Safety Study of Artificial Turf Containing Crumb Rubber Infill Made From Recycled Tires: Measurements of Chemicals and Particulates in the Air, Bacteria in the Turf, and Skin Abrasions Caused by Contact with the Surface

CalRecycle

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Executive Summary

Introduction

The new generation of artificial turf athletic fields often contains crumb rubber infill made from recycled tires. Crumb rubber infill serves as an artificial soil, supporting the artificial blades of grass, softening the surface, improving drainage, and helping to provide a high-quality playing surface for a variety of sports. However, tire rubber is a complex material, containing many naturally-occurring and man-made chemicals. Crumb rubber made from recycled tires has the potential to release a variety of chemicals and particles into the air. It also represents a potential site of bacterial growth and transmission to athletes using the fields (including methicillin-resistant *Staphylococcus aureus*, MRSA). Therefore, OEHHA has evaluated the following aspects of artificial turf safety for fields constructed with recycled crumb rubber infill.

Study Goals

Determine whether the new generation of artificial turf athletic field containing recycled crumb rubber infill is a public health hazard with regard to:

1. **Inhalation**: Do these fields release significant amounts of volatile organic compounds (VOCs) or fine particulates of aerodynamic diameter less than 2.5 microns ($PM_{2.5}$ and associated metals) into the air? If so, are the levels harmful to the health of persons using these fields?

2. **Skin infection**: Do these fields increase the risk of serious skin infections in athletes, either by harboring more bacteria or by causing more skin abrasions (also known as turf burns) than natural turf?

Methods

1. **Inhalation hazard**
   a. Measure $PM_{2.5}$ and bound metals in air sampled from above artificial turf fields during periods of active field use. Compare to concentrations in the air sampled upwind of each field.
   b. Measure VOCs in the air sampled from above artificial turf fields during hot summer days. Compare to concentrations in the air sampled from above nearby natural turf fields.

2. **Skin infection hazard**
   a. Measure bacteria on components (infill/soil and blades) of existing artificial and natural turf fields.
   b. With the cooperation of athletic trainers from colleges and universities in California and Nevada, measure skin abrasion rates for varsity soccer players competing on artificial and natural turf fields.

Results and Conclusions

1. **Inhalation hazard**
   a. $PM_{2.5}$ and associated elements (including lead and other heavy metals) were either below the level of detection or at similar concentrations above artificial turf athletic fields and upwind of the fields. No public health concern was identified.
   b. The large majority of air samples collected from above artificial turf had VOC concentrations that were below the limit of detection. Those VOCs that were detected were usually present in only one or two samples out of the eight samples collected per field. There was also little consistency among the four artificial turf fields with regards to the VOCs detected. Nevertheless, seven VOCs detected above artificial turf were evaluated in a screening-level estimate of health risks for both chronic and acute inhalation exposure scenarios. All exposures were below health-based screening levels, suggesting that adverse health effects were unlikely to occur in persons using artificial turf.
   c. There was no correlation between the concentrations or types of VOCs detected above artificial turf and the surface temperature.

2. **Skin infection hazard**
   a. Fewer bacteria were detected on artificial turf compared to natural turf. This was true for MRSA and other *Staphylococci* capable of infecting humans. This would tend to decrease the risk of skin infection in athletes using artificial turf relative to athletes using natural turf.
   b. The rate of skin abrasions due to contact with the turf was two- to three-fold higher for college soccer players competing on artificial turf compared to natural turf. This was observed for both female and male teams. Skin abrasion seriousness was similar on the two surfaces. The higher skin abrasion rate would tend to increase the risk of skin infection in athletes using artificial turf relative to athletes using natural turf.
   c. The sum of these effects on the skin infection rate for artificial turf relative to natural turf cannot be predicted from these data alone. Measuring the skin infection rates in athletes competing on artificial and natural turf might determine if there is a significant difference.

Recommendations

1. **Inhalation hazard**
   a. There was no relationship between surface temperature and the concentrations of VOCs detected above artificial turf fields. Therefore, there is no reason for recommending that field usage in the summer be restricted to cooler mornings as a strategy for avoiding exposure to VOCs.

2. **Skin infection hazard**
   a. Preventing skin abrasions should be given the highest priority for preventing skin infection. Protective clothing and equipment should be considered, especially when games take place on artificial turf.
   b. Treating skin abrasions should be given the next highest priority. Clean, disinfect and cover abrasions as soon as possible. Keep wounds clean and protected as they heal.
   c. Disinfecting artificial turf fields should be the lowest priority. Such efforts may have little effect given the lower numbers of bacteria detected on artificial turf relative to natural

turf (based on the results of this study) and the extensive literature suggesting that body-to-body contact is the primary mode of MRSA transmission.

d. It is not known if the abrasiveness of the new generation of artificial turf is primarily determined by the infill or by the blades of grass. Such information would be valuable for engineering new types of turf with decreased abrasiveness. Creating artificial turf with decreased abrasiveness for athletes, while still retaining its strength and durability relative to natural turf, represents a challenge in materials engineering.

Uncertainties and Data Gaps Remaining

1) **Inhalation hazard**
   a. It is not known if the following variables influence $PM_{2.5}$ and VOC release from artificial turf fields containing crumb rubber infill: field age, processing of tire rubber at cryogenic versus ambient temperatures, source of tire stocks (automobile versus truck tires, tire age at the time of processing).
   b. This study only measured $PM_{2.5}$ and VOCs above outdoor fields. Indoor fields have received much less attention. Since $PM_{2.5}$ and VOCs have the potential to accumulate in indoor venues, future testing indoors should be considered.

2) **Skin infection hazard**
   a. The skin abrasion rate for artificial turf may vary according to age group and type of sport.
   b. The skin abrasion rate may be different for fields containing crumb rubber processed at cryogenic temperatures compared to ambient temperatures.
   c. The skin abrasion rate may vary with field age.
   d. It is not known if skin abrasions caused by artificial and natural turf heal at similar rates.
   e. Few data exist to evaluate whether the bacterial populations of artificial and natural turf vary according to the weather or season

Chapter 1

A Screening-Level Evaluation of the Human Health Risks Posed by Volatile Organic Compounds in the Air Over Outdoor Artificial Turf Fields Containing Recycled Crumb Rubber Infill

Abstract

Air from above four artificial turf athletic fields containing recycled crumb rubber infill was analyzed for volatile organic compounds (VOCs). Nearby natural turf fields were analyzed for comparison. The fields, located in California's Central Valley, were sampled multiple times throughout summer days, from the cool early morning to the heat of the day in the afternoon. Air and field surface temperatures were also monitored.

Few VOCs were detected (most detection limits were around 1 $\mu g/m^3$). Most VOCs detected over artificial turf were present in only one or two of the eight air samples collected per field, demonstrating little consistency over time within each field. There was also little consistency between artificial fields with regard to the VOCs detected. In addition, VOC concentrations over artificial turf did not increase as the surface temperature increased by as much as 55^{o}F over the course of the day.

Comparing artificial turf to natural turf, seven VOCs met the following two criteria, suggesting that they originated from the artificial turf:

- Detected in at least two of the eight air samples collected from above an artificial field.
- Detected at a higher average concentration over that artificial field compared to the nearby natural field.

Chronic and acute exposure scenarios were constructed to estimate the exposure of soccer players to these seven VOCs via inhalation. A screening-level assessment of health risks was performed by comparing the estimated exposures to health-based screening levels. All exposures were lower than the screening levels, indicating that adverse health effects were unlikely in athletes using these fields. Uncertainties and limitations of this analysis are also presented.

Introduction

Rubber used to manufacture car and truck tires is a complex material, containing a variety of man-made and naturally occurring substances. Some of these are volatile. Therefore, it is not surprising that rubber made from recycled tires emits a number of chemicals. For example, in two studies conducted by the California Integrated Waste Management Board (CIWMB, 2003 and 2006), tire-derived indoor rubber flooring emitted 21 and 31 different volatile organic compounds (VOCs). Sections of artificial turf containing crumb rubber infill made from recycled tires were allowed to off-gas in chambers for 28 days (Moretto, 2007). A total of 112 VOCs were detected. In several independent studies, recycled crumb rubber was heated under laboratory conditions to determine what chemicals volatilize from the rubber at high temperature. A number of chemicals (VOCs and semi-volatile organic compounds, or sVOCs) were detected: Plesser and Lund, 2004, 12 chemicals; EHHI, 2007, 4 chemicals; New York State, 2009, up to 60 chemicals; Li et al., 2010, 11 chemicals.

Crumb rubber infill made from recycled tires is a major component of the new generation of artificial turf athletic fields. Given the findings that chemicals volatilize from crumb rubber, it is important to determine whether any of these VOCs reach high enough levels over these fields to constitute a health hazard to athletes using the fields. This question can be addressed by sampling the air over these fields, identifying the VOCs present, measuring their concentrations, and comparing those concentrations to health-based screening levels.

A number of air sampling studies have recently been conducted that focused on the new generation of artificial turf containing recycled crumb rubber infill. These are summarized in Table 1 along with the OEHHA study that is the subject of this report. All of these studies concentrated on outdoor fields except for the study by Simcox et al. (2010), which also included a single indoor field.

Using method TO-15 for VOC identification (U.S. EPA, 1999), TRC (2009) detected three VOCs from the TO-15 target list that were in the air over artificial turf but not upwind: 2-butanone, n-hexane, and chloroform. Four tentatively identified compounds (TICs) were also detected over artificial turf: isobutane, pentane, 2-methyl-1,3-butadiene, and 2-methylbutane. TICs are compounds that were not on the method TO-15 target list and therefore their identities and concentrations were estimated. Due to the low levels of these chemicals, none was judged by the authors to be a health hazard. Furthermore, the report stated that since the pattern of detection of these chemicals was not consistent, they were probably not released by these fields.

A total of 85 VOCs and 65 sVOCs were detected in the air over two fields comprising the New York State (2009) study. However, most of these were TICs with GC/MS peaks that only partially matched the reference scans. Therefore, their identities and quantities could not be determined with confidence. Since air samples were taken at various heights above each field and at various locations upwind and downwind of each field, both vertical and horizontal chemical concentration profiles could be constructed from the data. Correlations between height above or position across these fields and chemical concentration were not observed, suggesting that the fields were not the source of these chemicals. Nonetheless, 15 chemicals detected from above one field and 16 detected from above the other field were evaluated for noncancer risks to athletes using these fields. Eight chemicals were also evaluated for cancer risks. All evaluations considered the inhalation route of exposure only. The report concluded that there were no serious public health risks associated with the use of these fields.

In a recent study by U.S. EPA (2009a), most of the VOCs detected over three artificial turf fields were also detected in the upwind samples. From among the 56 VOCs analyzed, the only VOC that was detected over artificial turf but not upwind was methyl isobutyl ketone (MIBK, also known as 4-methyl-2-pentanone).

The air sampling studies discussed above, as well as the OEHHA study reported here, utilized stationary air samplers placed on the fields. In a study reported earlier this year (Simcox et al., 2010), both stationary air samplers and personal air samplers worn by study personnel were used. Possible contamination issues discussed in the report suggest that the personal air samples were not reliable. Therefore, considering only the data from the stationary samplers for the four outdoor artificial turf fields in that study, only two VOCs from the method TO-15 target list were substantially above background: cyclohexane over one field and acetone over another.

Table 1. Summary of VOC sampling parameters for five studies of outdoor artificial turf fields containing recycled crumb rubber infill.

Study	# of outdoor fields measured	# of air samples, per field/total all fields	# of air samples upwind of artificial field	Air collection method	VOC analysis method (# of target chemicals)	Were TICs identified?	Air sampling height above surface	Air sampling duration	Ambient air temperature range during sampling
TRC, 2009	2 artificial, 1 natural	4/16	2	6-L SUMMA canisters	EPA TO-15 (69)	Yes	3 feet	1 hour	79-94°F
New York State, 2009	2 artificial (same fields as in TRC, 2009)	8/18	1	Sorbent media in cartridges	EPA 5041A/8260B	Yes	At surface, 3 feet and 6 feet	2 hours	77-84°F
U.S. EPA, 2009a	3 artificial	3 or 6/12	1	6-L SUMMA canisters	EPA TO-15 (56)	No	3.3 feet	20 seconds	82-95°F
Simcox et al., 2010	4 artificial[1], 1 natural	1-2/13[2]	1	6-L SUMMA canisters	EPA TO-15 (60)	Yes	3 feet (all fields) and 0.5 feet (3 fields)	1 hour	68-87°F
OEHHA, 2010	4 artificial, 4 natural[3]	8/64	0*	6-L SUMMA canisters	EPA TO-15 (94)	Yes	4 feet	45 minutes	63-98°F

[1] Does not include one indoor artificial turf field.
[2] Does not include air collected via personal samplers.
[3] In each of four municipalities the artificial field and natural field were located at the same school or sports complex. In two cases the fields were adjacent, in one case they were separated by a parking lot, and in one case they were separated by a natural turf field.

In addition, one TIC was specific to a single artificial turf field: 2-methyl butane. The levels of total volatile organic compounds (TVOCs) were also evaluated. For three out of four outdoor artificial turf fields, the concentration of TVOCs was lower in air sampled from above the field than in the air sampled upwind of the field. The average TVOC concentration for the four artificial turf fields was 18 $\mu g/m^3$ compared to 26 $\mu g/m^3$ for four samples collected upwind of these fields and one sample from above a grass field. A human health risk assessment based on these data (Connecticut Department of Public Health, 2010) did not identify any elevated inhalation health risks to athletes using these outdoor fields.

It is well-established that the release of VOCs from a variety of materials increases with increasing temperature. This was demonstrated recently in a laboratory study in which the recycled crumb rubber infill used in the construction of artificial turf fields was heated to 77, 117 or 158°F (New York State, 2009). The VOCs released at the three temperatures were identified. Thirteen chemicals were detected at a greater frequency as the temperature increased. No chemicals showed the opposite relationship; i.e., fewer detects as the temperature increased.

A study is needed in intact athletic fields containing recycled crumb rubber, performed over the range of temperatures encountered during summer days, to quantify the relationship between field temperature and VOC concentration above the field. While the earlier studies listed in Table 1 did record surface and ambient temperatures, they did not measure VOCs at different temperatures on the same field. This was one goal of the present study.

