SYNTHETIC TURF FIELD TIRE CRUMB RUBBER AND EXPOSURE CHARACTERIZATION RESEARCH UNDER THE FEDERAL RESEARCH ACTION PLAN

Response to Comments from External Peer Reviewers

April 16, 2024

By

U.S. Environmental Protection Agency / Office of Research and Development (EPA/ORD)

Centers for Disease Control and Prevention / Agency for Toxic Substances and Disease Registry (CDC/ATSDR)

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1.0 Introduction

This report documents the results of an independent letter peer review of the U.S Environmental Protection Agency's (EPA's) draft report entitled, "Synthetic Turf Field Tire Crumb Rubber and Exposure Characterization Research Under the Federal Research Action Plan – Final Report," developed by EPA and the Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry (CDC/ATSDR).

Eastern Research Group, Inc. (ERG), a contractor to EPA, organized this external peer review and developed this report with the agencies providing responses to comments where appropriate. Section 2 of this report provides additional background; Section 3 describes the peer review process; and Section 4 provides the individual reviewer comments, organized by charge question, along with the agencies' responses.

EPA and CDC/ATSDR are reporting research findings in two parts. Part 1 communicates the research objectives, methods, results and findings for the tire crumb rubber characterization research (i.e., what is in the material). Part 2 includes data to characterize potential human exposures to the chemicals found in the tire crumb rubber material while using synthetic turf fields and includes the results from a supplemental biomonitoring study conducted by CDC/ATSDR to investigate potential exposure to constituents in tire crumb rubber. These research activities and the resulting findings do not provide an assessment of the risks associated with playing on or contact with the tire crumb rubber used for synthetic turf fields. Instead, these research results should inform future risk assessments.

2.0 Background

Over the past several years, parents, athletes, schools, and communities have raised concerns about the safety of recycled tire crumb rubber used as infill for playing fields and playgrounds in the United States. The public has expressed concerns that use of these fields could potentially be related to certain health effects. Studies to date have not shown an elevated health risk from playing on fields with tire crumb rubber, but these studies have limitations and do not comprehensively evaluate the concerns about health risks from exposure to tire crumb rubber.

Federal Research Action Plan

On February 12, 2016, CDC/ATSDR and EPA, in collaboration with the Consumer Products Safety Commission (CPSC), released a "Federal Research Action Plan on Recycled Tire Crumb Used on Playing Fields and Playgrounds" (FRAP). The purpose of the FRAP is to study key questions concerning the potential for human exposure resulting from the use of tire crumb rubber in playing fields and playgrounds. This information is important for any follow-up evaluation of risk that might be performed. The FRAP includes outreach to key stakeholders to obtain information to fill important data gaps, research to characterize constituents of tire crumb made from recycled tire rubber, studies to identify ways in which people may be exposed to tire crumb rubber based on their activities on the fields, and an analysis of existing scientific literature on the topic.

FRAP Research Protocol

Prior to initiating the study, federal researchers developed a research protocol, "Collections Related to Synthetic Turf Fields with Crumb Rubber Infill," which describes the study's objectives, research design, methods, data analysis techniques, and quality assurance/quality control measures to ensure the integrity of the following components of the research:

- Literature review and data gaps analysis
- Tire crumb rubber characterization research
- Human exposure characterization research

The study protocol was reviewed by independent external peer reviewers, CDC's Institutional Review Board (IRB), and EPA's Human Subjects Research Review Official. The data collection components of the study went through the Office of Management and Budget's (OMB's) Information Collection Request (ICR) review process. The OMB ICR process included a public comment period. On August 5, 2016, EPA, CDC/ATSDR, and CPSC received final approval from OMB to begin the research.

Status Report

A status report was released in December 2016 summarizing the agencies' activities to date, including:

- Stakeholder outreach
- Tire and tire crumb rubber manufacturing process
- Final peer-reviewed literature review/gaps analysis
- Tire crumb rubber characterization and exposure characterization research
- Use of recycled rubber tires on playgrounds
- Next steps and a timeline

For additional information visit http://epa.gov/tirecrumb.

The draft report of results on the FRAP was sent for external peer review in May 2018. EPA and CDC/ATSDR worked to address all peer review comments. The final report was released in two parts. Part 1 communicates the research objectives, methods, results and findings of the tire crumb rubber characterization research (i.e., what is in the material). Part 2 characterizes potential human exposures to the chemicals found in the tire crumb rubber material while using synthetic turf fields. Neither Part 1 nor Part 2 of this study, separately or combined, will constitute an assessment of the risks associated with playing on synthetic turf fields with recycled tire crumb rubber infill. The results of the research described in both Part 1 and Part 2 of the final report can be used to inform future risk assessments.

3.0 Peer Review Process

For this review, ERG identified, contacted, and screened qualified experts, and then proposed a pool of 12 candidate reviewers who had no conflict of interest (COI) in performing the review and who collectively met the following technical selection criteria provided by EPA – Experience in:

- Human Exposure Assessment
  - Characterization of chemical constituents
  - Human exposures associated with synthetic turf fields and/or crumb rubber infill
- Human exposure modeling
  - Characterization of human activity information through questionnaires and/or videography for exposure model development and application
- Analytical chemistry
  - Analysis of metals, volatile organic compounds (VOCs)/semivolatile organic compounds (SVOCs) in rubber and/or environmental media
  - Product emissions testing
  - Bioaccessibility/bioavailability measurements for chemicals in solid media
- Environmental microbiology

EPA verified that the experts in the candidate pool were appropriately qualified. From among these candidates, ERG then selected the following seven reviewers who collectively best met the selection criteria, were free of any conflict of interest, and could meet the review schedule.

- **Alesia Ferguson, MPH, Ph.D.:** Associate Professor, College of Public Health, University of Arkansas Medical Sciences
- **Panagiotis Georgopoulos, Ph.D**.: Professor, School of Public Health, Rutgers University
- **Tee L. Guidotti, MD, MPH**: Consultant, Occupational and Environmental Health
- **Maria Llompart, Ph.D.:** Professor, Department of Analytical Chemistry, University of Santiago de Compostela, Spain
- **Martin Reinhard, Ph.D.:** Professor Emeritus, Stanford University
- **P. Barry Ryan, Ph.D.:** Professor, Rollins School of Public Health, Emory University
- **Clifford P. Weisel, Ph.D.:** Tenured Professor, Environmental and Occupational Health Sciences Institute (EOHSI), Rutgers University

ERG provided reviewers with instructions; the review document, including Volume I (main report) and Volume II (appendices); and the charge to reviewers prepared by EPA. Reviewers worked individually (i.e., without contact with other reviewers, colleagues, the public, or EPA) to prepare written comments in response to the charge questions.

Reviewers completed their reviews and submitted their written comments to ERG, and ERG forwarded them to EPA. Both ERG and EPA checked the comments to ensure that reviewers had responded clearly to all charge questions. EPA indicated that no clarifications were needed on the reviewers' comments.

Section 4 of this report presents reviewer comments, organized by charge question. Comments are presented exactly as submitted, without editing, summarization, or correction of typographical errors (if any).

4.0 Responses to Charge Questions

4.1 Charge Question 1: Does the Executive Summary clearly, concisely, and accurately describe the major findings of the study for a broad audience, consistent with the body of the report?

4.1.1 Reviewer 1

Comment: Yes, the executive summary clearly and concisely describes the major finding for a broad audience. The summary should be clear that it does not complete a complete health risk assessment and stops short at computing daily doses.

Response: We agree with the reviewer's comment. Text has been included in the Executive Summaries of both the Part 1 and Part 2 Report to make it clear that we have not conducted a risk assessment.

Comment: It is true, as with all executive summary reports, that the readers have so many questions about methods immediately (i.e., how). This is normal and invites the reader to explore the various paragraphs. It would be nice to insert in the executive summary where each area of study is covered in more details. Therefore, the executive summary, for the bullet points on page xxxiii, insert chapters at the end of the points.

Response: We have added references to the technical sections and appendices in the Executive Summaries of both the Part 1 and Part 2 Reports.

Comment: Line 1203-line 1205-Please clarify whether this sentence applies to indoor and outdoor fields. Sentence before made a comparison of indoor to outdoor fields, leaving the reader unsure of the context for the following lines.

Response: The Executive Summary text has been edited for clarity regarding overall interpretation. Biological results apply to all participants. Clarification has been provided in the Biomonitoring Study (Part 2 Report, Appendix A).

Comment: Line 1211- Executive summary mentions toxicity testing of the bulk materials given the presence of multiple chemicals. Chapter 8 [sic – Chapter 6] [now Part 1 Report, Section 5], however, does not delve into what this toxicity testing of bulk materials could look like. Perhaps some examples might help. In addition, a conversation about toxic equivalents is possible. There is slight mention of whole material testing on line 1990 [sic –1992] (chapter 2). Therefore, a more extensive discussion on multiple chemical exposure can be explored.

Response: Toxicity testing of bulk materials is mentioned only as an example of a way to assess toxicity from multiple chemical exposures; however, further discussion is beyond the scope of this study.

Comment: After Line 1196: The executive summary authors could include a few sentences on the exposure modeling, and the 6 compounds used as an example. This can be added after the section on exposure characterization.

Response: The Executive Summary of the Part 2 Report now includes discussion of the exposure pathway modeling and six compounds.

Comment: Line 1184-Hydroxynaphthalene was often found in dermal wipes for the subjects in this study (especially for football player). Naphthalene, the parent product was low in tire crumb material. Some research can be conducted on naphthalene and naphthalene by products in and around the environment. Certainly, according to the US department of health and human services naphthalene is found in many household products (https://hpd.nlm.nih.gov/cgi-bin/household/brands?tbl=chem&id=240). The following article is of interest in demonstrating the ubiquitous nature of naphthalene. It is not a far stretch to see how individuals might have naphthalene and its byproducts on skin and in biological media from other sources.

Batterman, et al., (2012) "Sources, Concentrations and Risks of Naphthalene in Indoor and Outdoor Air" Indoor Air (available at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3307957/)

Response: Hydroxynaphthalene was measured in urine but not wipes. Very low levels of naphthalene were measured in dermal wipe samples (<0.01 ng/cm^2). A brief discussion of these findings is included in the Executive Summary of the Part 2 Report. Thank you for noting this reference. Additional details have been provided in the Supplemental Biomonitoring Study (Part 2 Report, Appendix A).

4.1.2 Reviewer 2

Comment: In general terms, it does, but some considerations should be taken into account:

Please indicate that recycled tire playgrounds, increasingly being installed in the Unites States, were not included in this study.

Response: Please see footnote (3) in the Executive Summary of the Part 1 Report.

Comment: The executive summary is very important. Therefore, if possible, it would be interesting to include the target chemicals in each family (metals, VOCs and SVOCs) for the tire crumb rubber characterization and for the exposure characterization, and to specify the crumb rubber and other matrices analyzed (including air, skin wipes, biological samples and so on), as well as the number of target compounds found above LODs or background levels in each case. This information could be included in one or several tables in the executive summary.

Response: We have elected to keep the Executive Summary a higher-level summary of the information presented in the report. A general figure is now included in the Executive Summary of both the Part 1 and Part 2 Reports showing the research schematic, including types of samples, matrices, and analyses. More details on target chemicals are provided in Section 2.0 of the Part 1 Report, and Section 2.0 of both the Part 1 and Part 2 reports are used to summarize key observations and findings in further detail.

Comment: In addition, the number of samples (or sampling facilities considered) should be indicated in all cases. Not only for the crumb rubber, but also for the personal air and other air samples, wipe dermal samples, and other samples included in the study.

Response: This information is included in the figure added to the Executive Summary of the Part 2 Report, showing a schematic of the exposure characterization study research.

Comment: Lines 1121-1123. The authors talk about average concentrations "…from <1 mg/kg for several metals and SVOCs to 15,000 mg/kg for zinc. In general, target analyte concentrations measured in this study were similar to concentrations found in previous studies of recycled tire crumb rubber". I think some more information should be given in the summary, especially regarding PAHs. For example: 15 out of the 16 EPA priority PAHs were found in all crumb rubber samples, and the average individual concentrations were above 1 mg/kg for many of the target PAHs in outdoor and indoor fields. In addition, the Sum15PAH was generally high, with values above 20 mg/g in most cases. In addition, the very high levels of other analytes such as 2-mercaptobenzothiazole (unfortunately it was not quantified) should be mentioned.

Response: We have elected to keep the Executive Summary a higher-level summary of the information presented in the report. In the Part 1 report, Section 2.0 was intended to provide a more specific and detailed summary of the tire crumb rubber characterization results, and includes a figure summarizing measurements for all 15 of the 16 priority PAHs measured. However, we do not agree that the 2-mercaptobenzothiazole non-quantitative results should be characterized as 'very high;' the non-quantitative results suggest it was present at substantially lower levels than benzothiazole and many other chemicals of interest.

Comment: Line 1144-1146. The authors say "In general, concentrations of many organic chemicals appeared to decrease with increasing field age and were generally greater for indoor fields versus outdoor fields". To be able to make a relation between field age and chemical concentrations, the same field should have been studied over several years. We do not know for certain if the differences between fields built in different years are due to weathering, vaporization, etc... or if the differences are due to differences in initial crumb rubber composition.

Response: The reviewer is correct that differences in initial composition cannot be ruled out, since none of the measurements was longitudinal. Revisions have been made to address this comment. However, the evidence most strongly supports weathering based on the observed differences across different chemicals.

Comment: Lines 1167-1168. The authors say "…suggest that people may be exposed to some of the chemicals associated with recycled tire crumb rubber infill material". Taking into account the results of this study and other previous studies, it is clear that people are exposed. Most of the target analytes, and in addition many non-target chemicals, have been found at least in the crumb rubber that enter into direct contact with players' skin; therefore, I recommend replacing "suggest" and "some of the chemicals" by "people are exposed to a large number of chemicals".

Response: Clarity has been added to the statement in the Part 2 Executive Summary and takes into account any necessary qualifications due to the limitations of this and other studies.

Comment: Regarding biological samples, the selection of target analytes, as well as the aim and purpose of the study based on the comparison of samples obtained before and after practice is not clear. Further explanation of target analyte selection and devolopment [sic] of conclusions would be helpful (i.e., acute or chronic exposure, pharmacokinetics of the chemicals and the short time interval considered).

Response: Clarifying details have been provided in the Biomonitoring Study (Part 2 Report, Appendix A).

Comment: Lines 1191-1195. The authors say "As an alternative to measurements, exposure levels may be estimated using exposure modeling. Modeled estimates for a select set of PAHs and metals that are expected in recycled tire crumb suggest that synthetic turf field users may have pyrene and benzo(a)pyrene exposures similar to, or somewhat lower than, typical background exposures, and exposures to zinc and lead that are substantially lower than background."

While the exposure characterization is only a small pilot study, the comparative study based on literature showing the exposure in other scenarios is even more limited. Please clearly indicate that these comparative studies were only performed for four (six?) chemicals and based on a very low number of previous published studies (papers). So, please modify the previous sentence since it could lead people to believe that exposure is not relevant, despite the fact that the exposure study and comparative study have a high level of uncertainty.

Response: The conclusion is necessarily qualified using the word "suggest" due to the limitations of this and other studies.

Comment: Conclusions

Lines 1201-1204. The following sentence should be revised to take into account my previous comments: "The results suggest that the amount of chemicals released into the air and biological fluids is relatively low, and for study participants, metals in blood and serum and urinary PAHs were similar before and after field activities and consistent with those measured in the general population, with the exception of selenium and 2-hydroxynaphthalene". In addition, the chamber air studies, where a large number of chemicals were found should also be considered here.

Response: Clarifying details have been provided in the Biomonitoring Study (Part 2 Report, Appendix A).

4.1.3 Reviewer 3

Comment: The Executive Summary could be more comprehensive.

Response: We have elected to keep the Executive Summary a higher-level summary of the information presented in the report and have provided more details in Section 2.0 of both the Part 1 and Part 2 Reports.

Comment: Determine key knowledge gaps.
Knowledge gaps are identified but buried in the text. They should be emphasized in the text and compiled in the Executive Summary.

Response: Additional language has been added about the key knowledge gaps, particularly in Section 1 in the Part 1 report.

Comment: Identify and characterize chemical compounds found in tire crumb used in artificial turf fields and playgrounds.
This goal has been accomplished using state of the art analytical techniques. Suggestions have been made on how to detect additional minor components. However, the overall strategy on how this would aid the decision process should be discussed. Is the expectation that additional risk drivers would be discovered?

Response: Section 2.4.3.6 of the Part 1 Report contains information on the purpose and approach of the suspect screening and non-targeted analyses.

Comment: Characterize exposures, or how people are exposed to these chemical compounds based on their activities on the fields.

1189: The investigators conclude that “exposures at synthetic turf fields should be considered in context with other sources.” It is unclear what is meant with “other sources.” The nature of other contaminant sources is bound to be site specific.

Response: The sentence was revised to clarify that, in this instance, we are referring to the tire crumb rubber in particular. While we agree that sources external to tire crumb rubber are likely to be site specific, we have elected to not lengthen this summary with a discussion of this topic. It is discussed in later sections of the Part 2 Report.

Comment: Identify follow-up activities that could be conducted to provide additional insights about potential risks.
Ecotoxicological risk analysis might shed light on the risks posed by crumb rubber to humans.

Response: We acknowledge the reviewer’s comment, but this is outside the scope of this study.

Comment: Indoor facilities provide a well-controlled setting for human exposure.

Response: We acknowledge the reviewer’s comment.

Comment: The role of ventilation at indoor facilities should be investigated.

Response: We acknowledge the reviewer’s comment, but this is outside the scope of this study.

Comment: The air stream of the ventilation at indoor facilities should be evaluated.

Response: We acknowledge the reviewer’s comment, but this is outside the scope of this study.

Comment: Maintenance personnel are expected to receive greater exposures and should be included in the study.

Response: We acknowledge the reviewer’s comment, but this is outside the scope of this study.

Comment: 1318: “identify current best practices for minimizing exposures.” Are these findings summarized in the report? Which techniques are included, washing, heating?

Response: We direct the reviewer to “Advice for Communities Concerned about Playgrounds with Recycled Tire Surfaces" provided on the Consumer Product Safety Commission’s website.

4.1.4 Reviewer 4

Comment: Specific:

p. xi "Many organic chemicals had higher concentrations in tire crumb rubber collected at recycling plants compared to synthetic turf fields. A few chemicals (e.g. lead and bis(2-ethylhexyl) phthalate) had higher concentrations in synthetic turf field infill than in tire crumb rubber collected at synthetic turf fields, suggesting that for some chemicals there may be contributions at fields from other materials or sources." Should be rewritten for clarity. Is this meant: The concentrations of organic chemicals released by tire crumb rubber collected at recycling plants showed higher concentrations compared to tire crumb runner collected from synthetic turf fields.
A few chemicals (e.g. lead and bis(2-ethylhexyl) phthalate) yielded higher concentrations when taken from infill in synthetic turf than in tire crumb rubber alone collected at synthetic turf fields without other additive materials, suggesting that for some chemicals there may be contributions at fields from other materials or sources."

> **Response:** Some of the clarifying edits suggested by the reviewer have been made in the text. However, the final part of the reviewer's comment is not correct - the important differences in lead and bis(2-ethylhexyl) phthalate were between infill samples from fields and tire crumb samples from recycling plants.

Comment: p. xii "While the results from these studies are not generalizable…" Then why use them? More correct to say that "While the exact measurements from these studies are not generalizable to all other activities, they provide a robust indication of exposure resulting from hard use in sports for which synthetic turf fields are often used.

> **Response:** While the study results are not generalizable, they did provide useful data and informed future activities.

Comment: p. xxvi. "When comparing pre- and post-activity concentrations, there was a significant difference for 2-hydroxynaphthalene, and this difference was greater when restricting to the seven football players." Consider rephrasing for clarity: "Comparing pre- and post-activity concentrations, there was a significant difference for 2-hydroxynaphthalene, and which was greater when analysis was limited to the seven football players."

> **Response:** We have revised for clarity, specifically: When comparing pre- and post-activity concentrations, there was a significant difference for 2-hydroxynaphthalene, and this difference was greater when the analysis was limited to the seven football players.

4.1.5 Reviewer 5

Comment: The Executive Summary describes all of the major components of this investigation clearly, concisely (more in a bit), and accurately and is, indeed accessible to a broad audience. Further, the data, summaries, and conclusions are quite consistent with what is found in the report. However, I found it very brief and somewhat superficial. I craved more "meat" in this section. While I am fully aware that this Section will be read by scientists and non-scientists alike, I think the document would be of better service if it were to contain more content. I am particularly concerned that there are a number of assertions made in the Executive Summary that are not at all obvious and made me wonder if they were to be supported by the data presented later in the Report. As a scientist, I immediately became skeptical of a number of the statements, which is off-putting to say the least. As this Section will be widely read, I urge the authors to consider additional material in which more explanation is brought forward so as to clarify many of these questionable issues. As I read the reminder of the Report, I note a number of places where data are present and displayed quite clearly in graphical format. I believe that judicious use of some of these graphs and figures- pictorial representations of the results- may prove quite useful and convince both the scientist and non-scientist reading this Section that the assertions are indeed supported by the data in the body of the Report. Such a presentation may include the most important exposures, e.g., zinc, a examples, to indicate to the reader the type of data that is forthcoming.

After reading through the entire Report, I find that the major findings reported in the Executive Summary are, indeed, supported by the data throughout the rest of the document. A solution to my perceived problems, thus, is to refer directly to the remainder of the report in the Executive Summary using phrases such as, "details can be found in Chapter XXX" below, or some such referential statement.

> **Response:** We acknowledge the reviewer's comment. We have provided a more detailed summary in Section 2 of both the Part 1 and Part 2 Reports to achieve this purpose. We added information about section topics to help guide readers to these Section 2 summaries in both the Part 1 and Part 2 report.

4.1.6 Reviewer 6

Comment: First, I would like to compliment the multi-agency effort to mount a coordinated, robust effort to understand and address a public concern associated with potential exposures to toxic agents present in the crumb rubber used in some artificial turf fields. Overall, the executive summary describes the major findings and is consistent with the body of the report. Two suggestions that I have are: 1) the first paragraph which provides a broad overview of how this issue evolved and the potential extent, makes no mention of artificial turf used in residences either in place of lawns or under play equipment. While those generally do not have crumb rubber infill, some under play equipment may. Since the executive summary will be the most widely read

portion of the document, a sentence to indicate that the use of artificial turf at residences were not included since they do not predominantly contain crumb rubber could be useful.

Response: There are a number of limitations to the study and elements that were considered outside the scope – these are discussed in Section 2 of both the Part 1 and Part 2 Reports.

Comment: 2) The sentences about the toxicity are in the conclusions (lines 1205-1212). I suggest that it be moved to a separate paragraph/section (entitled: Toxicological Characterization) before the conclusion. The paragraph should indicate that a literature review of the toxicity of the identified compounds was done and where data were available to provide their best estimate of toxicity in a database for subsequent use in a risk estimate. The three sentences about the dearth of information for some agents and the suggestion about toxicity testing of the "bulk" material could be in that paragraph. A single sentence then can be in the conclusions about the need for toxicity data for any key compounds that the exposure assessment suggests are important.

Response: Additional language summarizing the toxicological reference information has been added. Also, a footnote has been added to the Executive Summary of the Part 1 Report about the bulk toxicity testing.

Comment: The suggestion that 'Toxicity testing of the "bulk" material …' be done is not in the main text in the toxicology section, though mentioned in Chapter 2 as the first bullet under future research as "whole material" testing (Lines 1988-1993). It needs to be stated in Chapter 6 as well and guidance on how the "bulk" material should be obtained and prepared since that results from this report identified differences within fields, across fields, and between materials obtained from the manufacturers and from the fields. The guidance could also include issues of aging and location across the US. Further based on the report's evaluation of metals, SVOCs and VOC – what type of chemical characterization is recommended for the material subjected to "bulk" material toxicity study, what exposure route is recommended, what exposure durations should be used, what ages/gender should be tested, and should there be any treatment of the material before dosing. These and possibly other recommendation in the design of toxicity study should be discussed if this is a formal recommendation. While I agree with that toxicity testing of the "bulk" material should be done and noted in the executive summary, it needs to be supported in the main document in the toxicity chapter.

Response: Toxicity testing is mentioned in a footnote in the Executive Summary of the Part 1 Report and is now also mentioned in Section 5.0 of the Part 1 Report; however, it is outside the scope of the study to provide recommendations on approaches.

Comment: The first objective listed in the executive summery is given as:

- Determine key knowledge gaps.

While in the main document it is:

- Determine key knowledge gaps related to chemical characterization, exposure, human health hazards.

You might consider using the same language as was done for the other three objectives.

Response: The language has been adjusted to be consistent.

4.1.7 Reviewer 7

Comment: The Executive Summary is concise and generally clear, but it can be further improved by (a) incorporating quantitative information on specific elements of the study design and the study outcomes and by (b) clarifying a few concepts and statements that readers may find ambiguous.

Response: We acknowledge the reviewer's comment. The Executive Summaries of both the Part 1 and Part 2 Reports have been revised for clarity.

Comment: Specific information that could be added to the Executive Summary includes the actual numbers of chemicals (metals, VOCs and SVOCs) that were identified in the analyses conducted, the numbers of and types of fields studied in each of the geographic/census regions, etc. This type of information would provide a useful overview of the scope and range of the study described in the report (and is probably equally or more important than other details already present in the Executive Summary).

Response: A general figure is now included in the Executive Summary of both the Part 1 and Part 2 Reports showing the research schematic, including types of samples, matrices, and analyses.

Comment: It would also be useful to include in the Executive Summary a brief description of the distinction between chemicals intrinsic to the tire crumb rubber material and chemicals that co-exist with it in the synthetic turf, potentially even absorbed on the surface of crumb rubber (as discussed on page 135 of the report).

Response: A new sentence has been added to the Executive Summary of the Part 1 Report highlighting the volatile organic compound (VOC) observations and suggesting the potential presence of BTEX chemicals (benzene, toluene, ethylbenzene, m/p-xylenes, and o-xylene) from atmospheric absorption versus the potential intrinsic presence in the rubber of chemicals like methyl isobutyl ketone and benzothiazole.

Comment: Some examples regarding ambiguous terminology used in the report follow.

A first example is the word “background” which appears three times in the Executive Summary, each time in a different context:

- On lines 1131-1133 of page xxxiv it is stated that “[f]or most VOC and SVOC target chemicals, air emissions were low at 25 °C, and in many cases not measurable above the detection limit or above chamber background levels.”
- On page xxxv, lines 1171-1172, one reads: “these chemicals were often found at low concentrations or at concentrations only slightly above background, e.g., air levels for outdoor fields.”
- Finally, on lines 1194-1196 of page xxxvi, one reads: “synthetic turf field users may have pyrene and benzo(a)pyrene exposures similar to, or somewhat lower than, typical background exposures, and exposures to zinc and lead that are substantially lower than background.”

Presumably, the term “background” in the third statement above refers to residential and dietary exposures (i.e. a different context from the other two occurrences of the term), which may not be obvious to all readers. It should be noted that subsequent chapters of the report continue to use the term “background” in different contexts, but there, at least in most cases, the context is more obvious in the narrative in which the term appears.

Response: Edits were made to provide more specificity for the use of ‘background’ in this use. Also, a sentence was added to identify the two chemicals with consistently higher emission factors than other target analytes.

Comment: Another example of ambiguous terminology is the use of “target analyte(s)” (lines 1122-1123 of page xxxiv) and “target chemicals” (line 1132, page xxxiv): it is not clear whether it refers specifically to chemicals that “were previously identified as constituents and were expected based on the type of material analyzed” as per line 1120 of page xxxiv, or it includes the entire range of chemicals identified in this study.

- In fact, on page 220 (lines 5968 and 5969) of Chapter 3, it is explicitly stated that “many of the chemicals that were tentatively identified were not target analytes or suspect screening analytes in this study.” It should be clarified whether the Executive Summary conforms to this distinction between target analytes and other identified chemicals.

Response: Edits were made to clarify the description of results. For chemicals with quantitative measurements in this study we believe that the language is sufficiently specific, but the paragraph was split to provide a cleaner break between general and specific results.

Comment: A third example of ambiguous terminology can be found in the statement “[S]ince ventilation rates are lower indoors than outdoors, this may lead to potentially higher inhalation exposures.” (lines 1151-1152 of

page xxxv). The term “ventilation rate” can refer to either a human (or other organism) in which case it is related to inhalation rates (that are affected more by activity, such as running versus resting, than by microenvironmental setting), or to a building (or other enclosed structure), or even to a landscape (such as ventilation of an air basin). As it stands, the above statement in the Executive Summary can be interpreted in various, and potentially incorrect, ways.

