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Comprehensive multipathway risk assessment of chemicals associated with recycled ("crumb") rubber in synthetic turf fields

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ABSTRACT

Background: Thousands of synthetic turf fields in the US are regularly used by millions of individuals (particularly children and adolescents). Although many safety assessments have concluded that there are low or negligible risks related to exposure to chemicals found in the recycled rubber used to make these fields, concerns remain about the safety of this product. Existing studies of recycled rubber's potential health risks have limitations such as small sample sizes and limited evaluation of relevant exposure pathways and scenarios.
Objective: Conduct a comprehensive multipathway human health risk assessment (HHRA) of exposure to chemicals found in recycled rubber.
Methods: All available North American data on the chemical composition of recycled rubber, as well as air sampling data collected on or near synthetic turf fields, were identified *via* a literature search. Ingestion, dermal contact, and inhalation pathways were evaluated according to US Environmental Protection Agency (US EPA) guidance, and exposure scenarios for adults, adolescents, and children were considered.
Results: Estimated non-cancer hazards and cancer risks for all the evaluated scenarios were within US EPA guidelines. In addition, cancer risk levels for users of synthetic turf field were comparable to or lower than those associated with natural soil fields.
Conclusions: This HHRA's results add to the growing body of literature that suggests recycled rubber infill in synthetic turf poses negligible risks to human health. This comprehensive assessment provides data that allow stakeholders to make informed decisions about installing and using these fields.

1. Introduction

Synthetic turf fields containing recycled rubber (also called "crumb rubber") infill have been in use for decades. These fields typically consist of bottom backing layers composed of polypropylene, polyurethane, or latex, with polyethylene, nylon, or polypropylene blades woven into the material (Synthetic Turf Council, 2011). After the field is laid down, infill is added to soften the field and allow the individual turf blades to stand up (Fig. 1). One of the most common types of infill is recycled rubber, often mixed with sand (Synthetic Turf Council, 2011). Recycled rubber infill is typically made from recycled automobile and light truck tires, which are ground, shredded, and sorted into uniformly sized pieces (Synthetic Turf Council, 2011).

In the mid-2000s, a US Environmental Protection Agency (US EPA)[1] investigation identified the presence of lead in a synthetic turf field in New Jersey, and it was eventually determined that the source of the lead was a yellow pigment used on the synthetic turf's blades (US EPA, 2017a). This finding resulted in the initiation of multiple regulatory

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[1] US EPA, US Environmental Protection Agency; CalOEHHA, California Office of Environmental Health Hazard Assessment; ATSDR, Agency for Toxic Substances and Disease Registry; COI, Chemical of Interest; HHRA, Human Health Risk Assessment; COPC, Chemical of Potential Concern; RSL, Regional Screening Level; HQ, Hazard Quotient; RME, Reasonable Maximum Exposure; TTC, Threshold of Toxicological Concern; US FDA, US Food and Drug Administration; JRC, Joint Research Centre; PAH, Polycyclic Aromatic Hydrocarbon; UCL, Upper Confidence Limit; USGS, US Geological Survey; EPC, Exposure Point Concentration; UCLM, Upper Confidence Limit on the Mean; RAGS, Risk Assessment Guidance for Superfund; RIVM, Netherlands National Institute of Public Health and the Environment; ECHA, European Chemicals Agency; PCB, Polychlorinated Biphenyl; SVOC, Semivolatile Organic Compound; IRIS, Integrated Risk Information System; PPRTV, Provisional Peer-Reviewed Toxicity Value; HEAST, Health Effects Assessment Summary Tables; CalEPA, California Environmental Protection Agency; CSF, Cancer Slope Factor; RfD, Reference Dose; TEF, Toxicity Equivalency Factor; IUR, Inhalation Unit Risk; RfC, Reference Concentration; ELCR, Excess Lifetime Cancer Risk; HI, Hazard Index; TOSHI, Target-organ-specific Hazard Index; VOC, Volatile Organic Compound; IARC, International Agency for Research on Cancer; EFSA, European Food Safety Authority; $PM_{2.5}$, Particulate Matter with Particles 2.5 µm or Less in Diameter; PM_{10}, Particulate Matter with Particles 10 µm or Less in Diameter; NAAQS, National Ambient Air Quality Standards.

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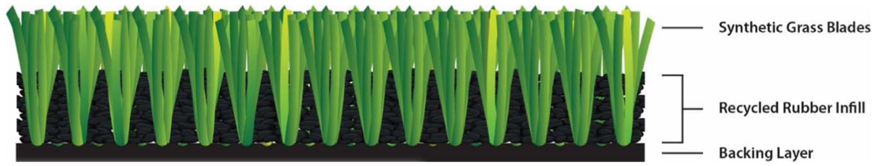

Fig. 1. Typical synthetic turf structure.

agency risk assessments, as well as a variety of peer-reviewed investigations, of various aspects of the potential risks of exposure to synthetic turf. Collectively, these investigations evaluated ingestion, inhalation, and dermal routes of exposure for chemicals in synthetic turf, as well as the mutagenicity of those chemicals and the impact of temperature on those chemical exposures. These assessments considered exposures to more than 100 different chemicals and have almost universally found that risks from exposure to chemicals in synthetic turf fields are low or below regulatory guideline levels. However, recent media coverage of cancer cases potentially associated with playing on synthetic turf fields, as well as studies that have identified carcinogens in recycled rubber, have reignited the debate surrounding the safety of synthetic turf. As a result, the California Office of Environmental Health Hazard Assessment (CalOEHHA) and a joint federal agency group (which includes the US EPA, the Agency for Toxic Substances and Disease Registry [ATSDR], and the Consumer Product Safety Commission) have initiated additional investigations of synthetic turf. Although these evaluations will likely assess the potential health risks from exposure to all of the components of synthetic turf, recycled rubber is currently the component of most concern. Some preliminary results of these assessments may be released in the coming year, but complete evaluations will likely take many years (*e.g.*, California's investigation is currently slated for completion in 2019).

One of the primary issues with the existing investigations of recycled rubber is that they do not include a comprehensive, multi-pathway risk assessment that is inclusive of all potential exposure pathways and all chemicals of interest (COIs). In order to provide additional information to stakeholders, our investigation intends to fill these data gaps by combining publically available data on the concentrations of chemicals in recycled rubber and air sampling data that have been collected to date, as well as by evaluating ingestion, inhalation, and dermal exposure pathways for the chemicals in recycled rubber used in synthetic turf fields in a comprehensive human health risk assessment (HHRA). While many previous studies of recycled rubber are limited by small sample sizes or have evaluated only one or two pathways, integrating all of the data available into one comprehensive evaluation will provide stronger evidence for any potential risks associated with exposure to the chemicals in recycled rubber.

2. Methods

2.1. Data identification and selection

We conducted a comprehensive review of the literature to identify studies containing information about the concentrations of chemicals in recycled rubber or air sampling data that could be used in our risk assessment. Because recent European evaluations of recycled rubber have been published (RIVM, 2017; ECHA, 2017a), we focused on data collected from North American rubber recyclers or synthetic turf fields. Searches conducted included:

PubMed:

- ("artificial turf" OR "synthetic turf" OR "crumb rubber" OR ""recycled rubber") AND (chemical OR risk)

Scopus:

- (TITLE-ABS-KEY ("artificial turf " OR "synthetic turf " OR "crumb rubber " OR "recycled rubber") AND TITLE-ABS-KEY (chemical OR risk)) AND NOT INDEX (medline)

Google Scholar Search Terms & Strategies:

- Search terms: "artificial turf" chemical risk
- Search terms: "synthetic turf" chemical risk
- Search terms: "crumb rubber" chemical risk
- Search terms: "recycled rubber" chemical risk

Google Internet Searches (evaluated the first 100 results for each search)

- "artificial turf chemical" "artificial turf risk," "synthetic turf chemical" "synthetic turf risk," "crumb rubber chemical," crumb rubber risk," "recycled rubber chemical, "recycled rubber risk"

In addition, we reviewed reference lists related to recycled rubber or synthetic turf compiled by various organizations (US EPA, 2016a; Synthetic Turf Council, 2017). We searched abstracts for relevance and obtained studies that evaluated either the chemical composition of recycled rubber, potential air emissions from recycled rubber, or the bioaccessibility of chemicals from recycled rubber. With one exception (discussed later), we only considered North American studies. In addition to literature sources, we contacted companies involved in the recycled rubber or the synthetic turf industries to request their testing data. Two of the companies we contacted provided data from independent laboratories for use in our evaluation. The sample data provided by these companies is provided in the Supplemental Materials (Supplemental Table S1). Because most of these data are for different lots (and sources) sampled over a number of years, each sample is designated as a separate study for the purposes of Table 1.

