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Exposure to naturally occurring mineral fibers due to off-road vehicle use: A review

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ABSTRACT

Background: The use of off-road vehicles (ORVs) is a popular source of outdoor recreation in the United States. While personal injury has been the focus of most epidemiologic investigations regarding ORV use to date, other health effects associated with ORV use have not been adequately examined. ORVs have been designed to operate in rugged, unpaved terrain, and ORVs can produce copious amounts of fugitive dust. ORV use in geographic regions with naturally occurring asbestos (NOA) and erionite (NOE) may result in the liberation of these minerals from underlying rocks and soil, which may put ORV participants at risk to potentially hazardous inhalation exposures.

Methods: A comprehensive narrative review of existing literature and reports relevant to off-road recreation and mineral fiber exposure was conducted. Manuscripts and reports included in the review were limited to those that contained quantitative data regarding concentrations of mineral fibers recorded during vehicular traffic on an unpaved road and publication in a peer-reviewed journal, official report composed by a government agency, or a report generated under the endorsement of a government agency. In addition, the potential public health impact of ORV use in regions with NOA/NOE was estimated by calculating the proximity of known mineral fiber occurrences to areas of ORV use.

Results: A total of 15 publications met inclusion criteria. Exposures to NOA/NOE observed from personal sampling in the included studies ranged from less than 0.01–5.6 f/cc. ORV position while riding in a group and vehicle speed were frequent determinants of measured concentrations. Multiple studies also suggest that children may experience higher exposures to mineral fibers in comparison to adult ORV riders. Information on ORV trails and 665 known occurrences of NOA/NOE was available for five states located in the western United States. Of these 665 known occurrences, approximately 80% (n = 515) were located within 20 miles of an ORV trail, and nearly a third were located within one mile.

Conclusions: Individuals who operate ORVs in regions where NOA/NOE is a component of the underlying soil or unpaved road may experience elevated exposures to mineral fibers. Given the prevalence of ORV trails in close proximity to these natural fiber occurrences, epidemiologic and surveillance studies of individuals who frequently engage in ORV use are recommended. Public health initiatives should concentrate on increasing awareness of these risks, allowing ORV users to make informed choices and take appropriate measures to limit these risks where possible.

Abbreviations: ORV, off road vehicle; NOA, naturally occurring asbestos; NOE, naturally occurring erionite.

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1. Introduction

The use of off-road vehicles (ORVs), including four wheel drive vehicles, all-terrain vehicles (ATVs), motorcycles, and other vehicles designed for off-highway use, is among the most popular outdoor activities in the United States (U.S.). In a report by the National Survey on Recreation and the Environment (2005–2007), an estimated 44 million Americans age 16 and older engaged in recreational activities involving ORVs within the past year (Cordell et al., 2008). Children were not included in this random-digit-dialed household telephone survey, and therefore, the number of Americans that use ORVs recreationally is likely higher. While the prevalence of ORV use among children and adolescents is unknown and likely varies by geographic region, one school-based survey in Iowa of 4684 children aged 11–16 found that more than 75% of the participants engaged in ORV use (Jennissen et al., 2014). ORVs are also used occupationally, and an industry study of ATV owners found that 21% of owners used ORVs for work or chores (United States Government Accountability Office, 2010).

Most epidemiologic studies and public health awareness concerning ORVs has focused on injuries and deaths sustained from their use (Brandenburg et al., 2007; Cvijanovich et al., 2001; Denning et al., 2014; Larson and McIntosh, 2012). In 2013, an estimated 99,600 people sought care at an emergency department for injuries experienced as a result of ATV use, and nearly a quarter of these injuries occurred in children (Consumer Product Safety Commission, 2015). In 2014, there were a reported 959 fatalities resulting from ORV use (Center for Disease Control and Prevention, 2015). Surveillance studies and efforts toward injury prevention are certainly warranted. There are, however, additional risks associated with ORV operation, which include inhalation exposure to fugitive dust (Buck et al., 2013; Goossens and Buck, 2009a; Goossens et al., 2012; Padgett et al., 2008).