The Office of Environmental Health Hazard Assessment (OEHHA), in consultation with CalRecycle, has performed air sampling to measure the concentrations of VOCs over artificial turf athletic fields in California. New generation artificial turf containing crumb rubber infill made from recycled tires was specifically targeted. Air samples were also collected from above adjacent/nearby natural turf athletic fields for comparison. Field locations were selected in California's Central Valley and sampling was conducted during the summer of 2010. In order to study the relationship between temperature (both ambient and surface) and VOC concentration, air samples were collected from early in the morning through late afternoon, alternating between artificial turf and natural turf. Throughout this period temperature measurements were also made at each field's surface and four feet above each field. This yielded a total of 64 air samples from eight fields, evenly divided between artificial and natural turf (Table 1), along with temperature data. These data allowed us to test the relationship between temperature and VOC concentrations over artificial turf, as well as estimate whether the chemicals constitute an inhalation risk to persons using these fields.

Methods

Air sampling

Schools and municipalities with artificial turf fields containing crumb rubber infill were identified from lists available on artificial turf installers' websites. Locations in California's Central Valley were chosen based on the probability that summer daytime temperatures would exceed the target temperature for air sampling of 90°F. Permission was obtained prior to sampling. Four separate schools or municipalities were sampled between June 8 and August 4, 2010. Each school or town sports complex had an artificial turf athletic field and an adjacent or nearby natural grass athletic field within a few hundred meters of each other (Table 2). Artificial field ages ranged from eight months to five years.

Table 2. Field characteristics

Town #	Venue	Configuration	Artificial field age
1	Town sports complex	An artificial turf and a natural turf field separated by a parking lot approximately 100 meters wide	1 year
2	Town sports complex	An artificial and a natural turf field 25 meters apart, separated by a concrete walkway and natural landscaping	8 months
3	High school	Artificial field in outdoor stadium and natural turf field 300 meters apart, separated by bleachers and another natural turf field	5 years
4	High school	Artificial turf field in outdoor stadium almost adjacent to natural turf field, separated by bleachers	2 years

Air samples were collected alternately on each artificial and natural turf field, beginning at approximately 8 a.m. and ending at approximately 5 p.m. Gas regulators allowed sampling over 45-minute intervals (flow rate of approximately 125 milliliters per minute). Samples were collected in six liter SUMMA canisters following a leak check to verify that each canister had the correct vacuum and did not leak after being connected to a regulator. The same two regulators were used for the entire study. All sampling was performed with duplicate canisters placed next to each other at the same spot on the artificial or natural turf field. Air intake occurred at four feet above each surface. Canisters were shipped by ground express to the analyzing laboratory within 1-2 days of sampling. Analysis was completed within the 30-day time limit recommended for sample storage (U.S. EPA, 1999).

Surface temperatures, as well as temperatures at four feet above each surface (ambient temperature), were monitored throughout the day. Wind speed and wind direction also were recorded.

Each day following air sampling at the athletic fields, two additional samples were collected within a few hundred meters of the Pacific Ocean at Fort Funston, in San Francisco. This location generally has strong onshore winds during the summer. These so-called “beach” samples were assumed to contain very low amounts of VOCs and were used as an additional check (in addition to the laboratory method blanks) for possible false positives in the samples collected from above the artificial and natural turf athletic fields.

Air samples were analyzed for VOCs according to U.S. EPA method TO-15. All analyses were performed by Environmental Analytical Services (San Luis Obispo, CA). The method TO-15 target list of chemicals used by this laboratory contains 94 target VOCs that can be reliably detected and quantified. These are shown in the Appendix along with representative method detection limits (MDLs; most around 1 $\mu g/m^3$) and reporting limits (RLs). The MDL was the lowest concentration of the chemical that could be detected. Concentrations from the MDL to just below the reporting limits were estimated by the analyzing laboratory and are indicated by a “J” qualifier in the tables. The reporting limits were the lowest concentration of the chemical that could be quantified with confidence. It coincided with the lowest point on the calibration curve. Exact MDLs and reporting limits varied slightly with each sample. Quality control tests were run every day that samples were analyzed. These tests included method blanks to detect false positives, duplicate control samples to measure relative percent differences, and laboratory control spikes to measure percent recoveries.

The laboratory also measured TICs. These were VOCs not on the U.S. EPA method TO-15 target list of 94 compounds. The identities and amounts of TICs were estimated, unlike the 94 chemicals on the target list (see above). Six were tentatively identified. However, the six TICs were ubiquitous in both artificial and natural turf field samples, as well as in the samples collected at the beach. Therefore, they were considered to be contaminants and are not evaluated in this assessment.

Soccer coaches survey

Permission was obtained from the California Youth Soccer Association (CYSA, northern division) to circulate a survey request to its member coaches via its newsletter. The coaches were asked to access an online survey form at their convenience. The survey questions included how many hours per year the different age groups engage in organized soccer play (school or club teams), and at what ages organized soccer play typically begins and ends. The survey was conducted in September 2009. There were 236 coaches who responded to the survey. The coaches were asked to tailor their responses towards enthusiastic soccer players, who tend to play the most soccer per year for many years.

Results

Concentrating field emissions to identify additional target chemicals

Our first priority was to sample the air above artificial turf to screen for TICs not on our target list of 94 VOCs (see Appendix). To concentrate the emissions from these fields, and thereby increase our chances of detecting TICs, a new, clean (with detergent and water) garbage can made of galvanized steel was inverted on an artificial turf field for 20 minutes. Then, the garbage can was tilted as little as possible and the SUMMA canister was placed inside and allowed to fill for 45 minutes inside the inverted can. The process was repeated with a second canister. The temperature inside the garbage can ranged between 96^{o} and 106^{o}F during sampling on artificial turf, while the outside ambient temperature ranged between 84^{o} and 88^{o}F. For comparison, two air samples were collected in a similar manner within a few hundred meters of the Pacific Ocean during a day with strong onshore winds (temperature usually in the high 50^{o}s to mid 60^{o}s). VOC concentrations were expected to be very low in these “beach” samples (see methods section). Table 3 shows the results for this phase of the study.

Six TICs were detected in the air above artificial turf: butanal, pentanal, hexanal, hexamethylcyclotrisiloxane, 2,3-dimethylnonane, and nonanal (data not shown). They are not among the 94 target VOCs (U.S. EPA method TO-15). However, they were ubiquitous in subsequent samples from artificial turf, natural turf, and the beach. Therefore, they were considered to be contaminants and were not evaluated in this assessment.

Among the 94 VOCs on the target list, five were also ubiquitous in samples taken from above artificial turf, natural turf, and at the beach: dichlorodifluoromethane, chloromethane, ethanol, acetone, and 2-butanone. Therefore, these five chemicals probably represent contamination rather than emissions from artificial turf. These chemicals were not evaluated in this assessment.

Table 3 shows 10 chemicals from the VOC target list that were detected above their MDLs. Only 4-methyl-2-pentanone (a.k.a., methyl isobutyl ketone) was detected in both artificial turf air samples and absent from both beach samples. In both cases the concentrations were above the reporting limit. This was the only instance in the entire VOC sampling study (apart from the five probable contaminants discussed above) that a VOC was present above its reporting limit in both duplicate samples. As mentioned in the introduction, 4-methyl-2-pentanone was the only artificial turf-specific VOC in a recent study (U.S. EPA, 2009). That only a single chemical became concentrated inside the garbage can to a level above its reporting limit suggested that subsequent sampling in the absence of the garbage can would detect few target list VOCs. This turned out to be the case (see below).

Table 3. Volatile organic compounds accumulating *inside a steel garbage can* inverted on artificial turf at town #2 [1]

Compound	Art[2]	Art	Beach[3]	Beach
Dichlorodifluoromethane	4.4	2.1 J	3.1 J	2.8 J
Chloromethane	2	0.9 J	1.3 J	1.7 J
Bromomethane	1.3 J	*	*	*
Ethanol	3.4 J	*	*	*
Acetone	44.5	15.8	17.2	15.9
2-Propanol	*	*	2.1 J	*
2-Butane	14.7	1.9 J	3.2	3
Cyclohexane	*	*	1.2 J	*
Benzene	*	1.3 J	*	*
4-Methyl-2-pentanone (methyl isobutyl ketone)	7.8	21	*	*

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated because the concentration detected was between the method detection limit (MDL) and the reporting limit (RL).
[3] Beach samples are described in the methods section.
Shaded values indicate concentrations of chemicals that were detected in both artificial turf samples and absent from both beach samples.
Another 84 volatile organic compounds from the target list were below their MDLs.

Monitoring field temperatures throughout the day

One goal of this study was to determine whether VOC concentrations above artificial turf fields were sensitive to field temperature. Therefore, each field was monitored for surface temperature and ambient temperature (measured at four feet above the surface) beginning early in the morning, when the day was cool, until the heat of the day in the afternoon. The artificial and natural turf fields chosen for monitoring at each town were either adjacent or within a few hundred meters of each other (Table 2).

Temperature profiles for the four artificial turf fields and four natural turf fields are shown in Figures 1-4. The data are consistent from town to town. Comparing the artificial turf to the natural turf at each town indicates the following:

- The ambient temperatures measured at four feet above each field were similar for the two surfaces.
- The surface temperature of the artificial field was always higher than the surface temperature of the natural turf field.
- The difference between the surface temperature of the artificial and natural turf was least early in the morning and greatest later in the afternoon.

Thus, the higher temperature of artificial turf relative to natural turf was evident on the surface, but not in the breathing zone (four feet above the surface) of young athletes using the fields. This has been reported previously for artificial and natural turf fields in New York State (New York State, 2009).

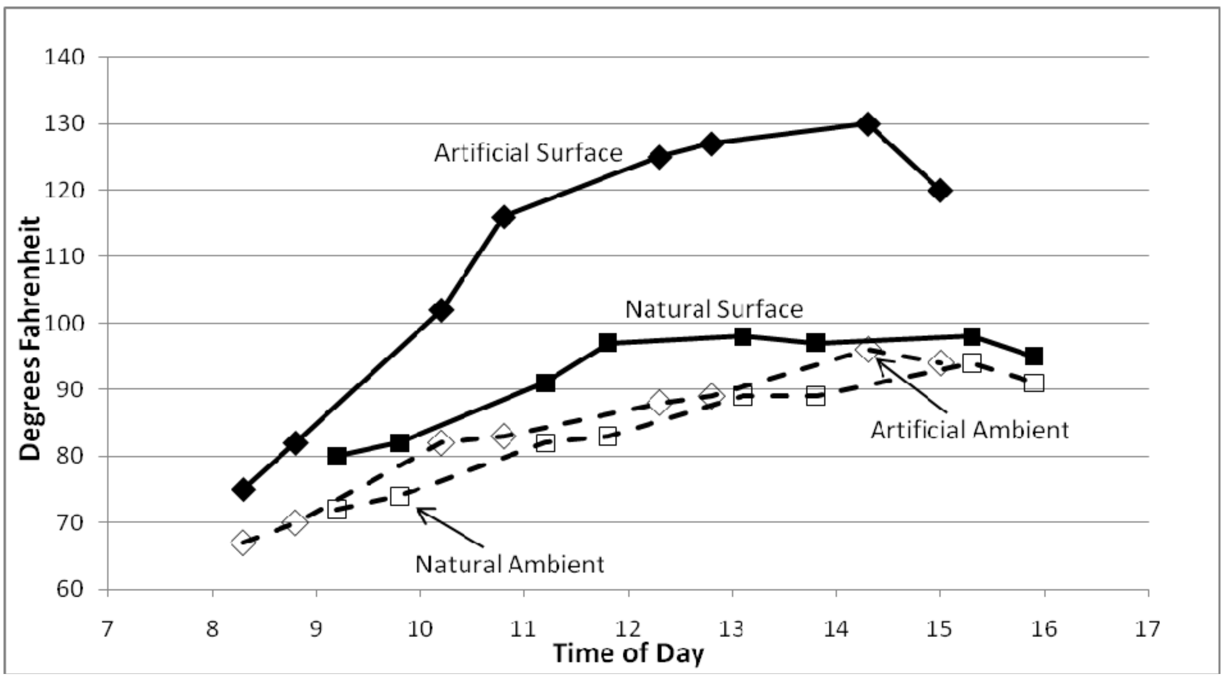

Figure 1. Surface and ambient temperatures of an artificial and natural turf field at town #1 during the day. Solid symbols: temperature of the indicated surface measured with a temperature probe. Open symbols: temperature measured at four feet above the indicated surface using a hand-held meter. Diamonds: data collected from artificial turf field. Rectangles: data collected from natural turf field.

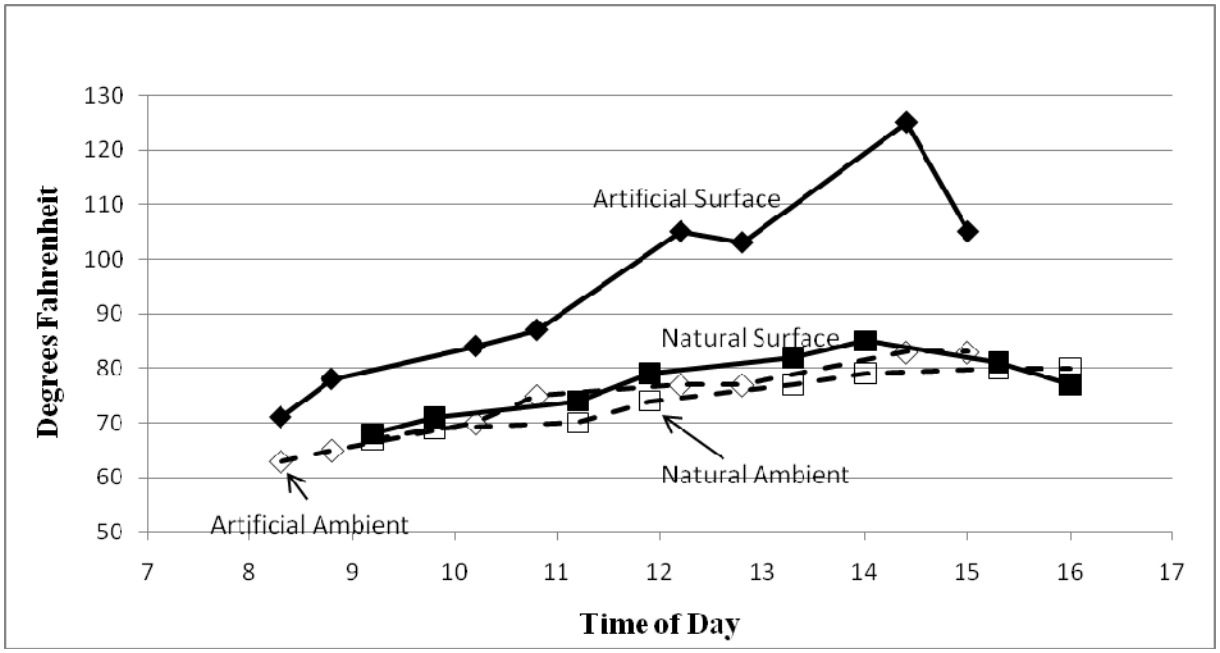

Figure 2. Surface and ambient temperatures of an artificial and natural turf field at town #2 during the day. Solid symbols: temperature of the indicated surface measured with a temperature probe. Open symbols: temperature measured at four feet above the indicated surface using a hand-held meter. Diamonds: data collected from artificial turf field. Rectangles: data collected from natural turf field.

