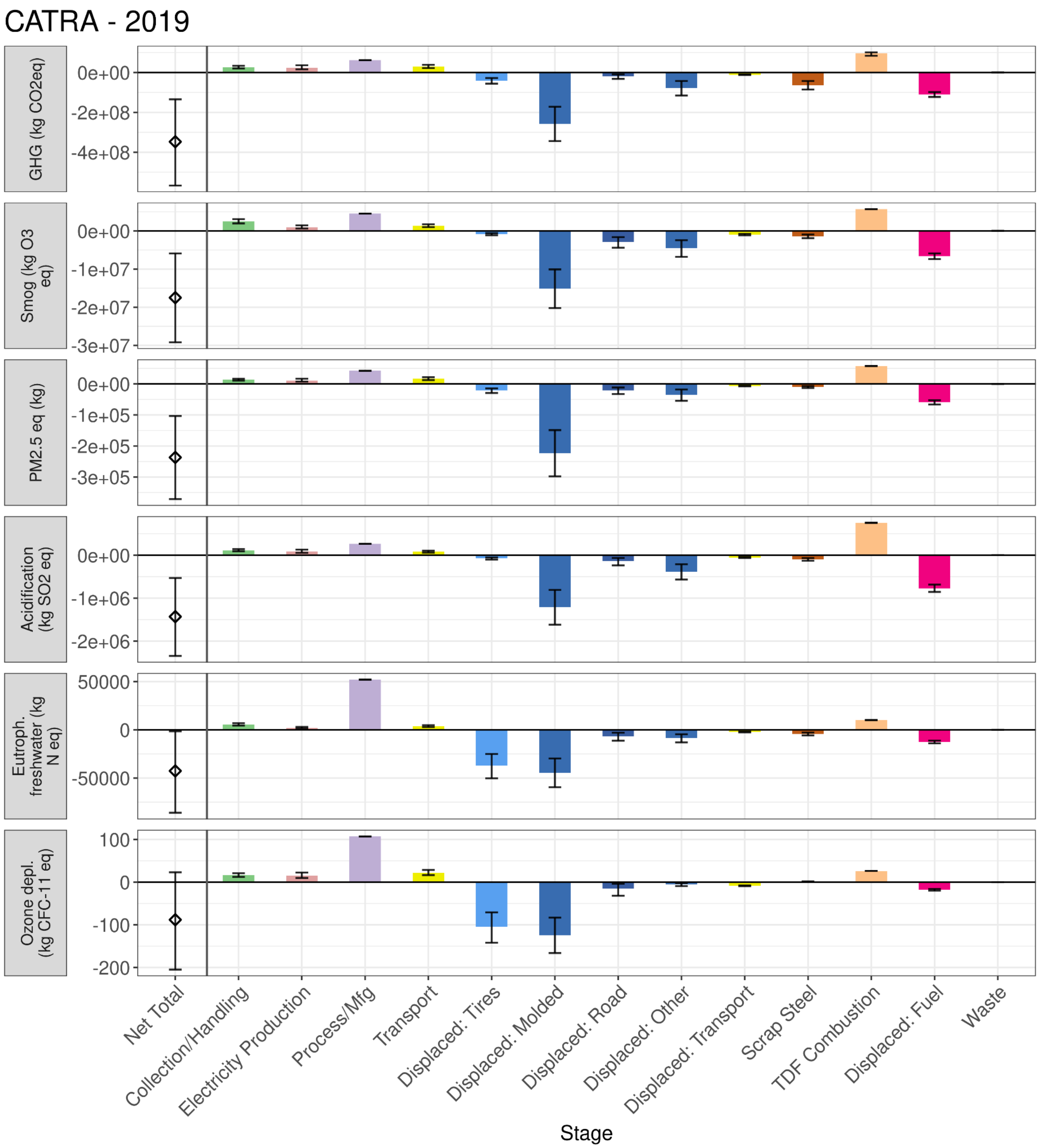

Figure 8 - Stage contributions to country-wide environmental impact indicator scores for managing 415 kt of scrap tires in Canada during 2019. Diamonds show the "net" impact score for each indicator. Negative bars show potentially avoided impacts of the displaced product (Table 3.18). Error bars include the combined result of foreground sensitivity (Table 4.2) and displacement sensitivity. Colored bars show contributions by stages in the tire recycling system.

4.3 Results per Tonne of Tires Processed

The impact category scores for different recycling routes are shown in Figure 9 as a set of stacked bars. Impacts of 21 different routes are shown per tonne of tires processed, in terms of 6 different categories. The different life cycle stages are shown as bar segments. In general, the routes that displace virgin rubber or new tires show consistent and robust benefits. Fully disaggregated results for each route are shown in the Tabular annex, and detailed graphical results for each route are shown in Appendix D.

The chart allows for the reader to compare different options for tire recycling on a consistent basis– the treatment of a tonne of scrap tires. On this chart, the absolute height of each bar indicates emissions that are attributable to the selected processing route, and thus are expected to happen, if a tire is processed using that route. The diamond indicates the “net effect”, which is the processing emissions *minus* the potentially avoided emissions from displaced production. The error bars around the diamonds indicate the range of likely outcomes considering the sensitivity parameters in the model (Tables 3.18 and 4.2).

The eutrophication and ozone depletion categories are dominated by the avoided burdens of displaced new-tire production, which is modeled using the USEEIO database. This observation is discussed in Section 4.4.1 below; however, the scores appear to be correct.

Reuse, culls displacing new tires
If culled tires are returned directly to use, then this route provides a very effective route to potential impact reductions because the burdens associated with new tire production are significant. However, the re-use of culled tires carries risks because the service history of the tire is not known.

Retread, displacing new tires
Displacement of new tire production leads to significant benefits for remanufactured (i.e. retreaded) tires. The most substantial incurred impact during retreading is the production of the replacement tread. The retread route shows net improvement in five of six categories (smog is essentially even), although the improvement in acidification is marginal.

Devulcanization, displacing primary rubber
The devulcanization process modeled here does not produce a perfect substitute for virgin rubber. However, the mechanical properties are such that it could replace up to 10% of the rubber in a product. One possible application would be use in tires.

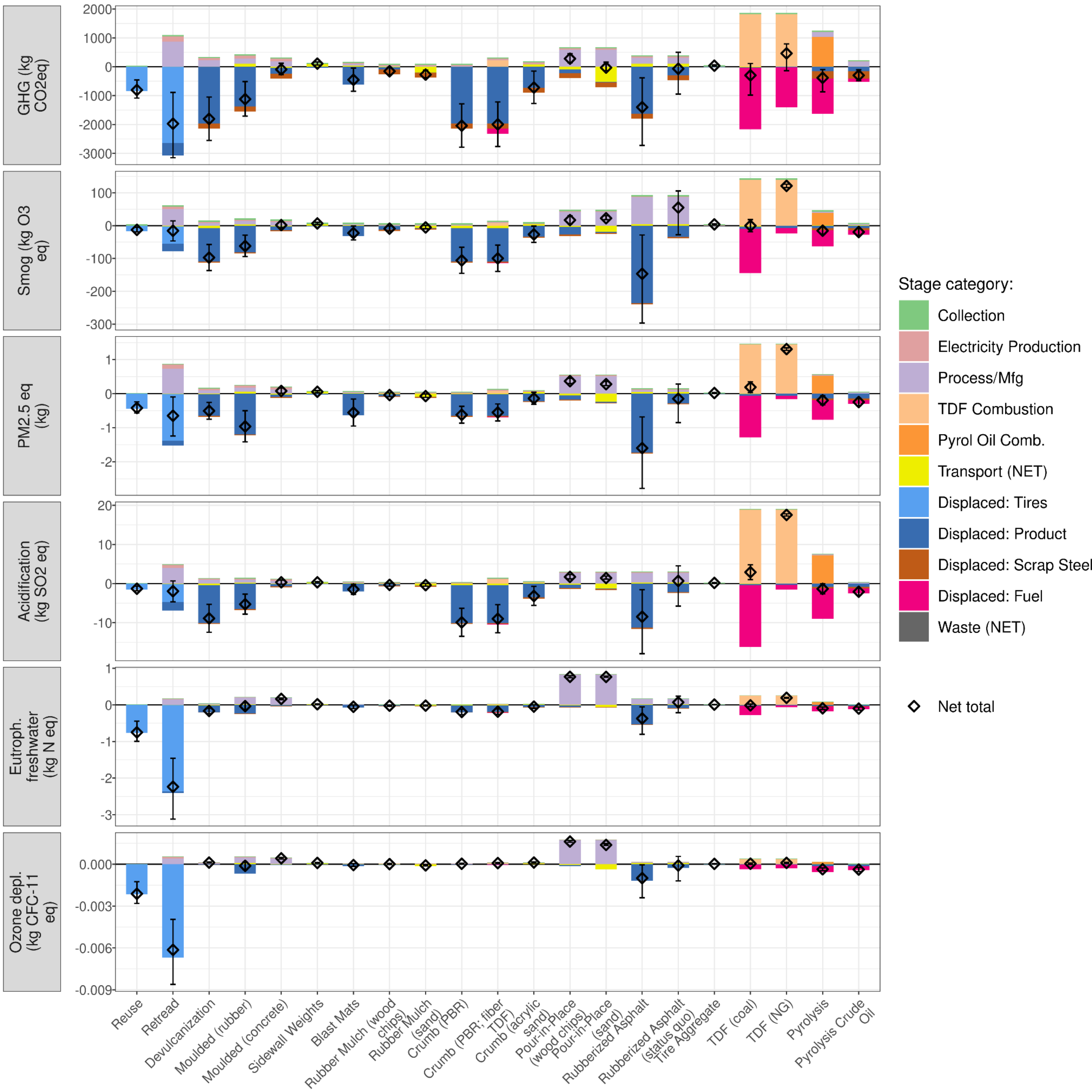

Figure 9 - Impact category scores per tonne of scrap tires for different management routes. Diamonds show the "net" impact of each route. Negative bars show potentially avoided impacts of the displaced products. Error bars include the combined result of foreground sensitivity (Table 4.2) and displacement sensitivity (Table 3.18). Each route uses national average grid electricity. Detailed charts for each route are provided in Appendix D.