We compiled the raw data from all the above sources into a database that also included brief descriptions of the analytical methods used and/or field sampling conditions reported in the studies. The data included were representative of many of the different environmental conditions present during the use of synthetic turf fields. The data we used in the risk evaluation included recycled rubber composition data from both virgin and aged synthetic turf fields, as well as indoor and outdoor fields, and air samples collected at indoor and outdoor fields. Table 1 provides the numbers of studies and samples that we compiled into the database.

Table 1
Summary of Information Sources Used.

Data Evaluated	Recycled Rubber Composition Studies	Outdoor Air Studies	Indoor Air Studies
Number of Studies with Data	37	7	2
Number of Samples	103	76	17
Number of Chemicals Evaluated	139	213	172

Table 2
Types of Data Sources Used.

Data Source	Recycled Rubber Composition Samples	Outdoor Air Samples	Indoor Air Samples
Peer-reviewed Literature	19	0	0
Regulatory Reports	30	63	17
Grey Literature	34	13	0
Industry Reports	20	0	0
Total	**103**	**76**	**17**

2.1.1. Recycled rubber composition data

We used recycled rubber composition data from regulatory agencies, peer-reviewed journals, and analytical data reports from laboratories identified in our literature review or provided by companies in the recycled rubber/synthetic turf industries. Table 2 provides information on the sources of the various data we used. "Grey" literature included reports from consultants, engineering firms, school districts, and other similar entities that we identified *via* Google internet searches. Industry reports included the data that were provided directly from industry sources or recyclers. We identified 37 individual studies containing data on at least 103 individual samples. In some cases, only minimum and maximum concentration data were available, so total sample numbers could not be determined. The samples included analytical results for 139 compounds. Although the multiagency (University of Connecticut Health Center, Connecticut Department of Environmental Protection, Connecticut Agricultural Experiment Station, and Connecticut Department of Public Health) study done in Connecticut was subsequently published in the peer-reviewed literature (Ginsberg et al., 2011a), for the purposes of Table 2, it was considered to be a regulatory report. Throughout the remainder of this article, this report will be referenced as University of Connecticut Health Center (2010) if the data from the study is being cited and Ginsberg et al. (2011a) if other portions of the study are being cited.

Only one rubber recycler and one synthetic turf manufacturer responded to our request for sampling data on recycled rubber infill. The data were provided in the form of analytical reports from independent laboratories. In general, the chemical concentrations found in these studies were consistent with those from the other data sources.

The studies we identified used a variety of analytical methods to determine the chemical composition of recycled rubber. In some cases, the methods were intended to provide estimates of exposure in environmental or biological systems (*e.g.*, leaching studies or biofluid extractions). While these studies were considered for the exposure assessment component of our evaluation, we only included sample data that were intended to characterize total chemical content (*i.e.*, "destructive" analyses or similar techniques) in the primary evaluation.

2.1.2. Air sample data

We identified seven studies that evaluated potential outdoor air emissions of chemicals associated with recycled rubber in synthetic turf fields. These studies included 76 individual samples and evaluated 213 compounds. We found only one study (University of Connecticut Health Center, 2010) that evaluated airborne chemicals associated with indoor synthetic turf fields containing recycled rubber infill. In order to provide a slightly more robust dataset for indoor air, we also included the only other study we found that evaluated indoor synthetic turf fields, which was conducted in Norway (Dye et al., 2006). Combined, these two studies included 17 samples that evaluated 172 compounds.

2.1.3. Selection of chemicals of potential concern

The process used to select chemicals of potential concern (COPCs) is illustrated in Fig. 2. Essentially, the initial list of COIs was composed of any chemical that was detected in either recycled rubber or air samples in our database. This initial list contained many chemicals that may be present at background levels in air samples or as artifacts of the analytical techniques used. However, we included these chemicals in our initial COI list in order to be comprehensive. Certain chemicals (calcium, magnesium, potassium, and sodium) were eliminated because they are essential nutrients with relatively low toxicity.

We conducted a screening-level analysis to identify the COPCs for the HHRA. We compared the maximum detected concentrations of chemicals found in recycled rubber and air samples against US EPA's risk-based Regional Screening Levels (RSLs) for residential soil (in the absence of any recycled-rubber-specific screening criteria) and air (US EPA, 2017b). The US EPA RSL screening guidelines (US EPA, 2017c) indicate that a target hazard quotient (HQ) of 0.1 should be used for "multiple chemical" risk evaluations; therefore, we used the US EPA RSLs for which non-cancer hazards are calculated with a target HQ of 0.1. For cancer risks, we used the RSLs that were calculated with a target risk of 1E-06. The US EPA RSLs are generic risk-based values derived from equations that combine conservative exposure parameters and toxicity factors that represent a Reasonable Maximum Exposure (RME) scenario for long-term or chronic residential exposures and are suitable for screening for recreational exposure scenarios, because the exposure frequency and duration for soccer players and spectators (the receptors of concern in our risk assessment) are lower than those for typical residential exposures. US EPA's RSLs are designed to address chronic effects. However, because acute effects generally occur at higher exposures levels, the RSLs are thought to be protective of acute effects as well. Analytes with maximum concentrations above the selected risk-based screening criteria were retained as COPCs for the risk evaluation.

A number of the COPCs evaluated in our risk assessment did not have published toxicity screening guidelines. To address this gap, we first attempted to identify a suitable surrogate compound that did have screening criteria. We chose surrogates by selecting compounds with structures that are similar to the COPCs and that were therefore expected to be toxicologically similar to the COPCs (see Supplemental Tables S2 and S3).

If we were unable to identify surrogate compounds for COPCs without screening criteria, we used a hierarchical method to evaluate the potential for health effects occurring as a result of exposure to these chemicals. We performed a Threshold of Toxicological Concern (TTC) evaluation to eliminate chemicals observed at very low levels that were unlikely to pose a health concern. For those chemicals detected in air samples, we used the value of 0.03 $\mu g/m^3$ as the threshold (Drew and Frangos, 2007). In general, Drew and Frangos (2007) used the US Food and Drug Administration's (US FDA) TTC dose (0.01 μg/kg-day) and adjusted this to an airborne concentration using standard inhalation exposure assumptions to reach a TTC level.

For each air COPC remaining after the TTC analysis, we searched the literature to determine whether the chemical was likely to be associated with tires or rubber, to screen out COPCs that are unlikely to be recycled-rubber-related. Google Scholar and Google were both searched, generally using the chemical name and "rubber" as the search terms. The results of these searches were scanned to determine whether the documents identified showed that each chemical might be used in the rubber manufacturing process or a degradation product of rubber. In addition, COPCs in air were screened against headspace and recycled rubber composition studies. If a COPC was not identified as being associated with rubber in the literature and also was not detected in either headspace or recycled rubber composition studies, it was excluded as a COPC. Air COPCs were also excluded if they were detected at less than double the concentration of control samples. This is consistent with the approach used by Ginsberg et al. (2011a).

Finally, any remaining COPCs were evaluated using the open source decision tree hazard estimation software Toxtree (version 2.6.13; http://toxtree.sourceforge.net; Patlewicz et al., 2008)[2] to determine

[2] Developed by Dr. Nina Jeliazkova (Ideaconsult Ltd.) on behalf of the Joint Research Center (JRC). Copyright European Union (2005, 2007, 2008).

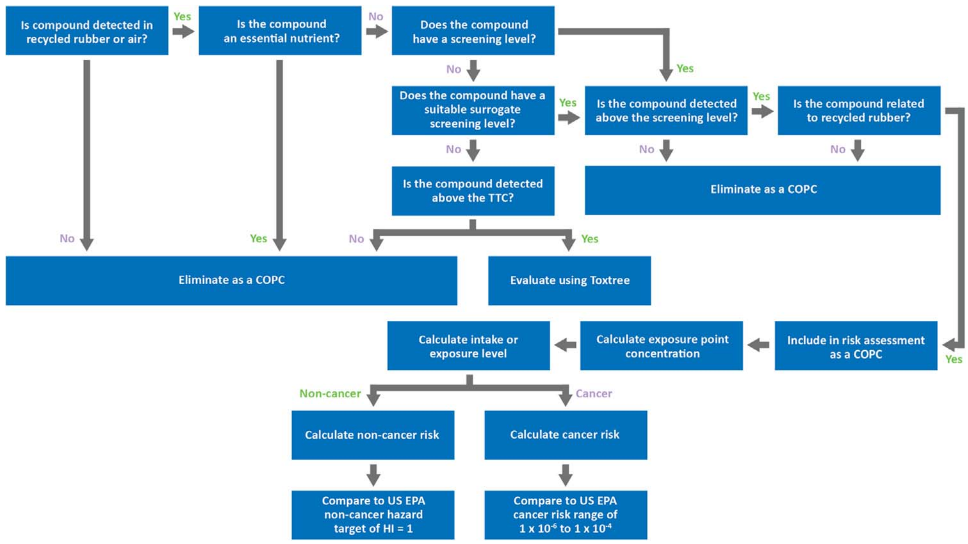

Fig. 2. COI/COPC identification process and risk assessment flowchart.

whether there were any alerts based on their chemical structures. Toxtree is a widely used program and is the European Union JRC's preferred method for the scientific validation of alternatives to animal testing (EURL ECVAM, 2017). Those chemicals without Toxtree alerts were deemed to be unlikely to pose toxicological concerns. Chemicals with alerts are evaluated in *Discussion*. The results of the screening-level analysis and the preliminary identification of COPCs for each exposure medium are summarized in Supplemental Table S4.