Response: We have made adjustments to the text for better clarity.

Comment: An issue that can cause confusion in the “Tire Crumb Rubber Characterization” section of the Executive Summary (pages xxxiv to xxxv) is the brief discussion of VOC and SVOC emission rates for two different temperatures, i.e. 25^{o}C and 60^{o}C. The selection of the two temperatures is not discussed; though 25^{o}C can presumably be considered representative of (quasi-“ideal” ambient conditions, either indoors or outdoors), the selection of 60^{o}C needs substantial justification. The fact is that on a hot sunny day artificial turf becomes very hot (in fact even exceeding 75^{o}C or higher – see, e.g. McNitt etal., 2007, and Thoms et al., 2014) and this can affect significantly the turf properties, including air emissions from its component materials (either intrinsic or absorbed by the tire crumbs). However, the air above the synthetic turf does not reach such high temperatures, resulting in transient gradients and phenomena that are not captured by steady-state chamber experiments.

Response: We have made adjustments to the text for better clarity.

4.2 Charge Question 2: In Chapter 1 of the report, are the goals, background, scope, and approach clearly articulated? Is there anything that should be added or changed to clarify this overview information? Please explain.

4.2.1 Reviewer 1

Comment: Yes, goals, background, scope and approach are clearly articulated. Here are some suggestions to improve understanding and clarity.

Line 1462-Suggest replacing the word released with transferred.

Response: The suggestion has been accepted and implemented.

Comment: Line 1507-Check if authors meant “could not” versus “could be”.

Response: The phrase has been adjusted for clarity.

Comment: Line 1509: Change “the information available” to currently available in the literature” for clarity.

Response: The phrase has been adjusted for clarity.

Comment: After 1524: mention the Exposure modeling and the general approach. Like the Executive Summary, there is very little mention of the exposure modeling. Also this chapter is really exposure and dose modeling. A risk assessment is not fully conducted given no relationship made to the toxicity of the compounds. This can be a next step.

Response: Text has been added to mention the exposure modeling and general approach.

Comment: Lines 1502-1521: This section could be organized a bit better for clarity. Specifically it hard to understand which subjects did what and which set of subjects are a subset of which group. Which subjects participated in the questionnaires, videotaping, and exposure measurement (i.e., wipes, biological sampling, personal air sampling).

Response: Some language has been added to clarify. More details are appropriately laid out in Section 4.0.

Comment: Please mention the IRB procedure/approval and consenting process in this chapter, for work with human subjects. Please mention payment structure, if any, for all participants.

Response: An overview of the IRB approval process has been added. Given the higher-level nature of this section, a reference has been added to the published *Research Protocol: Collections Related to Synthetic Turf Fields with Crumb Rubber Infill,* where details on the structure for providing gift cards as tokens of appreciation for participants are available.

4.2.2 Reviewer 2

Comment: In general, the chapter is clear but some considerations should be addressed:

Line 1230. Some in the public have raised concern….” Perhaps some media reports regarding worries should be indicated (e.g. There have been reports in the news saying that crumb rubber may cause cancers like Hodgkin’s lymphoma and leukaemia [sic]).

Response: Technical references are utilized to the maximum extent possible to provide needed technical information.

Comment: Lines 1259-1260 “Studies thus far have not shown an elevated health risk from playing on synthetic turf fields made with tire crumb rubber”. This sentence should be modified. The number of studies is low but in some of the studies researchers expressed some worries associated to the high number of chemicals present in the material, some of which are considered hazardous for health (including carcinogenic chemicals) and

environment. In fact, 8 of the PAHs found in rubber crumb are regulated by the EU in consumer products (ANNEX XVII TO REACH – Conditions of restriction)

"Articles shall not be placed on the market for supply to the general public, if any of their rubber or plastic components that come into direct as well as prolonged or short-term repetitive contact with the human skin or the oral cavity, under normal or reasonably foreseeable conditions of use, contain more than 1 mg/kg (0.0001 % by weight of this component) of any of the listed PAHs".

In addition, there is an EU restriction intention for PAH limitation in rubber granulates (expected submission date 20 July 2018). "Reason for restriction: Granules as infill material are characterized as mixtures. It is noted that **if the concentrations of carcinogenic PAHs are as high as the generic limit for mixtures supplied to the general public defined in REACH, there is a concern.** To ensure that no plastic and rubber granulate is placed on the market with such high PAH concentrations, a lower limit needs to be set." I think these considerations might be mentioned in the report. I also recommend considering the article Int. J. Environ. Res. Public Health **2017**, 14, 1050; doi:10.3390/ijerph14091050, (mainly the abstract and the background).

> **Response:** The nature of the study is to focus on the technical aspects of characterizing tire crumb and exposures, rather than on policy matters. Relevant references concerning the technical aspects of characterizing tire crumb and potential exposures are provided in Appendix C of the Part 1 Report, "State-of-Science Literature Review/Gaps Analysis".

4.2.3 Reviewer 3

Comment: *General*:

Overall, the goals and approach are clearly articulated. The background could be expanded by a discussion of the benefits of using crumb rubber as an infill material. Are the benefits primarily the economics of using a waste product for a useful purpose or are low-cost alternatives lacking?

> **Response:** The nature of the study is to focus on the technical aspects of characterizing tire crumb and exposures, rather than on policy matters. More information about the industry is available in Appendix A of the Part 1 Report, "Industry Overview."

Comment: The scope is limited to human exposure to crumb rubber components. If ecotoxicological effects considered immaterial, the rational should be explained.

Response: The study was designed as part of the "Federal Research Action Plan on Recycled Tire Crumb Used on Playing Fields and Playgrounds," which specified a focus on users of playing fields and playgrounds with recycled tire crumb infill material rather than ecological endpoints.

Comment: The overall investigative approach is quite complicated. A scheme and flowcharts displaying the relationship between the study components and the decision-making process would be helpful.

Response: A schematic showing the study's components is now included in both the Executive Summary and Section 3.0 of the Part 1 and Part 2 Reports for clarity.

Comment: The background discussion should explain the specific risks that were anticipated and why.

Response: It is important to note that the study was not designed to conduct a risk assessment; thus, it would be premature to state conjectures on anticipated risks.

Comment: What would be comparable "background" risks? Are background risks stemming from the local air contamination? Could second hand smoking, exposure to diesel fuel exhaust serve as a reference?
What would be the accepted risk level, for instance from benzene exposure? Would that have to be specified for each component?

Response: It is important to note that the study was not designed to conduct a risk assessment. Section 5.0 of the Part 2 Report discusses how we modeled estimates of background exposures from residential and dietary sources.

Comment: Specific:
1229-1230: What is the diameter of crumb sized material?

Response: Diameter sizes vary. A reference to reported approximate size ranges has been added.

Comment: 1231-1249: Classify components into major, minor, traces and impurities.

Response: The variety in manufacturing methods and chemicals used makes it difficult to generalize the components and their relative amounts across all forms of recycled tire crumb rubber. A major objective of the current study was to characterize and quantify, as much as possible, the variety of components.

Comment: 1260: Studies that address ecotoxicological risks should be referenced.

Response: The study was designed as part of the "Federal Research Action Plan on Recycled Tire Crumb Used on Playing Fields and Playgrounds," which specified a focus on users of playing fields and playgrounds with recycled tire crumb infill material rather than ecological endpoints.

4.2.4 Reviewer 4

Comment: p. 2. A brief summary of the CPSC plan for evaluation of tire crumb-related exposure on playgrounds would be very helpful.

Response: References were added to direct readers to information about the CPSC study.

Comment: p. 3. No mention is made of contact with the academic and research community, and their important contributions.

Response: We have interacted with the academic and research community, primarily at scientific conferences. Text has been added to clarify this.

4.2.5 Reviewer 5

Comment: While the goals, etc., are delineated clearly, there is still, in my opinion, a need for an overarching, context-setting paragraph. The paragraph beginning at Line 1262, begins to accomplish this but its placement, at the end of a long discussion of modestly-relevant background information, dilutes its impact. The expansion of this paragraph should be given a more prominent location.

Response: The paragraph in question was moved up to provide an overarching context, setting the material towards the beginning.

Comment: After this Introductory section, the authors do a good job articulating their intent via the bullet points in Lines 1277-1284. I am hoping that they draw the reader back to these questions in a review at the end of the detailed presentation, perhaps in a Conclusions section. The Chapters/Sections appear to follow this outline, but a concise Conclusion will be necessary.

Response: A Conclusions subsection has been added to the end of Section 2.0 of the Part 1 and Part 2 Reports. An overall set of concise FRAP Conclusions was added to the Executive Summary of the Part 2 report, and Summary Findings for the exposure characterization work are included in Section 2.0 of the Part 2 Report.

Comment: In lines 1277-1284, the others lay out their specific aims for the document in bullet points. To delineate the approach to these bullet points, the authors lay out specific Aims for this reports in lines 1455-1462. They then continue on describing the remainder of the report. I appreciate the "roadmap" for the reader as it gives guidance on where each component of the study can be found in this voluminous document.

Response: We acknowledge the reviewer's comment.

4.2.6 Reviewer 6

Comment: Chapter 1 clearly articulates the goals, background, scope, and approach of the project. The goals (or objectives as they are referred to in the document) are further elucidated into sub-objectives or aims for each section.

The only clarification I would suggest is what I indicated for the Executive Summary: No mention is made of artificial turf used in residences either in place of lawns or under play equipment. While those generally do not have crumb rubber infill, some under play equipment may. Clarification of why these materials were not included could be helpful.

Response: The study was designed as part of the "Federal Research Action Plan on Recycled Tire Crumb Used on Playing Fields and Playgrounds," and thus focused only on playing fields and playgrounds with recycled tire crumb infill material. Limitations of the study are discussed in Section 2.0 of the Part 1 and Part 2 Reports.

4.2.7 Reviewer 7

Comment: The goals, background, scope, and approach are in general clearly articulated in Chapter 1 of the report. However, the exact same recommendations that were discussed above, in the response to the first question (for the Executive Summary), regarding incorporation of quantitative information on specific elements of the study design and the study outcomes apply also to the narrative of Chapter 1. So, it would be useful to include here the total number of chemical "constituents" identified (the number 355 appears for the first time in Chapter 2, on line 1871 of page 19) as well as the numbers of chemicals in groups of concern (metals, VOCs and SVOCs). The distinction between intrinsic and absorbed constituents (appearing for the first time on page 48 of Chapter 2 and discussed further on page 135 of Chapter 3) should also be included in Chapter 1.

Response: Extant toxicity information was collected for 355 constituents. Information on the target number of analytes for metals, VOCs, and SVOCs has been added, as well as text about how some experiments could provide insights into constituents intrinsic to the rubber material versus constituents that may have been adsorbed over time.

Comment: Some specific points for clarification and/or improvement are listed here:

- It would be useful to add a "qualitative map" showing the distribution (via approximate location, since, as per the discussion on page 82, there was agreement to not reveal actual locations) of the 40 fields studied across the four census regions; it would also be useful to include information regarding the type and the locale/surroundings of these fields (e.g. suburban versus inner city, community versus military, etc.).
    - For example, on page 24 (lines 2042-2044) of Chapter 2 it is clarified that of the 40 fields considered, 21 ware community fields and 19 were military fields but no further characterization is offered.

Response: A map of the census regions has been added to Section 3.0 of the Part 1 Report. Only those field characteristics relevant for comparative analyses of the fields are provided in Section 3.0.

Comment:

- The year for the reference to Marsili on line 1249 of page 1 "(Marsili et al., 2015; …)" and correspondingly in the References (Chapter 7, page 377, lines 9058-9061) should be corrected to 2014. It should be noted that the correct year (2014) for this reference appears when it is cited in Chapter 2 (Tables 2-1, 2-2, 2-4 and 2-5).

Response: The correction has been made.

4.3 Charge Question 3: Chapter 2 presents a summary of results and findings. Are the major findings supported by the information and data presented in the report? Are there other major findings that have not been brought forward or information needed to substantiate the conclusions? Please explain.

4.3.1 Reviewer 1

Comment: Yes, the major findings are supported by the information presented, given mention of the great variability seen in the chemical concentrations and in the activity patterns. Here are some suggestions for improvements.

Table 2-1, Table 2-2: For the reader to quickly compare, it might be good to put the columns on outdoor results next to each other.

Response: The order of the columns in Tables 2-2, 2-3, 2-4, and 2-5 have been changed to group the recycling plant, indoor, and outdoor results for easier comparison across studies.

Comment: Line 1657: To put the microbial count on synthetic turf fields into perspective, it might be nice to compare to any other studies about typical counts found on surface of various types. We might get a bit more perspective on whether this is a concern. In addition, the exposure modeling could explore the potential exposure amount to biological agents from playing on turf. Below are two examples of articles exploring microbial counts. More relevant papers can be sought, paying attention to methods of collection and analysis (e.g. qPCR might be more relevant).

> Luksamijarulkul et al., 2015 "Microbial Air Quality and bacterial Surface Contamination in Ambulances During Patient Services" Oman Med (found at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4412456/)
>
> Hsu et al., (2016) "Urban Transit System Microbial Communities Differ by Surface Type and Interaction with Humans and the Environment" mSystems, V.1 (found at https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5069760/).

Response: Total bacterial counts alone should not be alarming as bacterial communities are essential for many ecosystem processes. To emphasize this point, text was added to include the general bacterial counts in some environments and surfaces that humans encounter daily. An effort was made to find references that utilized quantitative polymerase chain reaction (qPCR) to assess bacterial concentrations as the reviewer suggested, but most studies employ culture-based methods.

The following text was added to Section 2.1.2 (now Section 2.2.2) of the Part 1 Report, "Overview of Results and Key Findings":

> "There were no directly-comparable genetic studies found for either synthetic turf or grass playing fields. Small studies that cultured bacteria have found more colony forming units (CFU) for some bacteria at grass fields compared to synthetic turf fields (McNitt et al., 2007; Vidair, 2010), and two independent studies showed that the addition of rubber to soil significantly reduced concentrations of culturable bacteria and the metabolic activity of the natural microbial community (Goswami et al., 2017; Pochron et al., 2017). The presence of a bacterial community in synthetic turf fields is not surprising, however. Bacteria have been reported at similar concentrations in environments that humans encounter, such as indoor air (5.6 log10 bacteria-like particles [BLP]/m3), outdoor air (8.4 log10 BLP/m3; Prussin, et al. 2015) and common household items, including mobile phones (4.2 log10 gene copies of 16S ribosomal ribonucleic acid (rRNA) genes per phone; Koljalg et al., 2017) and kitchen hand towels (7.2 log10 CFU per towel; Gerba et al. 2014). It should also be noted that the human body harbors an estimated 13.6 log10 bacteria (Sender et al., 2016). In another study (Vidair, 2010), researchers cultured Staphylococcus and methicillin-resistant Staphylococcus aureus (MRSA) from samples collected at five synthetic turf field and two grass fields. In that study, 2 of the 30 samples collected from synthetic turf were positive for a species of Staphylococcus

compared to 6 of 12 samples collected from natural turf. No MRSA was detected on synthetic turf, while a single sample of blades from natural turf was positive for MRSA. Vidair (2010) concluded that their data indicated that the new generation of synthetic turf containing crumb rubber infill harbors fewer bacteria than natural turf, including Staphylococcus and MRSA."

Comment: Line 1698: mention the time for the bioaccessibility study. Also mention the justification for this time and how this compares to the typical time of typical play on turf for this bioaccessibility study, at least in relation to dermal absorption. When individuals do not shower immediately after play the compound may sit on the skin for a longer period.

Response: The extraction time (1 hour) for the bioaccessibility testing and the method references are given in Section 3.6.9 of the Part 1 Report. The extraction time (1 hour) is likely to be similar to or shorter than typical play time on turf fields, depending on players' age and sport type. However, one hour of extraction under constant rotation with the tire crumb submerged in the fluid, should provide sufficient time to reach an equilibrium between the tire crumb and the artificial biofluids. In addition, the chemical transfer between tire crumb material and artificial biofluid may be more "complete" than the actual dermal contact during the field play time, because all surfaces of the tire crumb would not be immersed in sweat for the entire contact time with skin during play. Since this section is a high-level summary of results and findings, it is not appropriate to add specifics (extraction time, justification, comparison to typical play time) into this section. Therefore, we respectfully decline to significantly alter the bullet point.

Comment: Line 1792: Mention whether the questionnaire contained questions on what subjects where [sic] doing before coming to the fields to play to access pre-exposures (I believe it did not).

Response: The full questionnaire is available in Appendix D. A question related to consumption of grilled, smoked, fried foods was included in the questionnaire.

Comment: Line 1865: Is there another way to reference "≤ 1.5 times higher". The brain is reading "less than and equal to and higher than in one sentence". The reader has to pause and clarify. Can you say on average 1.5 times higher (number 1.5 would of course change to the actual average)? Or you can say at most 1.5 times higher. This occurs a few times in the report in other chapters (e.g., 2688).

Response: The identified text, now in Sections 2.2.2 and 2.3.1.5 of the Part 2 Report, was revised to say "at most 1.5 times higher."

Comment: Table 2-3 (second to last row). Developing methods…add "collection" or "analysis" before the word methods to match what is really meant.

Response: Added "sample collection and analysis" to the table (now Table 2-1 in the Part 2 Report) to be more specific with reference to blood and urine samples.

Comment: Line 2037: I am a little confused about this throughout the document. ATSDR and EPA had agreement with six tire recycling plants. Did they not need agreements with three?

Response: To clarify, the text throughout was changed to clarify that sample collection agreements were reached with the six companies that operated the nine tire recycling plants at which samples were taken.

Comment: Line 2061-2062 mentions that potentially 15% of fields had standard practices to reduce exposure to tire crumb material. There is no further explicit mention here or in chapter 4 or 5 of what these practices might be. It would be of interest to look into what these practices might be and whether there was any correlation of reduced measures (concentrations and exposure measures) on these fields. The authors could have meant reduction to exposures to microbial agents (line 3918 in chapter 3). Please clarify that this section refers to only reduction in exposure to microbial agents and not chemical constituents. Clarify whether this is also the same at table 3-36 for a frequency of 6 that responded to practices in place to reduce tire Crumb exposure?

Response: There were insufficient responses to an open-ended question for specific practices to conduct an analysis to distinguish concentration and exposure measurements based on respondents' answers.

Comment: Line 2247" This comment is hard to understand. Please rephrase.

Response: The bullet (now in Section 2.4.3.4 of the Part 1 Report) was revised in an attempt to improve clarity.

Comment: Page numbering: Page numbers jump from 33 to 41. This occurred after a table or could indicate we are missing pages. The sections do seem to follow from each other though. Page numbers reverts to 41 again from chapter 2 to chapter 3.

Response: Pagination has been fixed.

Comment: Line 2268: Bold this section to indicate it is still part of the Figure 2-13 caption.

Response: Fixed.

Comment: Lines 2504 to 2508: The bioaccessiblity is in part driven by the concentration of the compound in the material, not only by the surface availability as mentioned.

Response: We have revised the sentence to reflect the reviewer's comment: "The observed higher lead concentrations in artificial gastric fluid from field samples could in part be driven by the higher lead concentrations in the field samples, as reported earlier in the section. Another possible explanation for the observed higher bioaccessibility from field samples is that some of the lead in synthetic turf field infill could come from external sources and be available on the surface of the infill rubber."

Comment: Line 2690: Someone might be interested in looking at dietary exposures and residential for two reasons, to illustrate how other exposure routes might be greater, but also to look at total exposures to these compounds. I do think these points can be explicitly stated in line 2682.

Response: The reviewer makes a very good point here. The following sentences were added to Section 2.3.1.5 of the Part 2 Report: "Modeling 'background' exposures may also inform approaches for estimating total exposures that synthetic turf field users may experience from all sources. Total exposure estimates would best be performed over an appropriate time interval, for example over a year, rather than the comparison of daily exposures that was performed here."

4.3.2 Reviewer 2

Comment: Yes, this chapter summarizes the project quite well.

Nevertheless, although given in other chapters, some information should also be included here:

2.1. Tire Crumb rubber characterization.

Please indicate the number of samples or sub-samples taken in each field.

Response: Our goal and purpose for Section 2.1 (now Section 2.2 of the Part 1 Report) was to provide very concise summaries of the general approach and key results for the study in a way that can be accessible for the non-expert reader. Somewhat more detailed information is provided in Section 2.7 (now Section 2.4 of the Part 1 Report), and all study details and results are provided for the interested reader later in the report.

Comment: Please include a table in this section with the target compounds and the detection limits.

Response: Our goal and purpose for Section 2.1 (now Section 2.2 of the Part 1 Report) was to provide very concise summaries of the general approach and key results for the study in a way that can be accessible for

the non-expert reader. Target chemical lists are provided in Section 3.1 of the Part 1 Report, and analysis-specific detection limits are provided in Appendix E.

Comment: Please include a table with the screening and non-target tentatively identified compounds, or at least some of the most relevant ones.

Response: Our goal and purpose for Section 2.1 (now Section 2.2 of the Part 1 Report) was to provide very concise summaries of the general approach and key results for the study in a way that can be accessible for the non-expert reader. A description of the methods, results, and interpretation of the suspect screening and non-targeted results are complex and are described in somewhat more detail in Section 2.7 (now Section 2.4), and in full detail in Sections 3.0 and 4.0 of the Part 1 Report. The following sentence was added to Section 2.1.2 (now Section 2.2.2): "Several SVOCs tentatively identified through suspect screening analysis included chemicals reported to be used as accelerators or anti-oxidants in rubber manufacture; however, more work would be needed to confirm chemical identities."

Comment: Emissions. Lines 1631-1643. Please indicate that the findings are mainly based on chamber tests instead of real field tests. Indicate the type and number of air samples obtained (both in real facilities and in chamber tests). Were air samples taken in real fields on summer and winter days to show the real effects of different temperatures? Please indicate the air temperature for the real air samples.

Response: A revision was made to clarify that the emissions testing was laboratory-based: "This study generated emission test results for VOCs and SVOCs using dynamic emissions testing chambers in the laboratory." Emission testing information is provided in somewhat more detail in Section 2.7 (now Section 2.4), and in full detail in Section 3.0 of the Part 1 Report.

Comment: Please indicate the target compounds found in the emission/air samples, both chamber tests and real samples.

Response: Our goal and purpose for Section 2.1 (now Section 2.2 of the Part 1 Report) was to provide very concise summaries of the general approach and key results for the study in a way that can be accessible for the non-expert reader. A description of the methods, results, and interpretation of the emission results are complex and are described in somewhat more detail in Section 2.7 (now Section 2.4), and in full detail in Sections 3.0 and 4.0 in the Part 1 Report.

Comment: Body fluids. Why were the bioaccesiblity [sic] tests only made for metals? Please explain here. Please indicate how many crumb rubber samples were used for the metal bioaccessibility tests. Was the crumb rubber particle size taken into consideration?

Response: The information regarding why SVOC analysis was not performed is included in Section 2.5.2 of the Part 1 Report, "Planned Work Not Completed in this Part of the Study." As this section is specific to results for performed analyses, additional information regarding SVOCs is not included here. The bioaccessibility testing was done on all samples, without separation by particle size, to most accurately reflect player contact. The number of samples has been added to the first sentence of the subsection.

Comment: 2.1.3. Summary. It would be nice to have a paragraph regarding the emissions of organic chemicals, the levels found in air and the most likely human exposure through inhalation, especially on hot days and in indoor facilities.

Response: A new paragraph has been added to Section 2.1.3 (now Section 2.2.3) of the Part 1 Report, "Tire Crumb Rubber Characterization Synopsis" to highlight key aspects of the emission research and what it may mean for human exposure. The results of this work could be applied in future modeling efforts to better predict the potential for inhalation exposures under different conditions and settings, but that modeling is beyond the scope and time available for this report.

Comment: 2.2.2 Please indicate the number of indoor and outdoor air samples collected, the number of facilities and the ambient conditions (mainly temperature), as well as the distance from the rubber surface. Please briefly describe the results obtained.

Response: Our goal and purpose for Section 2.2 of the Part 2 Report was to provide very concise summaries of the general approach and key results for the study in a way that can be accessible for the non-expert reader. Methods and results for the exposure characterization study are described in somewhat more detail in Section 2.7 (now Section 2.3), and in full detail in Sections 3.0 and 4.0 of the Part 2 Report. Some details on the number of fields and participants is provided in Section 2.2.1 of the Part 2 Report. A revision was included to note that the exposure study was performed at two outdoor fields and one indoor field.

Comment: In field dust samples. How many samples were collected and in how many indoor and outdoor facilities?

Response: Methods and results for the exposure characterization study are described in somewhat more detail in Section 2.7 (now Section 2.3) and in full detail in Sections 3.0 and 4.0 in the Part 2 Report.

Comment: Dermal wipe samples. Was only one wipe used for all the considered parts of the body? How many times was the wipe rubbed against the skin? Only once? Please include the corresponding information.

Response: Methods and results for the exposure characterization study are described in somewhat more detail in Section 2.7 (now Section 2.3) and in full detail in Sections 3.0 and 4.0 of the Part 2 Report.

Comment: To check if all the chemicals have been removed from the skin, a new fresh wipe should have been used. Otherwise, how can we assume that all the chemicals were removed from skin to establish the amount of compound per cm^2 of skin? The real values are likely to be higher. Wipe samples were extracted after application. What was the efficiency of the extraction method? Please, briefly comment on these aspects.

Response: The reviewer is correct. The dermal exposure resulting from play on the field may be overestimated, if some amount of target chemical was already present on the skin prior to practice, and may be underestimated, if the wipe sampling does not remove 100% of the chemical present at the skin surface. Ideally, wipe samples would have been collected at both the pre- and post-practice time points, and a subset of participants would have been asked to allow a second wipe to assess recovery efficiency. However, the amount of pre- and post-practice time with the participants was highly constrained; a decision was made to prioritize the available time towards collection of the pre- and post-practice urine and blood samples. This is a study limitation that is noted in Section 2.2.2, Section 2.4.1, and elsewhere in the Part 2 Report.

Comment: Regarding biomarker measurements in biological samples, please indicate the target chemicals in each matrix, and the reasons for choosing those chemicals. Why were only metals considered in blood samples?

Response: The target chemicals in each matrix are included in the tables in Part 2, Section 4. The serum metals, blood metals, and urinary PAH metabolites were chosen based on previous research and availability of analytical methodologies.

Comment: Please explain what information could be obtained considering the close proximity between sampling times (before and after activity) and the chemical pharmacokinetics. Is it only possible to evaluate acute exposure? What about chronic exposure?

Response: The intent of the study was not to look at chronic exposure but to evaluate exposures prior to and post-activity on the fields. This was a pilot scale effort to evaluate potential exposures and to determine if further analysis was warranted. The data collection protocol in this study aligns with previous studies that have demonstrated that an exposure-free period of 24–48 hours is often required for PAH biomarkers to

reach pre-exposure baseline (Zheng 2012, Brzeznicki 1997, Chien 2010, Viau 1995). More recently, data from Choi et al. 2023 demonstrated that the fractional urinary excretion of urinary PAHs ranged from 0.07 % to 11.3% and that most were excreted within 24 hours after exposure, though the obtained fractional urinary excretion values only reflected oral intake. For metals, there is not an expectation for concentrations of blood and serum metals to exhibit much change from before to after activity. However, comparison to the general population (NHANES) was possible.

Comment: Considering the very likely high exposure of goalkeepers, why were none included in the group of participants?

Response: Although we attempted to recruit full-time goalkeepers into the study, none volunteered to participate from the teams that were available. Among the youth soccer organizations, participants that spent part of their time at the goalkeeper position were recruited, but these participants spent only short time intervals in goalkeeper drills during their monitored practices.

Comment: Lines 1857. The comparison with other typical sources seems quite limited. For example, only one study was considered to establish the typical PAH levels in dust. The uncertainty is very large and the exposure estimates quite doubtful. In addition, only two PAHs, pyrene and benzo[a]pyrene, were considered.

Response: We agree and have clearly articulated the limitations of the exposure pathway modeling results in the introductory paragraph to Section 5.2 (Exposure Pathway Modeling Results).

Comment: 2.2.3 In Summary. Lines 1894-1897. Due to the uncertainty of the study and the limited previous studies regarding exposure, the last part of the following comment should be eliminated: “Taking into account the pilot nature of this study and attendant uncertainties, neither of these observations on their own can provide definitive answers that exposures may be low, ~~together they are supportive and consistent with results of recent studies~~”

Response: The finding is consistent with a number of studies. We deleted the word “supportive” but will keep the remainder.

4.3.3 Reviewer 3

Comment: *General*:
Results and findings summarized in Chapter 2 are consistent with the data presented in the body of the report. The authors should highlight findings were not anticipated and particularly significant. Which findings are potential show stoppers?