Assuming the devulcanized rubber does displace polybutadiene rubber (BR), this route has net-negative impact scores in five of six categories. For ozone depletion, the displaced BR production process has nil impact, so there is no displacement benefit. For GHGs, Smog, and Acidification, devulcanization is among the best performing routes.

Molded rubber, displacing primary extruded rubber or concrete
This route represents the production of molded products from crumb rubber with binder and heat. Although this process has high energy requirements, they are matched or exceeded by the impacts of producing the binder, which makes up less than 4% of the mass of the finished product. Still, molded tire-derived rubber shows a substantial net benefit across every category when compared to extruded primary EPDM rubber.

Concrete is made with cement, which has notably high emissions; however, the quantity of cement in the concrete mix modeled is low enough that the potentially avoided emissions are of the same order as the incurred process emissions, leading to a slight potential improvement on global warming, and increased impact scores in other categories.

Sidewalls, displacing gravel silage weights
Tire sidewalls are very inexpensive to produce; however, they must be shipped to a location where they are useful. This study assumes that tire-derived silage weights displace gravel bags, and that gravel is shipped a comparatively shorter distance. Consequently, this route has negligible benefits and results in a small net increase in all impact categories.

Blast mats, displacing steel blast mats
Tire-derived blast mats are the conventional choice in many cases. The alternative system, steel wire blast mats, is lighter per area covered (and thus easier to handle) but has shorter longevity. In the comparison between tire-derived mats and steel mats, the tire-derived mats are beneficial in all six categories.

Mulch, displacing wood chips or sand
Rubber mulch used in land cover results in marginal improvements in all categories. This route reflects pessimistic assumptions about the impacts of production: mulch production is modeled as identical to crumb, due to a lack of facility data to disaggregate these two activities.

Crumb, displacing primary rubber
This route reflects the use of tire-derived crumb in products in place of primary rubber, including tire-derived crumb displacing virgin crumb for infill. The polybutadiene process selected for displacement has high impact scores, leading to a higher net benefit for this route. If crumb displaces a lower-intensity material, the benefits will be reduced.

Crumb, displacing acrylic-coated sand infill
Because the use of tire-derived crumb for turf infill is in fact “business as usual” for the market, we applied a weaker economic displacement assumption to this product case (20-80%, 50% median). Even with this assumption, tire-derived crumb rubber has lower impact scores than acrylic-coated sand because acrylic production has high impact intensity.

Pour-in-place, displacing wood chips or sand
Pour-in-place uses appear to be unfavorable in most or all impact categories, almost entirely driven by the impacts of binder production. The only marginal case is in the global warming indicator for the pour-in-place displacing sand route, where the emissions from binder production are balanced by significant avoided transportation of sand.

In the case of pour-in-place displacement, the assumption that tire-derived products last longer than the displaced product is strong because the product is installed in a more permanent fashion.

Crumb in rubber-modified asphalt
Rubber-modified asphalt also shows significant advantages, but only under the assumption that roads produced with rubber-modified asphalt have longer service life. If road service life is assumed to stay the same (“status quo”), the advantage vanishes, and smog and eutrophication impacts are likely to increase.

Smog impact scores from rubber-modified asphalt are attributable to our modeling assumptions regarding the use of a substantial amount of diesel fuel to heat the mixture of bitumen and crumb rubber (see Section 3.5.13). If this amount of fuel use is not required, or if cleaner fuels are used, the incurred burdens for rubber-modified asphalt would be reduced.

TDA, displacing gravel
Tire uses that displace gravel (TDA, sidewalls) show negligible benefits and impacts. Shred requires minimal processing to produce but also has minimal potential benefits, because gravel also has relatively low impact scores.

TDF, displacing coal or natural gas
TDF combustion resulted in a small improvement in global warming, and net increases in impact in the other five categories under the base case assumption of displacing 90% coal; zero out of six categories showed improvement in the TDF-natural gas variant. TDF fuels with a higher mix of biogenic carbon (up to 45%) are indicated by the more-negative end of the sensitivity range; these conditions show more favorable performance with respect to global warming. On balance, TDF appears to be only a marginally beneficial route for tire disposal.

Pyrolysis
There are two routes modeled: In the “Pyrolysis” route, the pyrolysis oil is used as a fuel, and displaces combustion of fuel oil; in the “Pyrolysis Crude Oil” route, the pyrolysis oil is used as a refinery feedstock, and displaces production of crude oil. The two pyrolysis routes show modest net benefits in each of the 6 main impact categories. These benefits arise primarily because of the potentially avoided manufacture of carbon black (due to the recovered pyrolysis char), and the recovery of steel. For GHGs, the biogenic carbon content of tires also results in lower impact from combustion, compared to fuel oil. Higher biogenic carbon fractions up to 45% are also indicated by the more-negative end of the sensitivity range. For Eutrophication and Ozone depletion, the net benefit is primarily due to the pyrolysis process having lower impact scores than fuel oil mining and refining.

4.4 LCIA Data Quality Evaluation

The validity of the LCIA phase was checked using several methods. We compared impact categories using three different LCIA implementations:

- The TRACI 2.1 reference characterization factors, dating from 2012;
- A more recent TRACI 2.1 implementation that was distributed with USEEIO 1.1;
- ReCiPe 2016, as implemented in the OpenLCA reference LCIA methods pack.

First, we compared the list of *flowables* (substances by name, CAS number, or other identifier, that could be emitted into many environmental compartments) characterized by each method to identify flowables represented by different names (e.g. “nitrous oxide” is a synonym for “dinitrogen monoxide”). Although the complete set of flowables characterized is very large, we were able to establish that the most important substances were equally represented in all methods. Second, we compared the list of flowables *characterized* by the methods to the substances actually *emitted* by processes from different data sources, ensuring that the same emissions from each dataset were found to contribute to impact scores across the different methods. Finally, we computed unit impact scores for the different tire processing routes across all three methodologies. Five of the six indicators shared the same reference unit and could be compared directly; these are shown in Figure 10 below.

For the categories of global warming and ozone depletion, the indicators were nearly identical, and for acidification they were very close. For particulates, all three methods characterize PM2.5 as the reference unit, but in TRACI, emission factors for non-particulates were generally lower, i.e. for nitrogen oxides were 0.00722 kg PM2.5eq/kg and sulfur oxides were 0.0611 kg PM2.5eq/kg; these same factors in ReCiPe were 0.11 and 0.29 respectively. The results were similar for other compounds. This discrepancy should be kept in mind when comparing particulate emission results from this study with studies using the ReCiPe methodology.

For Eutrophication, ReCiPe implemented two different methods: marine eutrophication, measured in kg N-equivalent, and freshwater eutrophication, measured in kg P-equivalent. As noted above, TRACI included both “terrestrial” (i.e. emission to air) and freshwater eutrophication, both measured in kg N-equivalent, which we added together. Figure 10 shows the comparison of the kg N-equivalent methods, but the discrepancy is likely due to their different scopes.

For the category of Smog (ozone creation), the TRACI methods used kilograms of O_3 equivalent, while ReCiPe used kg NOx equivalent, so the indicators could not be compared directly. Further, ReCiPe reported smog in two different categories (human health impacts and ecosystem impacts). We found that many flows were characterized by both systems, but some were found only in one and not the other. TRACI (1,173 factors), run on an ecoinvent process, characterized 82 distinct substances, whereas ReCiPe (638 factors) characterized only 65; of these, 47 substances were common to both methods. The fourth-largest contributor to ReCiPe was unspecified non-methane volatile organic chemicals, which did not have an analogous TRACI factor. This flow accounted for 15% of the ReCiPe score for a typical ecoinvent process; however, this “substance” is not characterized with sufficient detail to evaluate its veracity. In the end, we trusted the TRACI method to be appropriately implemented.