2.2. Exposure scenarios

We selected a number of exposure scenarios to account for the variety of people (*i.e.*, "receptors") that might interact with recycled rubber *via* synthetic turf. These are presented in Table 3. We believe that these scenarios encompass the most common uses of synthetic turf fields and also are consistent with previous regulatory evaluations of potential exposures. In addition, the exposure scenarios selected are expected to be consistent with other potential recycled rubber uses (*e.g.*, other sport fields, playgrounds). While other exposure scenarios are also possible (*e.g.*, occupational, adult soccer players), the current controversy surrounding synthetic turf fields is mostly focused on cancer risks in young people exposed while playing sports. Thus, our assessment focused on this type of use. We also felt it was important to include exposures to younger children (child spectator), who might have a greater potential for hand-to-mouth exposures.

Exposure pathways, factors, and assumptions for these receptors are provided in Table 3 and Supplemental Tables S5 and S6. In general, the exposure pathways selected were based on professional judgment. For instance, while it was assumed that a child spectator would incidentally ingest recycled rubber, incidental ingestion was not considered to be likely for an adult spectator. A similar rationale was used when determining whether or not an adult spectator might be subjected to dermal exposures from recycled rubber. We selected exposure factors based on US EPA or other regulatory guidance or, when appropriate, professional judgment. We generally used US EPA guidance for receptors considered to have the "reasonable maximum exposure," which is defined as "…the highest exposure that is reasonably expected to occur at a site" (US EPA, 1989). Evaluating RME scenarios generally entails using upper-bound concentrations (as opposed to averages) and exposure estimates.

Often, when stakeholders are discussing the potential safety of recycled rubber fields, the assumption is made that there is a choice between using synthetic fields that subject users to chemical exposure from the recycled rubber therein or choosing "natural" soil fields that do not carry the possibility of chemical exposure. However, many of the chemicals often found in recycled rubber (*e.g.*, heavy metals, polycyclic aromatic hydrocarbons [PAHs]) are also found in natural soil. In order to provide context for the recycled rubber risk assessment, we also evaluated the same exposure scenarios using 95th percentile background levels of chemicals found in natural soil. Soil metal concentrations were obtained from the US Geological Survey (USGS, 2014). PAH data were obtained by averaging the 95th percentile values from a variety of studies (BEM Systems, Inc., 1998; MADEP, 2002; ENVIRON Corp. et al., 2002; Mauro et al., 2004; Rabideau et al., 2007; IEPA, 2013). These studies contained PAH concentration data for urban, suburban, and rural locations in multiple states. The concentrations from each study were averaged to obtain the values used in this risk assessment (Supplemental Table S7). Air concentrations of the chemicals identified as recycled rubber COPCs were taken from the control air samples included with the regulatory assessments of recycled rubber. Neither of the indoor air synthetic turf evaluations we identified collected control samples; thus, we did not include the indoor air inhalation pathway in the soil exposure scenarios evaluation. We used US EPA's default bioaccessibility assumptions for the soil COPCs when appropriate (*e.g.*, we used arsenic's default bioaccessibility of 60%).

Table 3
Exposure receptors/pathways evaluated.

Receptors	Incidental Ingestion	Dermal Contact	Inhalation (Outdoor)	Inhalation (Indoor)
Youth Outdoor Soccer Player (ages 6–18 years)	x	x	x	
Youth Indoor Soccer Player (ages 6–18 years)	x	x		x
Youth Composite Soccer Player (ages 6–18 years)	x	x	x	x
Adult Spectator			x	x
Child Spectator	x	x	x	x

This hypothetical natural soil field risk assessment was prepared to provide context for the recycled rubber results, and is not intended to be an accurate assessment of risks or hazards associated with playing on a natural soil field. Soil concentrations of chemicals vary widely from location to location, and our evaluation only considered a subset of chemicals actually found in soil. Pesticides, fertilizers, inorganic constituents other than metals (*e.g.*, nitrates), and numerous other chemicals are not included in our soil evaluation. Regardless, we believe this assessment is an important part of risk communication when discussing the results of any risk assessment associated with synthetic turf fields.

2.3. Exposure point concentrations

We calculated recycled rubber and air sample exposure point concentrations (EPCs) as the 95% upper confidence limit on the mean (UCLM) or the maximum detected concentration of the COPC in our dataset, whichever was lower. The 95% UCLM values were calculated with US EPA's ProUCL software, Version 5.1 (US EPA, 2016b) using the option that specifies whether a value is a non-detect. A summary of the datasets we used for the EPC calculations are presented in Supplemental Table S8.

2.4. Quantification of exposure

We calculated human intake levels for each COPC based on exposure equations from US EPA's Risk Assessment Guidance for Superfund (RAGS) (US EPA, 1989; Eqs. (1)–(3)). We used US EPA-recommended values for exposure parameters when possible and used professional judgment to derive some exposure parameters, when appropriate.

In our HHRA, we calculated cancer risks separately for carcinogens with mutagenic modes of action, to account for potentially increased susceptibility to mutagenic carcinogens during early life (US EPA, 2005). Equations for mutagenic compounds are detailed in the Supplemental Material.

2.4.1. Intake by incidental ingestion

For the incidental ingestion pathway, COPC intake was calculated as:

$$Intake\left(\frac{mg}{kg-day}\right)=\frac{C_{rubber}\left(\frac{mg}{kg}\right)\times B\times IR_{rubber}\left(\frac{mg}{day}\right)\times EF\left(\frac{days}{year}\right)\times ED(years)\times 10^{-6}\frac{kg}{mg}}{BW(kg)\times AT(days)} \tag{1}$$

where:

C_{rubber} = Concentration of the Chemical in Recycled Rubber (mg/kg)
B = Relative Bioaccessibility (the relative oral absorption fraction, unitless)
IR_{rubber} = Recycled Rubber Ingestion Rate (mg/day)
EF = Exposure Frequency (days/year)
ED = Exposure Duration (years)
BW = Body Weight (kg)
AT = Averaging Time (days)

The basis for each value used is detailed below.

2.4.1.1. Concentration of the chemical in recycled rubber (C_{rubber}). We used the 95% UCLM or the maximum detected concentration of the chemical in recycled rubber infill, whichever value was lower, as the EPC. The values used for our analysis are provided in Supplemental Table S8.

2.4.1.2. Relative bioaccessibility (B). A chemical's bioavailability can vary substantially depending on the media *via* which the exposure to that chemical occurs. US EPA guidance recommends making adjustments for the reduced bioavailability of certain compounds in soil (US EPA, 1989) and it is recognized that the bioaccessibility of many metals and organics from recycled rubber tends to be considerably lower than their bioaccessibility from food, water, or soil (Pavilonis et al., 2014; Zhang et al., 2008; CalOEHHA, 2007; RIVM, 2017; ECHA, 2017a). Although studies of the bioaccessibility of chemicals from recycled rubber are not the same as studies of the bioavailability of these chemicals, in this case, the results are assumed to be equivalent. To avoid confusion, we use the term bioaccessibility in our evaluation.