Off-road driving on unpaved surfaces can significantly increase the amount of total suspended particles, including both PM10 and PM2.5 (particulate matter <10 μm and <2.5 μm in aerodynamic diameter, respectively) (Goosens and Buck, 2014; Goossens and Buck, 2009a, 2009b; Williams et al., 2008) due to dust generation by shearing force and air turbulence (Goosens and Buck, 2014; Williams et al., 2008). Case studies of fugitive dust emissions from ORV use have identified vehicle type and speed, as well as soil characteristics, to be important factors in dust emissions (Goosens and Buck, 2014; Goossens and Buck, 2009a, 2009b; Williams et al., 2008), and the contents of the resulting dust reflects the composition of the soil (Goossens et al., 2015; Soukup et al., 2012). Some of these airborne particles can be elongated minerals that meet the dimensional criteria used to identify asbestos fibers, which we refer to as "fibers" in this review. In regions where they are naturally occurring, fibers of serpentine or amphibole asbestos or potentially hazardous fibers of other minerals, such as the zeolite erionite, may become a component of these generated dusts. Asbestos minerals occurring as a natural constituent of rocks and soils have been identified in the United States, most prominently in the West (Harper, 2008). Collectively, these materials have been referred to as naturally occurring asbestos (NOA). The fibers released by disturbing NOA may include hazardous mineral fibers that fit current U.S. regulatory definitions of asbestos (e.g. chrysotile) and others that may not (e.g. winchite or richterite). Erionite, an unregulated zeolite mineral, is also naturally occurring (NOE). Erionite additionally bears similar properties to asbestos, and inhalation of erionite fibers has been associated with malignant mesothelioma and other pulmonary diseases (Carbone et al., 2011; Ryan et al., 2011; Van Gosen et al., 2013).

In geographic regions where ORV use and NOA/NOE intersect, inhalation of fugitive dusts containing mineral fibers during vehicular travel on unpaved roads may be an exposure pathway of particular importance. Thus, the purpose of the current investigation is to examine the potential for airborne NOA/NOE fiber exposures associated with ORV activities on contaminated soils and gravels. Herein, we 1) review the existing literature on mineral fiber exposures resulting from vehicular travel on unpaved surfaces and, 2) examine the spatial relationship between known deposits of NOA/NOE in the United States and ORV trails.

2. Methods

A comprehensive search of published studies on ORV use and mineral fiber exposure was conducted using the MEDLINE database of the US National Library of Medicine accessed via PubMed and the Web of Science. The following keywords were included in the search: 'fiber', OR 'asbestos' OR 'erionite' OR 'amphibole' OR 'zeolite' OR 'dust') AND ('off-road vehicle' OR 'off-highway vehicle' OR 'ATV' OR 'recreational' OR 'traffic'). In addition, internet searches with these same keywords were conducted to identify reports and publications not available on either PubMed or Web of Science. Finally; personal communications with experts in the field identified additional reports. Publications that reported personal or stationary sampling results obtained during vehicular travel on an unpaved surface; either in the form of airborne concentrations or fibers in settled dust samples; were reviewed. An additional inclusion criterion was publication in a peer-reviewed journal or official report created by (or on behalf of) a government agency. The sampling results reported by these publications were synthesized and represent a narrative review of the available literature.

In order to visualize and identify locations of potential overlap between ORV use and NOA/NOE occurrences, known locations of NOA and NOE were overlaid with areas of ORV activity using geographic information systems (GIS). All GIS analyses were conducted using ArcGIS software (ESRI, Redlands, CA) and R Software Version 3.3.0. Locations of ORV use were identified by examining user uploaded GPS tracks from personal rides (Offroading Home, 2016). Trails were available for five western states (AZ, CA, CO, NV, and UT), and individual trails from each were downloaded and transformed from Google Earth Keyhole Markup Language (KML) files to shapefiles using the ArcGIS conversion utility. All trails were individually examined while overlaid with satellite images in order to visually verify that travel was completed exclusively on unpaved surfaces. Any trail that included travel on a paved road or highway was subsequently omitted. Trails that were duplicates of others were also omitted.

The locations of known NOA and NOE deposits were identified from multiple sources. The United States Geological Survey (USGS) has previously catalogued the location of known mines and natural occurrences of chrysotile and fibrous amphibole asbestos. This data was downloaded as a shapefile and projected as a map layer in ArcGIS (United States Geological Survey, 2014). Other known locations of NOA not described by USGS were merged into the USGS map layer. These included natural occurrences of fibrous amphiboles in Southern Nevada (Buck et al., 2013; Kleinfelder, 2014; Tetra Tech Inc., 2014) and Arizona (Metcalf and Buck, 2015). Locations of NOE were mapped using data provided in the supplementary material of Van Gosen et al. (2013), which describes the geological features of each occurrence and its corresponding latitude and longitude. The extent of ORV trails in close proximity to NOA and NOE sources was examined by calculating the total length of ORV trails within varying buffer radii (5, 10, 15, 20 miles) of each deposit. Trail lengths per buffer region were calculated using R Version 3.3.1.

Fig. 1. Off-road vehicle use in Nellis Dunes Recreational Area, near Las Vegas Nevada (from (Goosens and Buck, 2014)).