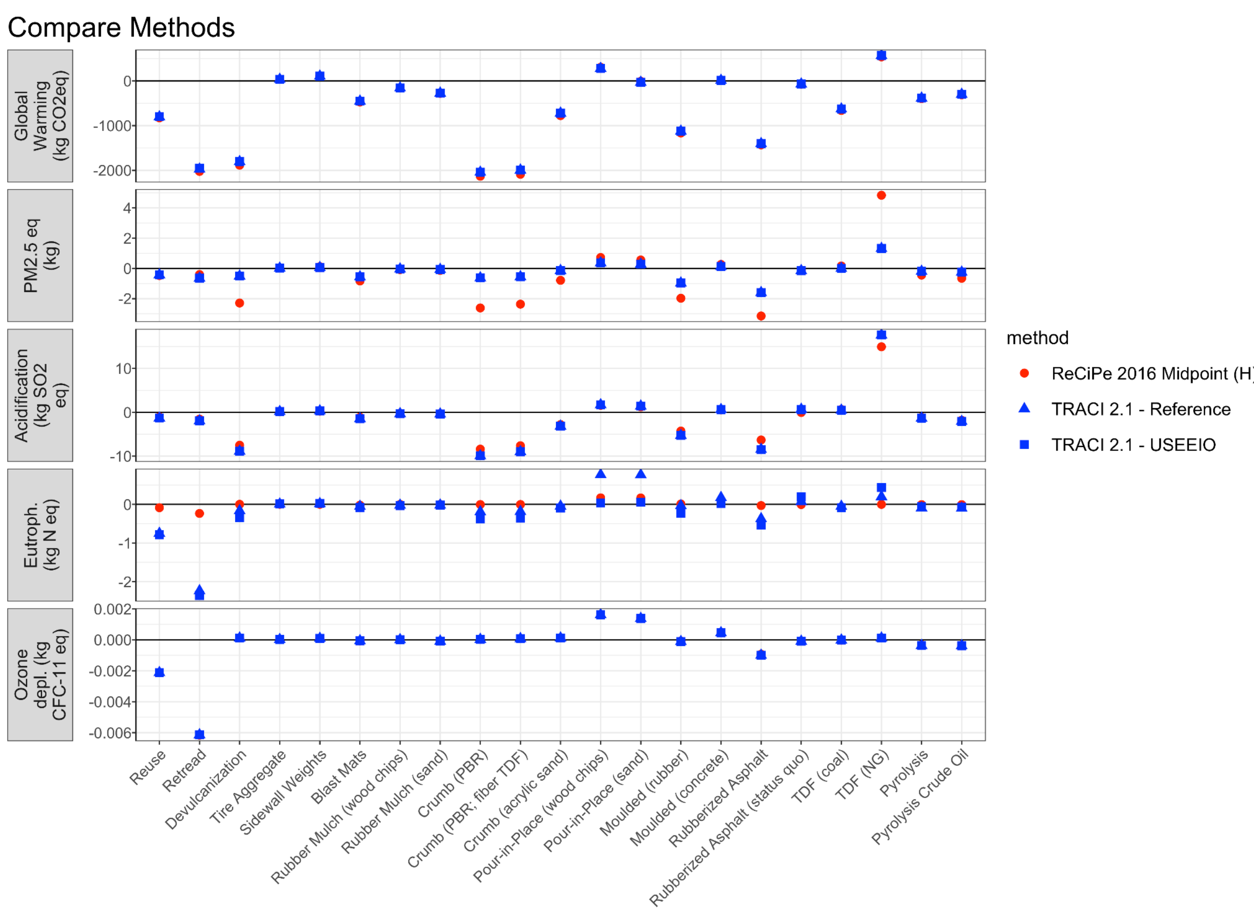

Figure 10 - Comparison of unit impact scores for different LCIA methodologies.

4.4.1 Eutrophication and Ozone Depletion

Displaced production of new tires, which is modeled using the USEEIO database, dominates the Eutrophication and Ozone Depletion indicators in Figure 9. This could be due to differences in flow coverage between the USEEIO and ecoinvent databases; however, inspection of the flow lists found general agreement between the characterized flows that were encountered in the two datasets. Specifically: flowables accounting for 99% of both Ozone Depletion and Eutrophication impact scores in the USEEIO process were affirmatively assessed in both the USEEIO and ecoinvent inventories, implying that the difference could not be caused by inconsistencies in flow lists. Nitrous oxide, which alone accounted for 85% of the USEEIO ozone depletion score, was in ecoinvent (this characterization was added to the TRACI ozone indicator); the only substance contributing more than 1% of the USEEIO score that was not found in the ecoinvent result was CFC-114, which contributed 1.8% to the score and which we could not find in the ecoinvent inventory. For eutrophication, the question was simpler, as the method only characterized 14 flowables, of which 13 were found in ecoinvent and only 7 were found in USEEIO.

Thus, the implication is that the higher scores for USEEIO result from a combination of the following: the broader scope of the USEEIO database; different data quality standards for the USEEIO database for flows relevant to ozone depletion and eutrophication; or authentically higher impacts in these categories for this activity.

4.4.2 Toxicity Screen

We review the toxicity indicators from the TRACI and ReCiPe methodologies to identify key focal points in the study regarding human health and ecotoxicity. Figures 11 and 12 show human health and ecotoxicity impact scores for each tire processing route, with uncertainty from the sensitivity studies. In general, we found the TRACI Reference and ReCiPe methods to be very closely correlated. The TRACI USEEIO method omitted metal characterization factors, thus allowing for easier detection of hotspots for non-metal emissions.

Human Health - Cancer

- Chromium emissions alone accounted for greater than 80 percent (and often greater than 95%) of toxicity impacts in the TRACI and ReCiPe human health-cancer indicators; thus, the indicators were effectively a screen for chromium emissions.
- The processes with the highest avoided chromium emissions per tonne of tires were avoided steel wire production for displaced steel blast mats (blast-mats route), avoided road construction (rubberized asphalt route), avoided coal combustion (TDF route), and avoided rubber production (molded route)
- The only route with notable incurred chromium emissions was retread, with the emissions attributed to new tread production.
- The TRACI USEEIO indicator, which omitted metal characterizations, was dominated by formaldehyde emissions in every route.

- Binder production, used in pour-in-place and molding routes, caused significant formaldehyde emissions.
- The only process with significant avoided formaldehyde emissions was new tire production from the USEEIO database. Meanwhile, the new tire production process was undetectable in the TRACI Reference and ReCiPe methods, probably due to omission of metals.

Human Health - Non-cancer

- TRACI Reference non-cancer results were also dominated by metals, including zinc, lead, mercury, vanadium, antimony, barium, and a few others. Zinc was the most significant, often accounting for roughly 50% of impact scores.
- In ReCiPe, zinc was still prominent but arsenic and antimony were more pronounced.
- The disposal of tire-derived fiber waste to landfill was a hotspot for non-cancer impacts; this may not be reflective of actual conditions (i.e. emissions of heavy metals may be inaccurately attributed to disposal of tire-derived waste in landfill)
- When zinc emissions from TDF combustion are included, they overwhelm all other contributions in the TRACI Reference method. They are discernible but far less significant in the ReCiPe method.
- Using the TRACI USEEIO indicator (i.e. excluding metals), scores were dominated by emissions of acrolein, carbon disulfide, and nitrobenzene. Hotspots were again the production of polyurethane adhesive (i.e. binder) for the molded and poured routes.
- Displaced production of new tires also showed large avoided impacts in TRACI USEEIO, but again did not register under the TRACI Reference or ReCiPe methods.

Eco-toxicity

- ReCiPe included terrestrial, freshwater, and marine ecotoxicity methods; TRACI only included freshwater toxicity. The diversity of indicators (TRACI Reference with metals; TRACI USEEIO without metals; three ReCiPe indicators) made it difficult to generalize the results.
- Results were not dominated by any single compounds, but methods that included metals were still dominated by metals scores (chromium, vanadium, antimony, copper, zinc, nickel)
- Avoided transport was a hotspot for ReCiPe terrestrial ecotoxicity methods.
- Aside from transport, major incurred emissions arose from electricity production in all routes, dimethyl sulfide production (devulcanization route), rubber production (retread route), and polyurethane binder production.
- Impacts from electricity production can be attributed to metals extraction during the construction of the electric grid. This same observation applies to many avoided ecotoxicity impacts from displaced production (which also utilize the electric grid).
- Excluding metals (using TRACI USEEIO), some notable flows were sulfuric acid, phenol, formaldehyde, cyanide, aniline, nitrobenzene, and pesticides.

- The pesticides only appeared in the displaced new-tires production (USEEIO) inventory, where they swamped out all other contributions.
- Hotspots when metals are excluded are similar to the other categories: polyurethane binder production (poured and molded routes), dimethyl sulfide production (devulcanization), and synthetic rubber production (retread).