Unfortunately, most of these studies do not contain sufficient data with which to calculate true chemical-specific bioaccessibility for more than a few of these chemicals. For several COPCs, we used data from recycled rubber bioaccessibility studies that suggest that these compounds have lower bioaccessibility in recycled rubber *vs.* soil. For PAHs, the Netherlands National Institute of Public Health and the Environment (RIVM) estimated that approximately 9% were bioaccessible (RIVM, 2017), and the maximum PAH bioaccessibility observed in Zhang et al. (2008) was 3%. In this risk assessment, we selected a bioaccessibility for PAHs of 0.06 (6%) based on an average of the highest results in Zhang et al. (2008) and RIVM (2017). For phthalates and phenols in recycled rubber, we used a bioaccessibility of 0.2 (20%) based on data from RIVM (2017). Finally, although no recycled-rubber-specific bioaccessibility was available for arsenic, we felt that using the US EPA default oral bioaccessibility of 0.6 (60%) for soil would be reasonable, because it seems unlikely that arsenic would be less tightly bound in a recycled rubber matrix than in a soil matrix (US EPA, 2012). For COPCs other than arsenic, PAHs, phthalates, and phenols, relative oral bioaccessibility information from either soil or recycled rubber is not readily available; therefore, we assumed a relative bioaccessibility of 1 (100%). Although the Pavilonis et al. (2014) study is a very thorough analysis of this issue, it is not possible to use the results of their analysis to inform our bioaccessibility assessment. This is primarily related to the fact that they obtained non-detect values in either their destructive analyses of recycled rubber, their biofluid extractions of recycled rubber, or both (depending on the chemical). While the Pavilonis et al. (2014) results qualitatively support that chemicals in recycled rubber have low bioaccessibility, we were not able to use them quantitatively. Given this issue, we used only the values obtained from RIVM (2017) and Zhang et al. (2008). The bioaccessibility values selected for each of the COPCs are provided in Supplemental Table S9.

2.4.1.3. Recycled rubber ingestion rate (IR_{rubber}). The recycled rubber ingestion rates selected for each of the receptors are provided in Supplemental Tables S5 and S6. For adults and youths older than 6 years of age, we used an ingestion rate of 50 mg/day as a surrogate for incidental recycled rubber ingestion. For children spectating soccer games at synthetic turf fields containing recycled rubber, we used an ingestion rate of 100 mg/day. These ingestion rates represent one-half of the upper-bound value for daily soil and dust ingestion (US EPA, 2014) and would likely overestimate the consumption of recycled rubber, because recycled rubber particles are generally larger than soil particles and only a limited amount of time each day is spent playing on these surfaces. We felt that using one-half the US EPA default soil ingestion rate for our analysis was conservative, because individuals likely only spend 1/8th of a day (or 3 h) on a synthetic turf field. In addition, while soil/dust ingestion may not occur consistently throughout the day, the character of this material (*e.g.*, larger particle sizes) likely lends itself to less ingestion than soil/dust. Our assumption is consistent with the evaluations by RIVM (2017) and the European Chemicals Agency (ECHA, 2017a), which both commented that ingestion rates for recycled rubber are likely much lower than soil.

2.4.1.4. Exposure frequency (EF) and exposure duration (ED). For the spectator and youth soccer player exposure scenarios, we generally used exposure frequency and duration values from Ginsberg et al., 2011a) (see Supplemental Tables S5 and S6). Ginsberg et al. (2011a) assumed that outdoor soccer players use artificial turf fields 4 days per week throughout the spring, fall, and summer (8 months) for a soccer match or practice (Ginsberg et al., 2011a). The youth indoor soccer player was assumed to use indoor artificial turf fields 1 day per week in the winter and spring (4 months) (Ginsberg et al., 2011a).

2.4.1.5. Body weight (BW). The body weights selected for each of the receptors are provided in Supplemental Tables S5 and S6. Based on US EPA guidance (US EPA, 2014), we used a mean adult body weight of 80 kg for the adult receptors and a mean child body weight of 15 kg for the child receptor (US EPA, 2011). For the youth soccer players, we used the age-weighted average body weight of 49 kg, which represents the body weight estimates averaged over the relevant exposure period (US EPA, 1991a, 2011).

2.4.1.6. Averaging time (AT). The averaging times selected for each of the receptors are provided in Supplemental Tables S5 and S6. For cancer risks for all receptors, exposures were averaged over a 70-year average lifetime (US EPA, 2014). For non-cancer hazards for all receptors, the averaging time is equal to the exposure duration multiplied by 365 days.

2.4.2. Intake by dermal contact

For the dermal contact pathway, dermal intake of COPCs was calculated using the following equation, per US EPA guidance (US EPA, 2004).

$$DAD\left(\frac{mg}{kg{\cdot}day}\right) = \frac{C_{rubber}\left(\frac{mg}{kg}\right) \times ABS \times AF\left(\frac{mg}{cm^2}\right) \times SA\left(\frac{cm^2}{event}\right) \times EF\left(\frac{events}{year}\right) \times ED(years) \times 10^{-6}\frac{kg}{mg}}{BW\,(kg) \times AT\,(days)} \quad (2)$$

where:

DAD = Dermal Absorbed Dose (mg/kg-day)
C_{rubber} = Concentration of the Chemical in Recycled Rubber (mg/kg)
ABS = Dermal Absorption Fraction (unitless)
AF = Recycled Rubber-to-Skin Adherence Factor (mg/cm^2)
SA = Skin Surface Area Exposed (cm^2/exposure event)
EF = Exposure Frequency (exposure events/year)
ED = Exposure Duration (years)
BW = Body Weight (kg)
AT = Averaging Time (days)

The three parameters that are unique to the dermal exposure equation – ABS, AF, and SA – are discussed below. The values used for the other parameters in this equation are the same as those provided in the incidental ingestion pathway section above.

2.4.2.1. Dermal absorption fraction (ABS). In general, we used dermal absorption values obtained from US EPA's dermal risk assessment guidance for soil (US EPA, 2004, Exhibit 30.4). Given that soil particles are generally smaller than recycled rubber particles and would present greater surface area for chemical contact, we deemed the use of these soil values as appropriate and likely conservative. For PAHs, bioaccessibility studies for dermal absorption from recycled rubber were available. RIVM (2017) reported that 0.2% of PAHs were bioaccessible to sweat biofluids. Thus, an ABS value of 0.002 was used for PAHs in our main analysis instead of the US EPA (2004) soil default of 0.13. The dermal absorption fractions used for other substances in the risk assessment are 0.03 for arsenic; 0.13 for naphthalene (because naphthalene was not included in the RIVM analysis); 0.14 for polychlorinated biphenyls (PCBs); and 0.1 for semivolatile organic compounds (SVOCs). Dermal absorption values are not available for the other COPCs, and US EPA does not recommend extrapolating generic values for COPCs without dermal absorption values (US EPA, 2004); therefore, we did not calculate dermal exposure for these constituents. The dermal absorption fractions selected for each of the COPCs are provided in Supplemental Table S9.

2.4.2.2. Recycled rubber-to-skin adherence factor (AF). Skin adherence factor values are not available for recycled rubber, so we used US EPA's recommended activity-specific soil-to-skin adherence factors for children and adolescents (US EPA, 2004) to calculate dermal absorption for receptors exposed to recycled rubber (see Supplemental Tables S5 and S6). The US EPA soil-to-skin adherence factor of 0.04 mg/cm^2 for children at a daycare playing indoors and outdoors was used to calculate intake for the child spectator. For the youth soccer player exposure scenarios, we used US EPA's geometric mean adherence factor of 0.04 mg/cm^2 for "Soccer Players #1 (teens, moist conditions)" (US EPA, 2004). To assess mutagenic compounds, we used the soil-to-skin adherence factor of 0.04 mg/cm^2 for all age groups. These factors were used because soil-to-skin adherence factors for specific ages are not available.

2.4.2.3. Skin surface area exposed (SA). We used a skin surface area of 2373 cm^2 for the child spectator (see Supplemental Table S5) based on US EPA's recommended value for assessing children's (birth to < 6 years old) dermal exposures, with exposed skin limited to that of the head, hands, forearms, lower legs, and feet (US EPA, 2014). We used a skin surface area of 4881 cm^2 for the youth soccer players (see Supplemental Table S6) based on the mean skin surface area of adolescents 6–18 years of age, with exposed skin limited to that of the head, hands, forearms, lower legs, and feet (US EPA, 2011).

2.4.3. Intake by inhalation of indoor and outdoor air

Particulates and organic compounds in recycled rubber can migrate into outdoor and indoor air. For the inhalation of indoor and outdoor air containing recycled-rubber-associated chemicals, we calculated an average daily exposure concentration using the following equation, per US EPA guidance (US EPA, 2009a).

$$EC = \frac{EPC_{air}\left(\frac{mg}{m^3}\right) \times ET\left(\frac{hours}{day}\right) \times EF\left(\frac{days}{year}\right) \times ED(years) \times CF1\left(\frac{1\,day}{24\,hours}\right) \times CF2\left(\frac{\mu g}{mg}\right)}{AT\,(days)} \quad (3)$$

where:

EC = Exposure Concentration (μg/m^3)
EPC_{air} = Exposure Point Concentration of the Chemical in Air (mg/m^3)
ET = Exposure Time (hours/day)
EF = Exposure Frequency (days/year)
ED = Exposure Duration (years)
AT = Averaging Time (days)
CF1 = Conversion Factor 1 (1 day/24 h)
CF2 = Conversion Factor 2 (μg/mg)

The values used for the AT, as well as their sources, are provided above, as well as in Supplemental Tables S5 and S6.