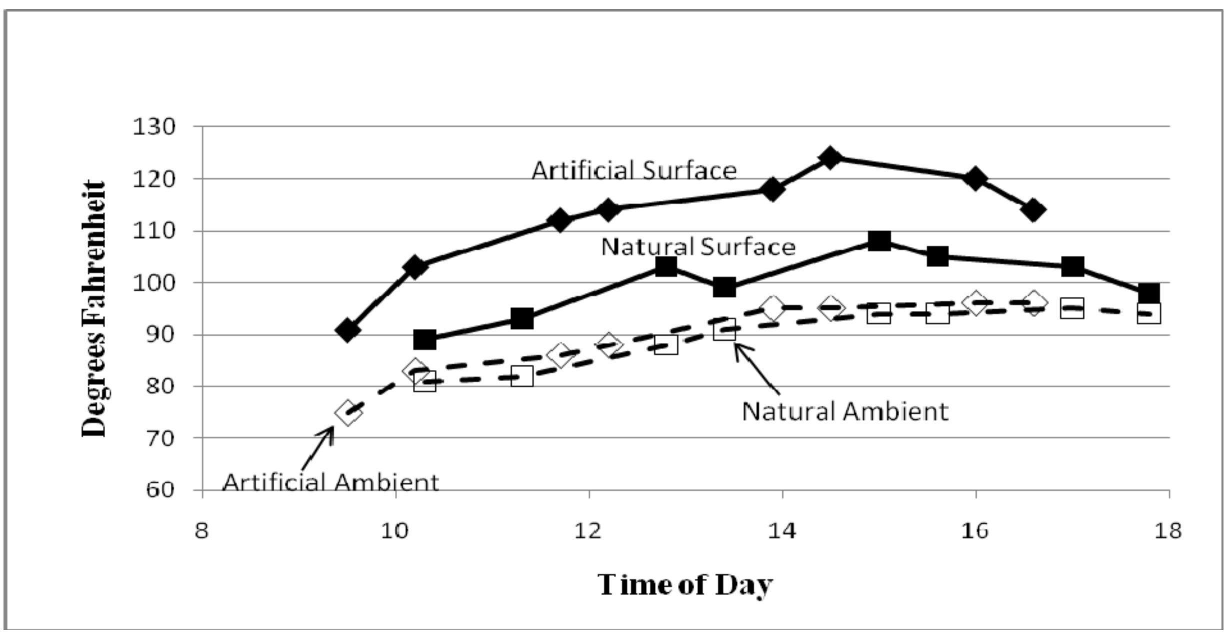

Figure 3. Surface and ambient temperatures of an artificial and natural turf field at town #3 during the day. Solid symbols: temperature of the indicated surface measured with a temperature probe. Open symbols: temperature measured at four feet above the indicated surface using a hand-held meter. Diamonds: data collected from artificial turf field. Rectangles: data collected from natural turf field.

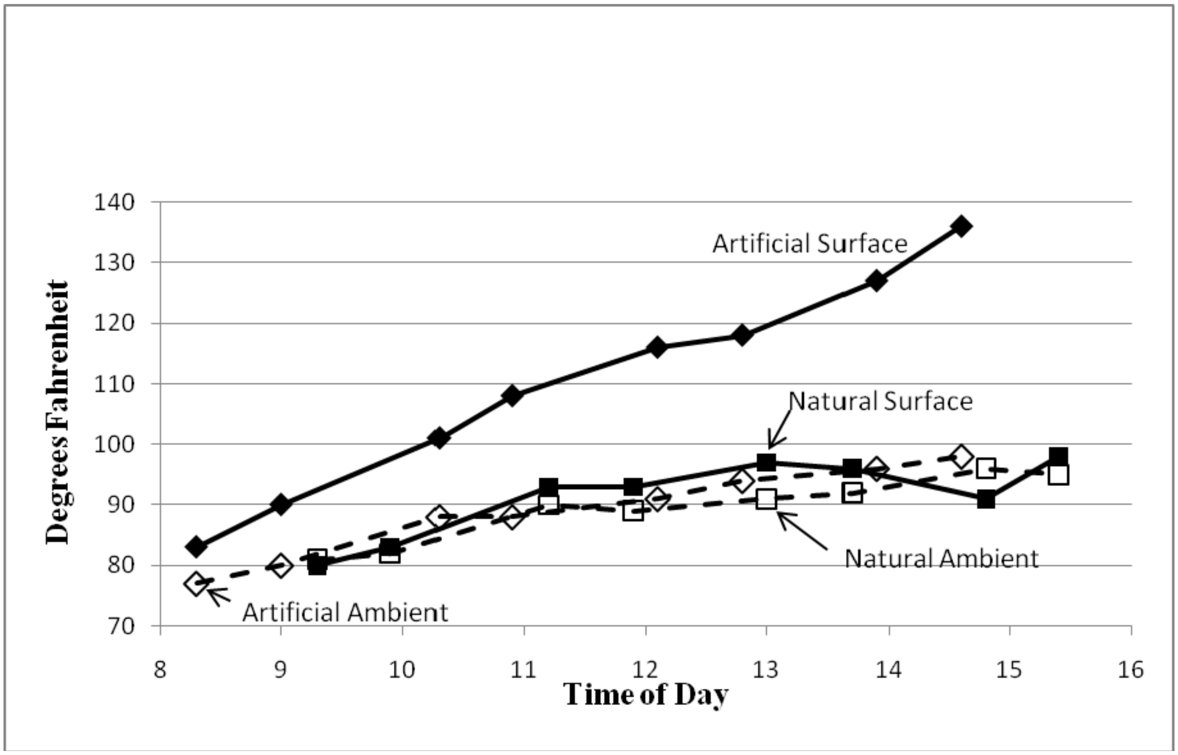

Figure 4. Surface and ambient temperatures of an artificial and natural turf field at town #4 during the day. Solid symbols: temperature of the indicated surface measured with a temperature probe. Open symbols: temperature measured at four feet above the indicated surface using a hand-held meter. Diamonds: data collected from artificial turf field. Rectangles: data collected from natural turf field.

Table 4. Summary of the temperature data collected from four artificial and four natural turf fields.[1]

Field type	Time interval	Ambient temp. range	Surface temp. range	Surface temp. change	Surface temp. change per ambient degree change[2]
Town #1					
Art field	8:15-15:00	68-96°	75-130°	55°	2.0°
Nat field	9:10-16:00	72-95°	80-98°	18°	0.8°
Town #2					
Art field	8:20-15:00	63-83°	71-125°	54°	2.7°
Nat field	9:15-16:00	68-80°	69-86°	17°	1.4°
Town #3					
Art field	9:20-16:30	75-97°	91-125°	34°	1.5°
Nat field	10:15-17:50	80-96°	89-109°	20°	1.3°
Town #4					
Art field	8:20-14:40	78-98°	83-137°	54°	2.7°
Nat field	9:20-15:20	81-96°	80-98°	19°	1.2°

[1] All measurements are in degrees (°) Fahrenheit.
[2] Calculated as follows: surface temperature change/ambient temperature change.

Table 4 above summarizes the results from Figures 1-4. The following conclusions can be drawn about the temperature sensitivity of artificial turf relative to natural turf:

- The maximum ambient temperatures at four feet above artificial turf and natural turf were similar (within 3°F).
- The maximum surface temperature of artificial turf was from 16-39°F higher than the maximum surface temperature of natural turf.
- For three of the artificial turf fields, the increase in surface temperature per increase in ambient °F was about twice that of the natural turf field (column six in Table 4), while for the artificial turf field in town #3 the increase on artificial turf was only slightly greater than the increase on natural turf (1.5 vs. 1.3°F).

Our goal in monitoring ambient and surface temperatures was to measure their influence on VOC concentrations. In this regard, the data in Table 4 show:

- The target ambient temperature of 90°F was achieved in three out of four towns.
- The increases in the temperature of the artificial surfaces (34, 54, 54 and 55°F) were relatively large. Given what is known about the relationship between temperature and VOC release from recycled crumb rubber (New York State, 2009), these increases are large enough to allow a robust test of the effect of temperature on VOC concentrations over artificial turf.

Air sampling: Town #1

Town #1 had a sports complex containing a new generation artificial turf field with crumb rubber infill, along with a number of natural turf fields. Air was collected from above the artificial turf field and one natural turf field. The temperature of the artificial turf surface increased 55^{o}F during the period of air sampling (Table 4).

Table 5 shows the VOCs detected over the artificial and natural turf fields in town #1. As discussed above, some chemicals were ubiquitous, appearing in most samples from both surfaces and from samples collected at the beach. Therefore, they were considered contaminants and are not evaluated in this assessment. For this data set those chemicals were dichlorodifluormethane, chloromethane, acetone, and 2-butanone. Another nine chemicals were detected; seven were specific to the artificial turf field and two were specific to the natural turf field. Six of these nine were detected in only one of eight air samples taken from above artificial or natural turf. The remaining three chemicals, 2-propanol, cyclohexane, and toluene, were detected in two of eight air samples taken from above artificial turf. For all nine chemicals detected over the two fields, most concentrations were between the MDL and reporting limit for each chemical. Comparing Table 5 to Figure 1, there was no pattern of increasing frequency of detection or increasing concentration with increasing temperature, despite the 55^{o}F increase in the temperature of the artificial surface over the monitoring interval.

Air sampling: Town #2

Town #2 had a sports complex containing multiple artificial (crumb rubber infill) and natural turf fields. Air was sampled from above one artificial turf field and one natural turf field. The temperature of the artificial turf surface increased 54^{o}F during the period of air sampling (Table 4).

Table 6 shows the VOCs detected over the artificial and natural turf fields in town #2. Five of the chemicals detected were ubiquitous (including method blanks) and therefore were considered to be contaminants and are not evaluated further: dichlorodifluoromethane, chloromethane, ethanol, acetone, and 2-butanone. Another 24 chemicals were detected; 18 were specific to artificial turf, three were specific to natural turf, and three were detected over both surfaces. From among the 18 artificial turf-specific chemicals, 13 were detected in only one of the eight air samples collected from above artificial turf. The other five were detected in two (m,p-xylene, o-xylene, 1,2,4-trimethylbenzene) or three (isopropylbenzene, 4-ethyltoluene) air samples from above artificial turf.

Benzene was noteworthy since it was detected in five of eight air samples from above artificial turf, compared to only one air sample from above natural turf. However, it was also detected at 0.75 $\mu g/m^3$ in one of the method blanks for this batch of air samples (canisters containing purified air samples). U.S. EPA (2009b) suggests that for chemicals detected in method blanks, field detects should be at least five to ten times greater; otherwise, they should be considered nondetects. Since these benzene field concentrations (all "J" qualified) were less than five times the concentration measured in the method blank, they were considered nondetects. Benzene was not detected over the fields in towns #1 and #3, and was detected at the same frequency (three of eight samples) over the artificial and natural turf fields in town #4.

Consistent with the data from town #1, most chemical concentrations in air samples from town #2 were between the MDL and the reporting limit (Table 6). The xylene isomers were exceptions in this regard, since all four detected concentrations were above the reporting limits.

Lastly, there was no pattern suggesting that the artificial surface released more chemicals as it heated up. Rather, more chemicals were detected earlier in the day, when the temperatures were lower. A possible reason for this may have been the winds, which were somewhat lighter on that date in the morning compared to the afternoon (varying between approximately 5 and 10 mph out of the southwest for most of the day).

Air sampling: Town #3

Town #3 had a high school with an artificial turf field in an outdoor stadium. Air was sampled from above that field and a nearby natural turf field. The temperature of the artificial turf surface increased 34^{o}F during the period of air sampling (Table 4).

Table 7 shows the VOCs detected over the artificial and natural turf fields. Consistent with the data collected from towns #1 and #2, Five VOCs were ubiquitous and are not evaluated further: dichlorodifluoromethane, chloromethane, ethanol, acetone, and 2-butanone. Another 11 chemicals were detected; seven were specific to artificial turf, one was specific to natural turf, and three were found over both surfaces. Eight of the 11 chemicals detected were present in only a single air sample per field. Toluene was detected in four samples from above artificial turf and four samples from above natural turf. As found for the other towns, most of the chemicals that were detected were present at concentrations above the MDL but below the reporting limit. Once again, there was no indication that the detection frequencies or chemical concentrations increased as the artificial surface heated up throughout the day.

Air sampling: Town #4

Town #4 had a high school with an artificial turf field in an outdoor stadium. Air was sampled from above that field and an adjacent natural turf field. The temperature of the artificial surface increased 54^{o}C during the period of air sampling (Table 4).

For this group of air samples (Table 8), acetone, benzene, and toluene were all detected in the method blanks. In addition, acetone and toluene were present in the air sampled at the beach. Therefore, these chemicals were considered contaminants in the air samples from this field.

For the other four chemicals detected on these fields, two were specific to artificial turf, one was specific to natural turf, and one was detected over both fields. All were detected in only one out of eight air samples per field, and in all cases the concentrations were below the reporting limit. There was no apparent surface temperature effect for these four chemicals.