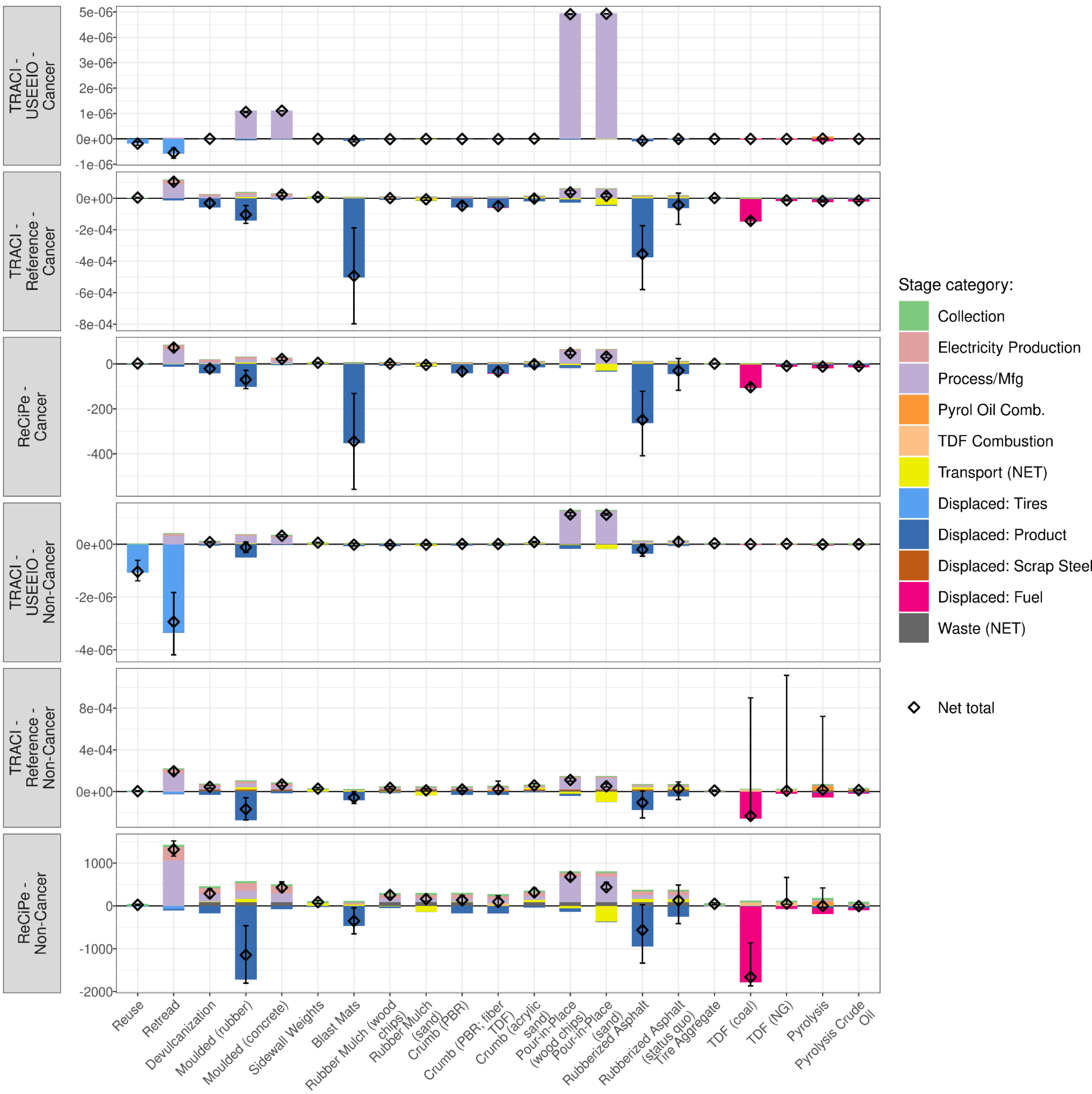

Figure 11 - Human health indicator results used in the toxicity screen. The TRACI-USEEIO method excludes metal flows, which dominate the other two methods. The long error bars

visible in the TDF case under TRACI Reference / non-cancer are attributable to the sensitivity test for zinc emissions.

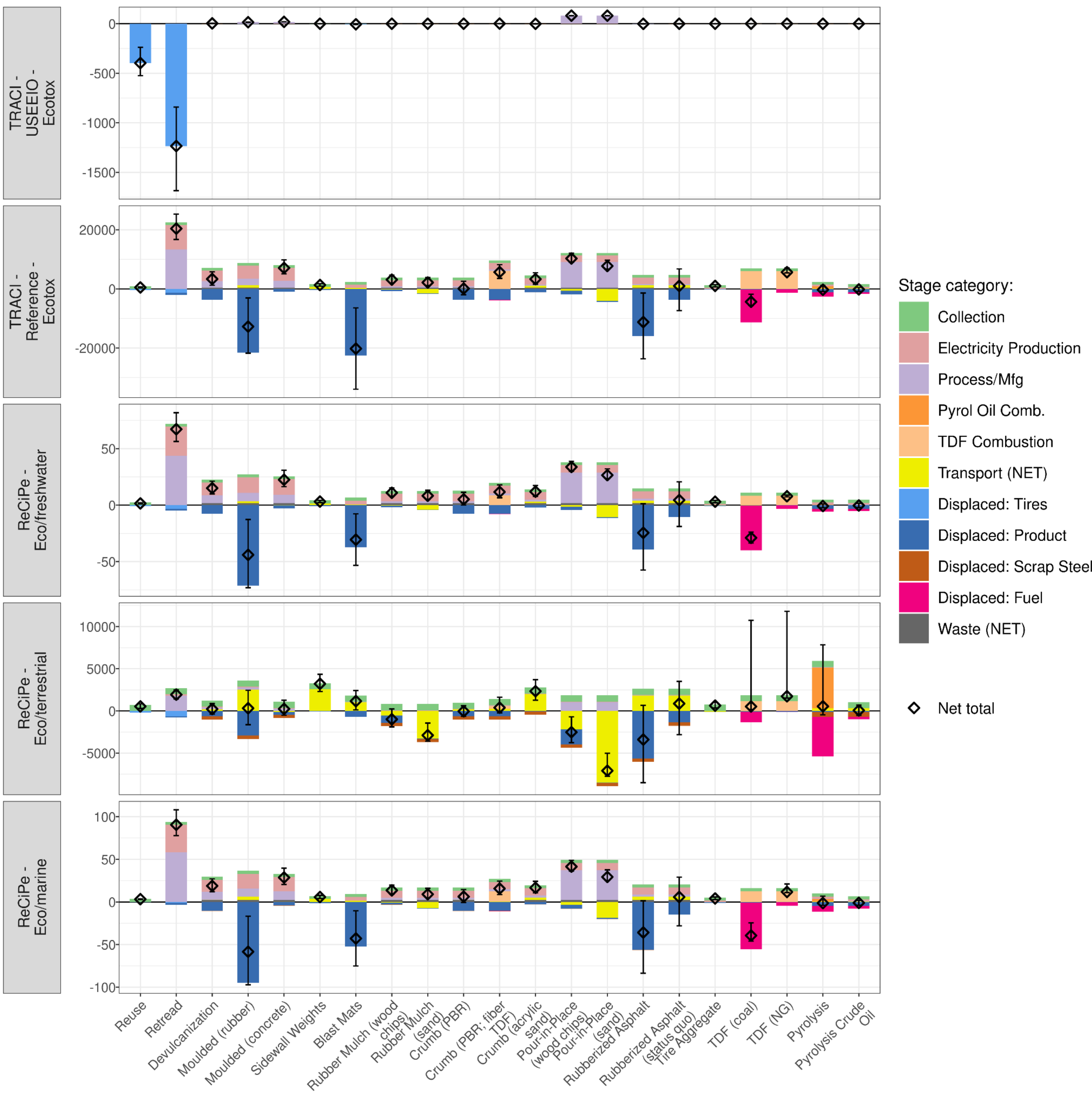

Figure 12 - Ecotoxicity category indicator results used for the toxicity screen. The TRACI USEEIO method excludes metal flows, which dominate the other two methods. Long error bars in the TDF cases are attributable to the sensitivity test for zinc emissions.

5 Life Cycle Interpretation

This study was designed and carried out to provide a structured life cycle framework to estimate the potential environmental implications of scrap tire recycling in Canada and provinces thereof.

The study scope is defined to allow comparison of the incurred impacts of tire recycling on the one hand (impacts of the Recycling system), and potentially avoided impacts on the other (associated with the Displacement system).

