

CATRA 2021 Scrap Tire Life Cycle Assessment

LCA Study

Final Version - Reviewed

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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.

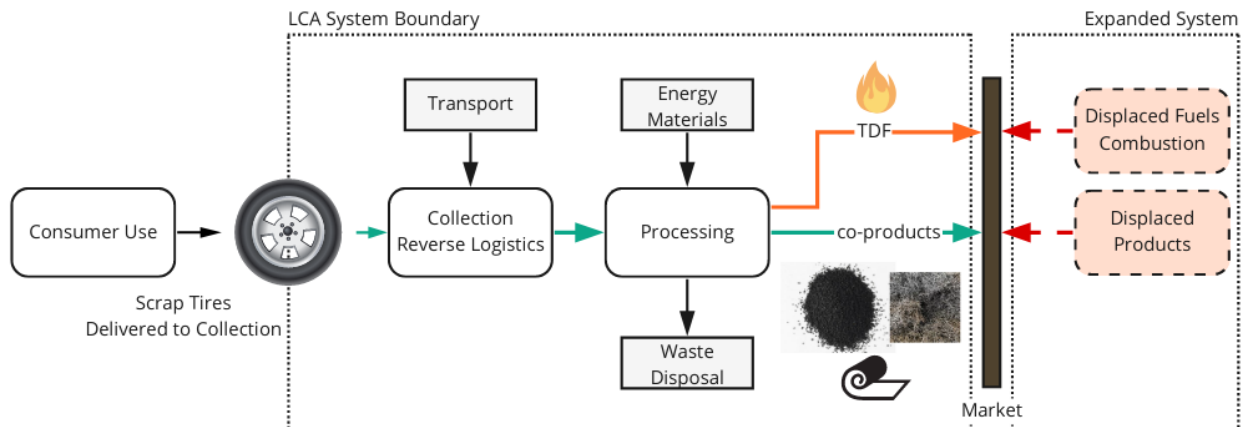


Figure 1 - Basic system boundary diagram. The LCA system boundary includes activities related to scrap tire management, while the expanded system boundary includes activities displaced by the products of scrap tire management.

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.

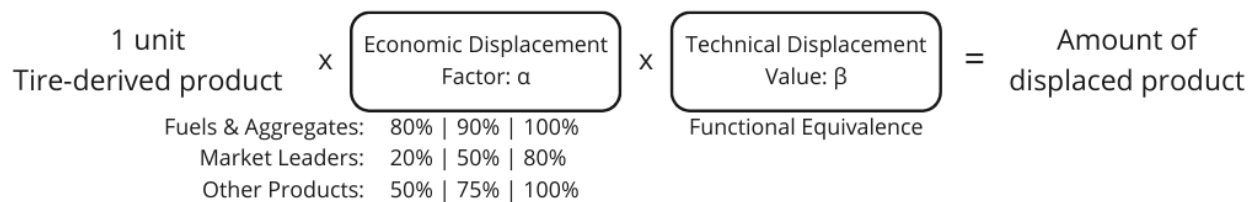


Figure 2 - Modeling displacement relationships.

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 PM_{2.5} 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.

(contents removed)

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
<i>Imports – from World</i>						
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
	<i>estimate \$15 CAD/kg kt – est.</i>	6.47	6.76	6.72	6.24	5.15
<i>Exports – to World</i>						
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
	<i>estimate \$15 CAD/kg kt – est.</i>	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.