2.4.3.1. Exposure point concentration of the chemical in air (EPC_{air}). We used the 95% UCLM or the maximum detected concentration of a COPC in air samples, whichever value was lower, as each COPC's EPC for the exposure calculations.

2.4.3.2. Exposure time (ET), exposure frequency (EF), and exposure duration (ED). Exposure time, duration, and frequency factors for all the receptors are provided in Supplemental Tables S5 and S6. In general, for the youth soccer player scenarios, we selected factors to be consistent with Ginsberg et al. (2011a). Ginsberg et al. (2011a) assumed that outdoor soccer players use artificial turf fields 4 days per week throughout the spring, fall, and summer (8 months total) for a 3-h soccer match or practice (Ginsberg et al., 2011a). For consistency with the Youth Outdoor Soccer Player, we assumed an exposure time of 3 h for the youth indoor soccer player (Ginsberg et al., 2011a)

2.5. Toxicity assessment

2.5.1. Overview of toxicity factors

As per US EPA guidance (US EPA, 2003), we obtained toxicity factors from a hierarchy of sources. Our primary source of toxicity factors was US EPA's Integrated Risk Information System (IRIS), with additional toxicity values obtained from US EPA's Provisional Peer-Reviewed Toxicity Values (PPRTVs), followed by tertiary sources such as the Health Effects Assessment Summary Tables (HEAST), the ATSDR, or the California Environmental Protection Agency (CalEPA). The toxicity factors we used are consistent with those used in the US EPA RSL Table (US EPA, 2017b).

In some cases, little information was available about the form of a compound present in recycled rubber. Therefore, in cases in which toxicity factors were available for multiple forms or species of a compound, we selected the value for the form that is either the most widely applicable or that resulted in the most conservative estimate of risk.

Toxicity factors for the COPCs are summarized in Supplemental Table S9, which also includes the source of the values and the form of the compound they are based on (when applicable).

2.5.2. Cancer slope factors and reference doses

We evaluated potential oral and dermal cancer risks and non-cancer hazards using dose-response relationships for carcinogenicity (cancer slope factors [CSFs]) and systemic toxicity (reference doses [RfDs]). As opposed to other COPCs, PAH CSFs are typically calculated on a relative potency basis, using the CSF for benzo(a)pyrene as the basis for comparison. For cancer risks, US EPA derived a CSF of 1 $(\text{mg/kg-day})^{-1}$ for benzo(a)pyrene (US EPA, 2017d). Then, the CSFs for other carcinogenic PAH compounds are estimated using a toxicity equivalency factor (TEF) that relates the cancer potency of that compound to that of benzo(a) pyrene. For benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, dibenzo(a,h)anthracene, and indeno(1,2,3-cd)pyrene, the CSF is based on the TEF recommended by US EPA (1993).

There are no US EPA-derived toxicity values based specifically on toxicity studies involving dermal exposures. In the absence of dermal-specific CSFs or RfDs, US EPA guidelines suggest using oral toxicity factors, but these values must be adjusted to be applicable to absorbed doses (US EPA, 1989, 2004). For cancer risk, this adjustment is made by dividing the oral CSF (for applied doses) by the oral absorption efficiency (*i.e.*, $CSF_{oral}/ABS_{oral} = CSF_{dermal}$), if the oral absorption efficiency is less than 50%. All COPCs with CSFs have oral absorption efficiencies greater than 50%; thus, no adjustment of these COPCs' oral CSFs were required, and the oral CSFs were used as the dermal CSFs. For non-cancer effects, this adjustment is made by multiplying the oral RfD (for applied doses) by the oral absorption efficiency (*i.e.*, $RfD_{oral} \times ABS_{oral} = RfD_{dermal}$). For antimony, we performed adjustments of the RfD_{dermal} as recommended by US EPA. For the other COPCs, the oral RfDs were used as the dermal RfDs.

2.5.3. Inhalation reference concentrations and inhalation unit risks

We evaluated potential inhalation cancer risks and non-cancer hazards using dose-response relationships for carcinogenicity (inhalation unit risks [IURs]) and systemic toxicity (reference concentrations [RfCs]). These values are presented in Supplemental Table S9.

2.6. Risk characterization

We examined cancer risks and non-cancer hazards for our chosen receptors across several possible exposure pathways (described above). The total cancer risk or non-cancer hazard for each receptor is the sum of these risks and hazards across all COPCs and exposure pathways.

2.6.1. Calculation of cancer risks

Cancer risks are characterized as the incremental probability that an individual will develop cancer during his or her lifetime due to being exposed to contaminants under the specific exposure scenarios evaluated, above the background risk of developing cancer in the course of daily life (referred to as the excess lifetime cancer risk [ELCR]). Cancer risks are expressed as a unitless probability (*e.g.*, 1 in 1 million or 1×10^{-6}). US EPA has established a target cancer risk range of 1E-06 to 1E-04 (US EPA, 1990, 1991b). Some state regulations, including those in Massachusetts (MADEP, 1995) and Minnesota (*i.e.*, MAR 4717.8000 to MAR 4717.8600; MDH, 2016), establish a target cancer risk of 1E-05.

We calculated cancer risks for each receptor, for all the exposure pathways and COPCs, according to US EPA guidance (US EPA, 1989). A receptor's total ELCR was the sum of the cancer risks across all COPCs and exposure pathways. Pursuant to US EPA guidance (US EPA, 1989, p. 8–12), we rounded the total cancer risks to one significant digit for presentation.

2.6.2. Calculation of non-cancer hazards

Risks from non-cancer effects are expressed as HQs rather than probabilities. We calculated HQs for each receptor, for all the exposure pathways and COPCs, according to US EPA guidance (US EPA, 1989). HQs were summed across all COPCs to calculate a hazard index (HI) for each receptor. As per US EPA guidance, overall HIs were rounded to one significant figure, and HIs for the individual exposure pathways were rounded to two significant figures (US EPA, 1989, p. 8-8).

US EPA considers an HI greater than 1 to exceed its target risk threshold. Because an HQ is simply a ratio of actual exposures to reference exposure levels (RfDs, RfCs, *etc.*), HIs do not represent the probability that an adverse health effect will occur. An HI less than 1 suggests that the chemical exposures are not likely to pose an appreciable risk of non-cancer effects occurring during a lifetime. An HI greater than 1 indicates only that a potential may exist for adverse health effects to occur as a result of a chemical exposure. Unlike cancer risks, non-cancer HIs are not additive across different age groups for a receptor. Typically, because child exposures are higher than adult exposures, the HI for a child receptor represents the greatest HI experienced by that receptor during his or her lifetime.

US EPA guidance recommends that non-cancer health effects be evaluated by summing the HQs for analytes that affect the same target organ or system; these sums are referred to as target-organ-specific hazard indices (TOSHIs) (US EPA, 1989). We reviewed the sources of non-cancer toxicity values (IRIS, PPRTV, ATSDR, CalEPA, *etc.*) for each COPC to identify the target organ explicitly stated as the critical effect and basis for the RfD derivation.

3. Results

Risk results, including TOSHIs, are provided in Table 4 (recycled rubber risk summary), Table 5 (recycled rubber TOSHIs), and Table 6 (natural soil risk summary). Detailed pathway-specific risk results are provided in Supplemental Table S10 and S11. Additional information on pathway specific risk and hazard drivers are provided in Supplemental Table S12. Figs. 3–5 provide a summary of the hazard and risk results for the exposure scenarios for both recycled rubber and natural soil fields.

For recycled rubber fields, the cancer risks for all receptors were below the *de minimus* risk of 1E-06 set by US EPA (1990, 1991b). The highest identified excess cancer risks were for the child spectator scenario, at 9E-07. In most cases, the chemicals that contributed the most

Table 4
Cancer risk and non-cancer hazard by pathway for recycled rubber fields.

Receptor	Cancer Risk	Hazard Index
Youth Composite Soccer Player	8E−07	0.3
Youth Outdoor Soccer Player	7E−07	0.3
Youth Indoor Soccer Player	2E−07	0.05
Adult Spectator	6E−07	0.08
Child Spectator	9E−07	1

Table 5
Target-organ-specific hazard indices by receptor for recycled rubber fields.