Response: We believe the stated conclusions are appropriate to the pilot scale nature of the exposure study. A follow up biomonitoring study was conducted and is being released with Part 2 of the report.

Comment: *Specific*:
1793–1811: "For 2-hydroxynapthalene, there was a statistically significant difference in mean concentrations when comparing pre- and post-activity levels (p-value = 0.041)," indicating that naphthalene was taken up by synthetic turf field users. What is the toxicological significance of this finding. Would one expect metabolites of similar compounds, e.g., t-octylphenol, benzothiazole, aniline, benzothiazoles, etc.? What is the expected pharmacological fate of these compounds in the body and the timespan between exposure and excretion?

Response: As this was a pilot scale effort, we did not discuss toxicological significance nor import. For PAH urinary metabolites, data from Choi et al. 2023 demonstrated that the fractional urinary excretion of urinary PAHs ranged from 0.07 % to 11.3% and that most were excreted within 24 hours after exposure, though the obtained fractional urinary excretion values only reflected oral intake. Neither the pilot scale effort nor the supplemental biomonitoring study looked at the chemicals referenced above.

4.3.4 Reviewer 4

Comment: p. 13. Use of word "bioaccessibility" in line 1643 is confusing because "body fluids" could refer to the simulated biological fluids of the test system or bodily fluids of a receptor. Suggest: "The amount of chemicals released from tire crumb rubber and solubilized into body fluids characterizes the potential exposure of a receptor to the chemical and that determines what is available for absorption (bioavailability).

Response: The sentence has been revised.

Comment: p. 15 and elsewhere. Selenium and arsenic are metalloids, not metals. This distinction may not be important for purposes of report.

Response: We have added the following footnote to Section 2.1.1 (now Section 2.2.1 of the Part 1 Report): "Among the target analytes, arsenic and antimony are commonly considered metalloids while selenium is sometimes considered a metalloid; these elements are included in the 'metals' category in this report for simplicity."

Comment: p. 15 This is first mention of "field dust", at least that this reviewer noticed. Needs to be defined, distinction made from dirt or displaced infill, and method of sampling at least briefly described. I cannot find any mention in Volume 2.

Response: The following sentence has been added to Section 2.2.2 of the Part 2 Report: "Field dust was obtained by placing infill from the synthetic turf field surface into a sieve and collecting particles < 150 µm for analysis."

Comment: p. 20. Tire crumb is sometimes added directly to soil and natural grass.

Response: The reviewer makes a good point regarding other unstudied uses of recycled tire crumb rubber. The following sentence has been added as a limitation in Section 2.4.4 of the Part 2 Report: "It was also beyond the scope of this study to evaluate the use of recycled tire crumb rubber as a soil amendment or natural grass top dressing."

Comment: P. 25. Lines 2078 to 2082 do not match lines 2074 to 2076 in terms of referent. This paragraph seems to say that as particle matter goes air tire crumb particle size is very large (no surprise) but may get somewhat smaller as infill is pounded during use. However, it does not follow that one explanation is crustal, atmospheric deposition or biogenic sources. Surely the study distinguished between tire crumb particles and crustal and coarse air pollution particulate matter. If not, looking at surviving sample by TEM should be enough to settle this easily.

Response: A new bullet point was created to separate the two points being made and the language was revised. While our scanning electron microscopy (SEM) work explored an approach for classifying small particles in synthetic turf field infill, we were not able to systematically apply that approach to the collected samples in the time available.

4.3.5 Reviewer 5

Comment: I appreciated the Section "Executive Summary" Section 2.1.2 Overview of Results and Key Findings at the beginning. This Overview Section summarizes important results in a digestible fashion. Those with a need for more details can then dive into the details of the rest of the Section, as well as the Appendices, if so desired. I do have mixed feelings about the logarithmic scale in the data representations, particularly.

Response: We agree that there are advantages and disadvantages of using logarithmic scales for the chemical concentration bar graphs. Because of the large range in concentrations among chemicals, many of the chemicals would be difficult to distinguish above the baseline, if we did not use a logarithmic scale. However, using a logarithmic scale reduces the ability to observe important differences in results across recycling plants, indoor fields, and outdoor fields for many chemicals. In summary, we elected to use the logarithmic scale here to allow presentation of multiple chemicals at once, while highlighting and illustrating important differences in subsequent sections.

Comment: The data reported in this section is extensive and well-reported. However, much of the exposure data reported is on a very small sample size- N<40. Reporting is done on a large number of measurements of many compounds in multiple classes However, these data area, at best, pilot level. The conclusions drawn are soft, and are described as such by the authors. While a substantial compendium of information is developed, the authors themselves caution on the use of these data in any generalized sense. Nevertheless, the data are very useful in the design and implementation phase of future studies as suggested and outlined in the report.

Response: We appreciate the thoughtful consideration of the data and how it is represented.

Comment: It would seem that the data collected in this study are illustrative, rather than definitive. The small sample size and provocative results beg for an additional systematic study design and implementation. However, such a study would be very expensive to carry out and would, by necessity, be far-flung with respect to geographical location. It is certainly within reason to think that a study would require multiple locations around the country and in differing seasons. Further, multiple formulations of tire-crumb fields would have to be investigated. This may well be cost-prohibitive. The end result maybe that this study will be the largest and most complete to be carried out.

Response: We appreciate the thoughtful consideration of the data and how it is represented. We believe that the results of this study will be useful to future investigations, if any, for informing where to focus and apply, what are typically limited, resources.

4.3.6 Reviewer 6

Comment: Chapter 2 presents a summary of the results and findings. The tables and figures provide an indication of the detailed findings and the information presented is supported by the more detailed results presented elsewhere in the report and appendices. I did not notice any major findings not included in this chapter. That said, the chapter appears to contain two levels of summaries, a brief, broad overview summary (of each class of contaminants analyzed, the activity characterization for the exposure, the toxicology literature), followed by a section on Research Limitations, and then a second level of summaries for each report chapter. When reading the chapter I had the impression that I was reading the same material twice (and in subsequent chapters, a third and fourth time – though that is more understandable since this chapter summarizes the rest of the text and appendices). It is unclear to me why this chapter is not organized as a single summary of the findings followed by the limitations at the end of the chapter.

Response: We have elected to provide a shorter summary at the front of this section, followed by some more details for the interested reader. The limitations have been moved to the end of the section.

Comment: Page 168, Line 5185/ Figure 3-49 indicated that the high variability in lead is driven by a single high lead concentration at an indoor field (~160mg/kg). While still below the bare soil standard and likely not from the crumb rubber it supports the concern raised by Pavilonis et al (Table 3-120, Appendix B Page 44) that lead at levels of concern could be on these fields and its level needs to be checked in the same manner as soil used for playgrounds. The authors have minimized any concern about lead exposure from playing on these fields. A caveat for lead sources beside crumb rubber for these fields is warranted.

Response: The text in Section 2.1.2 (now Section 2.2.2 of the Part 1 Report) was revised in two ways. First, lead and bis(2-ethylhexyl) phthalate were cited as examples where field concentrations were greater than recycling plant concentrations. Another sentence was added: "One synthetic turf field had a substantially higher measured concentration of lead (160 mg/kg) in its composite tire crumb rubber infill sample than other fields, while another field had similar levels in two of seven individual location samples. These results suggest sources of lead other than tire crumb rubber may be present at some locations."

4.3.7 Reviewer 7

Comment: The major findings and results that are summarized in Chapter 2 are certainly supported by the information and data presented across the full report. Some specific issues to be addressed are summarized here:

- Citations to Celeiro et al. 2018, Ruffino et al. 2009, Bocca et al. 2009, Gomes et al. 2010, appearing in Tables 2-1, 2-2 (page 12), Table 2-4 (page 28), Table 2-5 (page 32) are not listed in the References (Chapter 7); the citation to Kim et al. 2012, appearing in Tables 2-1 (page 12) and 2-4 (page 28) is included in Chapter 7, but is incomplete.

Response: The References section has been updated.

Comment:

- On page 15, lines 1738-1740 it is stated that the "numbers of exposure study participants included 32 for the questionnaire component, 25 for the exposure measurements sub-study, and 17 for the video activity. Fourteen participants provided urine samples and 13 participants provided blood samples." Similar statements appear throughout the report, but it needs to be clarified if these groups were all *mutually exclusive* (i.e. that, (a), there is no overlap among the 32 participants for the questionnaire component, the 25 for the exposure measurements sub-study, and the 17 for the video activity pilot study, and (b) there is no overlap among the 14 participants who provided urine samples and the 13 participants who provided blood samples).

- *If in fact the above groups were mutually exclusive, this would constitute a missing opportunity for cross-evaluation of different characterization methods and it should be listed in the study limitations (this is an item that applies to the next question).*

Response: The sentence has been revised to help clarify that, in fact, the participants in the exposure measurement and video activity portions of the study were subsets of the 32 people that provided responses to the questionnaire. The text has been further clarified to indicate that the 14 participants providing urine samples and the 13 participants providing blood samples were subsets of the 25 exposure measurement study participants.

Comment: The legends of Figures 2-4 (page 17) and 2-5 (page 18) should clarify what are the statistical metrics ("Values") that are compared; in Figure 2-3 (page 17) the legend explicitly states that in that Figure it is a comparison of Geometric Mean Values.

Response: This has been added to Figures 2-5 and 2-6, as well as 4-33 and 4-34 in the Part 2 report.

4.4 Charge Question 4: The limitations are summarized in Chapter 2. Are they clearly articulated and appropriate based on available data, the methods used, data presented this report, and the overall findings? Are there any gaps or information that needs to be added? Please explain.

4.4.1 Reviewer 1

Comment: The limitations are clearly stated. Here are a couple things related to improving the discussions on limitations:

Line 1888: Change "due, in part, to incomplete" to "in part due to incomplete". Also please clarify what the incomplete information means with reference to the dust adherence to skin?

Response: The suggested edit was made in Section 2.2.3 of the Part 2 Report, and the sentence was revised in an attempt to be more specific: "…. the magnitude of potential exposures is still somewhat uncertain, in part due to incomplete information regarding the amounts of field dust that adhere to the skin of synthetic turf field users and the amounts of dust and tire crumb rubber ingested."

Comment: Line 1998: It says that portions of biomonitoring data could be retained for future use. Please mention (here and in Chapter 4) whether any urine or blood samples were in fact retained.

Response: Participants who consented to allow their samples to be stored for future use had their samples retained.

Comment: Line 2009: Include examples (e.g.,) after mention lack of parameter value data. You could be referring to dermal adherence values, ingestion rates (although some of that was collected).

Response: The following sentence was added: "For example, the amounts of tire crumb rubber and field dust that adhere to the skin and the amounts of tire crumb rubber and field dust that are ingested are not currently available."

Comment: Line 2715-2717: give examples of the conservative values used and important exposure mechanisms that might be missed (e.g., deposition to skin).

Response: Specific examples have been added to this discussion. Here is the revised paragraph: "In some cases, conservative parameter values have been applied in order to inform conservative and protective assessments, but that could lead to exposure over-estimation. For example, RIVM applied a conservative tire crumb rubber ingestion rate of 0.2 g/event, which is higher than the 24-hour soil and dust ingestion values ranging from 0.01 to 0.06 g/day commonly used for residential exposure estimation. RIVM and ECHA also applied a conservative soil/dust dermal adherence factor of 0.001 g/cm^2, which is higher than reported amounts measured for residential or other relevant scenarios. In other cases, important exposure mechanisms may not be correctly accounted for that could lead to exposure under-estimation. For example, the amount of airborne tire crumb rubber fine particles could be higher in the direct breathing zones of some athletes than existing measurements suggest, potentially resulting in an underestimation of inhalation exposures."

Comment: Talk about why a full health risk assessment to determine cancer and non-cancer risks could not be performed in this report (e.g. great variability in findings, lack of toxicity measurement to multiple chemical exposures).

Response: The scope of the Federal Research Action Plan was not to conduct a full health risk assessment nor is there any intent to do so. A follow up biomonitoring study was conducted, the results of which are being released in conjunction with the Part 2 report.

Comment: Mention why probabilistic modeling was not conducted (i.e., lack of data) and therefore deterministic assessment were made using UCL with respect to the measures on daily dose.

Response: The following sentence appears in Section 2.7.5.5 (now Section 3.1.5 of the Part 2 Report): "The data are not adequate to support probabilistic exposure modeling approaches….This lack of robust data likely results in increased uncertainty in exposure estimation, and the data are not adequate to support

probabilistic exposure modeling approaches." There is additional discussion regarding probabilistic modeling in Section 5.0 of the report.

4.4.2 Reviewer 2

Comment: The limitations are quite well summarized.

2.5 Future Research. Regarding future research recommendations it is very important to identify other non-target chemicals that might have important consequences on health. In addition, the whole material toxicity is essential, due to the high complexity of the matrix.

Response: We agree with this and made it the first bullet point under Section 2.4.5 of the Part 2 Report, "Future Research Recommendations."

Comment: I would include some future research proposal regarding the environmental impact of these facilities, considering that an important part of the chemicals are probably released into the environment (e.g. air, run-off water).

Response: Environmental impacts are outside the scope of this study.

Comment: 2.7.3.6. Although they were only tentatively identified, please include a table with the non-target chemicals or at least some of the most relevant.

Response: The following sentence was added to provide examples for chemicals tentatively identified through suspect screening analysis: "Examples of chemicals tentatively identified through suspect screening include 2,2,4-Trimethyl-1,2-dihydroquinoline (TMQ, a tire rubber antioxidant) and other potential tire rubber chemicals that may be used as rubber vulcanization accelerators, rubber antioxidants or rubber antiozonants, such as:

- N,N'-Diphenyl-p-phenylenediamine (DPPD),
- N,N'-Ditolyl-p-phenylenediamine (DTPD),
- N,N-Dicyclohexyl-2-benzothiazolesulfenamide (DCBS),
- N-tert-Butyl-2-benzothiazolesulfenamide (TBBS), and
- N-Isopropyl-N'-phenyl-p-phenylenediamine (IPPD)."

Due to the complex nature of the methods, results, and interpretation for the non-targeted analyses described in Section 3.0 of the Part 1 Report and the lengthy, but highly uncertain, nature of the chemicals

included in the tables provided in Appendix R, we have elected not to include examples of non-targeted chemicals in Section 2.0 of the Part 1 Report. The key finding for the non-targeted analysis is that there are many non-targeted chemicals potentially associated with tire crumb rubber, but much more work would be needed to identify and quantify these chemicals.

Comment: 2.7.4. In this section emission factors have been calculated. I would include a comment indicating if these factors are, in general low, high, … and the relation with the possible intake.

Response: We have added a paragraph to Section 2.1.3 (now Section 2.2.3 of the Part 1 Report) to summarize the key findings for the more detailed results in Section 2.7.4 (now Section 2.4.4). The new summary paragraph characterizes our interpretation of the key findings for the emission testing and addresses the results with regard to the additional modeling that would be needed to estimate exposures.

Comment: 2.7.5.2 Please indicate the air samples considered.

Response: The intent of this recommendation is not clear to us. The first bullet describes the four types of air samples that were collected at the fields.

Comment: Lines 2545-2550. Could the lower values found in field dust be due to an incomplete solvent desorption from the wipe?

Response: The reviewer makes a good observation here. Our average recoveries from spike field dust control samples ranged from 36 – 72% for most SVOCs. It is not clear to us whether the dust control spiking procedure was adequate, whether the surrogate material used was different than the actual field dust, or whether the results truly represent relatively low recoveries from the field dust. Recoveries from the spiked field wipe control samples were higher, ranging from 62 – 144% for most SVOCs. The following sentence has been added to Section 2.3.1.2 in the Part 2 Report reflect the uncertainty in this comparison: “It is not clear whether the amounts of SVOCs in field dust were lower than the amounts in the tire crumb rubber or were a result of relatively-low extraction efficiencies from the dust.”

Comment: 2.7.6 Please indicate how the 355 chemicals were selected? Was the selection based on the non-target study, or only based on literature?

Response: The following sentence was added to Section 5.1 of the Part 1 Report: “To achieve this goal, a list of potential chemical constituents of interest was developed as part of the Literature Review/Gaps Analysis (LRGA), based on chemicals identified in the various research studies reviewed.”

4.4.3 Reviewer 3

Comment: *General*:
Overall, the limitations of the study are stated but in the body of the report not always easily recognizable. Highlighting them in the body of the report in italic, bold or as bullets would make it easier to absorb the information provided.

Response: The limitations of the study have been summarized in Section 2.0 of the Part 1 and Part 2 Reports.

Comment: *Terminology*: synthetic turf field implies that the rubber infill was synthesized for use as infill. However, in reality, it is a waste product that is sold as "synthetic."

Response: Synthetic turf fields are commonly understood to be the system of an underlying base layer or layers, backing material, and synthetic blade material. Recycled tire crumb rubber is often used as an infill material in synthetic turf field systems. We believe that the report is clear that the focus of the research is on the tire crumb rubber that is produced from recycled tires. We believe that the terminology used in the report is widely accepted in the United States.

Comment: *Specific:*
1581-1584. The mean content of small particles (sizes <0.063 mm) was 0.63 g/kg. Are more details known about the size distribution of the small size faction, i.e., the content of PM_{10}, $PM_{2.5}$, nanoparticles, etc.

Response: SEM analyses were performed on a subset of <0.063-mm size fraction to measure a distribution of particle sizes down to a size corresponding to nominal diameters of 5 – 20 microns. These results are reported in Section 3.2.10.6 (now Section 4.5.4 of the Part 1 Report). We have elected not to report the SEM size fraction analysis results in Section 2.0 of the report. The SEM methodology was unable to reliably resolve particles smaller than approximately 5 microns as part of bulk material collected from recycling plants and fields in this study.

Comment: 2538-2543: Unclear whether "next-to-field" samples are representative for the exposure of the users of the synthetic turf fields.

Response: We agree that there is considerable uncertainty as to whether next-to-field sampling locations are representative of personal exposures for people engaged in different kinds of activities at synthetic turf fields. We have added this sentence: "It is not clear how well air samples collected next to the field represent personal inhalation exposures, however, collecting accurate breathing zone air samples for the

wide range of chemicals present in tire crumb rubber is a challenge." There are further discussions regarding the challenges of personal air sample collection in Section 2.2.2 and Section 4.0 of the report.

Comment: 1630-1634: I am not sure whether leaching by water was considered a potential loss factor. Was the pertinent literature reviewed, I have not seen it (yet)? If not, one would have to conclude that volatile compounds such as naphthalene are evaporating.

Response: Yes, removal from rainfall or irrigation was considered as one of the possible mechanisms leading to losses of some chemicals from the rubber infill over time. Based on this reviewer comment, we explicitly added this to the second bullet in Section 2.2.3 of the Part 1 Report, where vaporization is also included as a likely factor. We discuss this further in Section 3.2.15.6 (now Section 4.10.4) and include a table of potentially relevant chemical parameters, including water solubility. Several studies reporting on the results of leaching experiments were cited and extracted as part of the Literature Review/Gaps Analysis (Part 1 Report, Appendix C). Several studies reported amounts of metals or SVOCs leached from crumb rubber; for SVOCs higher amounts of more water-soluble chemicals, such as aniline and benzothiazole, were measured as compared to the less soluble polyaromatic hydrocarbon (PAH) compounds.

Comment: 1695-1697: "Organic chemical concentrations were generally higher at indoor fields which have reduced weathering effects." The authors might refer to comment on page 15, 1763 – 1768.

Response: The following sentence has been added to Section 2.2.3 of the Part 1 Report: "Results from two sets of indoor air measurements in other studies support this finding (Norwegian Institute of Public Health and the Radium Hospital, 2006; Simcox et al., 2010), however, relatively few indoor fields have been studied."

Comment: 1763 – 1768: It seems to me that unpleasant crumb rubber odor would be noticeable at most facilities, but especially in indoor facilities. Surprisingly, odor was not mentioned as an issue.

Response: Odor has been mentioned by members of the public with regard to synthetic fields with tire crumb rubber infill, and there is a distinct odor associated with tire crumb rubber. However, attempting to identify the chemical(s) associated with the characteristic odor was not included as one of the research objectives for this study.

Comment: 1845-1848: The need for better sampling methodology is clearly identified.

Response: Yes. We appreciate the reviewer noting this need.

Comment: 1876-1888: The description of findings and limitations is vague and it is hard to assess their significance. The statement "these chemicals were often found at low concentration or at concentrations only slightly above background air levels for outdoor fields" is unclear. At outdoor fields, one would expect significant dilution of the contaminants emanating from the crumb rubber.

Response: This summary bullet has been substantially revised and split into two bullets in an attempt to provide more specificity and to more clearly convey the significance.

Comment: 1889-1898: The fact that the 2-hydroxynaphtahlene concentration in urine samples was elevated after relatively short exposures (hours?) at low concentration appears significant. How would this comparison look at indoor facilities? (OK, see Line 2000).

Response: The pilot scale effort did not include biological samples from indoor field users. The supplemental biomonitoring study included indoor field users and evaluated urinary PAH metabolites pre- and post-activity for participants who played on indoor fields with recycled tire crumb rubber infill.

Comment: What would be an intolerable increase? Are there situations with which we could compare these findings, e.g., from workers working with tires?

Response: In general, finding one or more PAH metabolites in urine does not imply that these will cause an adverse health effect. In the pilot scale effort and the supplemental biomonitoring study, the levels in study participants were compared to the noninstitutionalized general U.S. population using National Health and Nutrition Examination Survey (NHANES) data.

Comment: 1923, Section 2.4.1: I think there is info in the literature on the environmental behavior of the components of the other turf field materials that could be referred to.

Response: We agree; however, the number of research publications providing information on the potential for human exposure to chemicals from currently used synthetic fiber and backing material in synthetic turf field systems is limited. We believe that the currently on-going California-OEHHA research study will provide some additional information.

Comment: 1950 Section 2.4.1: I was wondering whether the authors searched the literature on exposure to tire wear particles from road traffic.

Response: We did not explicitly search for research publications on exposure to tire wear particles, but did come across several in the course of this work. It might be of interest to perform a relative assessment comparing exposures to tire wear particles and exposures at synthetic turf fields, but such a comparison was outside the scope of this study.

Comment: 2069: For 'fresh' tire crumb rubber samples from recycling plants, on average, 0.37 g/kg was found in the ≤0.063 mm fraction, and in synthetic turf field tire crumb rubber infill samples it was 0.63 g/kg. This suggests that abrasion of the crumb rubber particles during use generates smaller particles. This could be a significant finding because fines are the toxicologically most significant size fraction. This observation should be identified as a limitation. Was the same trend observed at indoors facilities? The comment below seems to imply that the differences were not statistically significant.

Response: We have modified the text, added a separate bullet point on this topic, and noted the limitations. We did see a higher mean amount of the smallest particle size fraction at outdoor fields compared to indoor fields, but the variability was very high, and it is not clear that this difference was significant. More work would be needed to determine the relative percentage of tire crumb particles within this size fraction versus particles from other sources (e.g., crustal, deposition, biogenic, and other materials) that may be present at the fields. While we evaluated a SEM electron probe microanalysis (EPMA) approach for assessing particle source, we did not have sufficient time to apply the method to the bulk of the collected samples.

Comment: 2119: This observation should be evaluated further by comparing indoor vs. outdoor fields. However, the comment 2233 states "No significant outdoor versus indoor differences were observed for metal concentrations in tire crumb rubber infill." It the finding statistically insignificant?

Response: As reported in Section 3.2.15 (now Sections 2.2.2 and 2.4.3.2), the average lead concentration measured at outdoor fields was 20 mg/kg, compared to an average of 31 mg/kg at indoor fields. The difference was not statistically significant. The higher indoor value was likely influenced by one maximum measurement result. Both results are higher than the average of 13 mg/kg measured for recycling plant samples. No revisions were made in this bullet.

Comment: 2136 Figure 2-7: Should be discussed in context with the leaching behavior of Pb and Zn.

Response: Please see the response to the comment below.

Comment: 2160: "…. possibly, rain-driven leaching." The literature data relevant to this supposition, if it exists, should be considered.

Response: A new bullet was added to Section 2.4.3.2 of the Part 1 Report to discuss the differences in zinc measured in recycling plant samples versus synthetic turf field samples: "Zinc was found, on average at statistically significant lower levels (p-value = 0.0063) on synthetic turf fields compared to 'fresh' material coming from recycling plants (15,000 vs. 17,000 mg/kg, respectively). Zinc has been shown to leach from tire crumb rubber in water. If additional research confirmed this trend at individual fields, rainfall and/or irrigation could be one possible explanation for the lower levels found at fields. In this study, however, there was no statistically significant difference in levels of zinc found in crumb rubber collected at outdoor and indoor fields, both had average concentrations of 15,000 mg/kg."

Comment: 2255 Figure 2-12: The difference of the semivolatile organic compounds (SVOCs) content in indoor vs. outdoor facilities is quite striking. With age, the difference increases. The conclusion that crumb rubber is a source of volatile organic vapors is significant and should be more emphasized.

Response: We agree that the differences between indoor and outdoor fields and differences across age groups, particularly at outdoor fields, are evident for many extractable SVOCs and for several VOC and SVOC emission factors. We have included those findings in Section 2.1.2 (now Section 2.2.2 of the Part 1 Report) as part of the key findings. We have also emphasized in our key findings and summary that exposures to tire crumb rubber constituents in indoor facilities is likely to be higher than those at outdoor facilities for the reasons noted by the reviewer. However, these results should be balanced by noting the relatively low emission factors, particularly at 25 °C, for many of the VOC and SVOC target chemicals.

Comment: 2352: What is the background value? The high zinc value clearly results from the crumb rubber.

Response (Assuming this refers to Line 2552): We have added the following sentence to the bullet in Section 2.3.1.2 of the Part 2 Report: "Zinc in tire crumb rubber likely contributed to the levels measured in the field surface wipes." Except for background air sampling, no other type of 'background' sample collection was performed for comparison to the wipe, drag sled, or dust samples. Collecting and analyzing meaningful and sufficient numbers of background samples, for example in the soil or on surfaces around the synthetic fields, was beyond the scope of this effort. In addition, we believe that interpreting the results would prove very difficult without first performing extensive research efforts to understand the dynamics of track-in, windblown, and atmospheric deposition, along with the variability in soils and surfaces around the field. We agree that the relatively-high zinc values in the wipe samples are likely due to zinc in the tire crumb rubber particles.

Comment: 2584: It is not explained why elevated PAH concentrations in urine are expected after only short periods of exposure to tire crumbs. The elevated concentrations of 1-hydroxynaphthalene could have resulted from previous practices.

Response: Recent data from Choi et al. 2023 demonstrated that the fractional urinary excretion of urinary PAHs ranged from 0.07 % to 11.3% and that most were excreted within 24 hours after exposure, though the obtained fractional urinary excretion values only reflected oral intake.

Comment: 2650-2562: Ingestion of what? Crumb rubber dust or something else?

Response: The statement was clarified by stating: "Ingestion of tire crumb rubber appears to be the most significant pathway of exposure…." (Section 2.3.1.5 of the Part 2 Report).

4.4.4 Reviewer 4

Comment: Limitations are clearly stated, possibly overstated.

p.18. Considerable discussion of failure of a clearly impractical sampling method, maybe overemphasizing difficult of obtaining exposure estimates for specific SVOCs and VOCs. They are almost certainly closely correlated. Another approach is to determine correlation with a compound that behaves predictably and use that to infer exposure.

Response: We appreciate the reviewer's thoughts regarding the discussion around personal air sampling in the report. One reason for the lengthy discussion is the importance placed on better measurements of inhalation exposures to vapors and particles, as indicated in public comments received on the report. The reviewer offers insight on an approach to use 'sentinel' chemicals, ideally as unique and specific as possible, as a tire crumb rubber constituent, for assessing exposures. If those sentinel chemicals can be measured well in the appropriate media, then estimation approaches can be used for correlated chemicals. The characterization research described here will, hopefully, offer insight both on candidate sentinel chemicals and the information on correlation that would allow an estimation approach. Ideally, a chemical or chemical metabolite that is highly reflective of exposure to tire crumb rubber that could be identified and used in future biomonitoring efforts. This thought is included as a future research recommendation for biomonitoring in Section 2.5 (now Section 2.4.5 of the Part 2 Report).

Comment: p. 19. Not every exposure assessment has to be repeated for American football. See p. 18. Simply comparing American football v. soccer for representative chemicals should be enough.

Response: We appreciate the reviewer's thoughts on this as this study is the first, we believe, to include American football players in activity and measurement assessments.

Comment: p. 20, 21. Worth clarifying that "uncertainty" here is specifically to estimating accurate exposure, but at these low levels uncertainty band is so far below known toxicity thresholds and in some cases ambient exposure that it does not represent appreciable uncertainty with respect to health risk. Therefore, 2.4.3 is not correct in that problem of comparing with other sources in ambient environment is not out of scope of this report but actually fundamental to it and the whole purpose of the investigation.