US Crumb Rubber Market Share, 2015

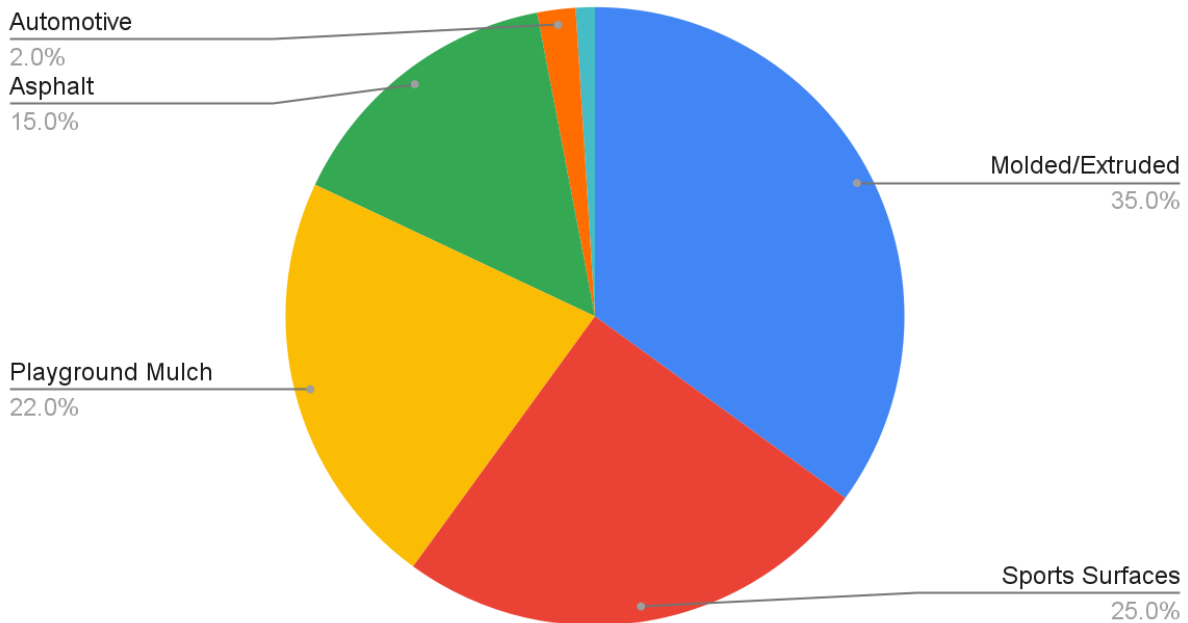


Figure 3 - US Crumb Rubber Market share, 2015 (source: RMA, 2016).

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. (redacted)