Target Organ/ System	Youth Composite Soccer Player	Youth Outdoor Soccer Player	Youth Indoor Soccer Player	Adult Spectator	Child Spectator
Developmental	NC	0.00088	0.00017	0.00014	0.000017
Endocrine	0.17	0.15	0.018	NC	0.96
Hematological	0.026	0.019	0.0072	0.0049	0.13
Hepatic	0.0040	0.0024	0.00029	NC	0.0116
Immunological	0.0018	0.0059	0.00099	0.0013	0.030
Neurological	0.00031	NC	0.00031	0.00031	0.00031
Reproductive	0.042	0.042	NC	0.042	0.042
Respiratory	0.0081	NC	0.0081	0.0081	0.0081
Skin	0.029	0.026	0.0032	NC	0.17
Systemic	0.042	0.028	0.0062	0.019	0.087
Urinary	0.010	0.0031	0.0069	0.010	0.010

Note:
NC = Not calculated, because there were no chemicals of potential concern (COPCs) for this target organ and receptor.

Table 6
Cancer risk and non-cancer hazard by pathway for natural soil fields.

Receptor	Cancer Risk	Hazard Index
Youth Composite Soccer Player	2E−06	0.1
Youth Outdoor Soccer Player	5E−06	0.2
Youth Indoor Soccer Player	–	–
Adult Spectator	2E−07	0.02
Child Spectator	6E−06	0.7

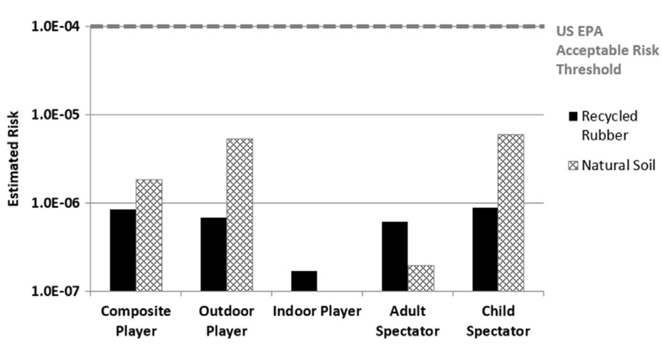

Fig. 3. Estimated additional cancer risk estimates for receptors evaluated.

to the calculated cancer risks are as expected given the composition of recycled rubber – generally PAHs (*e.g.*, benzo[*a*]pyrene), arsenic, and organic compounds that have previously been associated with recycled rubber (*e.g.*, 1,3-pentadiene, formaldehyde). Non-cancer TOSHIs for all the recycled rubber exposure scenarios (*i.e.*, all receptors) were also below US EPA's acceptable hazard guidelines (*e.g.*, HI < 1) (see Table 5). As with the cancer risks, the chemicals contributing significantly to the non-cancer hazards were mostly as expected: metals such as thallium and cobalt, as well as 4-t-octylphenol, an organic chemical used in the manufacture of rubber products. Because the

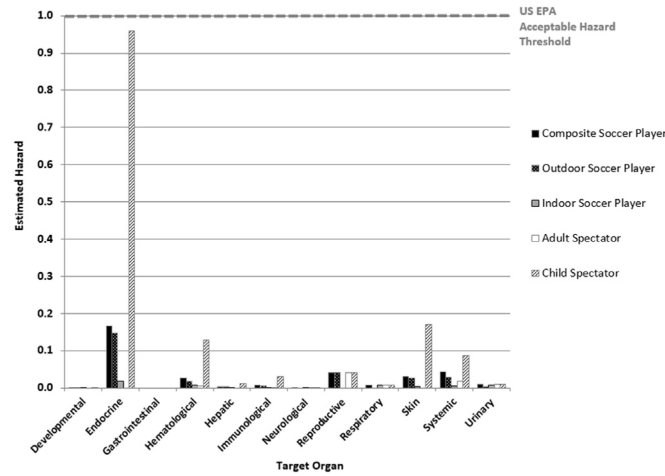

Fig. 4. Estimated recycled rubber non-cancer target-organ-specific hazards for receptors scenarios evaluated.

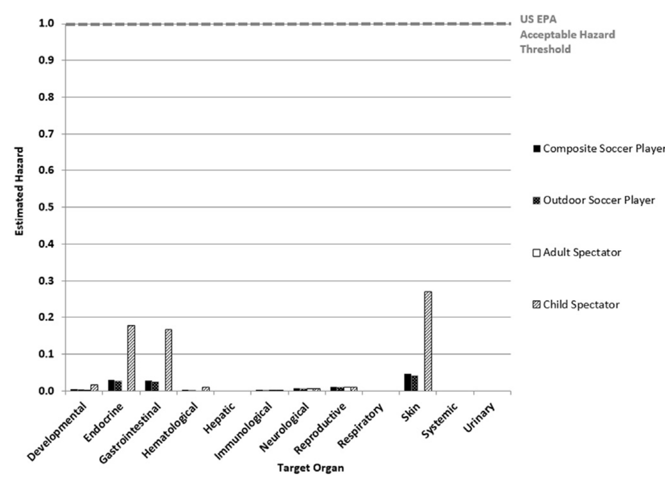

Fig. 5. Estimated natural soil non-cancer target-organ-specific hazards for receptors evaluated.

overall HI for the child spectator (HI = 1) was the highest of the recreational scenarios evaluated in this risk assessment, it was important for us to calculate HIs for groups of chemicals that impact a common target organ. For the child spectator, the majority of the non-cancer impact was related to potential ingestion of cobalt in recycled rubber. The TOSHI for cobalt exposure for the child spectator, as well as all other TOSHIs for this receptor, was below US EPA's acceptable hazard guideline (HI < 1) and is therefore unlikely to result in non-cancer effects. Further evaluation of cobalt in recycled rubber is included in the Discussion section.

The results of our evaluation of natural soil field exposure scenarios are very similar to the results of the recycled rubber field evaluation. Metals and PAHs contributed the most to the incidental ingestion and dermal contact risks and hazards, and background levels of some of the volatile organic compounds (VOCs) contributed the most to inhalation pathway hazards and risks. Although cancer risks for some of the natural soil field exposure scenarios were above US EPA's *de minimis* risk level of 1E-06, they were all within US EPA's target risk range of 1E-06 to 1E-04 (1990, 1991b). The cancer risk results for the natural soil field analysis indicate that, for each scenario (excluding the adult spectator), cancer risks associated with exposure to natural soil fields are consistent with (but higher than) those from exposure to recycled rubber fields. Similarly, the non-cancer hazard results for the recycled rubber and soil exposure scenarios were consistent, although the hazards were generally lower for natural soil fields. While the finding that estimated cancer risks are higher for natural soil than recycled rubber may at first seem counterintuitive, analysis of the background concentration data provided in the Supplemental Materials (Table S7) illustrates this is not surprising. The 95th percentile natural background levels of several carcinogens in soil are either higher (*e.g.*, arsenic) or similar (*e.g.*, PAHs) to the 95% UCLM levels found in recycled rubber. Considering the low bioaccessibility of these chemicals from rubber, it is not surprising that the risks from exposure to these chemicals in soil are higher than those from rubber. The comparison of 95th percentile concentrations to 95% UCLM concentrations does indicate that the relative risks should be interpreted with caution (*i.e.*, these are not the same statistic, and depending on the dataset, 95th percentile concentrations might be higher than 95% UCLMs). Further analysis of the impact of the bioaccessibility of chemicals on risk estimates is provided in the Discussion.

4. Discussion

Our comprehensive multipathway risk assessment for recycled rubber in synthetic turf fields found that cancer risks and non-cancer hazards were within the acceptable limits set by US EPA, even assuming RME conditions. These results are consistent with a number of preliminary or less-comprehensive studies of recycled rubber in synthetic turf fields performed by regulatory agencies in the US (NJDEP, 2007; CalOEHHA, 2007, 2010; New York Department of Health and Mental Hygiene, 2009; NYSDEC and NYSDOH, 2009; US EPA, 2009b; University of Connecticut Heath Center, 2010; Condon, 2015). They are also consistent with the recent findings of a RIVM investigation of synthetic turf fields (RIVM, 2017), which reported that it "is safe for people to play sports on synthetic turf fields with an infill of rubber granulate. Rubber granulate contains numerous substances which were found to be released from the granulate in very low quantities. This is because the substances are more or less 'enclosed' in the granulate, which means that the effect of these substances on human health is virtually negligible." ECHA also has recently completed a risk assessment of recycled rubber, and the Agency concluded, "ECHA has evaluated the risk of substances in recycled rubber that is used on artificial sports pitches. Based on the evidence, ECHA has concluded that the concern for players on these pitches, including children, and for workers who install and maintain them is very low" (ECHA, 2017a).

Cancer risks and non-cancer hazards calculated using our methods are similar to those identified in other risk assessments of recycled rubber synthetic turf fields. Table 7 compares the highest cancer risks and non-cancer hazards calculated in our evaluation, ECHA (2017a), RIVM (2017), Pavilonis et al. (2014), and Ginsberg et al. (2011a). Pavilonis et al. (2014) did not calculate a cancer risk, while RIVM did not calculate a non-cancer hazard. The results from the various risk assessments are remarkably consistent given the different datasets and methods used.