Response: The study purpose was not to compare to other sources; the uncertainty is related to not being able to comprehensively point to an exposure source.

Comment: p.22. Projection to proposing larger studies seems premature. Results of this study do not suggest that the risk warrants a large investment in exposure assessment. Exposure of children is most critical single issue and that can probably be inferred with acceptable precision (if not strict accuracy) from existing data and PBTK models. The operative language on this page would appear to be "should it be determined that such investigations are warranted".

Response: We thank the reviewer for noting the qualification, "should it be determined that such investigations are warranted."

Comment: p. 52. Pre-practice dermal samples would be useful in source apportionment but not risk assessment. Why were pre-practice dermal wipes not performed at all? Surely a subset of players arrive early or could have been invited to participate. A convenience sample is all that would be required to establish that players arrive at the field with lower or comparable skin levels, for this purpose. Failing that, non-participating audience members could have been used as a benchmark sample.

Response: Ideally, wipe samples would have been collected at both the pre- and post-practice time points, and a subset of participants would have been asked to allow a second wipe to assess recovery efficiency. However, the amount of pre- and post-practice time with the participants was highly constrained. A decision was made to prioritize the available time towards collection of the pre- and post-practice urine and blood samples. This is a study limitation that is noted in Section 2.2.2, Section 2.4.1, and elsewhere in the Part 2 Report. Given the potential dynamics of absorption and removal mechanisms during the practice period for chemicals that were on the skin prior to practice, interpretation of pre-wipe results would perhaps benefit from additional experimental work with volunteers. In retrospect, simply cleaning the skin areas to be

sampled before the practice period might have been the best approach and can be considered for future studies.

Comment: p. 57. One is left with the impression from this chapter that hazard assessment was carried to an extreme. It is not necessary to characterize all chemical constituents, and p. 55 correctly points out that "chemicals of like or similar classifications … follow the same pattern of exposure …." Thus, the observations on p. 56 and 57 seem to be overstated. The lack of robust measurements may not matter, if surrogate chemicals are not demonstrated at a level of toxicological significance and further documentation of activities is unlikely to change the risk assessment.

Response: The purpose of this particular effort was to compile extant reference information to better understand the scope of available information rather than doing a hazard assessment. The purpose was to provide as much information as possible to the public based on what was available at the time the work was accomplished.

4.4.5 Reviewer 5

Comment: The authors supply an honest and accurate assessment of the data they have collected, in particular, they caution the use of such data in a generalized sense due to small sample size, the restricted number of "fields" used, and the limited amount of data collected on the activities and factors influencing exposure. They particularly caution that they have not developed an understanding or development of alternative sources of the multiple compounds analyzed for dermal and urine/serum samples. Since biomarkers collected in these media integrate over all sources, they are not, given the design of the study, able to distinguish whether the exposure experienced to crumb tire materials are responsible for their results. However, measurement of specific compounds, particularly this associated with materials found in the manufacturing facilities- in biological samples- is strongly indicative of turf-associated exposures.

Confounding of indoor/outdoor effects with the age of the facilities (indoor and outdoor fields) is likely as the design presented different ages for these types of facilities. Other effects may be confounded as well. In particular, the difference in average age of indoor and outdoor facilities is of concern. The measured SVOC/VOC concentrations being higher in indoor facilities is likely due to effect of indoor facilities being "box" with limited air exchange relative to outdoor facilities swept by plug flow- advection (wind) carrying away emitted contaminants. However, the age of facility and likely differences of emission characteristics and material breakdown with concomitant increase in emissive surface area could be a concern. And these processes look like increased, or at least differential, emission patterns associated with location. I did not see an assessment of the differences in effective surface area between "new" and "aged" crumb material, but a I may have missed it.

Response: Yes, the potential confounding of indoor/outdoor and age effects was observed, with some data analysis and illustration provided in Section 4.0 of the Part 1 Report to address the issue. The reviewer brings up a good point regarding further potential confounding if tire crumb rubber breaks down into small particles over time, and whether the increase in surface area might lead to higher relative emission factors at older fields. We did not perform an assessment of differences in effective surface area for tire crumb rubber from newer and older fields. In Section 3.2.10.5 (now Section 4.5.3 of the Part 1 Report), we do report on differences in particle size fraction by field age group. In three of the four smallest size fractions, the average amounts in the oldest age-group fields are higher than in the newest age group fields, but there is considerable variability and the significance is unclear. When restricted to outdoor fields, our emission tests show decreasing emission factors with increasing age for most VOCs and SVOCs, so if there is a small particle effect that would tend to increase emissions as fields age, this effect does not appear to be strong.

Comment: I have concern about VOCs measured at 60 ^{o}C. I do not believe that the reasoning behind this was adequately explained. Is it because the authors believe that this represents a reasonable upper bound on Field temperatures experienced on outdoor field in hot climates? Not to quibble too much, but I would think 50 ^{o}C would be a more reasonable approach. Regardless, I commend the authors for considering the effects of elevated temperatures on the emission characteristics of these materials with regard to VOCs. It is necessary, as well, to perform these studies empirically, rather than theoretically, since there are numerous factors- binding of VOCs to other materials, diffusion rates, etc., that are difficult to model accurately.

Response: Assigning an upper temperature for emissions testing was a difficult decision due to the sparseness of reliable synthetic field temperature measurement data, particularly for the temperature of the tire crumb rubber on fields rather than the surface temperature. At the time the decision was made, a 60 °C temperature appeared to be a reasonable upper bound based on limited information. In a report based on a field in Connecticut with an air temperature of approximately 36 °C, the maximum field surface temperature for the grass fibers was 69 °C, but the maximum crumb rubber temperature at a 1-inch depth was 44 °C. It is not clear which temperature is most relevant for emissions from the tire crumb rubber. Field surface temperatures as high as 93 °C (at a Utah field) and 79 °C (at a Pennsylvania field) have also been reported in two other small studies, but these studies did not include measurements at depth in the tire crumb rubber infill. In an EPA summer study in 2009, the maximum field surface temperature measured was 50 °C, but the temperature was not measured at any depth in the infill. The California-OEHHA study has performed, but not yet reported results from, a high-quality set of temperature measurements at multiple depths and heights above the field for up to 35 fields with matching insolation measurements; these data

should be informative regarding potential temperature profiles potentially affecting emissions and exposures.

4.4.6 Reviewer 6

Comment: The research limitations are appropriate and clear based on the overall findings and gaps. They place the findings within the larger context of exposure to these substances.

Response: We acknowledge the reviewer's comment.

4.4.7 Reviewer 7

Comment: The discussion of the limitations of the work in this report, summarily presented in Chapter 2, is clear and informative with respect to the available data, the methods used, and the overall findings. Two specific areas that should be strengthened should include:

- Limitations in the interpretation (and corresponding validity) of data collected by performing chamber experiments at high temperatures, and
- Limitations in the validity and interpretation of point estimates developed via the exposure pathway modeling approach presented in Chapter 5.

These issues are also briefly identified in the following, in responses to questions 5 and 7, respectively.

Response: We noted the reviewer's comment and concern regarding chamber emission testing and test results in the response to Question 5. In the report, we highlight several findings related to the emissions testing that suggest a better understanding of the dynamics of chemical emissions from tire crumb rubber is needed, and the reviewer is correct that relating the laboratory chamber results to actual field conditions is challenging. We noted that for some VOCs (for example the BTEX compounds), it appears that the chemicals might be primarily surface absorbed from the atmosphere rather than intrinsic to the rubber in substantial amounts. These compounds were largely depleted during the 24-hour equilibration period prior to sample collection (at 60 °C); whereas, for example, the intrinsic VOC chemical methyl isobutyl ketone was not. We also discussed another concern that the chamber emission experiments may be producing measurements that overestimate long-term emissions occurring at fields, particularly for the SVOCs, and that longer duration tests might improve our understanding of emissions as they occur at the fields. In general, though, we believe the chamber experiments provide important information regarding differences in emissions between 'fresh' material from recycling plants and synthetic turf fields, the decreases in emission rates over time at outdoor fields, and important differences in emission rates at indoor versus outdoor fields.

To address the comments from this reviewer, and the earlier reviewer, regarding the laboratory chamber testing, we added the following paragraph to Section 2.4.4 of the Part 2 Report: “There are several potential limitations affecting the ability to interpret the laboratory chamber emission test results. First, we selected 60 °C as an upper-bound temperature condition, but this selection was based on sparse and incomplete information. In a report based on a field in Connecticut, at a measured air temperature of approximately 36 °C, the maximum field surface temperature for the grass fibers was 69 °C, but the maximum crumb rubber temperature at a 1-inch depth was 44 °C. It is not clear which temperature is most relevant for emissions from the crumb rubber. Temperatures as high as 93 °C (Utah) and 79 °C (Pennsylvania) have also been reported at the field surface in two other small studies, but these studies did not include measurements at depth in the tire crumb rubber infill. The on-going California- Office of Environmental Health Hazard Assessment (OEHHA) study has performed a set of high-quality field and air temperature measurements coupled with insolation measurements (i.e., measurements of the amount of solar radiation reaching the given area) at multiple depths and heights above the field for up to 35 fields; these data should be informative regarding potential temperature profiles potentially affecting emissions and exposures. Second, we have highlighted later in the report some findings that may affect interpretation of the laboratory chamber emission test results. Several findings related to the emissions testing suggest a better understanding of the dynamics of chemical emissions from tire crumb rubber is needed. Relating the laboratory chamber results to actual field conditions is challenging. We noted that for some VOCs, such as the benzene, toluene, ethylbenzene and xylene (BTEX) compounds, it appears that the chemicals might be primarily surface absorbed from the atmosphere rather than intrinsic to the rubber in substantial amounts; these VOCs were largely depleted during the 24-hour equilibration period at 60 °C prior to sample collection whereas, for example, the intrinsic VOC chemical methyl isobutyl ketone was not. We also describe that the chamber emission experiments may be producing measurements that overestimate long-term emissions occurring at fields, particularly for the SVOCs, and that longer duration tests might improve our understanding of emissions as they occur at the fields. In general, though, we believe the chamber experiments provide important information regarding differences in emissions between ‘fresh’ material from recycling plants and synthetic turf fields, show the decreases in emission rates over time at outdoor fields, and highlight important differences in emission rates at indoor versus outdoor fields.”

To address the second reviewer recommendation, the following paragraph was added to Section 2.4.3 of the Part 2 Report: “Exposure pathway modeling was performed for several chemicals associated with tire crumb rubber to assess potential exposures for adult and youth athletes using synthetic turf fields, to better understand which exposure pathways might be the most important, and to assess the extent and quality of information needed for successful modeling. Ideally, probabilistic modeling approaches would have been

used to develop distributions of exposure estimates. However, only point estimates of exposure were developed through modeling in this study due to the sparseness of data for several important exposure media and exposure parameters. Limitations in available data and exposure parameter values for synthetic turf field exposure scenarios results in uncertainties in the accuracy of the point estimates. The ability to interpret modeled exposures for exposure and risk assessments is limited by the lack of a more complete understanding of the distribution of exposures for people using synthetic turf fields with tire crumb rubber infill."

Comment: It should also be pointed out that on page 44, of Chapter 2 (lines 2285-2286) there is an intriguing statement, i.e. that: "[m]ultivariate analyses suggested significant interactions among field characteristics, including field region, for some tire crumb rubber associated chemicals." However, it is not clear where (and if) these significant interactions are presented/discussed in subsequent sections of the report (presumably they must be part of the analyses described in Chapter 3).

Response: We have included the method summary for the multivariate field characteristics modeling in Section 3.1.7.4 (now Section 3.7.4) and the results in Section 3.2.9.6 (now Section 4.10.6) of the Part 1 Report. We elected not to provide more information in Section 2.0 due both to the challenge of creating a concise explanation and because of the limitations of the small sample size and the limited ability to generalize these results beyond this study. We did not want to over-emphasize the importance of these findings in Section 2.0.

Comment: Despite the issues identified in the response to this and to the previous question, it should be emphasized that, overall, Chapter 2 does an excellent job in summarizing an enormous amount of new and useful information and in identifying limitations and data gaps in this information. This will be most valuable in informing the design and interpretation of future studies on the issue of exposures associated with synthetic turf fields.

Response: We appreciate the reviewer comment on the overall value of the summary result section of the report.

4.5 Charge Question 5: The results of the Tire Crumb Characterization are summarized and presented in Chapter 3 with attendant Appendices. Please comment on the overall approach for presenting the analytic results and describe any other recommended ways to present the analytic results to inform decision-making.

4.5.1 Reviewer 1

Comment: This chapter is reasonably laid out. Because methods are presented separately than the analytic results for each measure, some repetition occurs. To clarify, sometimes some methods are repeated under analytic to remind the reader of the particular methods for a particular sample. Authors can consider presenting the methods and results for a type of sample all together. Here are some other suggestions for improvements.

Response: We agree that there is some repetition in presenting method information in full in Section 3.0, and in several cases in summary in Section 4.0 to help frame the results presentation of the Part 1 and Part 2 Reports. Some repetition has been removed with technical editing. We have elected to keep the bulk of the methods description in Section 3.0 so that that the results can be conveyed more efficiently in Section 4.0.

Comment: Line 2751, where were the recycling plants located? Would regionally differences affect results.

Response: As we note in Section 3.2.1.1 (now Section 3.2.1 of the Part 1 Report), the nine recycling plants were located across all four U.S. census regions. We did not attempt any assessment of potential regional differences due to the small numbers.

Comment: Line 2863 and 2869 is confusing on why some recycling plants required consent and why some others did not.

Response: We have attempted to clarify this using the following updated text in Section 3.2.1 of the Part 1 Report: "Researchers aimed to recruit and seek consent from nine tire recycling plants producing tire crumb rubber for use as synthetic turf infill – five plants using an ambient production process and four plants using a cryogenic production process. Another goal was to recruit tire recycling plants across the four U.S. census regions. CDC/ATSDR and EPA participated in the recruitment effort and contacted seven companies operating tire recycling plants that produce tire crumb rubber for synthetic turf infill. Sample collection agreements were reached with six of those companies, resulting in successful sample collection at nine tire recycling plants operated by those six companies. The nine recycling plants were located across all four U.S. census regions. Six recycling plants used ambient processing and three used cryogenic processing."

Comment: In this section, lines 2863 through 2919, the report goes between saying researchers and CD/ATSDR ad EPA, then just CDC/ATSD. Please clarify roles for agency researchers upfront in this chapter and who was involved in what phase. After that please stick to "researchers:"

Response: Both CDC/ATSDR and EPA conducted recycling plant recruitment efforts mentioned in this section. CDC/ATSDR alone conducted recruitment for all community synthetic turf fields. Language has been updated for better clarity.

Comment: Line 2923: Please clarify what the 10 to 20 mesh means.

Response: We have edited the text in Section 3.3.1 of the Part 1 Report to add: "(typically 10 to 20 mesh or 0.84 to 2 mm)."

Comment: Section 3.1.1: Please clarify whether these recycling plants are outdoors and whether these storage bags or storage sacks are open and exposed, and how or whether this may affect concentration findings.

Response: We have revised the paragraph to provide further information about the sampling approach and to state that we did not implement research activities to assess potential impacts of storage conditions on tire crumb rubber constituents.

Comment: Line 2995: Please check about whether in results, the collection depth of 3 cm is mentioned.

Response: The following sentence was added to Section 3.2.3.2 (now Section 4.4.2 of the Part 1 Report): "Researchers collected tire crumb rubber infill from the top 3 centimeters (cm) of the synthetic turf field surface for chemical and particle characterization and microbial analysis."

Comment: Line 3565: A more accurate term for "dissolved" might be "placed" to see how much transfers. Dissolved suggest you intention is to remove all chemicals into the biological fluid.

Response: The terminology was changed as suggested.

Comment: Line 3577: Are your extracting tire crumb in artificial sweat? I may be confused about this process. Are you not placing tire crumb material in these biological fluid [sic] to see how much of a chemical transfer to the fluid (how much is bio-accessible). Perhaps consider rephrasing this section on the process. The title of this section might also need rephrasing to; Extraction of Tire Crumb Rubber Constituents (or chemical compounds) in Artificial Biofluids.

Response: We revised the section title of Section 3.6.9.2 of the Part 1 Report to "Extraction of Tire Crumb Rubber Constituents in Artificial Biofluids". We also made similar revisions in the text of this section (e.g., extract tire crumb rubber constituents, rather than extract tire crumb samples). The extraction in artificial sweat is described in the second paragraph of this section, because the artificial sweat extraction was conducted in tubes coated with artificial sebum, which is different than the extractions in artificial gastric fluid and saliva (in regular tubes).

Comment: Line 3733: Replace "Results" with "Concentrations"

Response: 'Results' was replaced with 'Concentrations' in all places where the adjustment for moisture was mentioned in this subsection.

Comment: Line 3733: This is a consideration about adjusting tire crumb concentrations based on moisture. Authors might need to consider how these concentrations are used in other assessments. For example, the adjusted concentrations based on removal of the moisture content is used as the numerator in the calculation of % bioavailability. However, the tire crumb material as is (with moisture), is used in the bioavailability tests and placed in containers with the biofluids. Some thought might be given to accuracy in these calculations. These adjusted moisture concentrations are however not used in exposures calculations (dust sample chemical concentrations are used) so I am not worried about this adjustment for any other purpose.

Response: It is correct that the bioaccessibility testing (numerator) used the tire crumb samples as is (without drying), while the constituent concentrations (denominator) were based on moisture-free contents. Since moisture levels are not available for all 82 tire crumb samples tested for bioaccessibility, we cannot adjust for moisture contents post-bioaccessibility testing. Based on available moisture results from 49 samples, the moisture contents in these samples are low. The median moisture levels in the field samples (n=40) and recycling facilities (n=9) are 0.81% (0.40%-6.22%) and 0.87% (0.52%-0.99%), respectively. Therefore, not-adjusting for moisture levels leads to a slight overestimate (about a factor of 0.01) of the calculated percent bioaccessibility results. We added a clarification to the results section.

Comment: Table 3-26: Future work could look at the chemical makeup of products applied to fields for treatment and maintenance affect the findings of the chemical makeup of tire crumb rubber of dust samples in this study.

Response: Specific information on the chemical makeup of these products is outside the scope of this current study.

Comment: Line 3916: Did the fields treated with biocides have less microbial counts. This analysis could be performed.

Response: An analysis of bacterial gene concentrations on fields with and without biocide application was performed. The following text and table were added to Section 3.2.19.3 (now Section 4.14.1), "Targeted Microbial Analyses" to assess the impact of biocides on microbial gene concentrations:

"Some fields were disinfected with biocides. In total, biocides were applied to 11 fields (4 outdoor and 7 indoor fields), while 5 fields (2 outdoor and 3 indoor) had missing information about biocide usage. An ANOVA of biocide usage on indoor and outdoor fields showed that biocides had a statistically significant association with reduced quantities of 16S rRNA genes in outdoor fields (Table 4-112). However, biocide usage had no significant impact on concentrations of 16S rRNA genes in indoor fields or the other microbial gene markers in either indoor or outdoor fields."

Table 4-1. Mean Quantities of Targeted Microbial Genes in Synthetic Turf Fields, with and without Biocide Application[a,b]

Gene Target	Synthetic Turf Field Data Set	With Biocide Application – N	With Biocide Application – Mean (log_{10} molecules/ g TCR)	With Biocide Application – Standard Deviation (log_{10} molecules/ g TCR)	Without Biocide Application – N	Without Biocide Application – Mean (log_{10} molecules/ g TCR)	Without Biocide Application – Standard Deviation (log_{10} molecules/ g TCR)	ANOVA *p*-value
16S rRNA gene	Outdoor	26	6.74	0.49	132	6.90	0.63	0.024
16S rRNA gene	Indoor	49	5.93	0.51	34	6.06	0.60	0.402
S. aureus SA0140 protein	Outdoor	26	0.05	0.23	132	0.05	0.33	0.691
S. aureus SA0140 protein	Indoor	49	1.03	0.79	34	1.00	0.91	0.993
mecA methicillin resistance gene	Outdoor	26	0.19	0.57	132	0.22	0.45	0.329
mecA methicillin resistance gene	Indoor	49	2.26	0.45	34	2.30	0.48	0.763

[a] log_{10} molecules/g TCR = log_{10} molecules/gram of tire crumb rubber; ANOVA = Analysis of variance; rRNA = Ribosomal ribonucleic acid

[b] Biocides were applied to 11 fields (4 outdoor and 7 indoor fields), while 5 fields (2 outdoor and 3 indoor) had missing information about biocide usage

Comment: Table 3-31: It was hard to understand that the 9 days per week meant. Can the table instead say "Not open"?

Response: The question included on the questionnaire is "how many days per week are the synthetic turf fields open at this facility during each season." For consistency, we have used this wording for the results table.

Comment: Table 3-47: Insert the units for the area ranges.

Response: The units were added.

Comment: Line 4291: Can you clarify. XRF measure surface concentration, yet its measures were substantially higher. That seems in contrast to what it should be.

Response: We appreciate this comment, as it has caused us to reflect further on the XRF analysis. In retrospect, we do not actually know the effective penetration depth for tire crumb rubber using the handheld XRF device in a test stand. The manufacturer suggests that penetration depths may be as deep as a few mm for heavier plastics like PVC. It is possible that the effective penetration depth was substantially or completely into the small tire crumb rubber particles. Therefore, we have revised the text to remove the statement about this being a surface measurement. We do not have enough information about why we would see higher concentration measurement results using XRF compared to digestion with ICP/MS. Our statement about not having an equivalent and suitable calibration material for the XRF analysis remains.

Comment: Line 4457: Some explanation may be warranted on the interaction between dust and sand content and chemical constituents in both. Potentially all materials (rubber and sand) break down to contribute to the dust particles. Dust also drifts from surrounding areas and comes from other sources just as human skin.

Response: We agree that the reviewer makes relevant points about sand, dust, and the potential for human exposure. We discuss this in Section 4.5.1.2 of the Part 2 report for field dust, wipe, and drag sled measurements at the exposure pilot study fields. However, Section 3.2.5.3 (now Section 4.6.3 of the Part 1 Report) is primarily aimed at understanding sand as a bulk infill component at synthetic turf fields. Therefore, we have elected not to include a broader discussion of dust and exposure in this subsection. To better frame the intent of this subsection, we have added the following text to

the opening paragraph: “Sand is sometimes used as a base layer or as a mixture with tire crumb rubber in synthetic turf fields. Sand and other crustal materials may also be present at fields from windborne deposition and track-in by field users.”

Comment: Line 5004 and Table 3-80: The statement says that all chemical had greater within plant variability that between plant variability. Add except for bensothiazole [sic] at the end of this statement.

Response: The table and text do distinguish the variability results for recycling plants, where the within-plant difference for benzothiazole is greater than the between-plant difference, and the variability results for synthetic fields, where the between-field difference is greater than the within-field difference.

Comment: Line 5294 replace the terms ‘increasing field age” with “older installation age category”. Some readers might want to read from left to right for “increasing” in the relevant tables. This should be done throughout for consistency as used on line 5399.

Response: The suggested change was made throughout Section 3.2.9.2 (now Section 4.10.2 of the Part 1 Report), where applicable.

Comment: Line 5414 to Line 5420 in bold to indicate part of the caption for Fig 3-61.

Response: The figure (now Figure 4-49) was revised to include recycling plant, indoor field, and outdoor field designations, eliminating the need for the text in the caption.

Comment: Line 5566: I think you should be clear that you fit a regression line to the concentration values to create a decay curve. These lines were not created using half-life or other predictive equations.

Response: In the paragraph preceding the figures (Part 1 Report, Section 4.10.4), we clarified that Figures 3-67 and 3-68 (now Figures 4-55 and 4-56) show field and recycling plant concentrations plotted against years since installation and their modeled relationships are shown as curves. We also clarified that the PAH and other concentrations are assumed to be exponentially distributed. We removed “decay” from line 5566; that paragraph now begins “The shapes of the curves”. We added a sentence to the figure captions stating that the modeled relationship between concentrations and years is shown as curves.

Comment: Line 5691; can you follow up this paragraph with overall findings, since results in a few tables are mentioned.

Response: The following paragraph was added to Section 4.10.5.2 of the Part 1 Report: "Overall, it is difficult to distinguish regional patterns in the SVOC analysis results. This may be due in part to uneven distributions of indoor fields across regions and distributions of outdoor field age. Ideally, the outdoor fields might be placed into climatic zones for assessing the relevance of heat, sun, and rainfall. However, the number of outdoor fields is too small to support a regional analysis based on multiple climatic zones. There might also be regional differences in the types of tires that are recycled to produce infill material, but the number of recycling plants in each region was too small to support a regional difference analysis. These results do suggest that regional differences are unlikely to be the most important characteristic underlying differences in SVOC levels in tire crumb rubber infill at synthetic turf fields."

Comment: Figure 3-76; Please clarify if the high peaks means [sic] possibly high concentrations on this spectrum, where counts on y axis). Does this mean there are potentially some chemicals with high concentrations that need to be further explored? We may be missing high exposures.

Response: The following was added to the paragraph preceding the figures (now Figures 4-63 and 4-64 of the Part 1 Report): "For the SVOCs in Figure 4-63, there are a number of chromatographic peaks that have higher intensities than benzothiazole, which was the most abundant target analyte in the analysis. For the VOCs in Figure 4-64, the target analytes methyl isobutyl ketone and benzothiazole had higher intensities than the other chromatographic peaks. The non-targeted analysis performed as part of this research is a first step in understanding the nature of those unidentified chromatographic peaks in terms of identity and abundance, and the potential relevance for human exposures."

Comment: Table 3-123 [sic assume Table 3-124 intended]: Consider keeping this table in the appendices and creating a summary table for the report. It is rather long [sic]

Response: The original table has been incorporated into Appendix S of the Part 1 Report and replaced with a summary table (Table 4-108):

Table 4-2. Summary of the Variability in Targeted Microbial Gene Quantities Measured in Replicate Samples from Each Field

Gene Target[a]	Number of Fields	% Relative Standard Deviation Mean	% Relative Standard Deviation Standard Deviation
16S rRNA gene	40	63.9	34.1
S. aureus SA0140 protein	17	154	79.2
mecA methicillin resistance gene	28	116	78.1

[a] rRNA = Ribosomal ribonucleic acid

4.5.2 Reviewer 2

Comment: The overall approach to presenting the results is suitable. The statistical parameters as well as the graphics used are very illustrative. In Figure 3-70, I would include the graphs for all the 15 PAHs.

Response: Due to the already lengthy nature of the report, we have elected not to show figures for all of the target PAHs and other analytes. We have selected several to highlight that are illustrative for a range of PAHs in Figure 3-70 (now Part 1, Figure 4-58) (phenanthrene 3-ring, pyrene 4-ring, benzo(a)pyrene 5-ring, and the sum of 15 PAH analytes). We do include the measurements results for all target analytes in the appendices.

Comment: I have some doubts about the methods:

3.1.6.7. Vortex extraction for 1-2 min seems to be quite a mild method to quantitatively extract all the VOC and SVOC from the rubber. Perhaps other more efficient extraction method should be used and compared in real samples. Please include a comment.

Response: We have added the following paragraph in Section 3.1.6.7 (now Section 3.6.7.1 of the Part 1 Report) to better explain the reasoning behind the method and to acknowledge that the method is not likely to completely extract SVOCs from the tire crumb rubber particles: “The solvent extraction method used in this study is not likely to completely extract all of the target chemicals contained in the crumb rubber particles. While this method is not a total extraction method, it is likely relevant with regard to the potential for human exposure. When combined with ceramic homogenizers, the vortex extraction method was fairly aggressive and very efficient in terms of throughput, which was very important given our tight timeline for completing the laboratory work. Prior to using this method, multiple sequential extractions were evaluated using this technique and it was determined that the majority of extractable organics were removed in the first extraction cycle. This method was also evaluated for linearity across tire crumb mass as well as precision of

replicates and was found to perform well across the range of semivolatile organics we were measuring. This method has an advantage compared to more aggressive extraction techniques in that it minimizes the potential for analyte losses due to no heating, solvent evaporation, or extensive sample handling. The use of solvents or methods that would approach total SVOC extraction would result in residues that would rapidly impair analytical systems and likely require more extensive time and effort in sample clean-up and result in greater potential for analyte losses. (It is also important to note that the results of this study are in general agreement with extractable SVOC measurement results from several other studies [shown in tables in Section 2] that used different extraction methods)."

Comment: The tentatively identified non-target chemicals should be listed.