5.1 Identification of significant issues

The following items should be kept in mind when reviewing the results:

- The scrap tire management system has the capability to reduce environmental impacts through the displacement of primary production. The extent of the environmental benefit depends on how much primary production is actually avoided.
- The choice of inventory models for describing displaced primary rubber in ecoinvent is limited to extruded EPDM rubber and unspecified polybutadiene rubber (PBR). These inventories are provided with minimal documentation and may not be representative of all cases in which tire-derived materials (crumb rubber, molded products, devulcanized rubber) are used as feedstocks. Ecoinvent's PBR process model is more GHG-intensive than the extruded EPDM model.
- Production of binder, assumed to be about 3.5% of molded products by weight (as 95% polyurethane, 5% latex) and 14% of pour-in-place products (as 100% polyurethane), was the largest contributor to incurred impact scores in the product systems in which it was used.
- Polyurethane binder production was also an important hotspot for toxicity impacts. Use-phase toxicity impacts of polyurethane binder (nor any tire-derived products) were not evaluated.
- Use of tire-derived aggregate in civil engineering projects, one of the most common end-use for tires in some regions, had very small impact scores and negligible benefits.
- Scrap steel recycling provided a nominal benefit to all routes that produced scrap steel, but this benefit was generally exceeded by the contributions of other materials.
- Impact scores from collection and material handling were small.
- Use of crumb rubber as an asphalt modifier has the potential to generate significant benefits from prolonged roadway life, but has little advantage if roadway life is not prolonged.
- The benefits of steel scrap recycling are most significant in the climate change and human toxicity categories. Note that these benefits do not apply when the steel scrap is stockpiled, so it is important to ensure that recovered steel is delivered to the scrap market.

5.2 Evaluation - Completeness and Consistency

The study included all relevant flows, subject to the exclusions and limitations discussed in Section 2.2. In particular, gate-to-gate inventory requirements during scrap tire collection, processing, and tire-derived product manufacturing, were modeled using all available information. The impacts of production activities were modeled based on primary data provided by tire processing facilities in the scope of the study.

The consequential system expansion method that is used is intended to show the potential implication of a policy or decision. In this case, the decision is about how to recycle tires, and what policies (if any) to use. As a consequence, the models in the Displacement system are “cradle-to-marketplace”, representing the activities that would be different if the tire were not recycled.

LCIA results were closely reviewed for completeness and consistency (Section 4.4). A range of toxicity impact category scores was reviewed to screen for important toxicity hot spots (Section 4.4.2). Quantitative toxicity assessment is unreliable, especially when using a combination of inventory data sources, but the screening approach we used allowed us to identify potential areas of concern qualitatively.

One area of inconsistency is the amount of material sent to disposal from tire recycling activities. The materials flows reported by processors contained a very small flow of material to disposal. The facility survey data for crumbing (Table 3.10) suggested that 10% of mass was recovered as tire fibers, and a further 10% was waste; however, these observations are not consistent with the material flows reported at the provincial scale. At the same time, there is a substantial difference between reported collections and reported products (57.0 kt of “missing mass”, see Tables 3.4a and 3.4b). It is possible that some of this mass is waste disposed to landfill, and that the impacts from landfill are likely underestimated.

5.3 Evaluation - Sensitivity

Sensitivity of the study results was analyzed with respect to four different perspectives.

1. Impacts were modeled according to a wide range of possible displacement relationships, including multiple potentially displaced products per tire-derived product (e.g. wood chips or sand for mulch; molded rubber and concrete; coal and natural gas).
2. Key parameters determining the resource intensity of processing activities were varied (including electricity, diesel fuel, propane, and transport distance).
3. The displacement relationship was varied for every displacement route, to account for uncertainty in the economic relationship between tire-derived products and potentially displaced products. In the most typical case, economic displacement ranged between 50-100%, with median results reporting a 75% displacement rate (i.e. one tonne of tire-

derived products displaces 750 kg of primary products, while growing the market for those products by 250 kg).

4. Key parameters relating to TDF combustion, including the emission of zinc during combustion, the biogenic carbon fraction of passenger tires, and the type of energy displaced, were also varied.

The results of the sensitivity analysis are as follows:

- The results of the study were robust to sensitivity analysis, showing that even with pessimistic assumptions regarding displacement and processing impacts, a net reduction in environmental impact scores was still likely in many cases.
- The net impacts of tire-derived fuel depended strongly on what type of fuel was being displaced. TDF displacing natural gas did not result in any environmental benefit.
- Some displacement relationships were notably superior to others: molded rubber displacing primary rubber was beneficial, but displacing concrete was disadvantageous. Rubber-modified asphalt was beneficial if roadway service life was lengthened, but not beneficial otherwise.

5.4 Limitations

We identified the following limitations to the study results:

- The study did not include an economic analysis of the potential market demand for tire-derived products. Products made from recycled materials can only provide environmental benefits if they are fulfilling a market demand in a manner that replaces primary production. Although we tested the sensitivity of our results to lower displacement rates, only market research can reveal whether specific tire-derived products can displace competing products made from primary materials.
- Our national-scale result assumes that a molded rubber product made of recycled material displaces a virgin rubber product 9 out-of-10 times (and a concrete one 1/10). This mix is based on information about molded rubber products produced in Ontario in 2017.
- Unit-scale (tonne-of-tires) results do not take into consideration the size of the potential market for the tire-derived products being produced.
- Results for Pour-in-Place surfaces and Molded products do not include an explicit uncertainty treatment for the amount of binder required.
- Pyrolysis and devulcanization models were based on laboratory-scale studies rather than production facilities. They may thus be unrepresentative of larger-scale operations.
- The impacts of rubber-modified asphalt production can be expected to vary widely over different roadway construction specifications and use cases. The model we constructed was based on the highest-quality data we could find, but it is not clear how closely the modeled case resembles actual conditions in the US or potential conditions in Canada. Further research in this area is warranted.

- The results presented in this report use a national average electricity mix in each processing route (see Section 3.3 for details of the scrap tire processing models). The uncertainty treatment does not include heterogeneous electricity mixes, in which some places at some times have an electricity mix that is considerably different than the national average). Provincial mixes will be used in the special reports for each province.
- The assumptions about playground surfaces represent rules of thumb for material depths and lifetimes. Different surfaces can present different risks/protection. Nonetheless, rates of injury due to different playground/sports surface are not included.

5.5 Overall Data Quality Evaluation

The results of this LCA study depend on a wide range of data sources, including:
- primary data describing the collection and fate of scrap tires in the province;
- primary data describing the operation of scrap tire processing facilities;
- data describing the combustion of tire-derived fuels, adapted from life-cycle inventory databases;
- secondary data from life-cycle inventory databases describing the operation of vehicles and equipment, generation of electricity, and other background processes;
- secondary data from life-cycle inventory databases describing the potentially avoided production of products displaced by tire-derived products;
- secondary data from an economic input-output database describing the production of new tires;
- observations, assumptions and expert judgments regarding the relationships between tire-derived and displaced products;
- life cycle impact assessment methodologies implemented by domain specialists.

Overall, the data quality of the inventory model is judged to be high and representative of the system under study.

- The primary data to describe key foreground processes is of very high quality and is judged to be highly representative of the scrap tire management system.

- Combustion processes for tire-derived fuels are based on proxy datasets for combustion of coal in a furnace and polyethylene terephthalate in an incinerator. No primary data was available to describe these processes. However, the processes were adapted to be consistent with key characteristics of the fuels, notably, fossil and biogenic carbon content, and energy content. We judge the proxy data to be adequate to support the conclusion, which is that the use of tires for TDF is not recommended.

- The use of EPDM rubber to represent the production of new treads in the tire retreading process is a low-quality proxy. This data set selection should be improved in a future investigation.

- Secondary datasets describing avoided production were carefully selected based on our understanding of the products being displaced. In most cases the selected datasets were suitable; however, there is a lack of suitable data describing the production of primary synthetic rubber, and no data describing the production of primary natural rubber. The proxy datasets we selected to model displaced rubber included extruded EPDM rubber, used to describe displaced molded products, and PBR rubber, used to describe displaced crumb rubber. Each of these data sets is suitable in some situations but not others. We judge these data sets to be adequate to support the conclusions, which are that both tire-derived crumb and tire-derived molded products are likely to have lower impacts than displaced primary rubber. However, this conclusion may not apply in all cases and is deserving of future investigation. The US LCI process for PBR rubber could be considered as a sensitivity case. Its unit impacts are lower than the ecoinvent process in 5 of 6 categories, including 43% lower global warming potential, but 200% higher ozone depletion potential.

- Secondary data sets were selected from a range of databases, primarily including ecoinvent but also including US LCI and the USEEIO database (see Section 2.2.6). These databases are prepared with differing practices and modeling assumptions. In particular, results that depend on displaced production of new tires (the culling and retread routes) may not be comparable to the results for other routes. In particular, the USEEIO database appears to report systematically-higher Nitrogen oxide emissions than the ecoinvent database, leading to higher scores in the ozone depletion and eutrophication categories for USEEIO processes.

- Sensitivity to uncertainty in observations, assumptions, and expert judgments were captured through sensitivity analysis, as detailed in Section 5.3.

- Data quality assessment of life cycle impact assessment methodologies is detailed in Section 4.4.

5.6 Conclusions and Recommendations

We have completed an LCA of the scrap tire management system in Canada. The overall quality of the data used in the model is good, and the goal of the study was met. In general, the impact indicator scores of recycling scrap tires are small compared to the potentially avoided impacts of some primary products. If tire-derived materials displace primary materials in the market, there are many cases in which a significant avoided burden could be realized.