Table 5. Volatile organic compounds detected in air sampled from above an artificial and natural turf field at town #1 during the day.[1]

	8:34[5]		9:33		10:33		11:33		12:32		13:28		14:40		15:37			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
Dichlorodifluoromethane	3.3J	2.1J	2.8J	2.4J	1.9J	2.3J	2.4J		1.9J	1.8J	2.9J	2.0J	3.2J	2.4J	2.3J	2.4J	2.1J	2.5J
Chloromethane	1.2J	1.0J	1.3J	1.0J	1.0J	1.0J	1.7J	1.0J	1.1J	1.0J	1.1J	0.8J	1.1J	1.2J	1.2J	1.2J	1.0J	1.1J
Ethanol	*	2.5J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Acetone	8.8	7.9	28.6	10.9	9.3	9.5	12.8	9.3	13.4	9.1	13.5	8.4	11.7	14.6	19.6	22.2	6.6	5.5
2-Propanol	*	*	*	*	*	*	*	*	*	*	*	*	2.1J	1.6J	*	*	*	*
2-Butanone	1.2J	1.7J	6.2	1.9J	1.6J	1.6J	2.3J	2.2	2.6	1.4J	3.3	1.1J	1.5J	2.3J	2.7	3.7	2.7	1.0
Hexane	*	1.2J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Tetrahydrofuran	*	*	*	*	*	*	*	*	3.1	*	*	*	*	*	*	*	*	*
Cyclohexane	*	1.9J	*	*	*	*	*	*	*	*	*	*	1.3J	*	*	*	*	*
n-Heptane	*	2.7	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Toluene	1.2J	11.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
m,p-Xylenes	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	2.6J	*	*
Isopropylbenzene	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	1.7J	*	*

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
[3] Nat = natural grass athletic field
* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated, registering between the method detection limit (MDL) and the reporting limit (RL).
[4] Beach samples are described in the methods section.
[5] Midpoints of 45-minute sampling intervals are shown in the table.
Another 81 volatile organic compounds from the target list were not detected in any sample (i.e., were below their MDLs).

Table 6. Volatile organic compounds detected in air sampled from above an artificial and natural turf field at town #2 during the day.[1]

	8:34[5]		9:33		10:33		11:31		12:30		13:44		14:43		15:43			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
Dichlorodifluoromethane	4.1	3.5J	3.6J	3.6J	3.6J	3.5J	4.5	3.5J	3.4J	3.6J	3.0J	3.3J	3.7J	3.0J	3.2J	3.7J	2.9J	3.1J
Chloromethane	5.1	1.4J	1.6J	1.3J	1.5J	1.6J	1.7J	1.4J	1.2J	1.5J	1.8	1.4J	1.9	1.1J	1.3J	1.3J	1.2J	1.2J
Chloroethane	1.7J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Ethanol	*	*	3.6J	*	*	4.6J	*	*	*	4.9J	13.9	3.2J	11.9	*	*	*	*	*
Acetone	263	17.6	16.6	14.4	7.8	80	15.2	12.6	9.7	15.7	227	17.3	30.2	10.3	16.6	14.1	8.8	9.9
2-Propanol	*	*	*	1.3J	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2-Butanone	14.1	3.2	3.9	1.7J	1.4J	6.0	3.3	1.3J	*	2.4J	44	2.2J	5.0	1.1J	2.5	1.9J	1.3J	1.5J
Tetrahydrofuran	1.2J	*	*	*	*	*	*	*	*	*	3.3	*	*	*	*	*	*	*
Cyclohexane	0.9J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Benzene	1.7J	*	*	*	1.6J	1.2J	*	*	1.8J	*	*	1.5J	1.7J	*	*	*	*	*
n-Heptane	2.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
4-Methyl-2-pentanone	*	*	*	*	*	*	*	*	*	3.5	1.4J	*	*	*	*	*	*	*
Toluene	4.6	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2-Hexanone	*	*	*	*	*	*	*	*	*	*	2.3	*	*	*	*	*	*	*
Octane	2.5	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Chlorobenzene	23.9	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Ethylbenzene	3.5J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
m,p-Xylenes	26.2	*	*	*	*	14.5	*	*	*	*	*	*	*	*	*	*	*	*
Nonane	0.9J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

	8:34[5]		9:33		10:33		11:31		12:30		13:44		14:43		15:43			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
o-Xylene	7.1	*	*	*	*	60	*	*	*	*	*	*	*	*	*	*	*	*
n-Propylbenzene	2.1J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Isopropylbenzene	3.2	1.5J	*	*	*	22.6	*	*	*	*	*	*	*	*	*	*	*	*
4-Ethyltoluene	1.6J	1.2J	*	*	*	12	*	*	*	*	*	*	*	*	*	*	*	*
1,3,5-Trimethylbenzene	*	*	*	*	*	38	*	*	*	*	*	*	*	*	*	*	*	*
Decane	8.9	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1,2,4-Trimethylbenzene	4.1J	*	*	*	*	20	*	*	*	*	*	*	*	*	*	*	*	*
sec-Butylbenzene	1.9J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Isopropyltoluene	2.6J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1,2,4-Trichlorobenzene	*	*	*	*	*	*	*	*	*	*	2.7J	*	*	*	*	*	*	*

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
[3] Nat = natural grass athletic field
* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated, registering between the method detection limit (MDL) and the reporting limit (RL).
[4] Beach samples are described in the methods section.
[5] Midpoints of 45-minute sampling intervals are shown in the table.
Another 65 volatile organic compounds from the target list were not detected in any sample (i.e., were below their MDLs)

Table 7. Volatile organic compounds detected in air sampled from above an artificial and natural turf field at town #3 during the day.[1]

	9:51[5]		10:59		12:00		13:07		14:13		15:20		16:19		17:22			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
Dichlorodifluoromethane	2.1J	2.8J	3.1J	2.4J	2J	2.6J	2J	2.5J	2.5J	3.2J	2.7J	2.8J	3.2J	2.5J	2.2J	2.7J	2.2J	2.2J
Chloromethane	0.7J	0.9J	1.2J	1.1J	1.0J	1.0J	0.9J	1.5J	0.8J	1.6J	1.1J	1.7J	1.1J	0.9J	1.2J	1.4J	2.5	0.8J
Ethanol	2.7J	3.3J	2.7J	*	*	*	3.5J	7.9	*	6.1	33.5	4.1J	3.6J	*	*	*	4.7J	*
Acetone	10.4	14.5	10.8	12.4	39.1	12	16.3	20.2	15.4	72.5	19	24.7	15.8	12	15.7	15.2	113	6.1
Allyl chloride	*	*	*	3.5	*	*	*	*	1.6J	1.1J	*	*	*	*	*	*	*	*
Vinyl acetate	*	*	*	*	*	*	*	3.4J	*	9J	*	*	*	*	*	*	*	*
2-Butanone	2.7	1.7J	*	*	2.8	2.8	3.3	2.2J	3	39.4	8	31.7	2.1J	1.2J	2.5	1.7J	5.6	5.2
Tetrahydrofuran	*	*	*	*	*	*	1.6J	*	*	*	1.4J	6.9	*	*	*	*	*	*
Toluene	*	2J	*	2.3J	*	2.6	2.6	*	3	*	3.1J	*	4	*	*	2.7J	*	*
2-Hexanone	*	*	*	*	*	*	*	*	*	1J	*	*	*	*	*	*	*	*
Chlorobenzene	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	5.1	*
m,p-Xylenes	*	*	*	*	6.2J	*	*	*	*	*	*	*	*	*	*	*	7.9	*
o-Xylene	*	*	*	*	24.5	*	*	*	*	*	*	*	*	*	*	*	1.9J	*
4-Chlorotoluene	*	*	*	*	1.2J	*	*	*	*	*	*	*	*	*	*	*	*	*
Isopropylbenzene	*	*	*	*	7.2J	*	*	*	*	*	*	*	*	*	*	*	*	*
4-Ethyltoluene	*	*	*	*	8.9J	*	*	*	*	*	*	*	*	*	*	*	*	*
1,3,5-Trimethylbenzene	*	*	*	*	20.1	*	*	*	*	*	*	*	*	*	*	*	*	*

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
[3] Nat = natural grass athletic field

* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated, registering between the method detection limit (MDL) and the reporting limit (RL).
[4] Beach samples are described in the methods section.
[5] Midpoints of 45-minute sampling intervals are shown in the table.
Another 77 volatile organic compounds from the target list were not detected in any sample (i.e., were below their MDLs).

Table 8. Volatile organic compounds detected in air sampled from above an artificial and natural turf field at town #4 during the day.[1]

	8:41[5]		9:38		10:36		11:32		12:27		13:20		14:14		15:07			
Compound	**Art[2]**	**Art**	**Nat[3]**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Art**	**Art**	**Nat**	**Nat**	**Beach[4]**	**Beach**
Acetone	*	*	*	*	*	*	*	*	*	*	*	*	7.9	12.7	3.2	10.9	*	5.8
2-Propanol	*	*	*	*	*	*	*	*	1.2J	*	*	*	*	*	*	*	*	*
Vinyl acetate	*	*	*	*	*	*	*	*	*	*	*	*	*	5.9J	*	*	*	*
2-Butanone	1.2J	*	*	*	*	*	*	*	*	*	*	*	*	*	*	2.1J	*	*
Isobutyl alcohol	*	*	*	*	*	*	*	*	*	*	*	2.9J	*	*	*	*	*	*
Benzene	3.9J	2.9J	*	*	*	*	2.7J	4.8J	*	7.6J	3.2J	*	*	*	*	*	*	*
Toluene	5	3.2J	3.1J	2J	2.8J	2J	2.1J	2.6J	2.2J	6.5J	3.4J	2.5J	2.5J	2J	2.9J	2.4J	1.7J	3.8J

[1] All concentrations are in micrograms per cubic meter of sampled air.
[2] Art = artificial turf athletic field
[3] Nat = natural grass athletic field
* Indicates compound was not detected (i.e., was below the method detection limit, MDL).
J Indicates the value was estimated, registering between the method detection limit (MDL) and the reporting limit (RL).
[4] Beach samples are described in the methods section.
[5] Midpoints of 45-minute sampling intervals are shown in the table.
Another 87 volatile organic compounds from the target list were not detected in any sample (i.e., were below their MDLs).

Comparing towns

The data from all four artificial turf fields in the four different towns can be compared to determine whether any VOCs were consistently detected above artificial turf. To do this, we first identified the VOCs that were reproducibly detected above any one of the four artificial turf fields; i.e., were measured in at least two of the eight samples collected from any artificial turf field. Those VOCs are shown in Table 9. Nine VOCs met this criterion (the probable contaminants discussed above are not included). Eight of these were reproducibly detected over only a single field. Toluene was reproducibly detected over two fields. It should be noted that at town #3, the natural turf field had as many toluene detects (4/8) as the artificial turf field. Taken together, these data demonstrate little field-to-field consistency with regards to the VOCs detected over artificial turf. One possible explanation is that the batches of recycled crumb rubber infill used to construct each field emitted different VOCs. Another possibility is that the small amounts of VOCs emitted by these fields usually did not accumulate to measurable concentrations in the open air. It may also be that the low levels detected in a few samples reflected concentrations of the ambient air.

Table 9. VOCs that were detected in at least two of eight air samples collected from above an artificial turf field (i.e., reproducibly detected in that field).

VOC	Artificial turf field where VOC detected in ≥ 2 samples	Artificial turf field where VOC detected in 1sample or not detected
2-Propanol	Town #1	Towns #2,3,4
Cyclohexane	Town #1	Towns #2,3,4
Toluene	Towns #1 and #3	Towns #2 and #4
m,p-Xylene	Town #2	Towns #1,3,4
Isopropylbenzene	Town #2	Towns #1,3,4
o-Xylene	Town #2	Towns #1,3,4
4-Ethyltoluene	Town #2	Towns #1,3,4
1,2,4-Trimethylbenzene	Town #2	Towns #1,3,4
Allyl chloride	Town #3	Towns #1,2,4

Each chemical in Table 9 can also be tracked in each individual artificial turf field to assess the consistency of its detection during the sampling day. Tables 5-8 show that there was little consistency over the sampling day. Most VOCs were detected in only a few samples per field and were below the MDL in the majority of samples. A low frequency of detection such as observed here suggests that if these chemicals are released by these fields, they are released at low levels. Such low level release might also help explain the relatively poor agreement between many duplicate samples (Tables 5-8).

It is also worth comparing the concentrated air samples collected from inside the garbage can inverted on the artificial field at town #2 (Table 3) to the samples collected from four feet above that field in the open air (Table 6). Among the VOCs detected inside the garbage can, 4-methyl-2-pentanone was the only one detected in both samples that was not detected in either beach control. Both samples were above the reporting limit: the concentrations detected were 14.8 and 21 $\mu g/m^3$. In contrast, 4-methyl-2-pentanone was only detected in one of eight open air samples collected from the same artificial turf field, at a concentration of 3.5 $\mu g/m^3$. A possible explanation is that the rate of 4-methyl-2-pentanone emission by this field was insufficient to reproducibly raise its concentration in the open air to above its MDL. Since this compound concentrated to a higher level inside the garbage can than any other VOC (contaminants such as acetone excluded), it was to be expected that few if any other VOCs would be reproducibly detected in the open air samples for this field. This turned out to be the case for all the fields in all four towns (Table 9).

Most of the VOCs shown in Table 9 were detected over field #1 (one year old) or field #2 (eight months old). These were also the newest fields in the study. Since VOC emissions from crumb rubber infill decreased over time in a laboratory study (Xi et al., 2010), it might be expected that more VOCs would be detected over newer fields.

Estimating the amount of organized soccer played on artificial turf fields

A number of managers of parks with artificial turf athletic fields mentioned that by far the heaviest use of their fields was for organized soccer leagues. This suggests that, currently, the athletes most heavily exposed to chemicals emitted by artificial turf fields are those playing organized soccer. To estimate the maximum time (worst-case scenario) children and adults spend each year playing soccer on artificial turf, we conducted a survey to estimate the time they spend each year playing organized soccer on all fields, artificial and natural.