Response: Five sets of tables are provided in Appendix R of the Part 1 Report that include complete listings of the highly tentative chemical identifications for the non-targeted analyses.

Comment: 3.1.6.8. Small chamber emission test. Please indicate how the size of the chamber, the air change per hour, as well as the amount of sample were selected. Why was 8 g of crumb rubber used in some tests, while 60 g were used in other cases? Please explain.

Response: To clarify, as reported, 15 g of tire crumb rubber was used for the VOC emissions testing and 10 g was used for SVOC emissions testing. The 60-g amount reported was used only for the silicone wristband testing that was performed as a separate set of experiments. To help clarify and explain the selection of the emissions testing conditions, the following new subsection has been added to Section 3.1.6.8 (now Section 3.6.8):

"3.6.8.2 Selection of Test Chambers and Conditions

Constituents such as VOCs and SVOCs can be released to the environment from tire crumb rubber under different environmental conditions. Laboratory chamber dynamic emission tests were performed to characterize the emissions of VOCs and SVOCs from tire crumb rubber and tire crumb rubber infill under two different chamber conditions (i.e., 25 °C and 50% relative humidity [RH]; and 60 °C and approximately 7% RH) and defined air change rates. The selection of appropriate testing chambers and test conditions is an important part of the testing. For VOCs, the small (53-L) chamber tests were selected to be consistent with methods described in the ASTM Standard Guide D5116-10 (ASTM, 2010). A chamber air exchange rate of one air change per hour, an equilibration period of 24

h, and a 15-g sample size were selected both for consistency with the ASTM method and through initial testing to determine the best conditions for obtaining usable analysis results. Selecting appropriate chamber systems and conditions for measuring SVOC emissions is more challenging. SVOC adsorption to chamber walls limits the use of chambers with large relative surface areas (such as the 53-L chamber) to experiments requiring long equilibration durations (many days to weeks). Therefore, micro-chambers were selected, having volumes of 44 or 114 mL, minimizing chamber to sample surface area ratios. Chamber air exchange rates of 28 – 32 air changes per hour, an equilibration period of 24 h, and a 10-g sample size were selected through initial testing for determining the best conditions for obtaining usable analysis results in reasonable time periods."

Comment: Micro-chamber emissions test. Please explain the selection of the chamber volume as well as the amount of sample.

Response: Please see previous response and text addition.

Comment: 3.1.6.9 [now 3.6.9] Extraction of tire crumb rubber in artificial biofluids.

How many tire samples were extracted? Were they from outdoor, indoor fields, or both?

Response: Eighty-two tire crumb rubber samples were used for the bioaccessibility testing, including samples from a recycling plant as well as individual and composite turf field samples. The text in Section 3.6.9.2, "Extraction of Tire Crumb Rubber Constituents in Artificial Biofluids" was updated to include the number of samples and breakdown by indoor/outdoor field.

Comment: 3.2.2 One important aspect that It was not included is the field watering frequency. Outdoor fields are watered quite often, especially in summer. The watering frequency should be indicated.

Response: A question regarding frequency of field watering was not included in the questionnaire. However, a moisture content analysis was included for much of the tire crumb rubber characterization analyses to account for watering and precipitation.

4.5.3 Reviewer 3

Comment: *General:*

The approach to identify production facilities and sites, the sampling and sample preparation methods, the analytical procedures and data evaluation methods are presented clearly and in adequate detail. Experts in their respective fields would find the information necessary to reproduce results. Fig. 3-10 provides a helpful schematic of the sampling approach.

Response: We thank the reviewer for the comment.

Comment: The exposure to bacteria is outside my area of expertise.
The section describing site selection, field management, etc., is quite long. The information could be summarized in a separate section.

Response: We have elected to retain the information in its current location rather than move it to a separate section or appendix. We believe that it is important to include complete site information to frame subsequent results descriptions. We prefer to retain the field owner/manager questionnaire information in this place as well.

Comment: The sampling design is statistically sound, as explained in Section 3.2.8.
One would want to know the compounds are the risk drivers, formaldehyde, benzene, styrene, methyl isobutylketone?

Response: The current study is not intended to be a risk assessment; assessment of risk drivers was not performed as part of this work.

Comment: *Specific*:
2821-2823: Is this classification based on quantity?

Response: We have added the following explanatory text to Section 3.1.1 of the Part 1 Report: "The primary analytes highlighted in the body of the report were selected from the larger list of chemicals based on their reported potential association with tire crumb rubber in this study or other studies, and in part because of their potential interest as well-known chemicals."

Comment: 2842: Why was naphthalene classified as secondary even though its metabolite was identified in urine samples.

Response: The primary and secondary designations were made prior to obtaining the 2-hydroxynaphthalene urinary metabolite measurement results. In the tire crumb rubber

characterization, naphthalene was consistently measured at concentrations considerably lower than those for phenanthrene and pyrene, two other PAHs with urinary biomarker measurements. Due to the effort involved, we have elected not to go back and add naphthalene to all of the tables in the body of the Part 1 report. Complete results are provided in Part 1 report appendices. Results for naphthalene, fluorene, pyrene, and phenanthrene measurements for all of the exposure study sample media relevant to the urine sample collection participants are reported in Tables in Section 4.5 in the Part 2 report, when these were available.

Comment: 3817: Font of Y axis is too small.
Response: We removed the figure because it is not needed to introduce Figures 3-17 and 3-18 (now Figures 4-5 and 4-6) in Section 4.0, "Tire Crumb Rubber Characterization Results" of the Part 1 Report.

Comment: 3899: Typo, only one indoor field ….

Response: The correction was made.

Comment: 3939: Hydrogen peroxide was used by some fields as disinfectant. Hydrogen peroxide could potentially degrade organic chemicals, especially in combination with metal catalysts. This may have led to a loss of organic compounds over time.

Response: Investigation into the cause of any loss of organic compounds over time is beyond the scope of the current study.

Comment: 4155 3.2.4.4 Scanning Electron Microscopy
4178 Table3-46: Typo synthetic.

Response: The correction was made.

Comment: 4164: projected area 700 μm^2 are specified per particle?

Response: Yes, that is the area per particle. Revision made to make it more specific in the text.

Comment: Figure 3-22: What are the "particle areas"? The projected area? Unclear

Response: The figure caption (now Figure 4-10 in the Part 1 Report) was revised to say: "Figure 4-10. Representative histogram of the frequency of individual particle areas observed in the bottom pan sample. µm = micrograms"

Comment: 4235-4238: Particles < 5 mm and nanoparticles are not detected. These are important analytical limitation and should be emphasized.

Response: The following sentence was added to Section 4.5.4.3 of the Part 1 Report to highlight the limitation: "The analysis approach did not allow study of potential tire crumb rubber particles < 5 µm nominal diameter, which limits current understanding about the presence of, and potential for exposures to, fine particles and nanoparticles."

Comment: 4345: The term emission factor should be defined. Based on the units, it is a specific rate.

Response: We believe that we did include an adequate definition of emission factor in this paragraph (Part 1 Report, Section 4.6.2.1), but added 'emitted' to perhaps help clarify: "Emission factor results are reported in units of ng/g/h, which is nanograms of analyte emitted per gram of tire crumb rubber per hour. Some emission factor statistics are reported as negative values..."

Comment: 4559: The literature on crumb rubber leaching might provide an answer to this supposition.

Response: The following changes and additions were made in Section 4.7.1.2 of the Part 1 Report: "The likely explanation for the differences include volatilization from the rubber on the fields over time and, possibly, rain-driven or irrigation-driven leaching. Water-based leaching has been demonstrated in the laboratory for several tire crumb rubber associated analytes, including some metals and several more water-soluble organic compounds, but with less evidence for PAH analytes (see *Literature Review/Gaps Analysis* report in Appendix C) ."

Comment: 4602 Section 3.2.6.2: Overall, extremely significant results.
5591: field maintenance practices, specifically treatment with oxidative disinfectants and other chemicals.

Response: The sentence in Section 4.10.4 of the Part 1 Report was revised as: "There is considerable variability for some chemicals that may be related to factors such as differences in initial concentrations, weather and climate effects for heat and rain or irrigation, field maintenance

practices (including possible degradation of organic analytes with oxidative disinfectants), activity levels and types, and refreshment with new tire crumb rubber infill material."

Comment: 5638-5655: This discussion is extremely significant in the overall context of the study.

Response: We acknowledge the reviewer's comment.

Comment: 5763: Statistical limitations: I am not sure what the implications are of these limitations. To what extent is the generalizability of the model limited? The following discussion of this issue is fairly abstract.

Response: We inserted additional discussion that the study design for the 40 fields sampled is not a probability-based sample, which potentially results in selection bias and lack of representativeness for the target population. We cited Lohr, 2009 as a reference. We clarified that the combination of the selection bias/lack of representativeness potential and sparsity for some combinations of the categorical data limits generalizability of the model results.

Comment: 5784 Table 3-111: What do these numbers mean? In caption, it says P-values.

Response: We changed the table title (now Table 4-95 in the Part 1 Report) to begin with "P-values for Final Linear Models of Selected Measurement Results…," expanded table footnote *a* to describe model fitting, and inserted a sentence at the end of the first paragraph in Section 3.2.15.8 (now Section 4.10.6 of the Part 1 Report) to describe the final model for lead as an example.

Comment: 5878 and discussion 5989-6002: I am not sure, a full picture of the cumulative exposure encountered by synthetic turf field users is possible, even with much a much greater research effort. Compare the synthetic turf field situation with the exposure to tobacco smoke where it took years to come to firm conclusions.

Response: The reviewer correctly identifies very significant challenges in cumulative exposure assessment for scenarios that involve complex chemical mixtures. Each additional study brings the scientific community improved and expanded knowledge to be able to better characterize exposures in these situations.

4.5.4 Reviewer 4

Comment: This chapter is overwhelming even to a reader with some familiarity with the technical details. Suggest preparation of a flow chart with graphics to provide a roadmap for the descriptions to follow.

Response: We have added a figure to the beginning of Section 3 in the Part 1 and Part 2 Reports to help illustrate the sample collection and analyses for tire crumb rubber characterization in one place. We hope this allows a better frame of orientation for the reader. We elected not to prepare a flow chart – such a figure might simply create more difficulty in understanding, given the large number of analysis types performed.

Comment: p. 49. Poorly worded passage: "…researchers enabled a previously consented field in a different census region to be eligible to participate." Do you mean, when sufficient samples could not be obtained for some reasons or no fields were available in a particular census area, a nearby field whose owners had previously consented to be part of the overall study was used."

Response: Not a nearby field, but rather a field(s) in an alternate census region(s). The language has been changed for greater clarity.

Comment: p. 80. Label on y-axis of Figure 3-15 is illegible in pdf. Is it "source"?

Response: It is "Sites". We removed this figure because it is not needed to introduce Figures 3-17 and 3-18 (now Figures 4-5 and 4-6) in Section 4.0, "Tire Crumb Rubber Characterization Results" of the Part 1 Report.

Comment: pp. 78 – 102. Was there any indication (most likely found on TEM if present, of particulate tire crumb of dimension <10 μm or less? <2.5? If so, did this fraction of the distribution compare to size-specific counts of ambient levels of rubber particulate matter of tire origin?

Response: The smallest effective particle size range characterized in the particle size distribution by SEM was in the approximately 5- to 20-μm range. The following sentence was added in Section 3.2.4.4 (now Section 4.5.4.3 of the Part 1 Report) to highlight the limitation in the lower particle size range characterization: "The analysis approach did not allow study of potential tire crumb rubber particles < 5 μm nominal diameter, which limits current understanding about the presence of, and potential for exposures to, fine particles and nanoparticles."

Comment: p. 106, 107. It is not necessary to redo, but in future distribution is more easily grasped visually when ordered from highest to lowest.

Response: We appreciate the reviewer pointing out the advantages of showing the plots as suggested to improve recognition of the distribution of results. On the other hand, the scatter plot approach does serve to highlight the variability of what was measured. Due to the effort that would be involved, we have elected not to re-order the plots.

Comment: p. 113. Results for 1,3-butadiene are particularly important and characteristic of rubber. This is worth commenting upon.

Response: To address the reviewer's comment, we have added the following sentences to Section 4.6.2.1 of the Part 1 Report to further highlight the value of measuring these two chemicals and to more specifically characterize the results:

"There is minimal information from previous studies regarding the presence and emissions of styrene and 1,3-butadiene from tire crumb rubber, and it is important to understand the extent that these two elastomer-building monomers might remain present and available for exposure."

For 25 °C emissions results:

"Notably, all formaldehyde measurements were below quantifiable limits for synthetic field tire crumb rubber infill, while 1,3-butadiene and styrene measurements were above quantifiable limits in only a few samples and the emission factors were low for these few samples (≤1.0 ng/g/h)."

For 60 °C emissions results:

"For 1,3-butadiene, measurements were above quantifiable limits in only a few samples, and for both 1,3-butadiene and styrene the emission factors were low (≤1.3 ng/g/h)."

Comment: p. 121. Not necessary to give corrected results but useful to provide an estimated range of correction factors to give an idea of how dilution with sand affects the result. (It is possible, although unlikely, that sand would grind particles and offset reduction in tire crumb emissions by weight.) [Note: This is done in one example on 0. 122.]

Response: We did provide an estimate of percentage difference in mean and median results for metals and SVOCs, using corrected and uncorrected results. The 'worst-case' example of approximately 50% was mentioned at the end of the subsection text, as noted by the reviewer (Part 1 Report, Section 4.6.3). We have added "…in this study…" to the first sentence of that paragraph. But, we have also highlighted what might be important for comparing other studies to the results from this study by adding this sentence to the end: "The impact in other studies that might have more combined rubber + infill samples, or higher fractions of sand in the infill, could be larger than the relatively modest impact for this study."

Comment: p. 242. Name Větrovský is misspelled. (May be a typo.)

Response: The name was misspelled in the report and has been corrected.

4.5.5 Reviewer 5

Comment: There is an enormous amount of data presented in Chapter 3 as there were a very large number of compounds selected for evaluation. The presentation appears to this reviewer to be presented in an appropriate manner. Data collection methods were discussed first, including methods of transport and storage. This was followed be information on extraction methods, and finally laboratory analysis. Once the samples had been completely analyzed, the data analytic presentation came into play.

Because of the large amount of data presented, the number of Table and Figures—exceeding 100 in the former and approaching 100 in the latter- is large. Some of the tables may be relegated to the Appendix, e.g., the CAS numbers given for each compound (See Tables 3.1-3.5) but the authors did make use of these tables to give reference information about the individual compounds. Hence, little would be

gained by this modification. The presentation of analytical methods, sampling procedures, etc., are quite necessary to understand the sampling and analysis methodology fully. There is little that could be gained by removing this, and perhaps much would be lost.

Response: We appreciate the reviewer's consideration of the information presented and presentation approach. Regarding Tables 3.1 – 3.5 in the Part 1 Report, we have elected to retain the CAS numbers in these tables, in part because there can be several alternate chemical names, especially for the SVOCs.

Comment: The data presentation, which include some summary statistics, but also box-and-whisker plots, appears to be well thought out as such simple graphical representation offer much insight into the data. I do have some concern with the widely varying ranges for the data, e.g., different metals being plotted in ranges that differ by multiple orders of magnitude. I might offer an alternative presentation of plotting metal concentrations, for example, on a log scale and placing several metals in the same figure. This may be my preference but another reviewer might suggest that such a presentation would offer more confusion than insight as distributions would be artificially compressed by the logarithmic scale. Further, one may reasonably argue that each compound or metal should be on its own figure since they are likely to be regulated differently and decisions on specific contaminants made differently.

In summary, I can offer no consistently better way to present the data. The presentation may seem overwhelming to some, but any other method of presentation maybe equally overwhelming given the size of the dataset at hand.

Response: We were challenged with presenting the large range of results concisely, but meaningfully. In Section 2.0 we did compile figures showing all metals and multiple SVOC digestion or extraction measurement results together. Because of the large range of concentrations, we used a log-scale y-axis so that all chemical bars would have observable heights. However, the use of a log-scale graph tended to mask some of the relevant differences among groups (recycling plant vs. indoor fields vs. outdoor fields). In the end, we decided to include tables in Section 4.0 of the Part 1 Report and the associated appendices that report all of the measurement results and illustrate important results using primarily single-chemical figures. Due to the large number of results, we also faced a challenge in figure development that was simplified by primarily creating figures one chemical at a time.

4.5.6 Reviewer 6

Comment: Chapter 3 and various Appendices provide sufficient detail to understand the approach for the physical, chemical and microbiological analytical measurements. This chapter contains a large amount of data which is done in an organized fashion, predominantly based on contaminant class. The presentation of the Quality Control and Quality Assurance data and the first level statistical analysis examining general differences across sample types, locations (e.g. indoor, outdoor, from manufacturers, geographic distribution), literature values, etc. are appropriate. The authors' rationales for some of the trends observed are consistent with what is known of the properties of the agents being measured. It should provide the basis for evaluation of the results for use in decision-making.

Response: We acknowledge the reviewer's comment.

4.5.7 Reviewer 7

Comment: The overall approach for presenting the analytic results of the Tire Crumb Characterization is quite thorough and clear. One, relatively minor, concern is that with the level of detail presented, some of the important findings reported in this Chapter do not "stand out" enough and could be missed if the reader is skipping through material. The use of "visual enhancement" approaches (such as text boxes) to identify important points within this long chapter would substantially enhance its readability.

Response: We have added several callout boxes to assist with readability.

Comment: Some specific minor issues that should be addressed are summarized here:

- Tables that can fit in a single page should be constrained from breaking in two pages; readability and utilization of Tables that actually span multiple pages can benefit from running headers (not just the variable lists) that are repeated on each page along with information of in-table page numbering (i.e. page 2 of 3).

Response: When possible, tables are positioned to fit on a single page. However, positioning of tables must also be balanced with the requirement to minimize white space and locate tables in close proximity to (but not before) their mention in the text. For tables that extend beyond one page, the table header row is repeated on each subsequent page; in addition, the table number and "Continued" (e.g., Table 1-1. Continued) will be added to subsequent pages to help orient readers.

Comment:

- Tabular listings of numerical data can benefit from consistent rules on the number of significant digits presented (in some cases, values listed with five or more significant digits in the "nano-range" may raise questions on how reliable these values are).

Response: In the majority of tables in Section 4.0 of the Part 1 and Part 2 Reports, we endeavored to be consistent in limiting the number of significant figures to two, both in recognition of the underlying level of precision the data support and also to make it easier for readers to compare and scan tables of results. In many cases, while we reported to only two significant figures, the measurement values were very small (many decimal places past zero). We believe that the values we are reporting are appropriate based on the amounts of chemicals measured at the analytical instruments, which had very good sensitivity. In fact, we often had to dilute the digest or solvent extraction samples to bring them to within the analytical range. There are several cases in the measurement precision tables in Part 1 Section 3.2.8.1 (now Section 4.9.1) where we report very small %RSD values. In these cases, the very small %RSD calculation results represent very small differences in reported measurement values, where the differences are probably not meaningful from an analytical precision sense. In these cases, we have replaced %RSD values that are less than 0.1% with "<0.1" in the tables.

Comment:

- The legend of Figure 3-13 [now Figure 3-14] is incomplete (missing the word "statistics" after "descriptive"); in fact this figure is redundant, as it appears to explain the standard boxplot concept, while not including a vertical scale makes it difficult to connect it to Figure 3-14 (on page 80) as per the text on lines 3806-3807 of page 79. Figure 3-14 would be more informative if the x-axis had an index providing a linkage to a table identifying the field by location and type.

Response: Perhaps the reviewer did not see that "statistics" is already in the second line of the legend for Figure 3-13 (now Figure 3-14 in the Part 1 Report). This example boxplot may look familiar, but we have over-plotted the individual data values and the mean, which are features that distinguish it from the standard boxplot available from the R package *ggplot2*. Figure 3-13 (now Figure 3-14) is not connected to Figure 3-14 [deleted]; we have removed Figure 3-14 as it was an example of a standard scatterplot. We changed the sentence to reference only Figure 3-13 (now Figure 3-14).

Comment:

- Figure 3-15 (on page 80) appears to be the same as Figure 3-18 (on page 98) but with the field identifier missing. Again, similarly to the statement above, this figure would be more informative if the index on the y-axis provided a linkage to a table identifying the field by location and type (it is peculiar that the 40 fields are identified in this figure by an index with range 10-59, with 30s missing; an explanation for this would be useful).

Response: We removed this figure because it is not needed to introduce Figures 3-17 and 3-18 (now Figures 4-5 and 4-6) in Section 4.0, "Tire Crumb Rubber Characterization Results" of the Part 1 Report. We have included a new table that lists the individual fields and their indoor/outdoor designation, installation age group, and census region characteristics. We also included brief text that explains starting at the number 10 to avoid leading zeros in our sample codes and that we did not use the ID numbers 29-39.

Comment:

- The comment above about a table identifying the fields by region/type applies to the index used in Figures 3-26, 3-27, 3-28, 3-29, and 3-30.

Response: We have included a new table that lists the individual fields and their indoor/outdoor designation, installation age group, and census region characteristics.

Comment:

- Results presented in Figure 3-26 (page 107) do not appear consistent with text on lines 4286-4289 of the same page and with Table 3-49 on page 108; clarification is needed.

Response: The results presented in Figure 3-26 (now Part 1 Figure 4-14) are for the metals ICP/MS analysis, while the results discussed in the text on the cited lines and in Table 3-49 (now Part 1 Table 4-35) are based on metals XRF analysis. We highlight and discuss the differences in results between the ICP/MS method and XRF method in the subsequent paragraph.

Comment:

- Figures 3-44 to 3-48 can become more "visually informative" by using the same y-axis scale for different boxplot series of the same chemical, allowing direct comparisons for the effects of different conditions.

Response: We have re-created the boxplots of recycling plants and field sites using a common y-axis for each chemical pair. As the reviewer commented, this approach allows direct comparisons of the distributions.

Comment: One issue that needs further attention and discussion is the design of experiments for characterizing emissions at high temperatures, in particular the statement on lines 4676-4680 of page 135: "a majority of the synthetic turf field measurements at 60 °C were below the average chamber background measurements, resulting in slightly negative results following background subtraction. It appeared that some VOCs were driven off of the tire crumb during the 24-hour equilibration period while in the test chamber at 60 °C prior to sample collection." Beyond the significant implications regarding the behavior of intrinsic versus absorbed constituents of tire crumb, this fact raises important question on the design requirements for chamber experiments that would adequately simulate real field situations.

Response: We agree with the reviewer's comment about the need to consider how emissions testing experiments, such as these, can best be applied to understand real-world emissions at fields and help inform how we consider exposures to emitted chemicals. At outdoor fields, tire crumb temperatures are often likely to vary across a diurnal cycle – warmer during the day and cooler at night. How might these short-term changes affect the emissions profile? How long should emissions tests be run to obtain emissions that best approximate those at the fields? Do different depths of tire crumb rubber infill affect net emissions at the field surface? Can we successfully predict above-field chemical air concentrations from these tests for a range of field types and conditions? While the current emissions testing work helps understand the range and types of chemical emissions that may be expected across a large number of synthetic turf fields, more directed experimental work at fields and in the laboratory would be required to answer some of these questions. The following paragraph has been added to Section 4.8.1 of the Part 1 Report:

"While the emissions testing performed in this study provides valuable information to help understand the types and ranges of chemical emissions from tire crumb rubber, it is not clear how well the test methods apply to the wide range of conditions at synthetic turf fields, and whether the results can be successfully applied to estimating real-world emission to inform exposure assessment. Conditions such as short-term changes in temperature (e.g. daily diurnal cycle), infill depth, effective ventilation rates at indoor and outdoor fields, or other factors may affect emissions

variability and net emissions at fields. More directed experimental work at fields and in the laboratory would improve our understanding about how well laboratory emissions testing can be used to model or predict exposures under different situations."

4.6 Charge Question 6: The results of the Exposure Characterization are summarized and presented in Chapter 4 with attendant Appendices. Please comment on the overall approach for presenting the analytic results and describe any other recommended ways to present the analytic results to inform decision-making.

4.6.1 Reviewer 1

Comment: The overall approach is acceptable for presenting these exposure characterization [sic]. Here are some suggestions for improvement.

Table 4-1 is a summary of the research areas and specific research activities for exposure characterization. This table can also be found in the Introduction. For consistency, also put this type of table at the beginning of Chapter 3 for Tire Crumb Characterization. In fact Chapter 3 is the densest Chapter and might need that table as a reminder of all the activities covered. To help the reader navigate these chapters, within the table insert the sections where this material is covered (e.g., 4.1.2.1 covers the first row of Table 4-1 for recruiting).

Response: We have added schematic overview figures to the beginning of the methods sections (Section 3.0 of the Part 1 and Part 2 Reports) to orient the reader.

Comment: Line 6318: There is a confusion of speaking in the past and present about whether biological samples were held for future analysis. Does this mean, some analysis have been conducted on the biological samples and you are still holding a portion for future analysis?

Response: Participants who consented to allow their samples to be stored for future use were retained. The pilot scale effort includes analysis for serum and blood metals and urinary PAH metabolites as described in Part 2, Section 4.5.3.1.

Comment: Section 4.1.1: Include an earlier discussion to help reader understand that the environmental measures in this exposure characterization section with be used in the modeling of human exposure as

opposed to the environmental measures (chemical concentrations found tire crumb characterization section). This is stated later, but a more direct explanation upfront is useful.

Response: The following paragraph was added to the end of Section 4.1.1 (now Section 3.1 of the Part 2 Report) to highlight the exposure modeling. "Exposure pathway modeling was performed for adult and child athletes using synthetic turf fields with tire crumb rubber infill, first using data available from the literature, and then again with data collected in this study. Six chemicals associated with synthetic turf fields and tire crumb rubber were selected for exposure pathway modeling. They were selected to provide a range of physical and chemical properties and because of the availability of previous measurement data. Adult and child pathway-specific exposure estimates were calculated for each of the six chemical substances and were compared to identify the predominant pathway for each chemical substance. Subsequent to the modeling of tire crumb-related exposures using previously existing and newly acquired measurement data, daily intakes of four of the chemicals were also estimated using available residential "background" concentrations to provide perspective on the relative magnitude of the crumb-related exposure estimates.

Comment: Figure 4-1: For the Off-Field Air sampling station, insert in brackets (background)

Response: The word 'background' was inserted in the figure.

Comment: Line 6399: Change "air sample inlet" to "air sampler inlet"

Response: Changed to 'sampler'.

Comment: Line 6495: Why remove debris and other large particles? Individual are exposed to chemicals in all these materials especially if they stick to human skin for a time period. The bioavailability may be lower from these materials than from dust however. Although note that the bioavailability from tire crumb material is used in the modeling estimates. There is one has to admit a mixing of data in the exposure algorithms.

Response: The goal of the field wipe and drag sled samples was to attempt to measure 'transferable' residues and small particles available at the field because we believe this may be the most relevant metric for dermal exposure and an important metric for ingestion exposure. We separately measured the chemicals associated with the larger tire crumb particles, but removed

them from the field wipe and drag sled samples so as not to confound interpretation of the transferable residue and small particle measures.

Comment: Line 6937: mentions the use of a trained phlebotomist to draw blood in the analysis part of the report. Mention this first in the section on collection of samples (i.e., in the field).

Response: Added to Part 2, Section 3.3.3.2.

Comment: Line 6949: Consider changing tittle to 'Online Video Activity Assessments for Synthetic Filed Users". Line 6950: Also consider changing the word "extant" to "online sources" throughout. Later it is referred to as publically [sic] available videos. Consider some consistency in terms to avoid confusion for the reader.

Response: The word "extant" was changed to "online sources" throughout this section; specifically, changed the sentence in Line 6950 (now the first sentence of Part 2 Section 3.5) from "In early 2017, a novel extant videography method" to "In early 2017, a novel videography collection method using online sources." The title of Section 4.1.5.1 (now Section 3.5.1 of the Part 2 Report) was changed from "Publicly-Available Video Assessment (Phase I)" to "Online Video Assessment (Phase I)". The first sentence of Section 3.5.1, "The extant videography (Phase I) work…" was changed to "The videography (Phase I) work using online sources…". Also, in Table 4-3 (now Table 3-1), "Exposure Characterization Research Areas and Specific Research Activities," changed the words "Using extant video data" to "Using video data from online sources."

Some on-line sources of videos are not publicly-available, therefore, this distinction needed to be made throughout this document.

Comment: Line 6956: The comment "a new videography method" is not entirely correct. Perhaps a better word is adapted. There are a number of published articles on methods to collect data from videotapes. Some use video-translation methods and some extract activity data by observation. Similar inter-observer and intra-observer measures for quality assurance are described. Similar quality assurance methods are also used. These articles should be quoted. This gives the reader some confidence in the methods as not new and commonly used to collect activity data for other scenarios: Here are some of those references.