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

CATRA, 2019

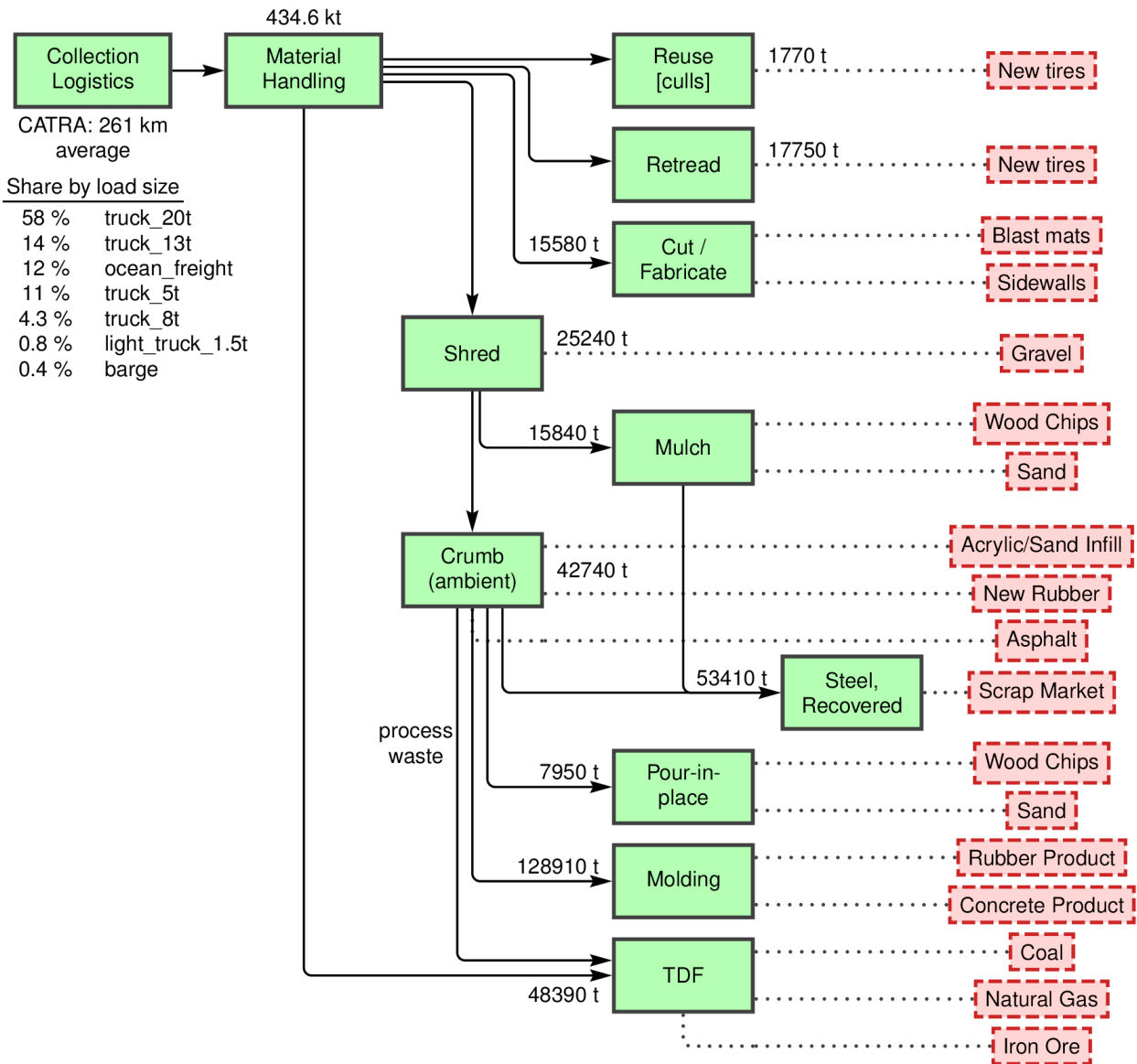


Figure 4 - Material processing of scrap tires throughout the study area, for the year 2019. Green boxes indicate processing stages and tire-derived products; red boxes indicate potentially displaced production activities. The fate of tire-derived material in this figure differs from the data shown in 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.

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. (redacted)

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

REMOVED	REMOVED
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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 (redacted)

direction	flow	amount	unit	source
input	whole_tires	1	tonne	
input	elec		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. (redacted)

direction	flow	value	unit	source
input	t_shred	1	tonne	
input	elec		kwh	Weighted average of 5 facilities
input	ng_m3		m3	Weighted average of 3 facilities
input	water_at_user		kg	Weighted average of 3 facilities

output	t_crumb		tonne	Weighted average of 6 facilities
output	t_steel		tonne	Weighted average of 5 facilities
output	t_fibre		tonne	Weighted average of 4 facilities
output	t_waste		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 polyurethane and latex.

Table 3.12 - Molded rubber product inventory. (redacted)

direction	flow	value	unit	Comment
input	t_crumb	1	t	
input	elec		kWh	average of 2 facilities
input	ng_m3		m3	average of 2 facilities
input	binder_mix		kg	average of 4 facilities
input	water_at_user		kg	average of 2 facilities
output	t_molded		t	

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. (redacted)

direction	flow	value	unit	Comment
input	whole_tires	1	t	
input	elec		kWh	average of 3 facilities, one v high
input	ng_m3		m3	average of 2 facilities
input	binder_heptane		kg	average of 2 facilities
input	new tread stock		kg	average of 3 facilities
output	t_retread		t	
output	t_crumb		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). Theecoinvent 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 (redacted)

direction	flow_ref	value	OTR_val	PLT_val	MT_val	unit
input	whole_tires	1	1	1	1	kg
input	elec					kWh
input	pyrol_facility					units
input	heat_ng_mj					MJ
input	water_at_user					kg
input	water_treatment					kg
output	pyrol_gas_to_self_use					kg
output	pyrol_char					kg
output	pyrol_liq					kg
output	t_waste					kg
output	t_steel					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 theecoinvent 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. (redacted)

	Energy Content [MJ / kg]				Carbon Content [kg C / kg]			
	char	liquid	gas	loss	char	liquid	gas	loss
Mixed Tires								
PLT								
MT								

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.

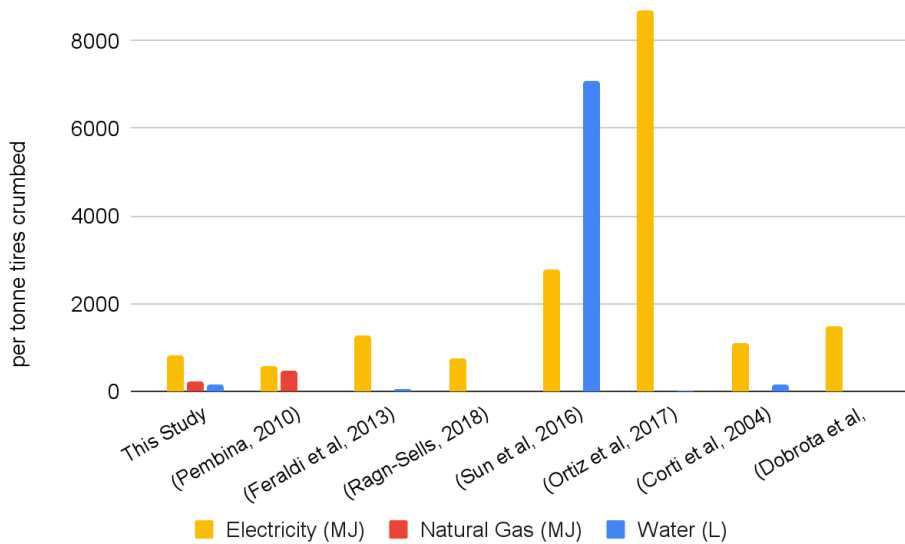


Figure 6 - Comparison of inventory requirements for scrap tire crumbing from literature sources.