Soccer coaches are in the best position to give accurate estimates of soccer playing time. Therefore, we obtained permission from the California Youth Soccer Association (CYSA, northern division) to circulate a survey to its member coaches via its newsletter. The survey was conducted in September 2009. There were 236 coaches who responded to the survey. The coaches were asked to concentrate their responses on the enthusiastic soccer players who tend to play the most soccer per year for many years.

Table 10 shows the coaches' estimates of how much time ardent soccer players spend in organized league play (including organized practices) as a function of age. The large standard deviations indicate the estimates varied widely. Organized league play peaks during high school. For all ages, the 95^{th} percentile values are approximately two- to three-fold greater than the average values. Since the coaches were asked to focus their estimates on enthusiastic players, we consider the average values to be the most appropriate values for estimating the exposure of each age group to VOCs. As shown in Table 10, high school players have the highest average usage hours per year, at 222 hrs./year. This value is used to adjust chemical concentrations in air in the following sections.

Table 10. California Youth Soccer Association (CYSA) coaches' survey of hours per year enthusiastic soccer players spend in organized practices and games[1]

School or adult years	Age in years inclusive	Average hours per year (standard deviation)[2]	95th percentile hours per year
Preschool/Kindergarten	4-5	31 (18)	64
Grammar	6-11	95 (100)	280
Middle School	12-14	147 (108)	320
High School	15-18	222 (152)	475
College	19-22	186 (151)	430
Adult	23-29	116 (103)	359
Adult	30-39	83 (52)	158
Adult	40-49	73 (55)	189
Adult	50-59	74 (83)	222

[1] Survey conducted in September 2009. There were 236 coaches who responded to the survey. Coaches were asked to concentrate on enthusiastic soccer players.
[2] Hours spent in organized soccer practices and games as part of an organized league (youth, school or adult) held on any type of athletic field.

Estimating VOC exposures to persons using artificial turf fields

The VOCs detected over the fields in Tables 5-8 were screened to determine whether any fulfilled the following two criteria:

- Detected in at least two of the eight samples collected from above one of the artificial turf fields, indicating their detection at that field was reproducible.
- Detected in the same artificial turf field at an average concentration (average of eight samples per field) that was greater than the average concentration of the nearby natural turf field (suggesting the artificial turf released the chemical into the air).

Seven chemicals satisfied the above two criteria. Two types of exposure estimates were made covering these seven chemicals, as shown in Table 11. The first was for chronic exposure and assumed that athletes use these fields for at least one year. However, we also assumed that field use is intermittent within any year. Therefore, the average chemical concentration detected over an artificial turf field was prorated for an exposure period of 222 hours/year (column five) as shown in footnote three of the table.

The second set of estimates in Table 11 address acute, one-time exposures. To estimate the highest acute exposure likely to occur, the highest VOC concentration measured on the field is selected (column three) without any time adjustment.

Table 11. VOC exposure concentrations for persons using artificial turf fields (all concentrations in μg/m³).

VOC	Town with artificial field with highest average VOC concentration	Highest VOC concentration over indicated artificial turf field (acute exposure) [1]	Average VOC concentration over indicated artificial turf field [2]	Value from column four averaged over 222 hrs of artificial turf field use per year (chronic exposure) [3]
2-Propanol	Town #1	1.9	0.9	0.02
Cyclohexane	Town #1	1.2	0.7	0.02
Toluene	Town #1	6.4	2.1	0.05
m,p,o-xylenes	Town #2	44.3	15.3	0.38
Isopropylbenzene	Town #2	11.6	3.8	0.10
4-Ethyltoluene	Town #2	6.3	2.2	0.06
1,2,4-Trimethylbenzene	Town #2	10.7	4.3	0.11

[1] The highest value from among the four time points per field. Each time point was an average of the two duplicate samples collected for that time point. For example, for m,p-xylene the 8:34 time point had values of 26.2 and 1.6 (1/2 the MDL), yielding an average value for the time point of 13.9. For o-xylene, the 10:33 time point had values of 60 and 0.8 (1/2 the MDL), yielding an average value of 30.4. Adding these two averages gives 44.3 for the three xylene isomers.
[2] To calculate the average chemical concentration over each field, nondetects were given the value of one-half the MDL, and the values for the eight air samples per field were averaged. For example, for m,p-xylene the average of the eight air samples (26.2+1.6+1.6+14.5+1.4+1.6+1.6+1.6) was 6.3. Similarly, the average for o-xylene was 9.0. Adding these two averages gives 15.3 for the three xylene isomers.
[3] Multiply values in the fourth column by 222/8760. The value of 222 is hours of artificial turf field use per year, and was taken from Table 10. It represents the age group playing the most organized soccer in a year (15-18 year-olds). The value of 8760 is the number of hours in a year.

Table 11 shows that the VOC exposure concentrations are approximately 100-fold lower for chronic exposures compared to acute exposures. Xylene exposures are the highest, at 0.38 μg/m³ and 44.3 μg/m³ for the chronic and acute scenarios, respectively.

A screening-level estimate of inhalation health risks to persons using artificial turf athletic fields

Two kinds of screening-level health risk estimates are presented below in Table 12. The first covers chronic exposures, in which average chemical concentrations over artificial turf fields prorated for an exposure period of one year (column four) are compared to chronic health-based screening values (column five). The second covers acute exposures in which the maximum chemical concentrations detected over artificial turf fields (column two) are compared directly to acute screening values (column three). Acute screening values were not available for isopropylbenzene, 4-ethyltoluene or 1,2,4-trimethylbenzene. Subchronic screening values were used instead, as described in the footnotes to the table. Screening values are published by authoritative bodies, usually governmental. They indicate the concentrations of chemicals in the air below which adverse human health effects are not expected.

None of the seven VOCs is on the California Proposition 65 List of Chemicals Known to the State to Cause Cancer. Therefore, cancer risks were not calculated.

Table 12. Screening-level estimates of health risks to persons breathing VOCs in the air above artificial turf (all concentrations in μg/m^3).

VOC	Highest VOC concentration over artificial turf[1]	Acute health-based screening value	VOC concentration over artificial turf averaged over one year[2]	Chronic health-based screening value
2-Propanol	1.9	3,200[3]	0.02	7,000[3]
Cyclohexane	1.2	10,300[4]	0.02	80,000[5]
Toluene	6.4	3,700[3]	0.05	300[3]
m,p,o-xylenes	44.3	22,000[3]	0.38	700[3]
Isopropylbenzene	11.6	4,000[6]	0.10	400[6]
4-Ethyltoluene	6.3	850[7]	0.06	85[7]
1,2,4-Trimethylbenzene	10.7	70[8]	0.11	7[8]

[1] Third column in Table 11.
[2] Fifth column in Table 11.
[3] OEHHA, 2010.
[4] A human study by Hathaway et al. (1991) yielded a lowest observed adverse effect level (LOAEL) of 1,030 mg/m^3. Dividing by a factor of 10 to extrapolate to a no observed adverse effect level (NOAEL) and dividing by another 10 for inter-individual variability yields an acute screening value of 10.3 mg/m^3.
[5] ACGIH, 1994. 8 hr time weighted average (TWA) occupational exposure limit of 350 mg/m^3 multiplied by 8 hr/day X 250 days/year X 1/(8760 hrs/year).
[6] IRIS, 2010. The acute screening value in the table above was derived from the chronic RfC by omitting the factor of 10 used to extrapolate from subchronic to chronic exposure.
[7] A study in the rat by Swiercz et al. (2000) yielded a no observed adverse effect level of 477 mg/m^3 for a four week exposure at 6 hrs per day and 5 days per week. Multiplying by (6 hr/24 hr) and (5 days/7 days) adjusts for exposure duration, giving an adjusted value of 85 mg/m^3. Dividing by 10 for rat to human extrapolation and 10 for interindividual variability gives a subchronic screening value of 850 μg/m^3. This value is used in the table above for the acute screen. Dividing by 10 for subchronic to chronic extrapolation yields a chronic screening value of 85 μg/m^3.
[8] U.S. EPA, 2007. The citation provided a subchronic and chronic provisional reference concentration (p-RfC). The subchronic p-RfC was used for the acute screen and the chronic p-RfC was used for the chronic screen.

The chronic exposure concentrations in column 4 range from approximately 64-fold (1,2,4-trimethylbenzene) to 4 million-fold (cyclohexane) lower than the corresponding chronic health-based screening values in column five. These large differences suggest that these chemicals do not pose serious inhalation health risks to athletes using these fields over extended time periods.

The acute exposure concentrations in column two are also lower than the corresponding acute screening values in column three. However, the differences are less than for the chronic screen, ranging from 6.5-fold in the case of 1,2,4-trimethylbenzene to almost 8,600-fold in the case of cyclohexane. It should be noted that a subchronic screening value was used to estimate the acute risk to 1,2,4-trimethylbenzene. If an acute screening value was available, the margin of safety would probably be significantly greater. Nonetheless, the differences between the VOC concentrations above these fields and their acute health-based screening values (Table 12) indicate that acute health effects are also unlikely to result from breathing the air over these fields.

Conclusions

Air sampling was conducted at a height of four feet above four artificial turf fields containing recycled crumb rubber infill. Nine VOCs from a target list of 94 chemicals were detected in at least two of eight air samples collected from above an artificial field throughout the sampling day (Table 9). Six of these were also detected over natural turf or in control "beach" samples.

The VOC concentrations above any one field, sampled at the same location on each field, exhibited little consistency over the course of the day (Table 5-8). There was also little consistency between artificial turf fields in different towns. Toluene was the only VOC that was detected in at least two of eight samples per field in two artificial fields (Table 9). A possible explanation for these findings is that artificial turf emits VOCs at low levels, such that their concentrations above the field are usually too low to be detected (i.e., below the MDL).

The surface temperatures of the artificial turf fields increased from 34 to 55^{o}F over the course of the day. This allowed a robust test of the effect of temperature on VOC concentrations over artificial turf. No effect of temperature was observed on the concentrations of VOCs over any of the fields, artificial or natural. Since in laboratory studies recycled crumb rubber infill emitted more VOCs as the temperature increased (New York State, 2009), the absence of a temperature effect in the field is consistent with the hypothesis that usually the VOCs were emitted at levels too low to be measured in the open air. Alternatively, the VOCs detected may have already been in the ambient air or may have been due to occasional laboratory contamination.

Despite the inconsistent detection of VOCs over artificial turf, the data were screened to identify chemicals that were detected in at least two of eight samples collected from an artificial field, and to determine whether the average concentration over that field was greater than the average concentration over the nearby natural turf field. The seven chemicals meeting these criteria were screened for acute and chronic health risks.

Acute exposures to persons using these fields were the unadjusted, highest VOC concentration detected over the artificial field (Table 11). Chronic exposures were calculated using the average VOC concentration over the field on the sampling day, averaged over 222 hours of artificial turf field use per year. These usage hours represent the time enthusiastic soccer players 15-18 years of age spend in organized practices and games in a year. The acute and chronic exposures were compared to health-based screening values in a screening-level estimate of health risks (Table 12).

For both the acute and chronic exposure scenarios, the large differences between the estimated exposure concentrations and the screening values suggest that adverse health effects are unlikely to occur in persons using these fields. Similar conclusions were reached in two other studies conducted within the past two years (New York State, 2009; Connecticut Department of Public Health, 2010).

Uncertainties

There are a number of uncertainties associated with our screening-level risk estimates presented in Table 12. Uncertainties that would tend to overestimate the health risks include:

- The chronic exposure scenario assumes that athletes play 100 percent of their organized soccer on artificial turf with crumb rubber infill. This is unlikely and therefore overestimates the risk.
- Air sampling during cold weather might detect fewer and lower levels of VOCs than detected during the hot summer weather in this study. If so, then using the data collected during the summer to estimate exposure for a year overestimates the exposure.
- Subchronic screening values were used to estimate the risks of acute adverse health effects for three VOCs. This would likely lead to an overestimation of risk.

Uncertainties that lead to underestimations of the health risks posed by the VOCs in the air over artificial turf containing crumb rubber infill include:

- The chronic exposure scenario assumes that athletes only play soccer on these artificial surfaces. However, athletes may participate in other organized sports that commonly take place on artificial turf fields such as football, baseball, and lacrosse. Participation in multiple sports would increase the exposures estimated here.
- Recycled tire rubber emits hundreds of VOCs (CIWMB, 2003). Our target list of VOCs contained 94 chemicals (U.S. EPA Method TO-15). Therefore, it was not possible to screen for all of the VOCs emitted by recycled crumb rubber. Since many remain unidentified, their concentrations above artificial turf, as well as their potential health effects, are unknown. However, the recent study by Simcox et al. (2010) suggests that the concentrations of unidentified VOCs over artificial turf are very low. This may be inferred from the finding that the levels of total volatile organic compounds (TVOCs) over artificial turf fields were no higher than the levels upwind of the fields and over natural turf.
- Another uncertainty relates to the chronic screening level developed here for cyclohexane (Table 12). An occupational standard was used to develop the screening level. Occupational standards may not be sufficiently protective for the general public, including the elderly and children. However, occupational standards are useful for screening-level risk estimates. In addition, the 4 million-fold difference between the cyclohexane screening level and the estimated exposure concentration suggests that the risk of health effects from exposure to cyclohexane is very low.

Study limitations

- The method used to calculate exposures (Table 11) assumed that samples with a chemical concentration below the detection limit (nondetects) contained that chemical at a concentration of one-half the MDL. Since either five or six of the eight field samples used to calculate each exposure concentration were nondetects, this has the potential to introduce significant bias into the calculation (Helsel, 2005). Development of more sensitive methods for reducing the number of nondetects in future studies will help reduce this source of bias.