Videography methods:

Video methods in the quantification of children's exposures. J Expo Sci Environ Epidemiol. 2006 May;16(3):287-98. Ferguson AC[1], Canales RA, Beamer P, Auyeung W, Key M, Munninghoff A, Lee KT, Robertson A, Leckie JO

Quantitative analysis of children's microactivity patterns: The Minnesota Children's Pesticide Exposure Study. Freeman NC[1], Jimenez M, Reed KJ, Gurunathan S, Edwards RD, Roy A, Adgate JL, Pellizzari ED, Quackenboss J, Sexton K, Lioy PJ. J Expo Anal Environ Epidemiol. 2001 Nov-Dec;11(6):501-9.

Hand- and Object-Mouthing of Rural Bangladeshi Children 3-18 Months Old. Kwong LH, Ercumen A, Pickering AJ, Unicomb L, Davis J, Luby SP. Int J Environ Res Public Health. 2016 Jun 4;13(6). pii: E563. doi: 10.3390/ijerph13060563.

Response: Starting at Line 6953 (now second sentence of Section 3.5.1 in the Part 2 Report), this sentence was changed from "This method was slightly modified" to "The adapted video translation part of this method was slightly modified…" for clarification. Also, the three references provided are now cited in this sentence. The next sentence in the paragraph was changed from "In addition, a new videography method was developed" to "In addition, an adapted videography method was developed."

We thank the reviewer for the videography method references; they have been added.

Comment: Line 7074: Please clarify whether the camera was placed on a tripod for the entire time of play and two videos captured of all the players at one time. Typically for videotaping methodologies (as mentioned in references above), a videographer follows a child of focus to be able to effectively keep hands and mouth in view for more accuracy of translating activity data (hand to mouth contacts). Therefore, a video per subject is produced.

Response: On Line 7074 (now Section 3.5.2.1 of the Part 2 Report) the sentence was changed to "An HXR-NX100 Full HD NXCAM camcorder (Sony Corporation, Minato, Tokyo, Japan) attached to a Manfrotto™ XPRO monopod (Lino Manfrotto + Co. Spa, Cassola, Italy) was used to record a selected participant athlete's activities while playing on the synthetic turf field simultaneously on two different Sony 32GB High Speed UHS-I SDHC U3 Memory Cards (Sony Corporation, Minato, Tokyo, Japan)" for clarification. In addition, this sentence was added to the paragraph: "Only one participant athlete was videotaped by the technician at a time."

The technician was not allowed to enter the field of play or run down the sidelines of the field to videotape each participant athlete (a limitation of this study). To ensure that play was not altered or

disrupted on the field, a technician used the zoom function on the camera attached to the monopod (at all times) to capture the micro-activities of each selected participant athlete on film.

Comment: Line 7143: Please note a videotranslation software program could have been used to capture these various types of activities (i.e., VideoTraq) following analysis of text files for extraction.

Response: No change. This paragraph in the methods section is describing the method used to code the selected micro-activities of individual participant athletes from the video files onto a paper template (by hand). It would not be appropriate to mention other possible methods (e.g., VideoTraq) that can be used to code the participant's target micro-activities in this section.

Comment: Line 7158: Error rate was found to be unacceptable during retraining, and therefore retraining was repeated to achieve an acceptable interobserver agreement. One technician however had already completed 95% of translations. Discuss how this might affect quality assurance for the translation of data, where this technician may have been losing some accuracy.

Response: The error rate for intra- and inter-reliability for two technicians was tested at the beginning and after 50% and 95% of the participants' video files were translated by technicians. For these technicians, the error rate was acceptable at the beginning of translating the video files and at 95% completion of the videos. At 50% completion (*not at 95% completion*), the error rate of 17% between the two technicians was slightly above the acceptable level (15%). So, the technicians translated the video file again and the error rate between the two was below 10%. The technicians then continued translating the remaining videos until being tested at 95% completion.

Comment: Table 4-5 is the same as Table 4-1 and seems repetitive.

Response: We agree. This was an error; we will only use the table one time.

Comment: Table 4-1: One added research activity could have been to compare the chemical concentrations found in biological samples (addressing any pharmacologically based pharmacokinetics mechanisms) with a modeled calculation of exposure over the exposure period for three routes of exposure. Not enough data may have been available for a particular compound and choosing a compound that is the least metabolized with appropriate clearance time is advisable. If there is no match with compounds found in dust, air samples with compounds, or their byproducts found in

biological samples then a number of issues may be occurring (sampling error, low concentration, lack of understanding of PBPK dynamics, etc.).

Response: We did perform exposure pathway modeling for several chemicals, using data collected at the exposure pilot study fields and the participant exposure study samples, including pyrene, which likely would be most relevant for the suggested comparison. However, this modeling was based on average measurements across all participants, not for individual participants that provided urine and blood samples for biomarker measurements. The greatest problem in comparing estimated exposures to measured biomarker levels is that uncertainties and variability in uptake, metabolism, and excretion (particularly due to hydration status and urinary dilution) limit the likely accuracy of such predictions. Given the relatively small number of participants and the uncertainties, we have elected not to perform such estimation comparisons.

Comment: Point to add to Introduction: Wipe samples on the body are reflective of exposure and can be compared with the modeling estimates of exposure to dust via the dermal route for chemicals. These wipe samples may however have been used for the residue loading on the skin. I believe the introduction to this chapter could better compare and discuss these various research areas (including PBPK modeling), data collection and full picture of how these variables overlap or relate to each other. It is possible to also add an illustration of the interactions between these research areas for exposure characterization. This affects understanding the results section and modeling later in Chapter 5.

Response: The reviewer is correct that the dermal wipe samples were used to measure residue loading on skin. These dermal wipe samples provide information that can be used in exposure models to avoid highly uncertain transfer rate estimates for dermal exposures. The data collection and modeling are described in Sections 5.1.1 through 5.1.4 but not in the Introduction to avoid redundancy.

Comment: Notice that in the exposure-modeling, uptake from the residue on the skin is being estimated using the bioavailability measures from tire crumb characterization. The bioavailability measures may be different.

Response: In the first pathway modeling approach described in Section 5.0 of the Part 2 Report, we used 'standard' dermal absorption factors from extant data to estimate dermal exposures from tire crumb rubber. In the second approach, we used the measured dermal loading results for metals and

SVOCs from this study in estimating dermal loading. We think it is likely that the bioaccessibility (and bioavailability) of chemicals from tire crumb rubber is likely to be substantially different for the larger tire crumb rubber particles versus the field dust and residue that was measured using the dermal wipe samples. More measurements would be needed, particularly for the field dust, to better understand the likely magnitude of any differences. In Part 2 Section we described this limitation:

> "A lack of data on bioaccessibility for chemical substances in crumb rubber field dust serves to increase the uncertainty of the route-specific exposure estimates for all three routes (see Figure 5-2)."

Comment: Only three fields are used in the Exposure Characterization study for dust and air sampling. Given the great variability in the tire crumb characterization for concentrations across a greater number of fields, there may be great variability in dust and air samples than reflected by sampling these three fields. This comment is also relevant to Chapter 5 on the exposure modeling.

Response: We agree with this comment. This is the reason that we first performed the exposure modeling using data collected across studies available in the literature. We addressed this comment regarding the impact of the sparseness of data, in part, by adding this paragraph to the limitations noted in Section 2.4.3 of the Part 2 Report:

"Exposure pathway modeling was performed for several chemicals associated with tire crumb rubber to assess potential exposures for adult and youth athletes using synthetic turf fields, to better understand which exposure pathways might be the most important, and to assess the extent and quality of information needed for successful modeling. Ideally, probabilistic modeling approaches would have been used to develop distributions of exposure estimates. However, only point estimates of exposure were developed through modeling in this study due to the sparseness of data for several important exposure media and exposure parameters. Limitations in available data and exposure parameter values for synthetic turf field exposure scenarios results in uncertainties in the accuracy of the point estimates. The ability to interpret modeled exposures for exposure and risk assessments is limited by the lack of a more complete understanding of the distribution of exposures for people using synthetic turf fields with tire crumb rubber infill."

We also explicitly note the lack of more robust data for relevant exposure media in the first bullet of Section 5.5 in the Part 2 Report, addressing conclusions of the adequacy of the data for exposure modeling.

Comment: Section 4.2.2.3: Mention memory recall limitations with respect to activities such as diving, falling. In general activities collected by questionnaire and answered by parents for the subjects may suffer from memory recall.

Response: Recall bias is a potential issue for questionnaire-based activity data collection. However, given that objective observations are impractical for large numbers of participants over multiple days and years of play, a questionnaire approach may be the best, or at least only practical approach to gathering this type of activity data. No change.

Comment: Line 7330: Abrasions (44% reported occasionally getting abrasions) can lead to an increase in absorption rate for compounds. This point can be mentioned Chapter 5 on exposure modeling.

Response: The point is mentioned in Chapter 5 in relation to the assumptions in the exposure estimates: "Despite participants in the Exposure Pilot Study reporting occasional abrasions, which could lead to an increase in absorption rate, dermal abrasions were not considered in these modeling exercises due to the complexity of physiological processes involved in vascular absorption and transport".

Comment: Table 4-26, 4-27 and 4-28; Why put ** and *** for when p values are a certain range. There are no p values in this range and confuses the reader. In other words, the reader is looking for these greater significance levels.

Response: Agree with the reviewer and have removed the footnotes "[a] $p \leq 0.05$, ** $p \leq 0.01$, and *** $p \leq 0.001$ significance levels" from these three tables.

Comment: Line 7582: Include at the end of the sentence "compared to Hockey players", given there were only 3 groups of different types of players.

Response: No change. For the 17 TCRS participants, they only played either soccer or football (<u>not field hockey</u>).

Comment: Figure 4-22 and 4-23: Line graphs do not seem an appropriate representation, also very little data to present.

Response: We appreciate your input; we have elected to keep these figures for completeness.

Comment: Line 7671: Higher activities can lead to higher inhalation rates but can also lead to greater sweat on the skin. This may promote deposition and adherence in skin.

Response: We added the following sentence to Section 4.4 of the Part 2 Report: "Higher activity levels can also lead to increased sweat production that may lead to increased adherence of field dust to the skin."

Comment: Line 7887: A more accurate term to "adherence" might be "deposition" to human skin.

Response: We believe that 'adherence' captures a wider range of processes for the transfer of chemicals to skin than does the term 'deposition'.

Comment: Table 4-47: Move to appendices and summarize in report.

Response: We have elected to retain the full dermal SVOC measurement results table in the body of the report.

Comment: Section 4.2.5.5: Please check if the unsuccessful outcome with VOC samplers is mentioned in the Introduction.

Response: We highlighted this outcome with a paragraph among the key results in Section 2.2.2 of the Part 2 Report. We have not included these kinds of overall results in Section 1 (Introduction).

Comment: Line 8075-8078: Results are mentioned of urinary PAHs but ends abruptly with no explanation on general findings.

Response: Additional information on the results is presented after the tables.

Comment: Line 8112: Please clarify what data?

Response: "Urinary PAH" has been added to clarify what data are being referred to.

Comment: Page 333-Page 334: Please mention the material composition of the wristbands. Also the wristband data collections seems arbitrary to the report and project in general. But if you choose to introduce it, mention some findings for the chemicals found in the wristband.

Response: We added 'silicone' in several places to denote the wristband material. While not the primary focus of the research, we did introduce the plan for wristband testing in our original research protocol due to the clear difficulties in personal measurements for athletes at synthetic turf fields and the need to explore alternative methods. We considered placing all of the wristband text in the appendices due to the imperfect fit in Section 4.0 of the Part 1 and Part 2 Reports, but decided to retain it to alert readers that the work was done. We did place all of the results tables from the wristband testing into the appendices (Part 1 Report, Appendix T and Part 2 Report, Appendix H).

Regarding the preliminary field testing described in Section 4.2.6.2 (now Section 4.6.1 of the Part 2 Report), we have added a summary of results from the wristband field sampling effort.

Comment: Page 334: Chapter 4 ends abruptly on the results for the wristbands. Include a conclusion to this Chapter across all the findings on exposure characterization.

Response: Summaries are included now in Section 2.0 of the Part 1 and Part 2 Reports.

4.6.2 Reviewer 2

Comment: The general overall approach for presenting the analytic results is suitable.

Response: We acknowledge the reviewer's comment.

Comment: General comments.

The number of fields where air samples were taken is quite low. The air temperature is not indicated.

Response: We agree that the number of exposure study fields is low, with three fields and four air measurement sets at those three fields. We have reported the field air and surface temperatures as part of the field metadata in Section 4.2.4 (now Section 4.4 of the Part 2 Report).

Comment: Since background levels are quite high, higher sampling rates or sampling times might be more suitable. In addition, the rubber crumb should be slightly stirred near the sampling locations to simulate real playing conditions.

Response: In most cases, the chemical concentrations in the background air collected upwind of the fields were in typical or expected ranges. In general, though, higher air sample collection rates for the SVOCs would have been preferred to ensure that all results would be above detection limits. We elected to use sampling times that represented the sports practice time for the participants to best represent the potential for exposures while activities occurring at the fields are likely to lead to suspension of particulates and to match the participant exposure times. Ideally, we would collect personal air samples since the amounts of suspended particulates may be highest in close proximity to the athletes during their activities. However, we could not safely collect particulate personal air samples for the range of athlete ages and activities in this study. The next best option was next-to-field downwind air sampling during the practice periods of high activity. We are hopeful that the California-OEHHA research study will provide some more proximate air measurements during periods of on-field activities.

Comment: It is a pity that the personal samplers, which would have given a more realistic degree of inhalation exposure, did not work as well as expected.

Response: We agree that this was an unfortunate outcome. Personal sampling that will be successful for a wide range of sports activities and age groups remains an important challenge for exposure assessments of athletes engaged in activities on synthetic turf fields.

Comment: Regarding the presentation of the analytical results:

I think it would be useful to include a column with the LODs in those cases where one of the columns of the table is %>LOD (e.g. Table 4-36).

Response: Due to the large amounts of information being reported and because the level of detection (LOD) status was evaluated using the 'raw' measurement units, which are not directly comparable to the final calculated units, we have elected not to include the detection or quantifiable limit values in the tables in the body of the report. The detection or quantifiable limit values are included for most measurement types in Appendix /B of the Part 2 Report in the original 'raw' measurement units that were actually applied. We will add to these Appendix B tables the detection or quantifiable limits that have been converted to the same units used to report the results for sample measurements, using nominal values for factors or amounts, but these nominal values may not be correct/applicable for all samples.

Comment: The information regarding the air samples (section 4.2.5.1) (information in tables 4-36, 4-37, 4-38) might also be given as bars graphs at least for some representative chemicals.

Response: This is a valuable recommendation. We have prepared and added air measurement bar graphs for several key SVOC and VOC analytes to better illustrate the results. This comment also caused us to added new figures to highlight selected results for the dermal measurement results.

Comment: The analytical results are well presented but due to the gaps and limitations, the information should be taken with caution.

Response: We concur with this observation. We tried to be careful to describe this as an exposure pilot study to help communicate the relatively tenuous nature of these results. We have elected to add, in Section 2.2.3 of the Part 2 report, the following summary conclusion:

"This study has provided important new and additional information about chemicals in tire crumb rubber and the ways field users may come into contact with this material and its chemicals; however, the magnitude of potential exposures is still somewhat uncertain, in part due to incomplete information regarding the amounts of field dust that adhere to the skin of synthetic turf field users and the amounts of dust and tire crumb rubber ingested."

4.6.3 Reviewer 3

Comment: *General*:
Methods are well thought out and described in great detail, but one tends lose sight of the forest studying the trees. The team evaluated the application of some novel sampling techniques, e.g., the silicone wrist-band passive sampling device, that will be helpful in future studies.

Response: We appreciate the reviewer's comments. We agree that Section 4.0 is quite detailed. We attempted to address this by bringing up into Section 2.0, the key findings, conclusions, and results for highlighting. We expect most readers will focus on the Executive Summary, Section 1.0, and Section 2.0. We have included the large amount of methods and measurement result reporting in Sections 3.0 and 4.0 for those readers that are looking for the highly specific technical information.

Comment: Some of the info could go into an appendix. The meta-data was collected based on what hypotheses and models?

Response: We have elected to present most of the results in the body of the report in Section 4.0 of the Part 1 and Part 2 Reports. We did place all of the silicone wristband results in the appendices of the Part 1 and Part 2 Reports. The metadata collection was not based on specific hypotheses or models, per se. The metadata are primarily descriptive in the context of this pilot measurement study. If larger future studies are performed, it may be possible to use some types of information in data analysis, for example assessing field and exposure measurements by temperature, individual activity level/type, and overall levels of activities at the fields. In this pilot study, the number of fields, participants, and measurements are insufficient for performing these types of factor analyses.

Comment: *Specific*:
6743: Meta-Data Collection: Air humidity might be significant variable. It seems not to be included in the table of collected meta-data shown in Appendix T.

Response: We did not measure air humidity during the exposure field study. In retrospect, that meteorological metric could be of interest.

Comment: 7726 Section 4.2.5.1: The air concentration data is difficult to interpret without the associated wind speed data. How was below-the-detection-limit data evaluated?

Response: We reported average and peak wind speed data during the participant exposure measurement periods in Section 4.2.4 (now Section 4.4 of the Part 2 Report). We collected wind direction information as well, along with schematic diagrams of sampling locations. For all three measurement days at outdoor fields, we successfully located the upwind background samples in locations where they remained upwind from the fields for the duration of the study. However, with only a few measurement periods, we did not perform any quantitative assessments of wind speed or temperature relationships with measured concentrations. Such an assessment would also need to consider field-specific tire crumb rubber analyte concentrations and perhaps overall activity intensity at the fields. Measurements below the detection limits were based on analytical method limits of detection. We elected to report and utilize all measurement values reported by the laboratory, even those below quantifiable limits, rather than applying substitution or statistically-based substitutions. We have added bar graphs to highlight results for selected air measurement VOC and SVOC results.

Comment: 7777 Table 4-36: Cobalt was detected in 33% of the samples. How median concentration calculated? The same question applies to benzo(g,h,i)perylene in Table 4-37. The same question applies to all tables with this type of information. It the procedure is included in the report, a reference should be given in the captions of the table. OK, found it on line 8409.

Response: We added the following footnote to the table to explain this result: "Although cobalt and rubidium had < 50% of the measured values above the quantifiable limits, all measured values from the analysis, including those reported by the laboratory that were below the MRLs, were used in the calculation of median values." In addition, this comment caused us to consider how the dermal results were reported, particularly with the high percentage of results below quantifiable limits for many of the SVOC analytes. We removed results showing mean and standard deviations since these metrics are not supportable for many of the analytes and replaced the results with median values.

Table 4-4. Exposure Pilot Study Participant Dermal Wipe Measurement Results for Selected Metals [a]

Metal	Participants	% > Minimum Reporting Limit	Hand Wipe Median (ng/cm^2)	Hand Wipe Maximum $(ng/cm)^2$	Arm Wipe Median (ng/cm^2)	Arm Wipe Maximum (ng/cm^2)	Leg Wipe Median (ng/cm^2)	Leg Wipe Maximum (ng/cm^2)

Comment: 7809 Table 4-38 and similar tables: should the detection limit be specified?

Response: Due to the large amounts of information being reported and because the LOD status was evaluated using the 'raw' measurement units, which are not directly comparable to the final calculated units, we have elected not to include the detection or quantifiable limit values in the tables in the body of the report. The detection or quantifiable limit values are included for most measurement types in Appendix B of the Part 2 Report in the original 'raw' measurement units that were actually applied. We will add to these Appendix B tables the detection or quantifiable limits that have been converted to the same units as the results are reported for sample measurements, using nominal values for factors or amounts, but these nominal values may not be correct/applicable for all samples.

Comment: 7914 Table 4-44: Empty column, some info missing?

Response: We have removed this column from the table.

4.6.4 Reviewer 4

Comment: This was a model activity survey for exposure assessment. Clear, easy to read, well illustrated.

See comments for pp. 49 and 52.

Should define drinking. Was this consumption of a beverage from any container, including just-uncapped bottles? Exposure by this route is presumed to be from contamination on lips or of container, but is this realistic?

> **Response:** The questionnaire did not specify type of container and was not necessarily intended to determine exposure route.

Comment: Suggest dividing this chapter between contact exposure and biomonitoring. Unwieldy as it is, combined.

> **Response:** We elected to keep the pilot-scale biomonitoring study results in this section. However, the Supplemental Biomonitoring Study is now addressed in a separate appendix (Part 2 Report, Appendix A).

Comment: p. 332, line 8244. Too colloquial: replace “can’t” with “cannot”.

> **Response:** The recommended change was made.

4.6.5 Reviewer 5

Comment: The Exposure Characterization Chapter was similar in many ways to the Tire Crumb Characterization presentation. The Chapter was organized in a logical fashion outlining first what data were to be collected, how they were to be collected, e.g., urine/blood collection, laboratory analysis description, and data analysis description. The presentation of the results was also similar with descriptive statistics presented, followed by box-and-whisker type plots, and some modeling analysis.

As was the case with the Tire Crumb Characterizations, there is a large amount of data presented. Also in a similar sense, this can be overwhelming. However, the data are described well, as are the results, and, if one puts in the time to go through the details, the result are presented in a digestible fashion.

Also similar to the previous Chapter, I can offer no real alternatives that would substantively improve the presentation. One needs the descriptions- and the pictures- of the way samples were collected in order to understand what was done. Further, the methods must be delineated to build confidence in the methods used. The results must be represented and summarized using statistical analyses. All of these were done effectively. There is a good deal of information to be digested, but with some discipline and study, it is all clearly laid out for the reader. I offer no insight on how it might be streamlined or presented more clearly.

Response: We thank the reviewer for the kind words.

4.6.6 Reviewer 6

Comment: Considerable thought went into the Exposure Characterization portion of this project as described in Chapter 4 and its Appendices. As with Chapter 3, a large amount of information is presented. The organization and approach for presenting the results is appropriate and logical. The exposure characterization provided should help improve our ability to estimate exposures to individuals and populations using these fields. As the authors indicated, one of the limitations of the study was the small number of individual who were included in the biomarker study. Only the urinary metabolite 2-hyroxynaphthalene had an overall statistical difference between the pre-post levels, but it precursor naphthalene was not found at elevated levels in the crumb rubber.

A visual examination of the individual figures (4-25 to 4-31) show an interesting pattern with subject 1 and 16 showing increases in pre-post for most metabolites and subject 15 a decline while the remaining subjects having smaller changes without an apparent consistency. While there are concerns from drawing inferences from data for individual subjects, these patterns could indicate that there is an artifact in the data or actual difference in exposures or metabolism across individuals.

Response: The recommended change was made.

Comment: One issue with interpreting urinary concentration is it is dependent not just on how much of a metabolite is excreted but also the volume of urine excreted. The authors used creatinine to correct for this. However, creatinine correction most effectively works for first morning urine in a hospital where the individual has been resting since it is a product of muscle metabolism. It is therefore questionable as to if it can correct for urine concentration following a high exertion sporting activity. I

suggest that the actual concentrations in the urine also be presented and if available a correction based on density.

Response: The recommended change was made. In addition, results using adjustment for specific gravity were also calculated and presented.

Comment: It would also be useful to indicate how much time before and after the sports activity the blood and urine samples were collected. Was that consistent for each individual? Since these compounds are not short lived in the body, a reasonable amount of variation can be tolerated.

Response: The recommended change was made.

Comment: Presumable the comparison to NHANES data are matched on age. Were they matched on anything else (ethnicity, location, urban/rural)? Dietary habits can have a major impact on the levels of some of the SVOC in the blood and their metabolites in urine. Similarly, where a child lives can affect the blood metal levels.

Response: The recommended change was made.

4.6.7 Reviewer 7

Comment: The overall approach for presenting the analytic results of the Exposure Characterization is comprehensive and detailed.

- On page 247, lines 6349-6351 it is stated that "[d]ue to scheduling issues and other factors, only three fields in two U.S. census regions were available for participant recruitment during the study time frame, specifically one indoor field and two outdoor fields." It would be useful (and presumably not violating confidentiality) to generically specify these regions and fields.

Response: Due to the small number of participating fields, we have elected to not include even general census region information for the exposure study fields. Given the small number, the information would have little value in results interpretation.

Comment:

- On line 6950, page 264, the phrase "a novel extant videography method was developed" would be more clear if re-stated as "a novel method for extant videography was developed."

Response: Based on a comment by another reviewer, the sentence was changed to "In early 2017, a novel videography collection method using online sources was developed…"

Comment: The "data manger" on line 7189 of page 271 should ne [sic] "data manager."

Response: This typo was corrected in the text.

Comment:

- This reviewer is wondering if alternatives to the "paper templates" shown in Figure 4-12 (page 267) and 4-13 (page 270), such as using a tablet or similar device for tallying, were considered.

Response: Yes. Other alternative methods were considered; however, to meet tight project deadlines, the paper template method was deemed the best way to produce high-quality micro-activity data quickly.

Comment:

- This reviewer is also wondering why RStudio was used for statistical analyses of activity data but not for chemical data (where SAS/STAT was used).

Response: They are both acceptable scientific software programs. The person performing the statistical analyses of the data was familiar with RStudio and not SAS.

Comment:

- As also mentioned in the response to the previous question, tables that can fit in a single page should be constrained from breaking in two pages (e.g. Table 43-33 on pages 293-294, Table 4-34 on pages 295-296, Table 4-36 on pages 297-298, Table 4-37 on pages 298-299, Table 4-42 on pages 304-305, etc.). Tables, such as 4-46 (starting on page 310) should have a running header with in-table page-numbering.

Response: When possible, tables are positioned to fit on a single page. However, positioning of tables must also be balanced with the requirement to minimize white space and locate tables in close proximity to (but not before) their mention in the text. For tables that extend beyond one page, the table header row is repeated on each subsequent page; in addition, the table number and "Continued" (e.g., Table 1-1. Continued) will be added to subsequent pages to help orient readers.

Comment:

- The color coding ("RED=increase, GREEN=decrease") in Figures 4-25 (page 318), 4-26, 4-27 (page 319), 4-28-4-29 (page 320) 4-30, 4-31 (page 321) is redundant.

Response: We have elected to retain the graph bar colors as a visual aid.

4.7 Charge Question 7: The results of the Exposure Pathway Modeling are summarized and presented in Chapter 5 with attendant Appendices. Please comment on the overall approach for presenting the analytic results and describe any other recommended ways to present the analytic results to inform decision-making.

4.7.1 Reviewer 1

Comment: The overall approach for estimates on human exposures is rushed. I would find this section the most interesting and of the most importance. Some time should be taken to explain the steps more clearly and to give example calculations. Below are some specific areas for improvement.

Response: Figure 5-1, "Process for generating pathway-specific exposure estimates using both existing data (on left) and new data from this exposure pilot study (on right)" and Figure 5-2, "Diagram of exposure pathway modeling, showing possible media for each route-specific exposure estimate" have been added to the Part 2 Report to explain the steps more clearly. An additional equation (Equation 5-4) has also been added to clarify calculations.

Comment: Line 8295: mention bystanders in a different sentence as a follow-up. You could hypothesize that there [sic] exposure are likely to be less (lower contact rates with fields, lower breathing rates, less sweat on skin).

Response: Although exposure to bystanders is not the focus of this section, an additional sentence has been added to Section 5.1.1 of the Part 2 Report, "Athletes may be exposed via the inhalation, dermal, and ingestion routes, while bystanders are likely to encounter only downwind gases and experience much lower exposures.".

Comment: Line 8335: Please give examples of what parameter values.

Response: The text (now in Section 5.1.1 of the Part 2 Report) was modified to provide an example of parameters taken from the handbook and parameters taken from other sources and text was

added to inform the reader of where to find the values: "Model parameter values were taken from EPA's Exposure Factors Handbook (U.S EPA, 2011b), where these values were judged to be applicable (e.g., inhalation rates). Where not applicable, parameter values more appropriate for the athlete exposure scenarios (e.g., exposure durations) were obtained from the literature or other EPA documents, as presented in section 5.1.2."

Comment: Line 8358: please mention to reader (since mentioned) the reason zinc was added as a second metal.

Response: Sentence was expanded to elaborate on why zinc was added (now in Section 5.1.1 of the Part 2 Report): "Upon further discussion, zinc was added to the chemicals of interest due to its presence in tire crumb rubber at relatively high concentrations."

Comment: A person may change their behaviors over time. Lifetime exposures could be calculated considering stages of exposures, using finding for this study for a person change in behaviors at different ages.