- It is likely that tire-derived products from the Canadian scrap tire management system resulted in avoided emissions through displaced production of primary rubber. All six impact category indicators showed a net improvement that was robust to sensitivity analysis regarding the displacement rate.

- For global warming, smog, particulates, and acidification, the magnitude of avoided impacts was probably at least twice the magnitude of incurred impacts. For eutrophication and ozone depletion, the magnitude of avoided impacts was probably about one and one half times the magnitude of incurred impacts.

- The largest contributor to impact scores in the scrap tire management system was combustion of PLT tires as TDF, followed by production of polyurethane binder used in molding and pour-in-place applications. Other important stages varied by impact indicator but included reverse logistics, diesel combustion, and combustion of tire-derived fiber.

- Of the 21 options modeled, 17 result in net negative GHG impact indicator results, meaning scrap tire management potentially reduces emissions for these use options (See Table A.2).

- The five modeled processing routes with the greatest potential for reducing GHG impacts included crumb rubber replacing PBR, retread, devulcanization replacing PBR, rubber-modified asphalt with roadway service life extension, and molded rubber replacing extruded EPDM.

- For TDA (replacing mined aggregate) and Sidewalls used as weights (displacing gravel-in-bag weights), the net result is very close to zero.

- For TDF displacing coal, the effects on global warming are slightly beneficial, while impacts are increased in the other five categories. This result arises from a model adjustment that corrects for the efficiency of displaced coal combustion; prior to the correction, TDF displacing coal showed a net benefit in three out of six categories. For TDF with a high proportion of biogenic carbon, the global warming impact is somewhat more favorable. For TDF displacing natural gas, no improvement is obtained.

- Both molded and pour-in-place processes require the use of a binder. Although the precise binder used may vary by manufacturer, this study used a polyurethane binder compound that was highly toxic and impact-intensive to produce. Molded and pour-in-place product manufacturers should assess their selection of binder.

- Large discrepancies between the amount of tires collected and the amount of tire-derived products produced were found in the material flow data. Provincial organizations should attempt to ensure that input and output mass reported by their processors is consistent and accounts for changes in stock of materials at the facilities.

- The possibility of zinc emissions from TDF combustion facilities should be investigated. In many cases, such as cement kilns, it is likely that most zinc is retained within the cement, but even a low emission rate can cause substantial toxicity harm.

- Devulcanization appears to show promise as a highly circular route to retain the value of tire-derived rubber. However, more study is needed to determine whether laboratory-scale parameters used in this study are an adequate proxy for commercial-scale devulcanzation.

- Pyrolysis performs better than conventional TDF in 4 of 6 impact categories when TDF displaces coal, and substantially better than TDF displacing gas (all categories). Pyrolysis of tires with a higher fraction of natural rubber (i.e. OTR tires) is likely to be moderately more beneficial than pyrolysis of PLT from a GHG perspective.

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Appendix A: Tabulated Results

Table A.1 - Contribution analysis of national-scale impact category indicator scores.

	Global Warming	Smog Air	Particulates	Acidification	Ozone Depletion	Eutrophication
	kg CO2 eq	kg O3 eq	PM2.5 eq	kg SO2 eq	kg CFC-11 eq	kg N eq
Primary rubber, in molded product, displaced	-2.55E+08	-1.50E+07	-2.22E+05	-1.20E+06	-1.24E+02	-4.42E+04
Heat, coal, cement kiln, displaced	-1.03E+08	-6.55E+06	-5.90E+04	-7.63E+05	-1.63E+01	-1.23E+04
Steel, displaced	-6.41E+07	-1.42E+06	-9.78E+03	-9.64E+04	1.31E+00	-4.32E+03
Primary rubber, displaced	-4.26E+07	-2.19E+06	-1.37E+04	-2.09E+05	-5.19E-01	-3.94E+03
Production of new tire, displaced	-4.11E+07	-8.37E+05	-2.16E+04	-7.28E+04	-1.04E+02	-3.69E+04
Mineral infill, displaced	-2.16E+07	-9.95E+05	-6.42E+03	-1.05E+05	-5.96E-02	-1.79E+03
Road construction, avoided	-1.84E+07	-2.78E+06	-2.00E+04	-1.26E+05	-1.25E+01	-6.07E+03
Transport, Displaced	-1.25E+07	-9.98E+05	-7.15E+03	-5.58E+04	-9.10E+00	-2.32E+03
Production of steel blast mat, displaced	-8.70E+06	-4.51E+05	-8.94E+03	-2.85E+04	-1.92E+00	-1.06E+03
Heat, natural gas, cement kiln, displaced	-7.44E+06	-9.03E+04	-5.74E+02	-6.58E+03	-1.53E+00	-2.87E+02
Concrete product, displaced	-3.24E+06	-1.87E+05	-1.25E+03	-8.87E+03	-5.24E-01	-4.05E+02
Gravel, displaced	-2.92E+06	-3.81E+05	-3.05E+03	-1.95E+04	-1.45E+00	-8.17E+02
Wood chips, displaced	-1.62E+06	-2.77E+05	-1.43E+03	-1.02E+04	-9.03E-01	-5.62E+02
Bitumen binder, displaced	-1.28E+06	-1.10E+05	-9.66E+02	-1.12E+04	-2.43E+00	-5.11E+02
Iron ore, in cement kiln, displaced	-5.78E+05	-1.90E+05	-1.64E+03	-9.18E+03	-4.38E-01	-3.76E+02
Sand, displaced	-2.46E+05	-3.36E+04	-3.13E+02	-1.57E+03	-1.12E-01	-6.80E+01
Gravel bag, displaced	-6.88E+04	-5.34E+03	-5.43E+01	-3.27E+02	-2.18E-02	-1.14E+01
Electricity Production CA-NF	5.38E+02	4.25E+01	3.40E-01	3.72E+00	9.73E-04	9.44E-02
Electricity Production CA-MB	4.65E+04	2.27E+03	1.34E+02	1.86E+02	1.03E-01	4.92E+00
Waste, Tire-derived, to Landfill	4.67E+04	6.39E+03	4.15E+01	2.76E+02	3.23E-02	1.38E+01
Processing, Pour in Place	1.35E+05	9.52E+03	1.17E+02	6.16E+02	3.91E-01	1.89E+02
Processing, Mulch	1.74E+05	4.44E+03	2.86E+01	2.48E+02	4.49E-02	1.15E+01
Transport, Sidewalls, Tubes, other	2.52E+05	1.16E+04	1.43E+02	7.04E+02	1.89E-01	3.19E+01
Steel, in Blast Mats	4.17E+05	1.52E+04	1.06E+02	1.11E+03	2.52E-02	4.91E+01

Heat production, Natural Gas	4.72E+05	5.73E+03	3.64E+01	4.17E+02	9.69E-02	1.82E+01
Electricity Production CA-QC	4.95E+05	3.99E+04	3.33E+02	2.64E+03	2.63E+00	9.27E+01
Transport, Surface replacement, tire derived	5.31E+05	2.44E+04	3.03E+02	1.49E+03	3.99E-01	6.74E+01
Transport, Shred, tire-derived	5.51E+05	2.07E+04	2.55E+02	1.37E+03	4.02E-01	6.00E+01
Electricity Production CA-BC	7.40E+05	2.93E+04	1.61E+03	1.95E+03	7.61E-01	6.56E+01
Transport, Processing waste	7.46E+05	3.43E+04	4.25E+02	2.09E+03	5.60E-01	9.46E+01
Transport, Blast Mat, Tire derived	7.73E+05	3.56E+04	4.41E+02	2.16E+03	5.81E-01	9.81E+01
Transport, Crumb rubber, in asphalt	1.29E+06	4.84E+04	5.95E+02	3.21E+03	9.39E-01	1.40E+02
Transport, Mulch, tire-derived	1.32E+06	5.35E+04	6.60E+02	3.43E+03	9.74E-01	1.52E+02
Electricity Production CA-SK	2.43E+06	8.81E+04	5.62E+02	8.39E+03	7.50E-01	1.69E+02
Asphalt Binder	2.63E+06	1.13E+06	7.25E+02	3.33E+04	6.81E-01	2.04E+03
Transport, Crumb rubber, tire-derived	2.69E+06	1.24E+05	1.53E+03	7.52E+03	2.02E+00	3.41E+02
Processing, Crumb	2.76E+06	7.06E+04	4.54E+02	3.94E+03	7.13E-01	1.83E+02
Electricity Production CA-ON	2.94E+06	1.48E+05	1.67E+03	1.03E+04	3.99E+00	3.96E+02
Transport, steel scrap, tire-derived	3.08E+06	1.42E+05	1.76E+03	8.62E+03	2.31E+00	3.91E+02
Material Handling	5.08E+06	1.33E+06	2.75E+03	4.74E+04	1.94E+00	2.61E+03
Electricity Production CA	5.98E+06	2.49E+05	3.85E+03	2.38E+04	3.51E+00	5.11E+02
Binders, Pour-in-Place	6.78E+06	4.86E+05	6.00E+03	3.15E+04	2.01E+01	9.71E+03
Electricity Production CA-AB	1.13E+07	4.15E+05	2.97E+03	3.98E+04	3.39E+00	7.96E+02
Processing, Retread	1.27E+07	7.47E+05	1.11E+04	6.01E+04	6.21E+00	2.21E+03
Transport, Molded Product	1.81E+07	8.34E+05	1.03E+04	5.07E+04	1.36E+01	2.30E+03
Combustion, Crumb in Fibre	1.92E+07	1.51E+06	1.57E+04	2.04E+05	3.32E+00	2.69E+03
Reverse Logistics	2.12E+07	1.14E+06	1.06E+04	6.45E+04	1.43E+01	2.90E+03
Combustion, Fibre	2.41E+07	1.34E+05	7.92E+01	3.84E+03	1.25E+01	2.41E+02
Processing, Moulded	3.55E+07	2.04E+06	2.39E+04	1.33E+05	7.87E+01	3.76E+04
Combustion, TDF-Whole Tires	5.26E+07	4.03E+06	4.18E+04	5.45E+05	1.06E+01	7.20E+03

Table A.2 - Net total impact category results for 21 processing routes. Green shading is used to highlight a net-negative result.