- The artificial turf fields comprising this study were sampled from eight months to five years after installation. Since the emission of many VOCs from crumb rubber infill decreased over time in laboratory tests (Xi et al., 2010), it is likely that VOC release would be greatest shortly after field installation. Whether VOCs emitted by newly installed fields accumulate to measurable concentrations in the air can be tested by sampling the air above new fields.
- This study covered outdoor fields made of artificial turf. However, artificial turf is also being used in indoor sports stadiums. VOCs released by indoor fields have the potential to accumulate, depending on the building's ventilation rate. A recent study by Simcox et al. (2010) found significantly higher concentrations of VOCs and sVOCs over an indoor artificial turf field compared to outdoor fields. However, some complications discussed in that report (such as no building ventilation on the day of air sampling) suggest that additional indoor fields should be sampled to determine if VOC levels over indoor artificial turf fields pose health risks. A Norwegian study (Dye et al., 2006) of artificial turf fields in indoor stadiums concluded that health risks were unlikely to result from the VOC and sVOCs in the stadium air.
- Our study analyzed VOCs in the air above four artificial turf fields. This is a small number compared to the number of artificial fields already in use and those to be installed in the near future. It remains possible that different lots of recycled crumb rubber emit different VOCs. Recent laboratory measurements by Simcox et al. (2010) demonstrated fairly good agreement between different samples of crumb rubber of similar age and the VOCs they emitted. However, some differences were detected.
- The new generation of artificial turf contains other materials in addition to crumb rubber infill, including synthetic blades of grass, backing material, and various types of adhesives. It is possible that some of the VOCs we detected may have originated from these materials rather than from the crumb rubber.

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Chapter 2

Is the New Generation of Artificial Turf Containing Recycled Crumb Rubber Infill a Significant Source of Airborne Particulate Matter (PM2.5)?

Abstract

Outdoor athletic fields made of the new generation of artificial turf containing crumb rubber infill from recycled tires were analyzed to determine if they release significant amounts of airborne particulate matter of aerodynamic diameter less than 2.5 microns ($PM_{2.5}$). Air above three fields was sampled for three-hour intervals during periods of active field use (soccer games or practices). For comparison, the ambient air was analyzed by sampling upwind of the fields. $PM_{2.5}$ was collected on pre-weighed Teflon filters followed by gravimetry to determine its weight. X-ray fluorescence (XRF) was performed on the filters from two of the fields to measure the elemental content of the $PM_{2.5}$. The weight of $PM_{2.5}$ in the air above two fields was below the limit of detection. For the third field, the weight of $PM_{2.5}$ was similar in the air above and upwind of the field (from 12 to18 µg/m^3). In the two fields analyzed by XRF, five elements were detected in the $PM_{2.5}$ at levels above the limits of detection: sodium, calcium, potassium, chlorine, and sulfur. Therefore, these elements could serve as markers for the $PM_{2.5}$ collected on the filters. The concentrations of all five elements were similar above and upwind of the fields, suggesting that the concentrations of $PM_{2.5}$ at both locations were also similar. Another 32 elements, including heavy metals such as lead, cadmium, mercury, nickel, arsenic, manganese, and chromium, were below the limits of detection. These data indicate that the new generation of artificial turf containing crumb rubber infill is not a significant source of airborne $PM_{2.5}$ or heavy metals associated with $PM_{2.5}$

Introduction

Airborne particulate matter with a mass median aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) is a potential source of human toxicity via the inhalation route. Due to their small size, upon inhalation these particles penetrate deeply into the lungs, into the region where gas exchange occurs. If these particles are deposited in this region, chemicals or metals they contain have the potential to pass quickly into the bloodstream. Increased $PM_{2.5}$ concentrations of 10 µg/m^3 correlated with increased incidences of human disease, including respiratory and cardiovascular disease (Ostro et al., 2006; Ostro et al., 2007; Peng et al., 2009; Zanobetti and Schwartz, 2009). Hospital admissions and mortality also increased with increased concentrations of $PM_{2.5}$. Importantly, the increases in hospital admissions, mortality and $PM_{2.5}$ occurred during time frames as short as one or two days, suggesting that acute exposure to elevated levels of $PM_{2.5}$ is sufficient to cause human toxicity. This is supported by studies of mice exposed via intratracheal instillation of $PM_{2.5}$ collected from ambient air, where it was acutely toxic to lung tissue (Wegesser et al., 2009). Thus, data from both laboratory studies of animals and epidemiological studies of humans indicate that $PM_{2.5}$ in the ambient air can be acutely toxic. The $PM_{2.5}$ discussed above was emitted into the air largely through combustion. Two examples are emissions from vehicles (particularly diesel) and emissions from wood fires. More recently, specific components of the $PM_{2.5}$ in the ambient air were shown to be particularly toxic. These included elemental carbon and organic carbon, both of which correlated with increased risks of hospital admissions for cardiovascular and respiratory diseases (Peng et al., 2009) and increased mortality (Ostro et al., 2007). Whether the $PM_{2.5}$ potentially generated by artificial turf fields containing crumb rubber infill would contain chemicals as toxic as those in the $PM_{2.5}$ generated by combustion, is not known.

The new generation of artificial turf often contains infill composed of recycled tire rubber. The rubber is processed (at ambient or cryogenic temperatures) into millimeter-sized pieces of rubber crumb that simulate natural soil. The process of mechanical grinding of rubber generated measurable levels of airborne PM_{10} (airborne particulate matter with mass median aerodynamic diameter of less than 10 µm; Chien et al., 2003). Both $PM_{2.5}$ and PM_{10} were detected in the air above ***indoor*** artificial turf fields containing rubber crumb (Dye et al., 2006), although the particulate matter in the ambient air was not measured for comparison. Recent measurements of PM_{10} (U.S. EPA, 2009) and both PM_{10} and $PM_{2.5}$ (New York State, 2009; TRC, 2009) over ***outdoor*** artificial turf fields suggest that these fields do not release significant amounts of particulate matter in either size class. In the case of $PM_{10,}$ the amounts of 12 elements (including seven heavy metals) in these particles were similar whether the air was sampled from above or upwind of these fields (U.S. EPA, 2009). These studies suggest that outdoor artificial turf containing rubber crumb does not release significant amounts of $PM_{2.5}$, PM_{10}, or PM_{10}-associated metals into the air. We have been unable to locate any data on the metals content of $PM_{2.5}$ sampled from above outdoor artificial turf fields. Therefore, our goal was to determine whether ***outdoor*** artificial turf fields containing rubber crumb are point sources for the release of $PM_{2.5}$ and $PM_{2.5}$-associated metals into the air. To accomplish this we visited three such fields and sampled the air both above and upwind of each field.

Methods

Permission was obtained from three San Francisco Bay Area cities to perform air sampling at city fields during soccer games or practices. One city manager estimated that 80-90 percent of field usage was for soccer. Air samples were collected during periods of active field use, since $PM_{2.5}$ generation or release into the air, if they occurred at all, were expected to be maximal at those times.

All three fields consisted of new generation artificial turf containing crumb rubber infill made from recycled tires. Fields #1, #2 and #3 were 26, 8 and 3 months old, respectively, at the time of air sampling. Each artificial turf field contained a marked soccer field. The artificial turf extended past the boundaries of each soccer field by at least three to five meters on every side. The air sampling equipment was placed about one meter from a sideline or endline of the marked soccer field, on the downwind side of the field. Wind speed and direction were monitored continuously with a wind meter and weather vane (Nielsen-Kellerman, PA). The prevailing winds in the San Francisco Bay Area tend to be out of the west or northwest during the spring and summer. Such was the case during all air sampling. There was no significant precipitation on the day preceding sampling or the day of sampling. Immediately before or after air sampling at each artificial turf field, air was sampled in an identical manner at a location a few hundred meters upwind of each field (see below).

Air sampling for $PM_{2.5}$ and associated metals was performed with a MiniVol Tactical Air Sampler from Airmetrics (Eugene, OR). This device pumps air through two impactors in series followed by a 47 mm Teflon filter. The first impactor removes particles with a mass median aerodynamic diameter of greater than 10 µm. The second impactor removes particles greater than 2.5 µm. The remaining particles less than 2.5 µm in diameter ($PM_{2.5}$) were collected on the pre-weighed Teflon filters (weighed at Chester LabNet in Tigard, OR, after equilibrating at the correct temperature and humidity for 24 hours). Filters were returned to the lab for weighing a second time (gravimetry) and measurement of metals by X-ray fluorescence (XRF).

For each of the three artificial turf fields, one air sample was collected from above the field (during active field use) and one sample from upwind of the field during consecutive three hour sampling periods. The next day this was repeated at the same two locations, again during active field use, yielding two "field" samples and two "upwind" samples per field. Air sampling was performed at a height of four feet above the ground to approximate the breathing height of children. The flow rate of pumped air was adjusted to five liters per minute, including correction for temperature and pressure according to the manufacturer's instructions. At this flow rate, 0.9 m^3 of air was sampled during each three hour period. A single-point flow rate check was performed with a calibrated manometer. The measured flow rate of the MiniVol Tactical Air Sampler differed from the calculated flow rate by less than one percent. Sample "blanks" were included for both gravimetry and XRF analysis. Sample "blanks" were filters that were treated exactly like the filters used for air sampling (i.e., all filters were weighed at the lab), but upon receipt by us were never removed from their packaging, prior to being sent back to the lab to be weighed for the second time.

Results

Table 1 shows the gravimetric data for air sampling above the three artificial turf fields. Filter net weights above the limit of detection (LOD) of 26 µg per filter were only collected at one of the fields (field #2). This suggests that the $PM_{2.5}$ concentrations in the air above and upwind of field #1 and field #3 were too low to measure by the gravimetric method used here. Extending the sampling period to 24 hours most likely would have increased the filter net weights to above the LOD; however, this also would have extended sampling to periods when the fields were not in use, complicating interpretation of the data.

Focusing on field #2, $PM_{2.5}$ concentrations ranged from 12 to 18 µg/m^3. There was good agreement between the two "field" samples (16 and 18 µg/m^3) and between the two "upwind" samples (12 and 16 µg/m^3). The "field" and "upwind" values were similar, indicating that the field was not a point source for the release of significant amounts of $PM_{2.5}$ into the air. Unfortunately, since only these four filter net weights (from among the 12 samples collected at the three fields) were above the LOD, statistical analysis of the difference between "field" and "upwind" values was not possible. However, the XRF data presented below indicate that the $PM_{2.5}$ collected from above or upwind of the fields had the same elemental composition, suggesting it originated from the same source.

Following gravimetric analysis, the filters from fields #2 and #3 were analyzed by XRF. This procedure allowed quantification of 37 elements associated with the airborne $PM_{2.5}$. The LODs for some elements were more than 1,000-fold lower than the gravimetric LOD. Thus, the XRF data allowed detection of $PM_{2.5}$ at much lower concentrations than gravimetry.

Table 2 shows the XRF data. The mass of sulfur (S) associated with $PM_{2.5}$ collected from above and upwind of both fields ranged from 13- to 35-fold higher than the LOD. These high sulfur levels relative to the LOD provide more confidence in the accuracy of the sulfur data compared to the gravimetric data presented in Table 1. The mass of $PM_{2.5}$-associated chlorine (Cl) collected from field #3 was even higher, ranging from 352- to 496-fold higher than the LOD. Potassium (K), calcium (Ca), and sodium (Na) collected from above field #2 were also higher than the corresponding LOD, although the sodium values were less than two-fold higher than the LOD (Table 2).

Table 1. $PM_{2.5}$ air concentrations above three artificial turf fields: gravimetric data.

Artificial turf field	Date sampled	[1]Sample type	[2]Net weight of each filter (µg)	[3]$PM_{2.5}$ air concentration (µg/m^3)
#1	4/29/09	Upwind	12	NC
#1	4/29/09	Field	19	NC
#1	4/30/09	Upwind	19	NC
#1	4/30/09	Field	13	NC
#1	4/30/09	Blank	12	NA
#2	5/9/09	Upwind	30	16
#2	5/9/09	Field	30	16
#2	5/10/09	Upwind	27	12
#2	5/10/09	Field	32	18
#2	5/10/09	Blank	13	NA
#2	5/10/09	Blank	20	NA
#2	5/10/09	Blank	14	NA
#3	6/6/09	Upwind	25	NC
#3	6/6/09	Field	12	NC
#3	6/7/09	Upwind	18	NC
#3	6/7/09	Field	16	NC
#3	6/7/09	Blank	16	NA
#3	6/7/09	Blank	19	NA
#3	6/7/09	Blank	11	NA
LOD (see footnote 2) = 26 µg/filter				

[1] "Upwind" samples were collected a few hundred meters upwind of each field; "field" samples were collected along the field's sideline or endline on the downwind side of the field during soccer games or practice; "blank" samples were filters that were never removed from their packaging prior to being returned to the laboratory for weighing.
[2] Filter net weights (filter weight after sampling minus filter weight before sampling) reported by the analyzing laboratory. Four values for field #2 were above the limit of detection (LOD) of 26 µg per filter [LOD = average of the seven "blank" net weights + (3.14 x standard deviation) = 15 + (3.14 x 3.5) = 26; (Keith, 1991)]
[3] Concentrations calculated by subtracting the field #2 average "blank" net weight (16) from each "upwind" or "field" net weight and dividing by 0.9 m^3 to correct for the amount of air sampled. NC = not calculated, since filter net weights were below the LOD. NA = not applicable.

The XRF data in Table 2 also allow a comparison between the "field" and "upwind" concentrations of these elements. Surveying all five elements, the concentration ranges of the "field and "upwind" samples were similar, indicating that the fields were not significant sources for the release of $PM_{2.5}$ containing these elements. These results compliment the gravimetric results.

Table 2. Air concentrations of elements associated with $PM_{2.5}$ collected from above two artificial turf fields.