3. Results

3.1. Sampling results

A total of 15 publications and reports containing sampling results met our inclusion criteria and were included in this review. A summary of the key characteristics and sampling results from each identified study is provided in Table 1 (additional details in Supplementary Table 1). Of these, 9 studies were conducted by or on behalf of the U.S. Environmental Protection Agency (US EPA) and the Agency for Toxic Substances and Disease Registry (ATSDR). The majority (n = 14) summarized sampling in the U.S., while 1 study was conducted near unpaved road surfaces in Italy. Seven studies identified amphibole asbestos fibers in their samples (Bruni et al., 2006; Buck et al., 2013; Ecology and Environment Inc., 2005; EPA, 2013a,b, 2014a; Perkins et al., 2008), chrysotile asbestos was reported in 6 studies (Agency for Toxic Substances and Disease Registry, 2007; Cooper et al., 1979; EPA, 2008a; ICF Technology Inc., 1994; Rohl et al., 1977; State of California EPA, 2005), 1 study identified both chrysotile and amphibole fibers (EPA, 2008b), and 1 publication identified erionite (Carbone et al., 2011). The range of personal exposures reported among the reviewed studies varied from a maximum of 5.6 f/cc during sampling in the Clear Creek Management Area, as measured by phase contrast microscopy (PCM) (Cooper et al., 1979), to concentrations lower than 0.01 f/cc during activity based sampling in Libby, MT, as measured by phase contrast microscopy equivalents (PCMe) (EPA, 2013a,b, 2014a).

The study design, source material, soil type, meteorological conditions, fiber type, sample collection, and analytical method differ among the sampling studies examined in this narrative review. Soil type and meteorological conditions such as wind speed and relative humidity, in particular, affect the amount of mineral fibers that may be liberated from source materials. Due to these discrepancies, the results of these studies may not be directly comparable. Notwithstanding these limitations, overall trends in the data can be derived. In studies that examined personal airborne exposures among multiple riders operating ORV vehicles simultaneously, trailing riders were exposed to substantially more dust compared to lead riders (Fig. 1). This is clearly demonstrated by Cooper et al. (1979) during scenarios performed in the Clear Creek Recreational Area (Cooper et al., 1979), and again by the EPA nearly two decades later (EPA, 2008a). During all simulations, lead riders had lower personal fiber exposures in comparison to trailing riders. For example, results by Cooper et al. (1979) revealed that trailing riders may experience exposures nearly seven times higher than that of a lead rider (5.6 vs. 0.9 f/cc; PCM). Likewise, sampling by the EPA indicated a positive linear trend between riding position and level of exposure (EPA, 2008a). Mean exposures between the lead and the last trailing rider were 0.56 vs. 0.07 f/cc (PCMe), respectively (EPA, 2008a). Similar testing was done by ATSDR in Ambler, AK, but comparisons between leading and trailing riders could not be made due to filter overloading (Agency for Toxic Substances and Disease Registry, 2007).

Studies with available stationary monitoring data found increased vehicular speed and distance from the roadway or trail to be determinants to exposure. Multiple studies in this review demonstrate that airborne fiber concentrations are inversely associated with distance from the road (Carbone et al., 2011; ICF Technology Inc., 1994; Rohl et al., 1977; State of California EPA, 2005). This is most evident in stationary samples collected in Garden Valley, CA and the Diamond XX community located near Copperopolis, CA. In Garden Valley, chrysotile fiber concentrations (PCMe) ranged from 6.3 s/cc at 5 feet from the roadside to 0.187 s/cc at 190 feet away (State of California EPA, 2005). At Diamond XX, mean fiber concentration (PCMe) measured at a distance of 25 feet (1.4 s/cc) was much higher compared to 75 (0.396 f/cc) and 150 (0.304 f/cc) feet downwind from the roadside at a speed of 15 vehicles per hour (ICF Technology Inc., 1994). Roadside sampling in Garden Valley and Diamond XX also found increasing vehicular speed and frequency can result in higher concentrations of airborne fibers. In Garden Valley, the airborne fiber concentration measured at 5 feet from the roadside during vehicular travel at 10 miles per hour was 0.755 s/cc, whereas concentrations rose to 6.3 s/cc during the sampling scenario under which vehicles were traveling at 25 miles per hour. The testing in Diamond XX, where vehicle speed was held constant, illustrates that the number of vehicles traveling on the roadway can greatly increase the amount of airborne fibers as concentrations were approximately seven times higher when the vehicle frequency increased from 5 to 15 vehicles per hour (0.19 vs. 1.40 s/cc, respectively) (ICF Technology Inc., 1994).