	Global Warming	Smog Air	Particulates	Acidification	Ozone Depletion	Eutrophication
	kg CO2 eq	kg O3 eq	PM2.5 eq	kg SO2 eq	kg CFC-11 eq	kg N eq
Unit-crumb	-2.04E+03	-1.06E+02	-6.21E-01	-9.92E+00	3.32E-05	-1.93E-01
Unit-crumb-with-tdf	-2.00E+03	-9.97E+01	-5.52E-01	-9.00E+00	7.97E-05	-1.85E-01
Unit-retread	-1.97E+03	-1.57E+01	-6.47E-01	-1.95E+00	-6.14E-03	-2.24E+00
Unit-devulc	-1.81E+03	-9.74E+01	-5.05E-01	-8.89E+00	1.17E-04	-1.65E-01
Unit-rap	-1.40E+03	-1.47E+02	-1.60E+00	-8.47E+00	-9.97E-04	-3.71E-01
Unit-molded	-1.12E+03	-6.21E+01	-9.63E-01	-5.28E+00	-1.12E-04	-3.36E-02
Unit-molded-chk	-1.12E+03	-6.21E+01	-9.63E-01	-5.28E+00	-1.12E-04	-3.36E-02
Unit-culls	-8.05E+02	-1.28E+01	-4.21E-01	-1.31E+00	-2.12E-03	-7.50E-01
Unit-crumb-infill	-7.21E+02	-2.69E+01	-1.41E-01	-3.17E+00	1.21E-04	-4.68E-02
Unit-blast-mats	-4.52E+02	-2.27E+01	-5.56E-01	-1.47E+00	-6.00E-05	-5.16E-02
Unit-pyrol	-3.84E+02	-1.54E+01	-1.93E-01	-1.34E+00	-3.62E-04	-9.31E-02
Unit-pyrol-oil	-2.98E+02	-1.95E+01	-2.46E-01	-2.09E+00	-3.81E-04	-1.01E-01
Unit-tdf	-2.98E+02	-2.76E-01	1.91E-01	2.91E+00	3.79E-05	-1.28E-02
Unit-mulch-sand	-2.73E+02	-5.50E+00	-7.08E-02	-3.97E-01	-8.38E-05	-2.03E-02
Unit-mulch	-1.57E+02	-9.20E+00	-3.99E-02	-3.27E-01	9.08E-06	-2.22E-02
Unit-molded-concrete	-9.24E+01	1.56E+00	8.03E-02	3.29E-01	4.22E-04	1.64E-01
Unit-rap-nm	-6.84E+01	5.49E+01	-1.49E-01	6.76E-01	-8.90E-05	7.00E-02
Unit-poured-sand	-3.11E+01	2.25E+01	2.79E-01	1.41E+00	1.38E-03	7.65E-01
Unit-agg	3.67E+01	3.76E+00	1.97E-02	1.67E-01	2.38E-05	7.98E-03
Unit-sidewalls	1.08E+02	6.62E+00	5.61E-02	3.22E-01	9.09E-05	1.73E-02
Unit-poured	2.80E+02	1.69E+01	3.68E-01	1.71E+00	1.62E-03	7.67E-01
Unit-tdf-ng	4.63E+02	1.21E+02	1.31E+00	1.76E+01	9.62E-05	1.93E-01

Appendix B: List of Background Processes

Table B.1 - List of background processes used in the model.

origin	activity id	name
WorldSteel	Glo-Value of Scrap	Glo-Value of Scrap
WorldSteel	Glo-Wire Rod	Glo-Wire Rod
ecoinvent.3.7.1.cutoff	35183e31-e27a-478d-8f2d-33ead7e6da05	gravel and sand quarry operation [RoW]
ecoinvent.3.7.1.cutoff	e2bf4920-58f8-4914-93ad-2eab72355330	gravel production, crushed [CA-QC]
ecoinvent.3.7.1.cutoff	4ef230b6-5710-412d-914d-1a0298a7cbbe	heat production, at hard coal industrial furnace 1-10MW [CA-QC]
ecoinvent.3.7.1.cutoff	aa40a0a9-d423-4af5-8c9c-a19645769915	heat production, heavy fuel oil, at industrial furnace 1MW [CA-QC]
ecoinvent.3.7.1.cutoff	649343d7-7b8d-4d44-8857-f66727815baf	heat production, natural gas, at boiler condensing modulating >100kW [RoW]
ecoinvent.3.7.1.cutoff	7a442e88-3264-4073-b75a-efa861dae0b8	market for bitumen adhesive compound, hot [GLO]
ecoinvent.3.7.1.cutoff	aeae93ed-b8ec-4932-8963-e0f208860536	market for carbon black [GLO]
ecoinvent.3.7.1.cutoff	551e1932-3042-4ee9-b278-6bfea1b72ac0	market for concrete, 35MPa [RNA]
ecoinvent.3.7.1.cutoff	56071bca-7dce-44b9-94c5-cf061fa78436	market for dimethyl sulfide [GLO]
ecoinvent.3.7.1.cutoff	4f243b76-f59b-4d9c-aaeb-4430a5d7460b	market for electricity, low voltage [CA-AB]
ecoinvent.3.7.1.cutoff	1b480a2f-15e3-492e-9008-4e4c2ee840d7	market for electricity, low voltage [CA-BC]
ecoinvent.3.7.1.cutoff	e267e0c0-a83a-457e-afe5-f686acad7fef	market for electricity, low voltage [CA-MB]
ecoinvent.3.7.1.cutoff	c41d8c52-96b3-4c65-8146-fe81e8098679	market for electricity, low voltage [CA-NB]
ecoinvent.3.7.1.cutoff	d32c0afb-6ea6-4866-ba8a-32d7755f2d7a	market for electricity, low voltage [CA-NF]
ecoinvent.3.7.1.cutoff	6ec21329-04a5-4b93-b3f1-c5c1aa8400c2	market for electricity, low voltage [CA-NS]
ecoinvent.3.7.1.cutoff	954a88fa-5591-4848-be1f-e457ee398867	market for electricity, low voltage [CA-ON]
ecoinvent.3.7.1.cutoff	68b22c11-da3b-4e62-aa67-05e14bc3b661	market for electricity, low voltage [CA-QC]
ecoinvent.3.7.1.cutoff	01f10ffc-6f6d-418c-9579-9cca9101f6d9	market for electricity, low voltage [CA-SK]
ecoinvent.3.7.1.cutoff	12949563-2103-4167-8138-eb5a78ee4dc4	market for gravel, crushed [RoW]
ecoinvent.3.7.1.cutoff	05059b8a-2660-40e7-af53-2c7900e69b6d	market for heavy fuel oil [RoW]
ecoinvent.3.7.1.cutoff	b4f71206-a692-4e19-93f6-4736deee953a	market for heptane [GLO]
ecoinvent.3.7.1.cutoff	40f55af1-6013-4710-9dfa-6a7425fb6e01	market for iron ore, crude ore, 63% Fe [GLO]
ecoinvent.3.7.1.cutoff	a1fd5da1-5d29-4f2b-844b-d66bd94ca08f	market for latex [RER]