Artificial turf field	Date sampled	[1]Sample type	[2]Na	[2]S	[2]Cl	[2]K	[2]Ca
#2	5/9/09	Upwind	3.95/3.82	0.61/0.67	4.96/5.51	0.12/0.13	0.18/0.18
#2	5/9/09	Field	3.70/3.54	0.51/0.56	4.66/5.18	0.11/0.12	0.14/0.14
#2	5/10/09	Upwind	2.25/1.93	0.65/0.71	3.52/3.91	0.07/0.08	0.12/0.12
#2	5/10/09	Field	2.92/2.68	0.70/0.77	3.55/3.94	0.09/0.10	0.15/0.15
#2	5/10/09	Blank	0.84/	0.01/	0.00/	0.00/	0.01/
#2	5/10/09	Blank	0.17/	0.00/	0.00/	0.00/	0.02/
#3	6/6/09	Upwind	[4]	0.35/0.39	[4]	[4]	[4]
#3	6/6/09	Field	[4]	0.32/0.36	[4]	[4]	[4]
#3	6/7/09	Upwind	[4]	0.27/0.25	[4]	[4]	[4]
#3	6/7/09	Field	[4]	0.25/0.28	[4]	[4]	[4]
#3	6/7/09	Blank	1.15/	0.00/	0.00/	0.00/	0.00/
#3	6/7/09	Blank	0.19/	0.00/	0.01/	0.00/	0.02/
[3]LOD			2.13	0.02	0.01	0.00	0.04

[1] "Upwind" samples were collected a few hundred meters upwind of each field; "field" samples were collected along the field's sideline or endline on the downwind side of the field during soccer games or practices; "blank" samples were filters that were never removed from their packaging prior to being returned to the laboratory for analysis.
[2] Concentrations of elements associated with $PM_{2.5}$. Each value to the left of the slash is the amount of element (in µg) detected on each filter by X-ray fluorescence (XRF). Each value to the right of the slash is the final air concentration (in µg/m^3) calculated by subtracting the average blank value for that field from the measured amount of element and dividing by 0.9 m^3 to correct for the amount of air sampled. Only those elements are shown where the amounts of both "field" samples were above the limit of detection (LOD, see footnote 3) and above the laboratory's 99.7 percent confidence minimum detectable limit (MDL). Another 32 elements (including lead) were measured but not included in the table since the values were below the LOD and/or MDL.
[3] Each limit of detection (LOD) was determined using the four sample "blanks" from the two artificial turf fields. A sample "blank" was a filter that was never removed from its packaging prior to being returned to the laboratory for analysis by XRF. The calculation was: LOD = average "blank" value + [(3.14) x (standard deviation)].
[4] Amount of element in one or both "field" samples was below the LOD and/or MDL.

Another 32 elements analyzed by XRF were below the LOD and/or laboratory MDL (minimum detectable limit, as reported by the analyzing laboratory, see footnote 1 to Table 3) (data not shown), and therefore were not detected in the $PM_{2.5}$ collected from either upwind or above the artificial turf fields. Some of the toxicologically important elements not detected were arsenic, cadmium, chromium, lead, manganese, mercury, and nickel (Table 3). The LOD for lead was 0.12 $\mu g/m^3$. Zinc was also below its detection limits (Table 3).

Table 3. Laboratory MDLs and calculated LODs for X-ray fluorescence (XRF) performed to detect selected elements in the $PM_{2.5}$ fraction collected from above or upwind of artificial turf fields.

Element	Laboratory 99.7 percent confidence minimum detectable limit (MDL[1]) in $\mu g/m^3$	Limit of detection (LOD[2]) in $\mu g/m^3$
Arsenic	0.057	0
Cadmium	0.15	0.26
Chromium	0.021	0.0024
Lead	0.09	0.12
Manganese	0.031	0.04
Mercury	0.011	0.14
Nickel	0.065	0.06
Zinc	0.076	0.02

[1] MDLs, reported by the laboratory performing the XRF, were based on uncertainties associated with calibration, counting statistics, peak overlap correction, and absorption correction.
[2] LODs were calculated as described in footnote 3 of Table 2.

Discussion

Once particles with a mass median aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) become airborne, they can travel for days over many miles. Their small size permits inhalation deep into the lungs, into the alveolar region where gas exchange occurs. If these particles are deposited in this region, they become a potential health concern, depending on their chemical composition.

The ground rubber infill used in the new generation of artificial turf is a potential source of $PM_{2.5}$. It has been reported that the grinding process itself generates particles of rubber in the 10 µm range (Chien et al., 2003; $PM_{2.5}$ was not analyzed in this study). It is not known if cryogenic processing of recycled tires into rubber crumb does the same. In addition, it is not known whether the mechanical forces produced by athletes running on these fields generate $PM_{2.5}$.

Prior to our study, some air sampling had been performed over indoor and outdoor artificial turf fields to measure $PM_{2.5}$ levels. In the case of **indoor** fields enclosed in covered stadiums (Dye et al., 2006), $PM_{2.5}$ was detected at concentrations up to 19 $\mu g/m^3$, about 50 percent of which consisted of rubber. However, in this study, $PM_{2.5}$ levels in the air outside of the stadiums were not measured, making it difficult to pinpoint the source of the indoor $PM_{2.5}$. Two studies showed that the $PM_{2.5}$ concentrations in the air over **outdoor** fields were not different from concentrations upwind of the fields, indicating that the fields were not significant sources of $PM_{2.5}$ release (TRC, 2009; New York State, 2009). The results of our study, covering three **outdoor** fields, are consistent with the two earlier **outdoor** studies.

Measurement of total $PM_{2.5}$ by gravimetry yielded values above the LOD at one of three fields (Table 1). This was not unexpected since a relatively small volume of air (0.9 m^3) was filtered during the three hour sampling intervals. Three-hour intervals were chosen to ensure that each sampling interval covered a period of constant and intensive field use, when $PM_{2.5}$ generation and/or release was expected to be maximal.

Looking specifically at the gravimetry for field #2, the $PM_{2.5}$ concentrations ranged from 12 to 18 $\mu g/m^3$. This range agrees well with mean concentrations reported for other U.S. cities and populous counties (Liu et al., 2009; Peng et al., 2009; Zanobetti and Schwartz, 2009). The gravimetric data for the three fields indicate the $PM_{2.5}$ concentration was above the LOD at one field and below the LOD at the other two. Comparing the two "field" values to the two "upwind" values for field #2, the concentrations are similar, suggesting the field was not a source of airborne $PM_{2.5}$. Therefore, for the three fields monitored for airborne $PM_{2.5}$, two had levels that were below the LOD and one had levels similar to the ambient level. These data suggest that the artificial turf fields are not significant sources of $PM_{2.5}$ release.

One possible explanation for our finding of similar $PM_{2.5}$ concentrations over and upwind of these fields is that these fields may not contain rubber particles in this size class. This possibility was tested by wipe sampling and vacuum sampling two artificial turf fields in New York State (New York State, 2009). The collected material was analyzed by light and electron microscopy to determine particle size. The chemical content of the particles was measured by Fourier Transform Infrared (FITR) spectroscopy. Particles fell into two size classes: a large size class in the millimeter range that contained rubber particles, and a small size class that averaged 5-7 microns in diameter composed of minerals such as quartz and calcite, along with biological material such as pollen and mold. Rubber particles were not present in the smaller (respirable) size class. This work suggests that crumb rubber infill does not contain significant amounts of rubber particles in the size class capable of becoming airborne $PM_{2.5}$.

The XRF measurements presented here were significantly more sensitive than the gravimetry. LODs were more than 1,000-fold lower for some elements compared to the gravimetry. Sulfur values from both fields ranged from 13- to 35-fold higher than their LOD (Table 2), providing a sensitive marker for the sulfur-containing fraction of the $PM_{2.5}$ collected from above and upwind of these fields.

The concentrations of sulfur associated with $PM_{2.5}$ ranged from 0.25 to 0.77 $\mu g/m^3$. This range is similar to the median value of 0.9 $\mu g/m^3$ for sulfur (as sulfate) reported for populous U.S. counties (Peng et al., 2009). Five elements including sulfur were measured at levels above their LODs, allowing their use as markers for $PM_{2.5}$ (Table 2). Comparing "field" to "upwind" concentrations of these five elements, the concentrations were consistently similar, indicating that field #2 and field #3 were not significant sources of $PM_{2.5}$. Combining the XRF and gravimetric results, the data indicate that these artificial turf fields do not release measurable amounts of $PM_{2.5}$ into the air.

Artificial turf also contains synthetic blades of grass that represent another potential source of $PM_{2.5}$. Green-colored dust has been detected in some older fields by wipe sampling, presumably caused by wear to the blades. In some cases this dust contained relatively large amounts of lead due to the use of lead-containing paint (NJDHSS, 2008). Crumb rubber made from recycled tires also contains lead, some of which is bioavailable (OEHHA, 2007; U.S. EPA, 2009). Lead-containing dust is a potential source of inhalation toxicity to athletes using these fields if the dust is in the $PM_{2.5}$ size range. Therefore, we performed XRF on the $PM_{2.5}$ collected from above these fields to measure its content of lead and other metals. All heavy metals analyzed, including cadmium, chromium, lead, manganese, mercury, and nickel, were below their LOD and/or laboratory MDL (Table 3). Arsenic and zinc were also below their detection limits (Table 3). Since the zinc content of crumb rubber made from recycled tires can exceed 1 percent by weight (U.S. EPA, 2009), our finding that zinc was below its LOD is consistent with the conclusion that crumb rubber particles were not included in the airborne $PM_{2.5}$.

Our XRF analysis of $PM_{2.5}$ had an LOD for lead of 0.12 $\mu g/m^3$. The 30-day average California Ambient Air Quality Standard for total lead is 1.5 $\mu g/m^3$, while the federal standard is 0.15 $\mu g/m^3$ for a three-month rolling average (CARB, 2008). Since lead and other heavy metals have a low volatility at the temperatures encountered on these fields, any metals released into the air by these fields would be bound to particulate matter. We did not detect lead or other heavy metals in the $PM_{2.5}$. Levels of PM_{10}-associated heavy metals were the same in air sampled from above and upwind of two artificial turf fields containing crumb rubber infill (U.S. EPA, 2009). Together, these two sets of data indicate that these surfaces do not release significant amounts of lead or other heavy metals bound to particulate matter in the respirable range.

This study has a number of limitations. Only three artificial turf fields were tested, and only two air samples were collected from above each field. The oldest field (field #2) was 26 months old at the time of testing. This is considerably less than the advertised lifespan for these fields of from 8 to 15 years. In addition, it is not known whether the $PM_{2.5}$ content of a batch of crumb rubber varies depending on the lot of tires or the particular tire recycling facility. Keeping these limitations in mind, our study, together with the studies from New York State (New York State, 2009; TRC, 2009), did not detect the release of $PM_{2.5}$ from a total of five fields containing crumb rubber infill. In addition, four fields (two fields also analyzed for $PM_{2.5}$) also were negative for PM_{10} release (New York State, 2009; TRC, 2009; U.S. EPA, 2009). Thus, the data collected to date from a total of seven different fields indicate that these fields are not significant point sources for the release of respirable particulate matter.

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Chapter 3

Identification and Quantification of Bacteria Cultured from Components of Artificial and Natural Turf Athletic Fields

Abstract

Outdoor athletic fields made of the new generation of artificial turf containing crumb rubber from recycled tires were analyzed for bacteria. Five artificial turf fields located at high schools, colleges, and universities in the San Francisco Bay Area were measured. Two natural turf fields were analyzed for comparison. Samples of crumb rubber infill from artificial turf or soil from natural turf were collected, along with blades of artificial or natural grass. Samples were cultured in the laboratory for bacterial identification and quantification according to the three most prominent species assay, along with quantification of methicillin-resistant *Staphylococcus aureus* (MRSA).

Artificial turf yielded from four to 10 different species of bacteria per field, compared to 11 to 14 species per natural turf field. Artificial turf also yielded fewer bacterial colony forming units (according to the three most prominent species analysis) per gram of material than natural turf, ranging from 0 to 53,000 CFUs (colony forming units) per gram of crumb rubber infill or artificial blades compared to 637,000 to 305,000,000 CFUs per gram of soil or natural blades from natural turf. Two of 30 samples (7 percent) from artificial turf were positive for a species of *Staphylococci* compared to six of 12 samples (50 percent) from natural turf (p=0.004 by Fisher's Exact Test). No MRSA was detected on artificial turf, while a single sample of blades from natural turf was positive for MRSA (p=0.3). These data indicate that the new generation of artificial turf containing crumb rubber infill harbors fewer bacteria than natural turf, including *Staphylococci* and MRSA. Environmental factors contributing to this difference may be the low moisture content and high temperature of artificial turf relative to natural turf.

Introduction

Staphylococcus is a genus of gram-positive bacteria commonly found on the surface of human skin. Normally, these skin bacteria cause no infection or health problems. However, under the proper conditions these bacteria can infect the skin, causing diseases such as impetigo and boils. *Staphylococcus aureus* (*S. aureus*) is a species that is particularly pathogenic to humans. If a skin infection of *S. aureus* moves internally, it can cause serious organ damage and death.

The methicillin antibiotics were originally very effective for treating *S. aureus* infections. However, over time strains developed that were resistant to this class of antibiotics, termed methicillin-resistant *S. aureu* (MRSA). Currently, these strains cause serious infections in hospitals, known as hospital-associated MRSA. The targets of hospital-associated MRSA are usually persons with other diseases and weakened immune systems (Boucher and Corey, 2008).

MRSA outbreaks also occur in healthy persons outside of hospitals. Such outbreaks are called community-associated MRSA. Risk factors may be absent. Cases of community-associated MRSA have been increasing rapidly over the last decade (Buss et al., 2009; Klein et al., 2009; Many, 2009). A number of such outbreaks have occurred in sports settings, particularly among athletes engaged in contact sports (Begier et al., 2004; Romano et al., 2006; Benjamin et al., 2007; Kirkland and Adams, 2008; Buss et al., 2009; Hall et al., 2009; Redziniak et al., 2009).

Most of these outbreaks were among sports with high frequencies of player-to-player skin contact: American football, wrestling, and rugby (Turbeville et al, 2006).

While player-to-player contact is considered the most important mode of MRSA transmission in sports outbreaks, possible instances of transmission via fomites (inanimate objects) have been reported, including soap bars (Nguyen et al., 2005; Miller and Diep, 2008; Hall et al., 2009), sensor wires used in fencing (MMWR, 2003), towels (MMWR, 2009), and weight room equipment (Kirkland and Adams, 2008). Turf itself has also been suggested as a fomite for MRSA transmission, following the identification of turf burns (i.e., turf-induced skin abrasions) as a risk factor for MRSA infection in outbreaks in professional (Kazakova et al., 2005) and college (Begier et al., 2004) football. Both of these football teams had home fields made of artificial turf, raising the possibility that artificial turf causes abrasions that are particularly susceptible to infection. However, turf burns suffered by football players on natural turf have also been associated with bacterial skin infections (Bartlett et al., 1982; Sosin et al., 1989). It appears that skin trauma constitutes a risk factor for MRSA infection whether it is caused by the playing surface, chafing from uniforms or protective equipment, body shaving, wrestling mats, or sensor wires used in fencing competition.