Including an analysis of background soils using the same assumptions in our assessment provided an interesting perspective on risks associated with synthetic turf fields. It is noteworthy that the chemicals that are often considered to be of concern in recycled rubber – heavy metals and PAHs – are also found in background soils, and in some cases are actually present at higher levels in soil than in recycled rubber. This finding also illustrates a possible source of uncertainty in our assessment. For those chemicals that are commonly found at background concentrations in air (*e.g.*, metals and many organic compounds), the sampling methods employed to develop the underlying data in our assessment could not distinguish those originating from recycled rubber and those originating from other sources, such as automobile exhaust. This particular aspect of uncertainty would lead to overestimation of risk in our evaluation, and thus would add another layer of conservatism. Additional uncertainties are described in the next section.

The cancer risks we calculated for the natural soil field exposure scenarios analysis were sometimes significantly higher than those from recycled rubber. This result is not intended to imply that playing on grass fields or playgrounds on natural soil would result in actual risk to receptors. We performed this analysis primarily to illustrate that employing US EPA's conservative standard risk assessment practices to assess surfaces that are considered to be "safe" or "natural" by most people can result in risk values that are higher than expected. Evaluating the results of the natural soil and recycled rubber risk assessments using the RME assumptions side-by-side provides context for the risks calculated for exposure to recycled rubber. The relevant interpretation is that both types of surfaces fall within acceptable risk and hazard guidelines and should not be considered to pose a public health issue.

In order to evaluate the impact of the bioaccessibility assumptions for recycled rubber we used in our evaluation, we performed a sensitivity analysis of this factor. We used three sets of bioaccessibility factors in this analysis: (1) the "lowest" bioaccessibility values, calculated for PAHs and metals from values derived from RIVM (2017) and Zhang et al. (2008); (2) the "best estimate" bioaccessibility values from our main RME analysis, derived by using the average of values from RIVM (2017) and Zhang et al. (2008); and (3) the "highest" bioaccessibility values, which were those used as default soil bioaccessibility values by US EPA. The highest bioaccessibility values were all 1 (100%), except for arsenic, which was 0.6 (60%). The results of these calculations are not rounded per US EPA guidance in order to illustrate the true impact on the risk and hazard values. The results of this sensitivity analysis are provided in Figs. 6 and 7.

The sensitivity analysis illustrates that bioaccessibility does have a significant impact on the calculated risks and hazards. When default soil bioaccessibility assumptions were used, the estimated cancer risks for three (child spectator, composite player, and outdoor player) of the five exposure scenarios had a cancer risk higher than 1E-06. However, these cancer risks are still well within the acceptable target risk range of

Table 7
Comparison of highest risk and hazard estimates from various published recycled rubber synthetic turf fields risk assessments with those from the current evaluation.

Reference	Highest Cancer Risk	Highest Non-cancer Hazard
Current Evaluation	9. E−07	1. E+00
ECHA (2017a) [a]	8. E−07	1. E−01
RIVM (2017)[a]	3. E−06	NC
Ginsberg et al. (2011a)	1. E−06	4. E−01
Pavilonis et al. (2014)	NC	8. E−03

Notes:
NC = Not calculated in this risk assessment.
For ECHA (2017a) and Pavilonis et al. (2014), the individual chemical hazard indices presented in the original references were summed to obtain the values in Table 7.
[a] Only PAH cancer risks were calculated in these two risk assessments.

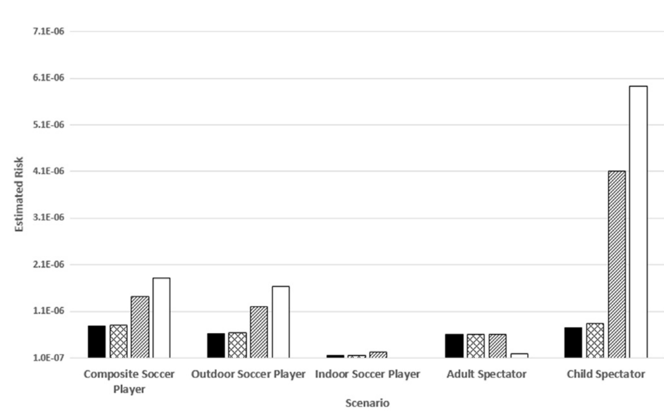

Fig. 6. Sensitivity analysis results for bioaccessibility (Cancer).

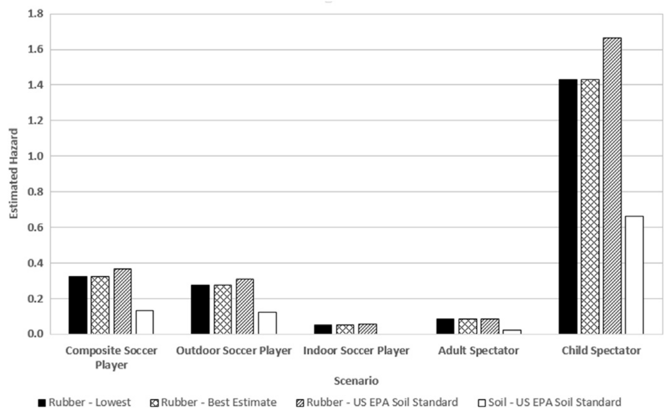

Fig. 7. Sensitivity analysis results for bioaccessibility (Non-Cancer).

1E-06 to 1E-04 set by US EPA (1990, 1991b) and are similar to the risks calculated for natural soil. For non-cancer hazards, using the default soil bioaccessibility assumptions resulted in an overall HI of 2 for one scenario (child spectator), which is above the guideline of 1. However, employing the more-appropriate full TOSHI analysis once again resulted in no exceedences of 1 (data not shown). As with the main RME analysis of recycled rubber, cobalt is the primary driver of the hazard analysis (discussed in more detail below).

A few chemical-specific issues relevant to recycled rubber risk should also be discussed. Based on the results of the non-cancer analysis, the most important issue to consider is the subject of cobalt toxicity and bioaccessibility. While cobalt is a known component of tires (ECHA, 2017a), the levels detected in our evaluation varied substantially. Cobalt was only detected in about 50% of samples, and the concentrations ranged from non-detect to 266 mg/kg. These levels are consistent with those found in the ECHA (2017a) analysis of recycled rubber, which found concentrations ranging from 3.5 to 268 mg/kg in recycled rubber. The incidental ingestion HI for cobalt for the child spectator receptor was slightly lower than 1 (0.96). While a number of studies have looked at cobalt bioaccessibility from recycled rubber, none provide enough detail for us to be able to calculate an appropriate cobalt bioaccessibility value for our risk assessment. The only reasonable approximation is from RIVM (2017), which calculated that a maximum amount of cobalt that could leach from recycled rubber would be 2 µg per gram of recycled rubber ingested. Using this value, the cobalt intake estimates in our assessment would be reduced more than 20-fold, which would significantly reduce the estimated hazard from this metal.

In addition, benzothiazole, a rubber-associated VOC, was identified as a risk-driver in the indoor player inhalation pathway. Given that the toxicity data for this chemical are based on a surrogate (the analysis was originally conducted by Ginsberg et al., 2011b), further defining the toxicity of benzothiazole would potentially provide more certainty in the assessment of this chemical.

Carbon black is also often a topic of discussion in recycled rubber evaluations. This chemical mixture is considered to be "possibly carcinogenic in humans (Group 2B)" by the International Agency for Research on Cancer (IARC, 2010) and makes up about 30% of tires (Moore, 2015). Existing assessments of recycled rubber toxicity are often criticized for not considering carbon black. There is some controversy related to the carcinogenicity of carbon black (IARC, 2010; Rausch et al., 2004). Regardless, the most likely explanations for potential carbon black carcinogenicity are either the associated PAHs or lung particulate overload (Valberg et al., 2006). Because most current risk assessments of recycled rubber (including this one) have considered the carcinogenicity of PAHs (the likely carcinogenic component of carbon black) and overall particulate concentrations, this issue does not impact our conclusions.

Overall, for the receptors evaluated, the results of our HHRA indicate that cancer risks and non-cancer hazards from chemical exposures associated with recycled rubber are below levels considered acceptable by US EPA.