Response: We agree that a person, particularly an athlete, will change his or her behavior and activity patterns over time; however, longitudinal lifetime exposure estimation is beyond the scope of this study. We feel that it would be imprudent, especially with the limited amount of available data, and not in keeping with the goals of this study to try to provide lifetime exposure estimates.

Comment: Line 8333 through 8350: Consider reorganization to explain the steps and the approach more accurately. First line 8333-8334 for the standard algorithms that were used. Then use bullet points for the sets of calculations made: 1) parameters from the literature 2) parameters collected in this study 3) comparisons made between the two sets of approaches (with the section numbers on where these components starts [sic] and stop.

Response: Figure 5-1 was added to the Part 2 Report to more clearly explain the steps of the modeling exercises using existing data and field measurements.

Comment: Line 5.2.1: Rename to say "Exposure estimates using data from existing studies (or previous studies)."

Response: Retitled to "5.1.2 Synthetic Turf Field User Exposure Estimation Using Existing Measurements."

Comment: Now and then be sure to be clear and remind the reader when you are using data from the literature and data collected in this study (exposure characterization, chapter 4). For example, line 8401: insert 'from the literature" after "measurement" and Table 5-2-title: After "weighted averages" include "from the literature".

Response: The words "from the literature" were added to the line noted in the comment. Additional edits were made to ensure reader recognizes the source of the data. Tables were not renamed, as the section was reformatted to make the distinctions more clear among the different sources of data (existing measurements, pilot study measurements, and background).

Comment: Table 5-7: Please clarify if the dermal adherence factor used is for dust adherence for comparison with this study or soil/sand adherence to skin.

Response: The source for the adherence factor in Table 5-7 of the Part 2 Report is now listed as "U.S. EPA, 2011b[a], Chapter 7, Table 7-4." Footnote "a" to the table states, "Calculated using body part percentages and adherence factors per body part."

Comment: Table 5-8: Please clarify if inhalation rate was measured in this study, or this is the inhalation rate that is used when making estimates using other parameter data in this study. This first section is also focused on using data from the literature. This table also has a column for dermal exposure (g/cm2) is this the result of exposure modeling for the dermal route using EPA algorithms or is the dermal loading on the skin from estimates of the dermal wipes. All other numbers in this table seem to be exposure parameters used in the exposure algorithms and this dermal estimates [sic] needs to be explained.

Response: The source for the inhalation rates is now listed as "U.S. EPA, 2011b, Chapter 6, Table 6-2 High Intensity (converted to m3/hr)." The dermal "exposure" label was in error and has been corrected to "dermal adherence (g/cm^2)."

Comment: Title 5.2.2: Retitle for Clarity: Exposure Estimation using Data from this Exposure Characterization Study (so we know it is using mostly data from Chapter 4).

Response: Retitled Section 5.2.2 (now Section 5.1.3 in the Part 2 Report) to "5.1.3 Synthetic Turf Field User Exposure Estimation Using Exposure Pilot Study Measurements."

Comment: Line 8496-8499: This somewhat confusing. We are talking about using data from this study and switch back to tire crumb concentrations in the extant literature, when this study (Chapter 3 has tire crumb characterization). If in fact tire crumb concentrations were used in the previous section for estimates of exposure using data in the literature, make this clearer in the previous section. Then in this section just say for exposure concentrations that dust concentrations/ or wipe sampling residues were used here and were believed to be more reflective of what might be occurring.

Response: The entire paragraph (now in Section 5.1.3 of the Part 2 Report) was edited for clarity.

Comment: It is possible subjects can be exposure to chemical concentration in the dust that is present (dust adherence mechanism, in the sand that is present (sand/soil adherence mechanism), in the tire crumb materials (residue contact) and even dust or residue deposition to the skin. So multiple mechanism of exposure for the dermal route could be occurring. A schematic of the exposure mechanisms to human skin relevant to this scenario could be included here, mentioned which mechanisms are addressed and which are not due to lack of data or strong evidence of a non-relevant pathway mechanism.

Response: We agree that additional mechanisms may exist; however, the level of detail suggested by the reviewer is beyond the scope of a screening-level assessment and is inconsistent with the level of detail applied to the other routes and pathways.

Comment: Line 8500: Clarify if this is bioaccessibility from tire crumb materials vs from dust, where concentration in dust and dust adherence are used in the exposure calculation. However on line 8510 dermal wipes are mentioned as providing the chemical loading on skin indicating residue adherence mechanisms for dermal exposure. Please clarify is whether residue adherence or soil adherence to human skin calculations were used for dermal exposure. Provide an example calculation in this section illustrating the parameters and calculations used. If a residue adherence (from wipe sampling is used) the equation would only need the bioaccessibility. The dust sampling could be used in two ways. I am getting confused in this section and the reader maybe getting confused. The dermal exposure equation in 5-3 is for exposure to a chemical in dust and soils. A slightly different equation would be used for residue loading/adherence to skin from the wipe samples.

Response: For the modeling using exposure pilot study measurements, dermal wipe data was used instead of adherence calculations. The following sentence was added to Section 5.1.3 of the Part 2 Report for clarity: "With the additional dermal wipe sample concentrations, the use of adherence factors was avoided, and loadings on skin were used in the exposure algorithms." The text was altered in several places for clarity. Dust was collected in the exposure pilot study to identify any differences in concentration between crumb granules (used in the extant data modeling) and crumb dust.

Comment: Line 8614 through line 8626: It would be useful to look back at the equations (kind of a sensitively analysis) and say which parameter to driving these outcomes.

Response: We agree that a sensitivity analysis would be useful, particularly for identifying important areas of subsequent research. Moreover, while we believe that a sensitivity analysis would be useful for determining the most impactful parameters in each route-specific equation, we do not believe it would offer much insight into the relative contributions among the different routes, as discussed in this section of text.

Comment: Section 5.4: Another possible modeling estimates is the daily exposure for a person who plays on turf for 2 hours a day and add this to the residential/background exposures (exposures that occur for the other 22 hours of daily life).

Response: We agree that adding the contributions from using turf to the contribution from background exposures would make sense for a comprehensive risk assessment, our reasons for estimating residential/background exposures were to provide perspective for the magnitude of the turf-related exposures.

Comment: Section 5.4: Is the intent of this section to show that exposures on synthetic turf field may not be of concern giving residential exposures for some compounds being much higher. I think authors need to make this statement more explicit.

Response: The intent was merely to provide context and perspective. As such, the following sentences were added to Section 5.1.4 of the Part 2 Report: "Estimates of exposures to chemicals from tire crumb rubber on synthetic turf fields among athletes and bystanders can be put into the context of exposure to these same chemical substances in typical residential settings, including the

contribution from dietary sources. The purpose of this comparative analysis was to present 'background' concentrations encountered in residences and the resulting daily intake estimates provide some perspective on the magnitude of the estimated daily dose for synthetic turf field users."

Comment: This chapter is really exposure and dose modeling (since in the end you produce daily doses from the three routes of exposure).

Response: We agree, but have chosen to call it simply "exposure" modeling to avoid any implication that pharmacokinetic modeling was performed.

4.7.2 Reviewer 2

Comment: The exposure Pathway Modeling is out of my expertise field. Nevertheless, I would like to include some comments:

Prolonged/chronic exposure should be considered or at least, a comment should be added.

Response: Both "average daily dose" (averaged over a year using assumed frequency of exposure events) and "daily dose" are presented in Tables 5-13 and 5-14 of the Part 2 Report. "Average daily dose" represents prolonged exposure, whereas "daily dose" represents the exposure on the day of use. We feel it is outside the scope of this exercise to estimate lifetime exposures.

Comment: Only six chemicals were considered and in some cases data was missing.

Response: While the six chemical substances are only a very small subset of the large number of substances found in tire crumb rubber, they represent the substances most commonly measured and studied in literature on tire crumb and provide a range of physical and chemical properties.

Comment: The recoveries in field dust were quite low, so exposure could be underestimated.

Response: Yes. This adds additional uncertainty to the highly uncertain estimates, and we stress the uncertainty in both the dermal absorption and incidental ingestion estimates in Section 5.0 of the Part 2 Report.

Comment: Regarding dermal contact, we should remember that in many cases the chemicals will be in contact with the skin for hours since 50 % of the players do not take a shower after playing.

Response: While this is definitely true, the use of absorption fraction, instead of absorption rate, in the screening-level algorithms avoids the use of a time component.

Comment: In dermal studies, perhaps the size of the wipe is not suitable to rub the skin surface. In addition, a second wipe should have been used to show if the chemicals were efficiently removed from the skin. Moreover, the wipe recoveries based on spiked samples might not well represent the real recoveries from the wipe samples, and dermal exposure might be underestimated.

Response: We disagree that the size of the wipe is unsuitable for the measurements. While the observation about removal efficiency may be true, we think that using measured dermal loadings (even if not entirely accurate) still greatly reduces the uncertainty compared to estimates that use highly uncertain soil adherence values together with concentrations measured in large tire crumb granules.

Comment: The data taken from literature to evaluate different scenarios especially residential are very limited and the values used for each chemical substance and matrix (e.g. dust) are based on only a single study (see table 5-13).

Response: The uncertainty in the data is stressed throughout this section. We have edited the text in Section 5.1.4 of the Part 2 Report to state the following: “This analysis of residential and dietary exposure has several limitations, principally due to the availability of only sparse data, often from studies conducted decades ago.”

Comment: As the authors of the report establish “The process of modeling through the use of algorithms that rely on exposure factor parameters required some large assumptions”. Taking in to account that only 6 substances were evaluated and other kind of limitations commented by the authors, the uncertainty does not allow to establish any clear conclusion; therefore, the precautionary principle should be considered or, at least mentioned.

Response: The uncertainties are described throughout the text and in editing the text, we sought to make sure that we did not give the impression of having clear conclusions. Moreover, in the conclusion section (Section 5.5 of the Part 2 Report), we stress the challenge of cumulative exposure

assessment: “Finally, a large number of inorganic and organic chemical substances have been found to be associated with tire crumb rubber. These chemicals have a large range of chemical and physical properties that affect how they are released from the tire crumb rubber material and absorbed in the body. It remains a challenge to accurately estimate inhalation, dermal, and ingestion exposures across this large range of chemicals, and even more of a challenge to estimate potential risks on a cumulative exposure basis.”

4.7.3 Reviewer 3

Comment: A conceptual schematic would be helpful.

Response: Figure 5-1, “Process for generating pathway-specific exposure estimates using both existing data (on left) and new data from this exposure pilot study (on right)” and Figure 5-2, “Diagram of exposure pathway modeling, showing possible media for each route-specific exposure estimate” have been added to the Part 2 Report.

Comment: *Specific*:
8370: Data extraction was limited to air, dust, tire crumb or crumb rubber, field surface residue, and bioaccessibility measurements were considered relevant. Results of leachate studies were excluded even though one could argue that all leachable components are ultimately bioavailable.

Response: We believe that the leachate studies are more relevant to ecological assessments than to human exposure during use of fields.

Comment: 8370: The reason leachate studies were excluded was not given.

Response: Leachate studies are more relevant to ecological studies and do not contribute to this study and the routes of exposure that were investigated. Bioaccessibility measurements (quantified in the tire crumb characterization study) are more pertinent to the scope of this study. The words “(deemed more relevant for ecological studies)” were added to line in Section 5.1.2 of the Part 2 Report as an explanation.

Comment: 8614: The bioavailability of the PAHs that were ingested should be specified.

Response: Text was corrected to remove the word “bioavailability,” as bioavailability was not measured. Bioaccessibility was only measured for metals.

Comment: 8624: Specify the uncertainties of refer to the section where they are indicated.

Response: Text was added to Section 5.1.2 of the Part 2 Report listing assumptions that lead to increased uncertainty related to adherence of tire crumb to skin, dermal absorption estimates in the absence of bioaccessibility data, lack of consideration of dermal abrasions, and unknown ingestions rates.

Comment: 8744 Figure 5-14 - 16: Specify units, mg/kg-day?

Response: Units added to all figures.

Comment: 8795: I wonder whether an upper limit based on worst case scenarios can be given for many chemicals.

Response: Due to the vast range in physicochemical properties and limited information on concentration, we do not believe it would be feasible (or meaningful) to try to estimate upper limits based on worst case scenarios.

Comment: 8830-8834: What is the recommendation on how to solve this problem?

Response: The following statement now follows in Section 5.5 of the Part 2 Report: "Studies that investigate biomarker identification of chemical substances found in tire crumb rubber can contribute to exposure modeling for a more robust exposure profile."

4.7.4 Reviewer 4

Comment: p. 335. Introductory paragraph is unduly nihilist. The rest of the report demonstrates that considerable data exist and that what is missing probably can be reasonably estimated with confidence. The dermal and ingestion pathways do not require highly accurate estimation, as the values are low and now known for surrogates.

Response: The text of the introductory paragraph was edited to stress that current lack of data (and resulting over-reliance on default values) is the motivation for the pilot exposure study.

Comment: Most significant message of chapter for this reader is that ingestion is a more significant route of exposure than expected.

Response: Section 5.3 of the Part 2 Report, "Comparison of Synthetic Turf Field User Exposure Estimates Using Extant Data and Exposure Pilot Study Data" has been edited to more clearly state that incidental ingestion is more significant for SVOCs in the study and dermal absorption is more important for metals in the study.

4.7.5 Reviewer 5

Comment: The Expose Pathway Modeling Chapter presents information on modeled exposures in a matter analogous to many other exposure pathway modeling approaches. I see no innovation in the way the modeling was done nor in the way it was presented. However, one is not especially interested in innovation in this analysis but rather in what the results are and how they might be compared to other results in turf-related exposure or more general exposures to these classes of compounds. The presentations are clear and adequate for the purposes of this presentation. I do not think it is in the purview of this presentation to offer new and novel presentation of the results in this work. The author have [sic] succeeding in presenting the modeling input parameters- most are from the Exposure Factors Handbook or similar documents- and are the best available.

Response: We thank the reviewer for the kind words.

Comment: It is of note that the authors themselves note (See Lines 8524ff and Conclusions) that the quality of the input data for many of the parameters of interest, most notably dermal absorption and inhalation absorption, are not well known. This limits the quality of the resulting models and forces a "Scenario" approach to the exposure estimation whereby several of the parameters are "assumed" as a simple deterministic value. Sensitivity analysis, or a full Monte Carlo approach would be a superior methods [sic] for such estimation, but even such approaches are not likely to improve the estimations but rather results in a "spread" of the expected values due to model uncertainty and parameter uncertainty. Further, such was not the intent, as this reviewer sees it, of this section. But rather, this section was meant to give an idea, based on the pilot level data collected, on what the exposure might be. Until such time as a better understanding of dermal and lung epithelial penetration is at hand, models of this type will be limited and subject to substantial uncertainty.

Response: We agree that such a simple deterministic modeling approach is far from ideal, but is necessitated by the lack of sufficient data to estimate true variability in many of the parameters. We agree that, due to model uncertainty and parameter uncertainty, a full Monte Carlo approach

would only provide more information on the "spread" of the expected values, but believe that such information would be of limited utility due to a lack of information on the true variability in the model parameters.

4.7.6 Reviewer 6

Comment: The Exposure Pathway Modeling uses a simplistic approach to predict exposure levels, which is appropriate since there are limited data to describe the activity patterns and potential exposures levels for users of these fields. This overall project has greatly advanced the quality of the inputs for the modeling effort to predict and bound some of the exposures and to inform decision-making. The authors do indicate though that there still are limitations. The comparison between the synthetic turf field and background exposures is important in order to place the exposures within perspective.

Response: We thank the reviewer for the kind words.

Comment: I suggest that a sensitivity analysis be conducted where possible across the model inputs to identify which input has the largest effect on the exposure and risk estimates. Such an analysis might guide any future efforts to improve the exposure modeling.

Response: We tried a simple sensitivity analysis but found that it was not very helpful due to chemical-specific differences in the contributions from the different exposure routes.

4.7.7 Reviewer 7

Comment: In this reviewer's opinion, the Exposure Pathway Modeling presented in Chapter 5 and associated appendices, constitutes the least well-developed component of the work presented in this report (probably reflecting insufficient time available for a more comprehensive modeling analysis to be completed in this phase).

Response: The section has been reorganized and heavily edited to increase clarity. Unfortunately, we believe that even with the addition of data from this small pilot exposure study, the data are not adequate to support more comprehensive exposure modeling analysis, as described in the Conclusions section.

Comment: The list of Acronyms and Abbreviations includes SHEDS, the Stochastic human exposure and dose simulation model (page xxx, line 1044), so it was disappointing not to see this model used in this

work (or even mentioned anywhere in the report), or in general a probabilistic/distributional calculation method applied to at least a subset of the scenarios considered in the study.

Response: The original intention was to use SHEDS-Multimedia modeling, but insufficient data were located and generated. The list of Acronyms and Abbreviations has been corrected to remove SHEDS.

Comment: The calculation of point estimates of exposure and dose for exposure pathways is indeed a useful exercise that provides valuable perspective on the relative importance of exposures occurring at the synthetic turf fields versus those occurring in other settings (e.g. residential) and via alternative pathways (e.g. dietary ingestion); however, the quantitative interpretation of results from such point estimates is limited. So, though, clearly, for many of the chemicals considered the dietary pathway would be dominant, the dose metrics calculated using point estimates of exposure parameters and inputs are not generalizable. The parameters and inputs employed (e.g. those listed in Table 5-12, page 354 and Table 5-13, page 355) with "mean" estimates used, cannot be claimed to represent, especially in combination, any "average" or "representative" real-world situation: both the uncertainty and the variability in most of these parameters are so high that necessitate a systematic probabilistic/distributional simulation (ideally using 2-D Monte Carlo, to explicitly distinguish known variabilities from uncertainties). As an example, the EPA EFH (Exposure Factor Handbook) dietary consumption estimates do not include foodstuffs that may be significant part of the diet of children and young adults; as another example, consumption of dietary supplements needs to be considered in exposure studies involving athletes, etc. It should be recognized, of course, that a statement on the need for probabilistic exposure modeling vis-a-vis critical constraints in time and resources, constitutes more of a statement of principle rather than a recommendation, or even a criticism, for the present study. Nevertheless, it would be useful if the report included a discussion recognizing the need for future studies to include systematic probabilistic analyses aiming to characterize both mean tendencies and tails of the exposure and dose distributions.

Response: While we would welcome probabilistic analysis, we believe that available data (including data produced in this exposure pilot study) are insufficient. The first bullet in Section 5.5 of the Part 2 Report states, "The data are not adequate to support probabilistic exposure modeling approaches. For many chemicals found to be associated with tire crumb rubber infill on synthetic turf fields, there is a lack of robust data for many exposure media, including air (particularly in athlete

breathing zones), field surfaces and field dust, and dermal residue loadings." We hope that this analysis can guide future data collection. In the Conclusions section we identify several parameters for which better data would be required to perform a probabilistic analysis, such as: distribution of tire crumb rubber particle size fractions in breathing zones under different athletic activity conditions; ingestion rates during athletic activities; skin adherence for both dry and wet skin; dermal adsorption rates for organic chemicals associated with tire crumb rubber; and respiratory and gastrointestinal absorption rates for the same chemicals.

4.8 Charge Question 8: The Toxicity Reference Information is summarized and presented in Chapter 6 along with Appendix W. Does this chapter present a clear and accurate characterization of the available toxicological information?

4.8.1 Reviewer 1

Comment: This chapter does make a clear and accurate characterization of available toxicological information.

Authors could explore for the 6 chemicals where calculations were made on the exposure estimates (daily dose) whether with the toxicological information estimates could be made on non-cancer and cancer risks. See the following article on calculating cancer and non-cancer risks assessments.

Int J Environ Res Public Health. 2018 Jan 4;15(1). pii: E67. doi: 10.3390/ijerph15010067. Risk Assessment for Children Exposed to Arsenic on Baseball Fields with Contaminated Fill Material. Ferguson AC[1], Black JC[2], Sims IB[3], Welday JN[4], Elmir SM[5], Goff KF[6], Higginbotham JM[7], Solo-Gabriele HM[8].

Response: Cancer and non-cancer risk assessments are outside the scope of this study. The information and results provided in the report can inform future exposure and risk assessments.

4.8.2 Reviewer 2

Comment: Yes, I think the information provided is quite complete.

Response: We acknowledge the reviewer's comment.

4.8.3 Reviewer 3

Comment: *General*:

The availability of existing data is explained. It seems to me that it should be possible to draw pretty firm conclusions regarding risks with the available information. The next step of the risk assessment process should be outlined, which would be, presumably, enhanced cancer risk?

Response: Cancer and non-cancer risk assessments are outside the scope of this study. The information and results provided in the report can inform future exposure and risk assessments.

Comment: *Specific*:

8925: On 167 of the 355 constituents that were examined, toxicology data were available. This indicates that a significant fraction of the components have been toxicologically evaluated, probably in the context of applications other than rubber tire. Developing toxicological data on the remaining 188 appears unfeasible and calls for alternative toxicological approaches (other than a compound-by-compound testing). The toxicological significance of the 167 constituents should be commented on.

Response: The toxicological information available on the 167 compounds varies widely and is discussed briefly.

Comment: In 6.3 Results (Lin 8881-8886), a reference is made to a database (Excel spreadsheet) that is available online. The link to this database should be given here.

Response: The link to the database has been added.

Comment: Table 6-2 (Line 8884) lists different toxicological databases and not 32 specific constituents referred to on Line 8930. I think, the correct table is Table 6-3.

Response: Yes. This should have been Table 6-3, which is now split into two tables in the Part 1 Report – Table 5-3 and Table 5-4. The table reference has been corrected.

4.8.4 Reviewer 4

Comment: These are standard references. Nothing obscure or requiring explanation.

Response: We acknowledge the reviewer's comment.

4.8.5 Reviewer 5

Comment: I begin this portion of my review by noting that my expertise lies well removed from toxicology. Nevertheless, I can comment on the reference material presented in Chapter 6. The standard refences used in toxicological analysis for exposure science are called here, these include IRIS, CalEPA, OSHA, ATSDR, IARC, and others. The Chapter is relatively brief consisting primarily of a table presenting the databases used in developing toxicological insight for this work. Perhaps the most useful part of this Chapter is Table 6-3, which offers a compendium of toxicological information on compounds if interest in tire crumb exposure. It is far from comprehensive with regard to the compounds presented; there are hundreds of compounds emitted by tire crumb fields, and toxicological data on only a small fraction are presented. However, these data represent those compounds for which the data exist. The presentation is silent on the need for more data, but this is certainly a crying need. Perhaps the best way to present that is as has been doing, i.e., show how many compounds are emitted and how few of which have quality toxicological data available.

> **Response:** We direct the reviewer to Appendix U of the Part 1 Report and/or to the online spreadsheet for a summary of available toxicological data, including gaps.

Comment: The data are presented in a clear and readily accessible fashion. Table 6-3 is a useful tool for anyone contemplating studies of tire crumb in that the main components, including metals, SVOCs, and VOCs are presented and referenced. One cannot present what does not exist.

> **Response:** We acknowledge the reviewer's comment.

4.8.6 Reviewer 6

Comment: Chapter 6 and appendix W provide information on the toxicity of the compounds and metals identified in the crumb rubber along with a database summarizing the outcomes and endpoints. It is readable and clear, though I am not qualified to judge its completeness. See my comment in response to charge question 1 about including a discussion of toxicity testing of "bulk" material. That recommendation needs to be included in this section with advice on how to select the materials to be tested.

Response: A related study from the National Institutes of Environmental Health Sciences, National Toxicology Program is exploring bulk toxicity testing. A reference to this study has been added in the Part 1 Report.

4.8.7 Reviewer 7

Comment: The Toxicity Reference information summarized and presented in Chapter 6 and Appendix W [now Appendix U] appears to be utilizing exclusively the eleven sources listed on tables 6-1 and 6-2 (pages 363-364 and 365, respectively) and not considering various ongoing efforts for toxicity characterization, including current endocrine disruptor listings. This approach, i.e. limiting the sources to databases and documents reflecting the assessments of state, federal and international agencies and organizations, may be a justifiable choice from various perspectives, but at the same time it may be missing new and evolving information that is currently being collected and/or analyzed. Recognizing the well-known tenet that "absence of evidence does not constitute evidence of absence," it may be useful to expand accordingly the range of information used for toxicity characterization. A starting point can be USEPA's "Chemistry Dashboard," accessible at URL https://comptox.epa.gov/dashboard provides a comprehensive overview of available information (with corresponding information sources) for over 750,000 chemicals, that includes multiple categories and attributes of toxicity information (the DSSTOX database). In fact, DSSTOX is mentioned on page 218 and the dashboard has been used, and is referenced in the report under review on pages 201 and 219, to retrieve chemical properties presented in Table 3-105 (page 201) but it does not appear to have been used for toxicity information. Nevertheless, the "consolidated spreadsheet" format used in Table 6-3 for the 31 "selected" chemicals of concern (the selection of which deserves some further explanation accompany Table 6-3), provides a useful/convenient way of comparing the information available from the eleven agencies and organizations; it is not clear, however, if that the same format will be used for the data to become available through the yet unspecified URL referenced on page 365 (line 881) and on page 371 (line 8892) for all the chemicals of Appendix W.

Response: It would take considerable effort to compile other toxicological information; such efforts could be undertaken by others in the future. Text has been added about the selection of chemicals for Table 6-3 (now Tables 5-3 and 5-4 in the Part 1 Report) and the URL to the online spreadsheet has been added.

4.9 Charge Question 9: Appendix E summarizes the approach to and results of the study's Quality Assurance and Control. Please comment on the overall approach for presenting this information. How adequately do the QA/QC approaches ensure the quality of the results of this research?

4.9.1 Reviewer 1

Comment: The appropriate number of controls were tested, precision of equipment was addressed, and limits of quantification determined. In addition, it appears that equipment was properly cleaned and calibrated. It is good to see that appropriate decisions were made to exclude findings when great uncertainty was found (e.g., high recoveries for 2-hydroxybenzothiazole). It was also good to see different measurement technique used (GS/MS vs. LC/MS)

Response: We acknowledge the reviewer's comments.

Comment: Some minor violations were found (page 122). Right after there should be a comment about whether these minor violations affected the quality of data.

Response: Text was added to Appendix E (Section E.2.3) of the Part 1 Report, to include details on whether the minor violations affected the quality of the data, and to state that the overall quality and conclusions of the study were not adversely impacted.

Comment: Page 140: There is such variability with the chamber background methods. This produced great uncertainly and resulted in negative numbers (which makes no sense) for emission concentrations at 25 and 60 degrees C. Additional work is needed to control these chamber experiments, clean out chambers, and come to great consistency in background measures.

This was mentioned previously. Page 183: "To maintain high intra- and inter-person accuracy of coding the videotapes, the two technicians translated two additional participants' videotapes -- after completing 50% and 95% of the total videotapes (n = 17)." This retraining could have been completed when both translator [sic] had completed 50% of videotapes.

Response: As stated in the text, the intra and inter-observer reliability of the two technicians translating the video files was retested after 50% of the participant video files were completed (and repeated after 95% of the video files were completed).

4.9.2 Reviewer 2

Comment: General comments

The amount of data is very high. In some cases the use of bar diagrams might help to show some results.

> **Response:** We developed summary bar graphs for metals, many PAHs, and other analytes in tire crumb rubber characterization measurements and included these in Section 2 of the Part 1 report. For the exposure characterization, we developed example bar graphs for air measurements and box plots for dermal measurements in the Part 2 report.

Comment: Although quantitation limits are defined, I cannot clearly see how they were calculated in each case.

> **Response:** Due to the number of different analytical methods applied and the additional length that would be needed to present all reporting limit derivations, we elected to not include these.

Comment: Why are MRL given in m/v (µg/L)? (e.g. Table E-8). Since crumb rubber is a solid matrix, is [sic] should be expressed as µg/g or ng/g.

> **Response:** We converted reporting limit values to units as presented for sample measurements and these are included in Part 1 Appendix E.

Comment: For recovery studies in crumb rubber the amount of sample and the amount and concentration of spiking solution should be indicated (spiking procedure). The number of spiked samples should also be indicated.

> **Response:** Numbers of spiked samples and amounts spiked have been added to table footnotes in the Part 1 report Appendix E.

Comment: Page 118. E.3. 1 Since there are no standard methods for the analysis, the comparison with other methods and powerful extraction techniques might help determine if the procedure is truly efficient in totally extracting the chemicals from tire crumb rubber. In my opinion, vortex extraction for 1-2 min may be insufficient to recover the entire target VOC and SVOC present in the samples.