There are at least two different explanations for an association between turf burns and infection by MRSA. First, the turf itself might harbor the bacteria, transferring it to the athlete’s skin during player contacts with the turf that are forceful enough to cause a turf burn. Alternatively, the turf might not be a significant source of MRSA. Rather, turf burns may be efficient portals of entry for the bacteria during subsequent player-to-player contacts. This study addresses the possibility that the new generation of artificial turf containing crumb rubber from recycled tires is itself a significant source of MRSA and other *Staphylococci* species. Artificial turf and natural turf fields have both been sampled for bacterial culture to measure their content of bacteria in general, and *Staphylococci* (including MRSA) in particular. The possibilities that the new generation of artificial turf causes more and more serious turf burns than natural turf are addressed in a companion study in this report.

Methods

Seven soccer fields were analyzed for bacteria. Five were artificial turf and two were natural turf. All were on the grounds of colleges, universities, or high schools located in the San Francisco Bay Area. Fields #1-4 were sampled on September 29, 2009. Fields #5-7 were sampled on October 12, 2009. Weather on the earlier date was cloudy to sunny, breezy and in the lower 60s (^{o}F). Weather on the later date was cloudy, with lighter winds, and in a similar temperature range.

Two different components of the fields were collected: artificial infill or natural soil and blades of grass (artificial or natural). For artificial turf fields, the infill was a mixture of recycled crumb rubber and sand. Grass blades from artificial turf were most likely made of polyethylene.

Soil and infill samples were taken from the topmost inch of material. Therefore, some of the material was exposed to the sun and some was shielded. A stainless steel spatula was used to scoop up the soil or infill. The spatula was kept in a solution of 70 percent isopropyl alcohol, wiped with a sterile alcohol pad, and waved in the air to dry prior to sample collection. All artificial or natural blades of grass were taken from the layer that was exposed to the sun. A stainless steel scissors was used to cut and collect the blades. The scissors was cleaned as described above for the spatula. Disposable nitrile gloves were worn during sample collection. All infill, soil, and blade samples were placed into pre-weighed sterile polystyrene conical tubes and then into a chest containing ice. Samples were shipped by overnight mail to the analyzing laboratory (LA Testing Inc., Pasadena, CA). Approximately 1-2 grams of soil or infill and approximately 0.30 to 0.90 grams of blades were collected per sample.

Each field was sampled in three different locations for both infill/soil and blades. The locations were just outside of each soccer penalty area at midfield, and inside of the circle at center field.

Samples were analyzed according to the following methods. The three most prominent bacterial colonies were quantified by culturing. Identification was through use of the API system (bioMerieux, Inc., Durham, NC) and other biochemical tests. Methicillin-resistant *Staphylococcus aureus* (MRSA) was also quantified by culture in selective medium containing the antibiotic.

Results

Table 1 shows the results of the assay for the three most prominent types of bacteria cultured from each sample. The soil and blades from natural turf yielded a greater variety and greater numbers of bacteria compared to infill and blades from artificial turf.

Table 1. Counts and identification of the three most prominent types of bacteria cultured from artificial or natural turf athletic fields.

Location on field	Field component	Sample weight (g)	Bacteria[1] in sample ([4]CFU/g)	Analytical sensitivity ([4]CFU/g)	Bacteria[1] identified
Field #1, artificial turf					
1	Infill[2]	2.2	5,510	46-455	*Brevibacterium* species, *Pseudomonas stutzeri, Rhodococcus* species
1	Blades[3]	0.034	0	2,940	None
2	Infill	1.75	57	57	*Bacillus pumilus C*
2	Blades	0.034	0	2,940	None
3	Infill	1.5	53,300	667	*Leifsonia aquatic, Pseudomonas fluorescens*
3	Blades	0.031	0	3230	None
Field #2, natural turf					
1	Soil	1.09	4,210,000	91,700	*Bacillus cereus, Pseudomonas putida, Staphylococcus* coagulase negative
1	Blades	0.062	305,000,000	1,610,000	*Arthrobacter, Pantoea dispersa, Pseudomonas luteola*
2	Soil	1.57	637,000	63,700	*Enterobacter cloacae,* presumptive *Bacillus* species
2	Blades	0.084	10,500,000	1,190-119,000	*Pantoea agglomerans, Staphylococcus* coagulase negative

Location on field	Field component	Sample weight (g)	Bacteria[1] in sample ([4]CFU/g)	Analytical sensitivity ([4]CFU/g)	Bacteria[1] identified
3	Soil	0.804	1,370,000	124,000	*Bacillus pumilus C, Staphylococcus lentus*
3	Blades	0.08	97,500,000	1,250,000	*Chryseobacterium meningosepticum, Staphylococcus aureus, Staphylococcus xylosus*
Field #3, artificial turf					
1	Infill	1.9	105	53	*Corynebacterium propinquum, Micrococcus luteus*
1	Blades	0.042	0	2,380	None
2	Infill	1.57	0	64	None
2	Blades	0.034	32,300	2,940-29,400	*Micrococcus luteus, Staphylococcus warneri*
3	Infill	2.0	50	50	*Micrococcus luteus*
3	Blades	0.026	11,500	3,850	*Arthrobacter* species
Field #4, artificial turf					
1	Infill	1.88	53	53	*Arthrobacter* species
1	Blades	0.03	0	3,330	None
2	Infill	1.38	73	73	*Pseudomonas oryzihabitans*
2	Blades	0.031	0	3,230	None
3	Infill	2.14	1,170	47	*Acinetobacter baumanni, Arthrobacter* species, *Microbacterium* species
3	Blades	0.036	2,780	2,780	*Bacillus* species
Field #5, artificial turf					
1	Infill	0.475	843	211	*Brevibacterium* species, *Micrococcus luteus, Sphingomonas paucimobilis*
1	Blades	0.036	0	2,780	None
2	Infill	1.64	854	61	*Micrococcus luteus, Rhodococcus* species
2	Blades	0.049	2,040	2,040	*Rhodococcus* species
3	Infill	1.93	1,760	52-518	*Aeromonas hydrophila/caviae, Micrococcus lylae*
3	Blades	0.034	0	2,940	None
Field #6, artificial turf					

Location on field	Field component	Sample weight (g)	Bacteria[1] in sample ([4]CFU/g)	Analytical sensitivity ([4]CFU/g)	Bacteria[1] identified
1	Infill	2.2	1,870	46	*Arthrobacter* species, *Brevundimonas vesicularis, Rhodococcus globerulus*
1	Blades	0.035	0	2,860	None
2	Infill	1.46	342	69	*Arthrobacter* species, *Kurthia sibirica, Staphylococcus hominis ss novobiosepticus*
2	Blades	0.028	0	3,570	None
3	Infill	1.57	255	64	*Curtobacterium albidum, Leifsonia aquatic*
3	Blades	0.023	17,400	4,350	*Cytophaga fermentans, Kurthia gibsonii, Microbacterium terregens*
Field #7, natural turf					
1	Soil	0.665	7,960,000	150,000	*Bacillus cereus/thuringiensis, Pantoea agglomerans, Rhizobium radiobacter*
1	Blades	0.133	56,400,000	752,000	*Brevibacterium* species, *Curtobacterium pusillum, Staphylococcus lentus*
2	Soil	1.04	2,500,000	96,300	*Aeromonas hydrophila/caviae, Pseudomonas luteola*
2	Blades	0.093	881,000	10,800	*Aeromonas hydrophila/caviae, Pantoea* species 3
3	Soil	0.653	14,100,000	153,000	*Pantoea* species 3, *Pseudomonas luteola, Staphylococcus sciuri*
3	Blades	0.08	192,000,000	1,250,000	*Aeromonas hydrophila/caviae, Microbacterium* species

[1] Bacteria were from among the three most prominent types.
[2] Infill was a mixture of recycled crumb rubber and sand in all cases.
[3] Blades refers to blades of grass, either artificial or natural.
[4] CFU = colony forming units.

The two natural turf fields averaged 12.5 different bacterial species per field (range: 11-14 species per field) compared to 6.2 species per field (range: 4-10 species per field) for the five artificial turf fields. This suggests that natural turf supports a more varied community of bacteria than artificial turf. Note that the two natural turf fields supported the growth of six different species of *Staphylococci* compared to two different *Staphylococci* species in the five artificial turf fields (Table 2). Two of these, *S. aureus* and *S. sciuri*, are well known human pathogens (Klein et al., 2009; Stepanovic et al., 2005). Both were detected on natural turf but not on artificial turf.

Table 2. Occurrence and pathogenicity of *Staphylococci* species cultured from components of artificial or natural turf athletic fields.

Staphylococcus species detected	Sample type	Pathogenic in humans?
Artificial turf **(5 fields tested)**		
S. warneri	blades	Generally nonpathogenic
S. hominis ss novobiosepticus	infill	Possible opportunistic pathogen
Natural turf **(2 fields tested)**		
Staphylococcus species (coagulase negative)	soil	Possible opportunistic pathogen
Staphylococcus species (coagulase negative)	blades	Possible opportunistic pathogen
S. lentus	soil	Generally nonpathogenic
S. aureus	blades	Pathogenic
S. sciuri	soil	Pathogenic
S. xylosus	blades	Generally nonpathogenic

With regard to the number of bacteria on these surfaces, the 12 samples of natural turf yielded between 637,000 and 305,000,000 bacteria per gram of material. The 30 samples of artificial turf yielded far fewer, ranging from 0 to 53,000 bacteria per gram of material. Eleven of the artificial turf samples contained no culturable bacteria at all: 10 of these were blades and one was infill (Table 1).

All samples were also cultured to determine whether they contained MRSA. A single blades sample from natural turf was positive for MRSA (Table 3). No MRSA was cultured from artificial turf components.

Table 3. Methicillin-resistant *Staphylococcus aureus* (MRSA) cultured from artificial or natural turf athletic fields.

Field # and type	Location on field	Field component	Sample weight (g)	[4]MRSA in sample ([3]CFU/g)	Concentration reporting limit ([3]CFU/g)
#1 artificial	1	Infill[1]	2.2	None detected	45
#1 artificial	1	Blades[2]	0.034	None detected	2,941
#1 artificial	2	Infill	1.75	None detected	57
#1 artificial	2	Blades	0.034	None detected	2,941
#1 artificial	3	Infill	1.5	None detected	67
#1 artificial	3	Blades	0.031	None detected	3,226

Field # and type	Location on field	Field component	Sample weight (g)	[4]MRSA in sample ([3]CFU/g)	Concentration reporting limit ([3]CFU/g)
#2 natural	1	Soil	1.09	None detected	92
#2 natural	1	Blades	0.062	None detected	1,613
#2 natural	2	Soil	1.57	None detected	64
#2 natural	2	Blades	0.084	None detected	1,190
#2 natural	3	Soil	0.804	None detected	124
#2 natural	3	Blades	0.08	1,250,000	1,250
#3 artificial	1	Infill	1.9	None detected	53
#3 artificial	1	Blades	0.042	None detected	2,380
#3 artificial	2	Infill	1.57	None detected	64
#3 artificial	2	Blades	0.034	None detected	2,941
#3 artificial	3	Infill	2.0	None detected	50
#3 artificial	3	Blades	0.026	None detected	3,846
#4 artificial	1	Infill	1.88	None detected	53
#4 artificial	1	Blades	0.03	None detected	3,333
#4 artificial	2	Infill	1.38	None detected	72
#4 artificial	2	Blades	0.031	None detected	3,226
#4 artificial	3	Infill	2.14	None detected	47
#4 artificial	3	Blades	0.036	None detected	2,778
#5 artificial	1	Infill	0.475	None detected	211
#5 artificial	1	Blades	0.036	None detected	2,778
#5 artificial	2	Infill	1.64	None detected	61
#5 artificial	2	Blades	0.049	None detected	2,041
#5 artificial	3	Infill	1.93	None detected	52
#5 artificial	3	Blades	0.034	None detected	2,941
#6 artificial	1	Infill	2.2	None detected	45
#6 artificial	1	Blades	0.035	None detected	2,857
#6 artificial	2	Infill	1.46	None detected	68
#6 artificial	2	Blades	0.028	None detected	3,571
#6 artificial	3	Infill	1.57	None detected	64
#6 artificial	3	Blades	0.023	None detected	4,348
#7 natural	1	Soil	0.665	None detected	150

Field # and type	Location on field	Field component	Sample weight (g)	[4]MRSA in sample ([3]CFU/g)	Concentration reporting limit ([3]CFU/g)
#7 natural	1	Blades	0.133	None detected	752
#7 natural	2	Soil	1.04	None detected	96
#7 natural	2	Blades	0.093	None detected	1,075
#7 natural	3	Soil	0.653	None detected	153
#7 natural	3	Blades	0.08	None detected	1,250

[1] Infill was a mixture of recycled crumb rubber and sand in all cases.
[2] Blades refers to blades of grass, either artificial or natural.
[3]CFU = colony forming units.
[4]MRSA = methicillin-resistant *Staphylococcus aureus*.

Table 4 summarizes the data from the two bacterial analyses (three most prominent bacteria and MRSA). Focusing first on the MRSA data (right-most column), the incidences of occurrence of this species on the two surfaces were low and not significantly different. However, when all *Staphylococcus* species were considered together (second column from the right), their incidence of occurrence on natural turf was significantly greater than on artificial turf.

Table 4. Summary data for the three most prominent bacteria and MRSA cultured from artificial turf and natural turf components.

Field type	# of fields sampled[1]	Bacteria species per field[2]	Bacteria per gram of infill/soil and blades[2]	Samples positive for *Staphylococci*[2]	Samples positive for MRSA[3]
Artificial	5	4-10	0 to 53,000	2/30[4]*	0/30[5]
Natural	2	11-14	637,000 to 305,000,000	6/12[4]*	1/12[5]

[1]As described in materials and methods, three soil/infill samples and three blades samples were collected per field.
[2]Three most prominent bacteria assay.
[3]MRSA assay.
[4]$p=0.004$ by Fisher's Exact Test
[5]$p=0.3$ by Fisher's Exact Test
*indicates statistical significance of $p \leq 0.05$

Discussion

The goal of this study was to determine whether the new generation of artificial turf harbors bacteria, including MRSA and other *Staphylococci*. Few data have been collected that address this topic. For a MRSA outbreak in a professional football team, wipe-sampling of the artificial turf (old-generation Astroturf®) in the parts of the field with the highest number of tackles did