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; Ortiz-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 m³, 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 m³. 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 m³ (converted from 14 lb/ft² for a 6-inch layer (Stutz et al., 2003)), and the density of wood chips is 0.38 tonne per m³.

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/m³. 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 CO₂ 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 inecoinvent, 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 (NO_x) 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 PM_{2.5} 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 (NO_x). 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 (O₃) 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 CO₂-equivalent of greenhouse gases, 13.8 kt O₃-equivalent of smog-creating compounds, and 126 tonnes PM_{2.5}-equivalent particulates, among other indicators. At the same time, potentially avoided impacts from displaced production totaled 592 kt of CO₂ equivalent, 33 kt O₃-equivalent smog, and 385 t of PM_{2.5}-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

CATRA, 2019

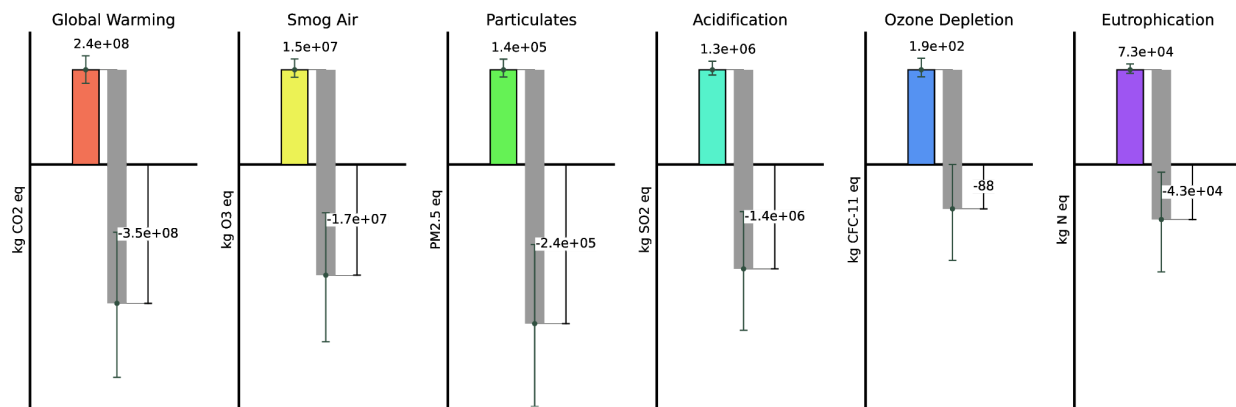


Figure 6 - National results in graphical form, each category normalized to incurred impacts.

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

CATRA, 2019, TDF

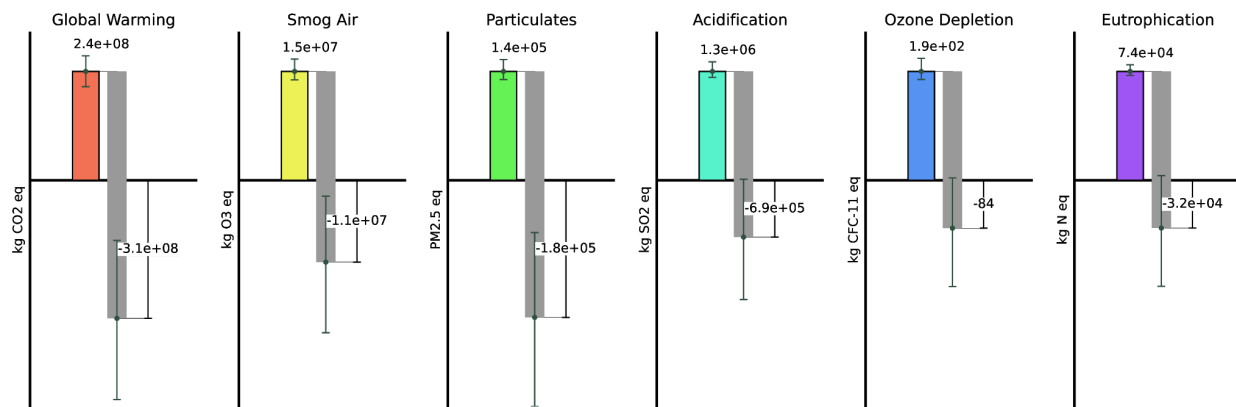


Figure 7 - National results in graphical form, each category normalized to incurred impacts; TDF variant.

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.

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