> **Response:** We have added the following paragraph in Section 3.1.6.7 (now Section 3.6.7.1 of the Part 1 Report) to better explain the reasoning behind the method and to acknowledge that the

method is not likely to completely extract SVOCs from the tire crumb rubber particles: "The solvent extraction method used in this study is not likely to completely extract all of the target chemicals contained in the crumb rubber particles. While this method is not a total extraction method, it is likely relevant with regard to the potential for human exposure. When combined with ceramic homogenizers, the vortex extraction method was fairly aggressive and very efficient in terms of throughput, which was very important given our tight timeline for completing the laboratory work. Prior to using this method, multiple sequential extractions were evaluated using this technique and it was determined that the majority of extractable organics were removed in the first extraction cycle. This method was also evaluated for linearity across tire crumb mass as well as precision of replicates and was found to perform well across the range of semivolatile organics we were measuring. This method has an advantage compared to more aggressive extraction techniques in that it minimizes the potential for analyte losses due to no heating, solvent evaporation, or extensive sample handling. The use of solvents or methods that would approach total SVOC extraction would result in residues that would rapidly impair analytical systems and likely require more extensive time and effort in sample clean-up and result in greater potential for analyte losses. (It is also important to note that the results of this study are in general agreement with extractable SVOC measurement results from several other studies [shown in tables in Part1 Section 2] that used different extraction methods)."

Comment: Table E-25. Since the results are expressed in ng/g, I think the MQL ranges refer to the tire crumb and not to the tire crumb extracts. Please correct if necessary.

Response: We converted reporting limit values to units as presented for sample measurements and these are included in Part 1 Appendix E.

Comment: In the emission test (chamber tests) and air sample analysis, the blanks and background levels suggest that the setup of the experiments should be revised for future studies. In addition, in real air sample analysis, larger sample volumes should be used (higher flows and times).

Response: The results of this study can inform future emission testing and field air sampling procedures. We agree that, ideally, larger air sample volumes would be collected during field air SVOC measurements to improve detection of more compounds of interest. However, there were practical reasons for the methods that were applied in the exposure pilot study. We explain these

reasons in Section 3.3.1.1 of the Part 2 report: “A medium-volume sample collection rate (20 L/min) was selected, instead of a high-volume collection rate, due to the need for portability (i.e., the ability to be deployed around the country), the need to minimize the footprint of equipment next to fields with sports activities, the limited time available for setting up and taking down equipment, and the uncertainty surrounding the availability of electrical power needed for high-volume sampling. Calculations made from previously reported field measurements suggested that approximately 3- to 5-m3 samples would provide adequate detection limits for important tire crumb constituents, such as pyrene and benzothiazole.”

Regarding the challenges in personal air sampling, we included this paragraph in Section 2.2.2 of the Part 2 report: “Collecting personal air samples for research participants engaged in active athletic activities is challenging. The concentration of analytes of interest are generally low, the activity durations are short, and player safety must be a priority in collecting samples, particularly for children. In this study, a small, passive VOC air sampler with high effective sampling rates was attached to the upper backs of a practice jersey worn by each study participants during their usual athletic practice sessions on synthetic turf fields. When collecting air samples from the football players, one sampler was destroyed and another damaged during vigorous tackling activities; all other samples were successfully collected. The samplers did not perform as desired, however, with inconsistent effective sampling rates measured in testing based on both laboratory chamber and field conditions, and low recoveries of the two highest concentration analytes, benzothiazole and methyl isobutyl ketone. Additional research would be required to determine if any personal air sampling devices can be successfully used in research studies with youth participants. It may be necessary to limit personal air sampling to adult volunteers willing to wear more bulky samplers with pumps and certain types of activities.”

Comment: The QA/QC approaches are in general suitable. Nevertheless, the high blank and background levels in some cases made it impossible to get quantitative results (e.g. chamber emission samples).

Response: We agree that for several target analytes relatively high chamber background levels in emissions testing and in the pilot exposure study field measurements made it impossible to obtain accurate measurements. This partly reflects the challenge of methods aimed at including large numbers of analytes and the time and effort needed to assess all materials and methods and take steps to reduce background levels of all analytes.

Comment: In addition, and as is mentioned in the appendix, the time limitations and the difficulty to collect air and dust samples makes caution necessary when considering the exposure section conclusions.

Response: While there are some limitations for the field air and dust sampling and analysis, overall the methods were successful for providing quantitative measurement results for many of the target analytes of interest associated with tire crumb rubber.

Comment: In addition, the field and lab recoveries (see Table E-59) in dust are very low (below 50 % for most SVOCs). Why was benzo(a)pyrene, one of the two selected PAHs for exposure modeling, not included in the Table?

Response: Field dust lab and field control results for four target analytes were inadvertently left out of the table (now Table B-25 in the Part 2 report). The results have been added. The recovery of benzo(a)pyrene from the field dust surrogate material was 38.1 ± 4.3%. The report text discusses these relatively low results; it is not clear whether recoveries are actually low or whether the surrogate matrix was not successfully spiked with target analytes. For example, benzo(a)pyrene recoveries in the SVOC air and field surface wipe samples ranged from 72 to 85%.

4.9.3 Reviewer 3

Comment: The QA/QC approach followed EPA guidelines. The analytical data appear to be of high quality without exception.

Response: We acknowledge the reviewer's comment.

4.9.4 Reviewer 4

Comment: This reviewer defers to his lab colleagues but a cursory scan seemed complete and acceptable.

Response: We acknowledge the reviewer's comment.

4.9.5 Reviewer 5

Comment: I am moderately concerned about the order of presentation. The quality assurance program is extensive and excellent in this study. This is especially noteworthy with respect to the number of

individual groups that were involved. However, under Section E.2.3 Technical Systems Audits, one of the main discussion points focuses on the shortcomings notes. There were nine Technical Systems Audits (TSAs) performed. To be honest about it, when a TSA is done, those performing the Audit have to find something in order to justify their existence. While it is clearly stated that none of the findings have a significant effect on the data, the presentation of bullet point with led of "Incomplete", "Insufficient", "…not managed properly" give the impression that the data quality may be suspect. If one were reading this quickly, the bullets would be what stands out, not the text before it. While I certainly appreciate the honesty and commend the humility of the authors, I think this emphasis, so early in the discussion of Quality Assurance, gives one pause. The authors may wish to supply a more realistic evaluation of the effectiveness of the Quality Assurance program, perhaps emphasizing that there were nine TSAs that only showed a few minor shortcomings- all studies have them- but also displayed the strengths of the QA program. Be assured: I do not advocate soft-pedalling problems, but, in this case in particular, there is no need to be the least bit apologetic about the quality of the data turned out. The QA program was strong, well-implemented, and thorough. This is the story that should come out, not one that suggests there was something amiss with the studies quality assurance and control. The strong Quality Assurance of this program should give the reader confidence in the result of the study. I think even this relatively benign set of bullets on shortcomings is problematic. I would think it less so if it were to be placed in a less prominent location.

Response: Language was added to Appendix E (Section E.2.3) of the Part 1 Report to address the requirements and effectiveness of the Quality Assurance program.

4.9.6 Reviewer 6

Comment: The extensive QA/AC presented in Appendix E indicates that the appropriate approaches and methodologies have been used to ensure the quality of the results of the research. It is presented in fashion that enabled me to judge that the data were of high quality.

Response: We acknowledge the reviewer's comment.

4.9.7 Reviewer 7

Comment: The Quality Assurance and Quality Control narrative is quite detailed, but, in this reviewer's opinion, it would greatly benefit from some graphical schematics (in the form of flowcharts and

diagrams) that would provide to the reader visual summaries and overviews of the procedures followed in the study.

Response: Although graphical schematics that summarize the procedures in the study are not included in Appendix E, the appendix does include enough detail to describe what quality plans and reviews were conducted, the outcomes and quality control that was addressed are described throughout.

4.10 Charge Question 10: Is the overall report logical, clear and concise? Have the authors clearly presented, synthesized, and summarized the results of the study in a clear manner easily understood by interested stakeholders? Please explain.

4.10.1 Reviewer 1

Comment: The study report is well-written with very few grammatical errors. It is clear and concise and is one the better reports I have seen, although Chapter 5 on exposure modeling is rushed and requires more detailed explanations of the data used and why. Although at first my opinion was that sections of the report are repetitive in describing study design and methods (i.e., at the beginning of each chapter), I have since changed that opinion. Occasionally researchers will print only a chapter of a report to obtain information they immediately need to reference. Have a quick description in each chapter is then advisable. There are chapters however where, methods, and then results are presented, that could be organized more concisely to avoid repetition of methods and procedure in the results sections again (chapter 3 and chapter 4). So the results then repeats many details. If methods, analysis, results for a sample type were reported together this would cut down repetition.

Response: The report has been released in smaller portions, which may improve readability. With regard to Section 5.0, substantial editing has been performed, with more graphical presentation of the approach, along with updated tables and results discussion.

Comment: The report, I believe is reasonable to understand by most, where interested stakeholders would have some science and health background. Some chemical-physical mechanisms (i.e., evaporation, deposition, chemical reactions) may not be automatically understood by the average layperson. Chapter 5 on exposure modeling needs a few examples calculations for especially the dermal route of exposure to clarify residue transfer versus soil transfer (use of dust loading vs. residue loading from the wipes).

Response: Equation 5-5 was added to Section 5.1.3 of the Part 2 report to show how residue loading from the wipes was used instead of soil adherence.

Comment: There are some tables that should be moved to the appendices and summarized in this report as mentioned before. Consider what other tables are two long and contain repetitive data for each chemical that can be combined in some way.

In general tables are well laid out and well labeled.

Response: Given the very large sets of measurement results generated in this study, we tried to find a good balance for the highlighted and select results included in the body of the report, while including complete results in the appendices. Although some of the tables in the report body are dense, we think we have the right balance: Section 2.0 contains high-level summary information suitable for most readers; Section 4.0 contains an array of results for select chemicals and data analyses with more detail and discussion to highlight the results for readers looking for more details, and the appendices contain very long tables that include all results.

Comment: There should be some warning to readers to print the report in color. I would normally suggest that tables use shading to accommodate those who cannot print in color, but there are other graphs that are not conducive to black and white.

Response: We thank the reviewer for the suggestion.

Comment: Occasionally or for all the tables, authors can bold numbers that were discussed or of interest. In large tables with lots of numbers, this can bring the reader to immediately notice large or low concentrations or exposure values of interest.

Response: We appreciate this recommendation. We have attempted to address this by highlighting select results in the body of the report, particularly in our selection of graphical illustrations, while placing the complete data results in appendices. We have also elected to highlight results of interest in the short text descriptions associated with the tables and figures. Because there are many results that may be of interest to different readers, we have not attempted to highlight particular results through the use of bold type in the tables.

4.10.2 Reviewer 2

Comment: Due to the amount of studies/information presented, it is quite difficult to be concise and to explain everything in a clear manner. But due to the difficulty and complexity of the study, in general terms I think the information is clearly presented.

Response: We acknowledge the reviewer's comment.

4.10.3 Reviewer 3

Comment: I think data could be integrated to a greater extent by using more schematics. What decision will be made based on the report? It remains unclear, how data generation is related to the decision process. What is the take home message of the study? The authors seem to withhold their professional judgment.

Response: We have added call out boxes in Parts 1 and 2 that highlight the key messages from each portion of the study. The purpose of the study is to fill in key data gaps.

4.10.4 Reviewer 4

Comment: Overall, yes, but there were some awkward passages as noted above. However, because it is very long and detailed, presentation is overwhelming to most readers. Suggest a simplified version to be prepared as Volume 3, written by non-experts but reviewed, to make material more accessible to lay persons and community groups.

Response: We acknowledge the reviewer's suggestion and are considering a final summative volume once the study is complete.

4.10.5 Reviewer 5

Comment: I think the authors have done a good job of organizing the material in a logical and complete manner. The flow of the document is good and is quite complete.

Response: We acknowledge the reviewer's comment.

Comment: I have mentioned concerns about the Executive Summary. I understand the need to compromise on that given the diversity of the likely stakeholders for this work. Many of the stakeholders are likely to be technical people with specific interests and knowledge. The Sections after the Executive Summary should serve their needs. On the other hand, a significant fraction of the readers are likely to be non-technical people- policy makers, local and state government officials, lay people, etc., who may find the later Sections tough sledding. The Executive Summary is designed for their reading. But this may be problematic for those with a more technical bent, as I outlined above. But I believe that the necessary compromise has come down too far on the side of the non-technical stakeholder. Those wishing to know more may feel that the Executive Summary does not give them what they need and, therefore, reduce their confidence in the Report as a whole.

Response: Given that most stakeholders will only read the Executive Summary and/or Volume 1 of both the Part 1 and 2 Reports, the authors have elected to ensure it is accessible to as broad an audience as possible. We are considering a final summative volume once the study is complete.

4.10.6 Reviewer 6

Comment: Overall the authors have organized the report in a logical and clear fashion. There is some repetitiveness, but due to the extent and importance of the data collected that is acceptable. The results are presented and summarized in an understandable fashion for a range of stakeholders.

Response: We acknowledge the reviewer's comment.

4.10.7 Reviewer 7

Comment: The answer to the first question is that the report is in general logical and clear, though some of its Chapters cannot be described as concise. Nevertheless, in this reviewer's opinion, for a scientific/technical report, it is preferable to be thorough and detailed, even at the expense of brevity. In fact, Chapters 1 and 2 manage to convey the essence of the study design and findings, while being sufficiently concise.

The answer to the second part of this question depends, of course, on the precise definition of "interested stakeholders" (i.e. whether stakeholders include the general public). The report, thanks to the level of detail it provides, will be easily understood by scientists and regulators, even if they are not directly familiar with many specific aspects of the problem at hand and with the methods used in the studies conducted. So, for agencies, the report provides a valuable resource of data and factual

information that can be used by agency staff in the development of material that would focus on informing the public.

Overall, the authors of this report, and everyone who contributed to the work described in it, should be commended for accomplishing an almost-Herculean task, given the complexities of the problem studied.

Response: We thank the reviewer for their comments.

4.11 Charge Question 11: Are there relevant literature or data sources that are not included in this report but should be added? Are there any gaps of available information that should also be considered?

4.11.1 Reviewer 1

Comment: Please see Question 6 for adding relevant papers on videotaping and video-translation methods. See Question 1 for paper on naphthalene. See Question 2 on papers on microbes. See question 8 for paper on risk assessment. See Consider adding more papers on multiple chemical exposures and the limitations. This is a paper of a part of a series that might be of interest.

Environ Toxicol Chem. 2018 May;37(5):1235-1251. doi: 10.1002/etc.4091. A chemical activity approach to exposure and risk assessment of chemicals: Focus articles are part of a regular series intended to sharpen understanding of current and emerging topics of interest to the scientific community. Gobas FAPC[1], Mayer P[2], Parkerton TF[3], Burgess RM[4], van de Meent D[5], Gouin T[6].

Response: Thank you. Additional references for relevant sections were added as appropriate. In particular, we added additional descriptions and references of more recent work as a preface to the literature review/gaps analysis white paper included as Appendix C in the Part 1 report.

4.11.2 Reviewer 2

Comment: Regarding chapter 1 background, I think Watterson's article as well as EU restriction and EU proposal intention on PAHs should be commented (see charge question 1).

Response: This report is not intended to inform any specific policy objective.

4.11.3 Reviewer 3

Comment: Leachate and ecotoxicological information was excluded without explanation although such information could be helpful.

Response: Leachate and ecotoxicological information is outside the scope for this study.

4.11.4 Reviewer 4

Comment: Not that this reviewer is aware of.

Response: We acknowledge the reviewer's comment.

4.11.5 Reviewer 5

Comment: I noted no gaps. The literature review covers all available information for which I am aware. It is well-referenced and contains sufficient information to exist as a stand-alone document.

Response: We acknowledge the reviewer's comment.

4.11.6 Reviewer 6

Comment: I do not know of additional relevant literature or data sources that should be added. The authors highlighted the data gaps that still exist.

Response: We acknowledge the reviewer's comment.

4.11.7 Reviewer 7

Comment: The following literature sources provide additional useful information:

- Benoit, G., & Demars, S. (2018). Evaluation of Organic and Inorganic Compounds Extractable by Multiple Methods from Commercially Available Crumb Rubber Mulch. Water, Air, & Soil Pollution, 229(3), 64.
- Bleyer, A. (2017). Synthetic Turf Fields, Crumb Rubber, and Alleged Cancer Risk. Sports Medicine, 47(12), 2437-2441.
- Bleyer, A., & Keegan, T. (2018). Incidence of malignant lymphoma in adolescents and young adults in the 58 counties of California with varying synthetic turf field density. Cancer epidemiology, 53, 129-136.
- Canepari, S., Castellano, P., Astolfi, M. L., Materazzi, S., Ferrante, R., Fiorini, D., & Curini, R. (2018). Release of particles, organic compounds, and metals from crumb rubber used in synthetic turf under chemical and physical stress. Environmental Science and Pollution Research, 25(2), 1448-1459.

- Celeiro, M., Dagnac, T., & Llompart, M. (2018). Determination of priority and other hazardous substances in football fields of synthetic turf by gas chromatography-mass spectrometry: A health and environmental concern. Chemosphere, 195, 201-211.
- Devitt, D. A., Young, M. H., Baghzouz, M., & Bird, B. M. (2007). Surface temperature, heat loading and spectral reflectance of artificial turfgrass. J. Turfgrass Sports Surf. Sci, 83, 68-82.
- Jim, C. Y. (2017). Intense summer heat fluxes in artificial turf harm people and environment. Landscape and Urban Planning, 157, 561-576.
- Liao, C., Kim, U. J., & Kannan, K. (2018). A Review of Environmental Occurrence, Fate, Exposure, and Toxicity of Benzothiazoles. Environmental science & technology, 52(9), 5007-5026
- McNitt, A. S., Petrunak, D. M., & Serensits, T. J. (2007, June). Temperature amelioration of synthetic turf surfaces through irrigation. In II International Conference on Turfgrass Science and Management for Sports Fields 783 (pp. 573-582).
- National Academies of Sciences, Engineering, and Medicine. (2017). Using 21st century science to improve risk-related evaluations. National Academies Press.
- Pochron, S., Nikakis, J., Illuzzi, K., Baatz, A., Demirciyan, L., Dhillon, A., … & Singh, R. (2018). Exposure to aged crumb rubber reduces survival time during a stress test in earthworms (Eisenia fetida). Environmental Science and Pollution Research, 25(12), 11376-11383.
- Thoms, A. W., Brosnan, J. T., Zidek, J. M., & Sorochan, J. C. (2014). Models for predicting surface temperatures on synthetic turf playing surfaces. Procedia Engineering, 72, 895-900.
- Vineyard, M. F., LaBrake, S. M., Chalise, S., Clark, M. L., Conlan, S. T., & Porat, Z. H. (2018). PIXE Analysis of Synthetic Turf. Environment and Ecology Research, 6(1), 60-65.
- Wagner, S., Hüffer, T., Klöckner, P., Wehrhahn, M., Hofmann, T., & Reemtsma, T. (2018). Tire wear particles in the aquatic environment-A review on generation, analysis, occurrence, fate and effects. Water research, 139, 83-100.
- Watterson, A. (2017). Artificial turf: contested terrains for precautionary public health with particular reference to Europe?. International journal of environmental research and public health, 14(9), 1050.

Response: We thank the reviewer for identifying additional references. Some have been added, where appropriate.

4.12 Charge Question 12: Please provide any other comments or suggestions for improving this report.

4.12.1 Reviewer 1

Comment: This was mentioned previously:

Page numbers (Vol 1) missing from 33 through 41. The sections 2.7.3.4 seems to follow 2.7.3.3 and line numbers are continuous. Then after page 57, page numbers revert to 41, but line numbers are continuous [sic]

Response: The necessary corrections have been made.

Comment: It is a well thought out project recognizing data-gaps and uncertainties. I see great variability in the chemical constituent measures at recycling plants and at synthetic turfs using tire crumb material (both indoors and outdoors) likely producing great variability in human exposures. There could be great variability in chemical constituents over time and affected by environmental conditions. I do believe there should be a follow-up in the future with a similar study of this magnitude. More focused smaller studies should continue to look at gathering more information about unknown constituents, variability in some chemical constituents, degradation and reaction mechanisms, and the variability in human behavior on these types of fields.

Response: We appreciate the reviewer's recommendations for future research activities that could be considered to improve our knowledge on this topic.

Comment: I am somewhat bothered by negative numbers for concentrations in tables, based on adjusting concentration by subtracting background levels (e.g., line 3800). This either means the backgrounds levels have changed or there or errors in analytical methods. Seems better to not report these numbers at all or to set to background levels. Some problems occurred with use of two chambers for emissions testing that might have created this problem. This is also a quality assurance issue.

Response: All laboratory-reported values were used in data analyses, even when below the quantifiable limit (in-lieu of using substitution or other censored data approaches). Some results appear as negative values due to subtraction of blank or background measurements; these negative values were retained in tables, figures, and calculations and were not arbitrarily set to zero. We believed it was best practice to retain and show the negative results, as they were part of the resulting distribution of corrected results. We recognize that the negative results do not have a physical basis and can be difficult or confusing for readers to understand. In most cases, these results indicate little to no measurable presence of the target analyte in the sample. The results do not necessarily suggest errors in the analytical methods since there is variability, on a relative basis, in background levels of blank quality control samples, especially at low concentrations. Given the variability at low concentrations, it is not surprising that a substantial fraction of the results would be corrected to negative values if there is little target analyte in the sample. The variability was higher for the chamber background samples. This conservative approach makes it less likely that we would report false positive or inflated concentration values where they are not warranted. We have added footnotes to all tables in the Part 1 and Part 2 Reports with negative results to help explain

this to the reader: “Several results are reported as negative values. This is a result of the subtraction of chamber background values from the sample measurement results. Although this does not represent a physical reality, the negative results are retained as part of the distribution of corrected results.”

4.12.2 Reviewer 2

Comment: All the comments have been made throughout this revision report.

Response: We acknowledge the reviewer’s comment.

4.12.3 Reviewer 3

Comment: 2751-2757: The terms synthetic and fresh tire crumb rubber material imply that the rubber infill was synthesized for use as infill. However, in reality, it is a waste product that was optimized for a different purpose, tire rubber, and therefore not synthesized for use with human contact in mind.

Response: The ‘fresh’ tire crumb rubber only refers to the tire crumb rubber at the recycling plant that has not been used yet either for synthetic turf tire crumb rubber infill or any other uses. An explanation has been provided in Section 1.0 of the Part 1 Report that the tire crumb rubber material is produced by recycling used tires. The phrase “newly manufactured from used tires” has been added to Section 3.1 of the Part 1 Report for clarity.

Comment: 5757: The report contains statistical terms (jargon) not everybody is familiar with. An effort should be made to make statistical conclusions more easily understandable, or, provide an easy to understand summary of the statistical data evaluation methods.

Response: We think it is important to describe, in some detail, the statistical methods using appropriate terminology in the detailed technical sections of the report. However, we agree that more plain language is needed for readers not familiar with statistical methods and terminology. We have attempted to use a somewhat plainer language approach in Section 2.0 to describe and summarize results. In the case of the multi-variate field characteristic modeling, we have made a very simple description and statement of results with little to no technical jargon in Section 2.0.

Comment: 5878 and discussion 5989-6002: I am not sure, a full picture of the cumulative exposures encountered by synthetic turf field users is possible, even with much a much greater research effort.

Compare the synthetic turf field situation with the exposure to tobacco smoke where it took years to come to firm conclusions. The discussion seems to imply that further characterization of the minor components is a necessary and fruitful research avenue. The question is: what would be gained with respect to decision making with respect to the use of crumb rubber as an infill?

Response: We acknowledge the reviewer's comment. The discussion necessarily points out that the non-targeted analysis does not sufficiently inform potential considerations of cumulative exposures for users of synthetic turf fields with crumb rubber. The utility of such information is not discussed.

Comment: Instead of just looking at the athletes' exposure, include maintenance and installation workers, site attendants, etc. Studying these people may show a clearer picture of crumb rubber exposure.

Response: Looking beyond persons who play on synthetic turf fields is outside the scope of this study.

4.12.4 Reviewer 4

Comment: This is an outstanding body of work and should be considered a model of conventional Source-Exposure-Receptor risk assessment. However, it is overkill in its exhaustive approach to issues that do not represent an appreciable problem, as with exposures close to LOD. We cannot do this for every exposure of community concern.

Response: We acknowledge the reviewer's comment.

4.12.5 Reviewer 5

Comment: I have no further comments after those given above. This is an excellent and thorough document, indicative of a great deal of work. The authors should be commended.

Response: We acknowledge the reviewer's comment and appreciate the complements.

4.12.6 Reviewer 6

Comment: Suggest that Tables in Chapter 4 which have frequency and percentage in the table (the latter in parenthesis) should have the title say frequency (percentage) [sic]

Response: We believe that the table column headings are adequately descriptive and prefer not to lengthen table titles further. No change.

Comment: Page 299 Line 7795 the VOC were probably measured on adsorbent samplers not filters as stated.

Response: The reviewer is correct that these would be best not described as filters. This change was made:

"The Carbopack™ X FLM sorbent tube samples from the two field air samplers and one upwind (off-field) background air sampler at each field were analyzed for VOCs."

Comment: Page 304, Table 4-42 needs to have the heading aligned with the table.

Response: The necessary adjustments have been made.

Comment: Page 336 Table 5-1. While elemental lead and zinc are insoluble in water, some of the salts are. So the form of the metal is important. This should be stated in the table rather than the current way it is expressed.

Response: A footnote was added to the table stating, "Metal salts are soluble in water."

Comment: Page 346 Table 5-11. The scenarios (1, 2 and 3) should be defined in a footnote in the table. They are not defined until page 356 lines 8703-8704, though they are given as the x-axis in several figures.

Response: The scenarios have been replaced by age range groupings as defined in Table 5-5.

4.12.7 Reviewer 7

Comment: Suggestions for improving specific chapters/sections of this report were included in the answers to the questions discussed above. Some general observations/recommendations, incorporating certain of the above-mentioned points, are summarized here:

- The report reviewed can be improved by incorporating clear and detailed diagrams/flowcharts summarizing the overall procedures as well as the steps/modules involved in these procedures, especially those employed in the exposure characterization study and the pathway modeling

studies. Currently only one flowchart (Fig. 5.1 on p. 338) is provided, and though it only covers a very small and simple part of the analyses described in Chapter 5, it nevertheless provides an example of visual overview/summary that facilitates and consolidates the reader's understanding of the procedure described in the textual narrative. The readability and comprehension of this report would be enhanced through the development and incorporation of more detailed diagrams and schematics (as well as of text boxes identifying/summarizing important points, in a visual style that has been in fact used in various past EPA reports).

Response: We agree that the text describing the pathway modeling in the exposure characterization study was somewhat unclear and convoluted. Rather than adding additional schematics or text boxes, we have revised the text to improve clarity.

Comment:

- A substantial improvement of the exposure pathway modeling component of report (e.g. probabilistic/distributional modeling, systematic sensitivity and uncertainty analysis, etc.) may not be feasible in the short term, as it would clearly require substantially greater effort than the development of the flowcharts recommended above; nevertheless, identifying and describing the types of data that will allow the future implementation of distributional modeling can enhance the present report and offer a valuable path for moving forward.

Response: We believe that the data collected in the study simply are not robust enough to support probabilistic/distributional modeling. The numbers of samples with measurements above the limits of detection are not sufficient to estimate meaningful distributions for each age group. Certain types of measurements (e.g., breathing zone air) could not be collected because the equipment would pose an injury risk during athletic activities and the entire range of activity levels and frequency of contact with turf could not be sampled. Moreover, data are not available for some of the important parameters needed to estimate exposure (e.g., skin adherence rates for tire crumb rubber particles of various sizes). We name and describe the specific types of data that are needed for a valuable path for moving forward in the Conclusions of Part 2, Section 5.

Comment:

- Developing, deploying and maintaining an online Knowledge-Base that will facilitate access to the data collected/developed through the work described in this report, would be a very valuable resource for supporting future efforts in this area.

Response: A complete set of compiled results is being made available through publication of this report and appendices.

Comment:

- Furthermore, the work described in the report under review can provide the groundwork for initiating and implementing a systematic analysis of Aggregate Exposure Pathways (AEP) for individuals and populations that interact with synthetic turf microenvironments, and of associated multiple, potentially overlapping, Adverse Outcome Pathways (AOP) for identified relevant chemicals of concern. Such an analysis would follow the framework outlined in the 2017 report of the National Academies of Sciences, Engineering, and Medicine, "Using 21st Century Science to Improve Risk-related Evaluations." Recognizing the potential value of this framework in the present report and placing the issue under consideration in the proper context of assessing complex multipathway exposures to complex mixtures of agents associated with multiple (but not independent) adverse outcome pathways (e.g. relating to endocrine disruption and carcinogenicity) will be an important step towards designing and completing improved future studies on the potential impacts of synthetic turf.

Response: We acknowledge the reviewer's suggestion.