5. Limitations and uncertainties

Although our risk assessment used RME assumptions in an attempt to ensure that cancer risks and non-cancer hazards were not underestimated, the data have some limitations that introduce uncertainties into our results. First, a number of chemicals detected in recycled rubber did not have specific toxicity factors. While we addressed these gaps by using standard toxicological methods (*e.g.*, selecting structurally similar surrogates, performing a TTC evaluation), these methods have inherent uncertainties. For instance, the screening levels of many of the chemicals in the US EPA RSLs list are below the TTC screening levels of those chemicals developed by Drew and Frangos (2007, 216–2071) and based on US FDA methods. It is uncertain whether the use of the TTC method is conservative for these chemicals. In addition, for 24 chemicals, we were unable to identify suitable surrogates, and the TTC evaluation results for these chemicals did not preclude them from further review. For these chemicals, we used Toxtree to determine whether they had genotoxic or carcinogenic potential. There were no structural alerts in Toxtree for 21 of the 24 chemicals. The three chemicals that did have structural alerts are identified below. Given the concerns about cancer in athletes using synthetic fields with recycled rubber, we felt it was important to investigate these compounds further to assess their carcinogenic potential.

- *Decanal* – Naturally produced in the body. Multiple agencies (*e.g.*, US EPA, European Food Safety Authority [EFSA], ECHA) have concluded that decanal is not genotoxic, and it is not listed under California's Proposition 65 or by IARC as a carcinogen (JECFA, 1998, 2002; US EPA, 2008a; EFSA, 2013; T3DB, 2014; CalOEHHA, 2016; ECHA, 2017b).
- *Fluorene* – Not listed under California's Proposition 65 as a carcinogen, deemed "not classifiable" by IARC and US EPA, and not considered to be a "complete carcinogen" or genotoxic by ATSDR (IARC, 1983; ATSDR, 1995; CalOEHHA, 2016).
- *3-Phenyl-2-propenal* – Although it has the potential to be genotoxic, this compound is actually the fragrance known as cinnamaldehyde. It is derived from a plant and is mainly used as a flavoring or fragrance. It has been found to be non-carcinogenic in animal studies and is not listed under California's Proposition 65 as a carcinogen (Bickers et al., 2005; US EPA, 2008b; CalOEHHA, 2016). In addition, this compound is unlikely to be related to turf emissions and was only found in indoor air samples in our assessment.

Another limitation of our analysis is that although we included a large number of samples in our assessment, some COPCs were analyzed in only a limited number of those samples. However, we feel that the use of 95% UCLM or maximum values for these chemicals limits the uncertainty introduced by this issue (*i.e.*, while there are fewer maximum concentration samples, the use of the maximum concentration provides some assurance that risks are unlikely to be underestimated). This is also supported by the RIVM (2017) finding that there is not significant variability in the concentrations of chemicals detected in recycled rubber. As stated in Section 2.1.1, in some cases the literature only included minimum and maximum concentration data and we were unable to identify the underlying data for these statistics. In the absence of the underlying data, we included a small number of minimum and maximum values in the calculation of the 95% UCLM for some chemicals. The inclusion of these statistics in the 95% UCLM calculation resulted in a smaller sample size than if we had been able to obtain the full underlying dataset. The literature generally provided both the minimum and maximum values from the same underlying dataset. We would expect the overall impact on the 95% UCLM to be minor because the full range of detected values are expected to be symmetrically distributed between the minimum and maximum statistics.

There are a number of additional uncertainties inherent in our analysis, as with any risk assessment. These include a variety of factors, from data collection, to the analytical methodologies employed, to toxicity and exposure assessment. The factors that we feel contribute significantly to the overall uncertainty in this assessment are briefly discussed below.

- *Use of soil exposure factors.* For some of the US EPA exposure equations, we have assumed that recycled rubber would behave similarly to soil. For example, we have assumed that recycled rubber would adhere to skin in a similar fashion to soil. In general, we believe the larger particle size associated with recycled rubber (*vs.* most soils) would mean that an evaluation using this assumption would likely overestimate exposure rather than underestimate exposure. However, this is speculative, and the different surface chemistry/physics of the two materials could potentially counteract the particle size effect.
- *Use of one-half of default soil ingestion rates.* Soil ingestion rates used by US EPA in risk assessments assume that both soil and dust are incidentally ingested by children. As discussed above, soil and dust may (or may not) behave similarly to recycled rubber. We believe it is unlikely that children or youths of any age would consume 50 or 100 mg of recycled rubber every time they play on a recycled rubber field. This sentiment is echoed in the ECHA (2017a) risk assessment: "In our estimations, we assumed that children may swallow 50 mg granules in one event which is around 50 granules. For adults, we estimated the amount to be 10 mg. These estimations are lower than that [sic] was used in the recent report (RIVM, 2017) where it was concluded that the oral route estimations were highly conservative because of the unrealistic ingestion amounts."
- *Lack of air sampling for some metals.* For example, cobalt was detected in recycled rubber samples but was not evaluated in air sample studies. Given the limited bioaccessibility of metals from recycled rubber, the uncertainty introduced by this factor is likely to be small.
- *Evaluation of only recycled rubber.* Our evaluation focused exclusively on chemicals associated with recycled rubber, because that is the material in synthetic turf that has raised the most concerns in public and regulatory environments. As described previously, synthetic turf fields are composed of multiple materials, including backing materials, synthetic turf blades, and sand. If there are significant chemical exposures associated with these materials, our analysis would probably not have identified them. However, there are other studies in the peer-reviewed and regulatory literature that have evaluated some of these materials and found that chemical exposures from them are not likely to be of concern.
- *Use of air sampling data rather than theoretical approaches.* It would be possible to theoretically calculate both particulate and VOC concentrations released from recycled rubber fields. It is possible that this approach might identify additional COIs or result in higher (or lower) concentrations of the chemicals identified in our evaluation. However, given the availability of actual air sampling data for indoor and outdoor athletic facilities and the uncertainties in this modeling approach, we felt that using the actual air sampling data was a more reasonable method. Additionally, the maximum $PM_{2.5}$ (0.048 μg/m^3) and PM_{10} (31.8 μg/m^3)[3] concentrations measured in outdoor air in the vicinity of synthetic turf fields were less than US EPA National Ambient Air Quality Standards (NAAQS) for particulate matter.
- *Lack of indoor facility data.* We only identified one North American study that evaluated indoor air concentrations at a synthetic turf athletic facility (a second Norwegian study was included in our evaluation, due to the lack of data in this area). Indoor athletic facilities have a number of factors that complicate chemical evaluations, including different air exchange rates and multiple other sources of chemical emissions (cooking facilities, maintenance vehicles, *etc*.). More-detailed studies of these facilities are necessary in order to understand the influence of these factors on chemical risk.
- *Focus on athlete and spectator scenarios.* There are many other receptors that could be added to this assessment, including workers at athletic facilities, adult soccer players, and users of other types of surfaces that incorporate recycled rubber. Although we believe our results represent an RME scenario and are most relevant to the public health issue that has been raised regarding recycled rubber in synthetic turf fields, it is possible that other, more highly exposed populations exist.

[3] Particulate matter with particles 2.5 μm or less in diameter and 10 μm or less in diameter, respectively.

The limitations and uncertainties discussed above are likely compensated for by the use of exposure assumptions that are intended to provide conservative cancer risk and non-cancer hazard results. These assumptions include:

- Use of maximum and 95% UCLM COPC concentrations.
- Assumption of 100% bioaccessibility for all COPCs except for arsenic, phthalates, phenols, and PAHs.
- Assumption that all soccer games/practices are conducted on the same synthetic turf field containing the maximum/95% UCLM COPC concentrations.
- Use of soil exposure parameters that likely overestimate ingestion as well as dermal adherence for recycled rubber.
- Assumption that the youth composite soccer player receptor is playing soccer year-round for 4 days during three seasons and 1 day during one season likely overestimates risks for much of the US population.
- Assumption that outdoor and indoor soccer games are played for 3 h. The assumption that indoor soccer players spend 3 h at a soccer match or practice contributed to an overestimate of the risk, given that the typical game length for indoor games is 60 min (four 15-min quarters), while the outdoor games are 90 min long (two 45-min halves). In addition, many youth soccer players on the lower end of the age range (< 12 years of age) attend games and practices of reduced length (30- to 60-min games) based on their age.

6. Conclusions

This comprehensive, multipathway risk assessment demonstrates that the use of synthetic turf fields containing recycled rubber infill would not result in unacceptable risks or hazards to adults or children under US EPA's risk assessment guidelines. This result is informative for the communities that have installed these types of surfaces and the millions of children and adults that use synthetic turf fields yearly. Our results are consistent with those of more-limited investigations performed by a variety of regulatory agencies in the US, as well as recent studies of synthetic turf fields performed in the Netherlands and by ECHA. While additional analytical data and comparison to background chemical concentrations could be used to further refine the results of our evaluation, our findings provide useful information for stakeholders seeking to evaluate possible health risks posed by the use of recycled rubber infill in synthetic turf fields.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2017.09.019.

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