ecoinvent.3.7.1.cutoff	81b973cb-cbd8-4d70-8294-96648bec7bd4	market for limestone, crushed, washed [RoW]
ecoinvent.3.7.1.cutoff	39f08131-4338-483a-8dce-c9405e66ac3c	market for lubricating oil [RoW]
ecoinvent.3.7.1.cutoff	1c7ad6e6-5994-4a86-b0ae-dbf150629519	market for nitrogen, liquid [RoW]
ecoinvent.3.7.1.cutoff	2f6e3164-fd35-44ff-8777-bf6708b2bd16	market for polybutadiene [GLO]
ecoinvent.3.7.1.cutoff	870c8542-a349-446f-824c-8c9d51eba176	market for polypropylene, granulate [GLO]
ecoinvent.3.7.1.cutoff	760df49e-4e2a-450e-b98a-99b0620575ce	market for polyurethane adhesive [GLO]
ecoinvent.3.7.1.cutoff	405f5ca0-dea0-4827-a481-ea034c63b318	market for synthetic rubber [GLO]
ecoinvent.3.7.1.cutoff	2fa71d60-1a0a-45d4-ae6d-003b19a94b09	market for wood chips, wet, measured as dry mass [CA-QC]
ecoinvent.3.7.1.cutoff	68831154-9883-4c2c-b5a4-546161595956	market group for electricity, low voltage [CA]
ecoinvent.3.7.1.cutoff	85f3b919-a018-4a11-8e1c-fff727ba4027	mechanical treatment facility construction, waste electric and electronic equipment [GLO]
ecoinvent.3.7.1.cutoff	4c7b2d52-cb09-4ab4-8da7-c89d35086e6e	methyl methacrylate production [RER]
ecoinvent.3.7.1.cutoff	6866f2c3-23c4-4baa-a830-6d29533ba4b2	petroleum refinery construction [RoW]
ecoinvent.3.7.1.cutoff	b8eadcf3-caa0-4506-9ba2-7445e17330c6	polyethylene production, high density, granulate [RoW]
ecoinvent.3.7.1.cutoff	2027b929-68e9-4f21-8f82-690c2f7c1bb0	road construction [RoW]
ecoinvent.3.7.1.cutoff	d1eac75e-587d-4c7e-9b71-ff129e68da83	steel production, converter, unalloyed [RoW]
ecoinvent.3.7.1.cutoff	d87ab216-dbc9-41ae-aa7c-b7780cf0462d	transport, freight train, diesel [US]
ecoinvent.3.7.1.cutoff	d2d2b27c-9abd-4b56-8165-db7e368cfe61	transport, freight, inland waterways, barge [RoW]
ecoinvent.3.7.1.cutoff	66af14d7-2f51-451a-9f50-31fb89ec81e9	transport, freight, lorry 16-32 metric ton, EURO6 [RoW]
ecoinvent.3.7.1.cutoff	d7402739-2d82-4a92-a976-3673a20de21a	transport, freight, lorry 3.5-7.5 metric ton, EURO6 [RoW]
ecoinvent.3.7.1.cutoff	95cb6b4c-ed9b-480a-8801-bf335fb18cac	transport, freight, lorry 7.5-16 metric ton, EURO6 [RoW]
ecoinvent.3.7.1.cutoff	3f512dc1-a6df-4da3-af08-dbdd5ad37f3f	transport, freight, lorry >32 metric ton, EURO6 [RoW]
ecoinvent.3.7.1.cutoff	809e9326-4503-4589-a9a8-ff823c4ea0a1	transport, freight, sea, container ship [GLO]
ecoinvent.3.7.1.cutoff	a8a3e4bd-506d-43cf-8a59-9a831752d787	treatment of inert waste, sanitary landfill [RoW]
ecoinvent.3.7.1.cutoff	3ed311a5-d27f-4566-94ec-39ae3b4cf302	treatment of waste polyethylene terephthalate, municipal incineration [RoW]
ecoinvent.3.7.1.cutoff	f6b79881-e923-4115-8b20-351a963e739f	weaving of synthetic fibre, for industrial use [GLO]
ecoinvent.3.7.1.cutoff	299a38e1-e621-466f-ab10-477e3b8cae16	wire drawing, steel [RoW]
lcacommons.useeio.2.0.1	a130e170-9777-367e-a488-22b708bd7471	Rubber tires [United States]

lcacommons.uslci.fy21.q1	d6ad7035-5498-3237-8abd-50e93b1eef89	Diesel, combusted in industrial equipment [Northern America]
lcacommons.uslci.fy21.q1	4eec7a31-b920-3f91-b7c3-924f2aa92ecc	Liquefied petroleum gas, combusted in industrial boiler [Northern America]
lcacommons.uslci.fy21.q1	fa60e60f-73f0-3e20-bb3a-073e4a9469cc	Polybutadiene, butadiene rubber, BR, at plant [Northern America]
lcacommons.uslci.fy21.q1	c2300fc3-5496-3d12-9135-67dc0ef740c9	Transport, barge, diesel powered [Northern America]
lcacommons.uslci.fy21.q1	bf6e7378-4e08-3698-a3a7-c9cc90fcbc07	Transport, light commercial truck, diesel powered [Northern America]
lcacommons.uslci.fy21.q1	7de9c230-fd0f-3478-be87-f80181132faa	Transport, train, diesel powered [Northern America]
models_2_mod	combustion-pygas	combustion-pygas
models_2_mod	combustion-pyrol_liq	combustion-pyrol_liq
models_2_mod	combustion-rubber	combustion-rubber
models_2_mod	combustion-rubber_mt	combustion-rubber_mt
models_2_mod	combustion-rubber_otr	combustion-rubber_otr
models_2_mod	combustion-rubber_plt	combustion-rubber_plt

Appendix C: Facility Survey Instrument

<attached>

Appendix D: Stage Contribution Charts

This section includes stage contribution analysis charts for each of the 21 unit processing routes.
<attached>

Appendix E: Tabulated Data

<attached>

Contents of the attached spreadsheet:

Sheet Name	Category	Description
Headliner	Results - National	Summary Positive-negative chart, derived from CATRA-2019
Scrap-Flows	Material Flow	Total collections by province
Scrap-Logistics	Material Flow	Total freight requirements by mode
Tire-derived-products	Material Flow	Products produced from tires according to official reports, All except Ontario
Tire-derived-products-ON	Material Flow	Products produced from tires according to official reports, Ontario
Trade	Material Flow	International Trade Statistics for relevant products
US-Crumb	Material Flow	Data about the disposition of crumb rubber in the US in 2015
Displacement	Modeling	Work area for preparing the tables of displacement relationships in the report
_displacement_raw	Modeling	Copying input data from another sheet
displaced-products-2019	Modeling	List of products displaced by tire-derived products and fuels in the 2019 scenario
Markets	Modeling	Our assumptions regarding the end-uses of tire products by province
flownames	Modeling	A utility sheet used to look-up flows used in the model
background	Modeling	List of background processes used in the model in all scenarios and sensitivity cases
CATRA-2019	Results	Summary results by stage and impact category, Canada-wide (7 provinces)
CATRA-2019-tdf	Results	Canada-wide results showing TDF displacing natural gas instead of coal
BC-2019	Results	Summary results by stage and impact category, BC
AB-2019	Results	Summary results by stage and impact category, AB
SK-2019	Results	Summary results by stage and impact category, SK

MB-2019	Results	Summary results by stage and impact category, MB
ON-2019	Results	Summary results by stage and impact category, ON
QC-2019	Results	Summary results by stage and impact category, QC
NL-2019	Results	Summary results by stage and impact category, NL
Unit-SUMMARY	Unit-Results	Net results across all categories for all unit scenarios
Unit-culls	Unit-Results	Culls displacing new tires
Unit-retread	Unit-Results	Retreaded tires displacing new tires
Unit-agg	Unit-Results	Tire-derived aggregate displacing gravel
Unit-sidewalls	Unit-Results	Tire sidewalls displacing silage weights
Unit-blast-mats	Unit-Results	Tire-derived blast mats displacing steel blast mats
Unit-mulch	Unit-Results	Tire-derived mulch displacing wood chips
Unit-mulch-sand	Unit-Results	Tire-derived mulch displacing sand
Unit-crumb	Unit-Results	Tire-derived crumb displacing primary rubber
Unit-crumb-with-tdf	Unit-Results	Tire-derived crumb displacing primary rubber, with fibers/waste routed to TDF
Unit-crumb-infill	Unit-Results	Tire-derived crumb displacing acrylic/sand infill
Unit-poured	Unit-Results	Tire-derived crumb, used in pour-in-place application, displacing wood chips
Unit-poured-sand	Unit-Results	Tire-derived crumb, used in pour-in-place application, displacing sand
Unit-molded	Unit-Results	Tire-derived molded products displacing extruded synthetic rubber
Unit-molded-chk	Unit-Results	Check model, showing Unit-molded with processing impacts disaggregated
Unit-molded-concrete	Unit-Results	Tire-derived molded products displacing concrete products
Unit-tdf	Unit-Results	Tire-derived fuel displacing coal
Unit-tdf-ng	Unit-Results	Tire-derived fuel displacing natural gas
Unit-devulc	Unit-Results	Devulcanized rubber displacing primary rubber
Unit-pyrol	Unit-Results	Pyrolysis oil combustion displacing heat from fuel oil, and carbon black
Unit-pyrol-oil	Unit-Results	Pyrolysis oil displacing fuel oil production, and carbon

		black
Unit-rap	Unit-Results	Tire-derived crumb used in rubberized asphalt, including avoided road construction
Unit-rap-nm	Unit-Results	Tire-derived crumb used in rubberized asphalt, excluding avoided road construction (a.k.a. "status quo")

Appendix F: Critical Review Report

<attached>