Passenger vehicles, including sport utility vehicles (SUVs), also generate airborne fibers, which may subsequently result in personal in-cabin exposures (Bruni et al., 2006; Buck et al., 2013; Carbone et al., 2011; Cooper et al., 1979; EPA, 2008a; Perkins et al., 2008). Amphibole asbestos was found in all nine personal samples (mean = 0.049 f/cc; PCM) during activity based sampling completed by Perkins et al. (2008) in Fairbanks, AK where study personnel drove with the windows down while driving behind a heavy duty vehicle. Sampling in Clear Creek by the EPA shows that traveling in an SUV with the windows closed and recirculating the air reduces exposures (0.14 f/cc; PCMe) in comparison to when the windows are open (0.22 f/cc; PCMe). However, NOA fibers may still penetrate the cabin interior. Carbone et al. (2011) found mean fiber exposures of 0.022 f/cc (PCMe) inside cars and buses from travel on gravel roads containing NOE, and Cooper et al. (1979) reported an exposure of 0.4 f/cc (PCM) during personal sampling completed by a park ranger driving a pick-up trucking in the Clear Creek. These studies, however, do not explicitly state which results were obtained while windows were open or closed.

EPA sampling in Clear Creek demonstrates that children may experience higher fiber exposures in comparison to adult riders (EPA, 2008a) as a child's breathing height is closer to the ground, corresponding to higher dust concentrations (Goossens and Buck, 2014). During ORV simulations, a subset of riders wore a second sampler lower on their body to represent the shorter stature of children. The lower samplers were found to have higher fiber concentrations under all scenarios (ATV, motorcycle, and SUV riding). The highest concentrations were observed during ATV simulations. Samples taken from the adult breathing zone during this scenario had a mean concentration of 0.317 f/cc (PCMe), whereas the mean concentration of samples taken at a lower height was 0.440 f/cc (EPA, 2008a).

Besides operating an ORV or passenger vehicle, low intensity activities like bicycling can also liberate mineral fibers from the

Table 1
Reviewed publications and corresponding exposure data.

Reference	Location	Fiber Type/Geology	Study Design/Methods	Results				
ATSDR (2007)	Ambler, AK	Chrysotile/ultramafic rocks	Personal and stationary samples were collected during ATV travel on a gravel road				Mean PCME (f/cc)	
				Personal				
					Lead Rider		0.051	
					Trailing Rider		>0.212	
			Personal samples were taken from lead and trailing riders—riders did not switch roles	Stationary				
					Roadside		0.212	
					Background		0.012	
Bruni, Pacella et al. (2006)	Biancavilla, Italy	Fluoro-amphibole/alkali volcanics	Samples were collected in areas with high dust emissions due to unpaved roads	Detection frequency: 20/27				
			Distance to road and traffic conditions not specified	Airborne sample range: 1–20 f/L				
Buck et al. (2013)	Southern Nevada (Las Vegas, Henderson, Boulder City)	Amphibole/ hydrothermal veins in granite intrusions	Dust traps were placed in areas downwind and adjacent to dirt roads	All samples (n = 43) found to contain fibrous amphiboles—primarily actinolite				
			Dust samples were collected from tire surface and personal clothing after driving and walking on unpaved roads	All amphibole fibers and 97% of amphibole particles had aspect ratio >3:1.				
Carbone, Baris et al. (2011)	Dunn County, ND	Erionite/gravels from water-laid ash flow tuffs					Mean (s/cc)	Detection Frequency
				Transportation inside vehicle (all)	TEM: 0.235	37/41		
					PCMe: 0.022	26/41		
			Car: personal samples were taken during travel on a gravel road; scenario completed with and without windows closed	Inside car	TEM: 0.100	3/3		
					PCMe: 0.010	3/3		
			Bus: scenario completed along a school bus route with samplers located at front and rear of bus; scenario completed with and without windows closed	Inside bus			TEM: 0.270	–
							PCMe: 0.020	–
			Stationary (roadside) sampling was conducted adjacent to a road near a school bus stop in ND	Roadside			TEM: 0.108	–
							PCMe: 0.012	–
			Bicycling: scenario was conducted using two sampling pumps attached to a trailer behind a bicycle	Bicycle	TEM: 0.59	–		
					PCMe: 0.05	–		

Table 1 (*Continued*)

Reference	Location	Fiber Type/Geology	Study Design/Methods	Results				
Cooper, Murchio et al. (1979)	San Benito County, CA	Chrysotile/ultramafic rocks		Rider	Run 1 (f/cc)	Run 2 (f/cc)	Run 3 (f/cc)	
			Motorcyclists maintained position during runs 1 and 2—rode freely during run 3	1	0.9	0.6	0.3	–
				2	5.6	3.0	1.9	–
			Personal sample was taken during patrol by ranger in pickup truck	3	2.3	3.0	3.2	–
				4	4.3	4.9	2.9	–
			Stationary sample collected 12.9 km away from road	5	2.8	4.4	1.7	–
				6	5.3	3.1	2.9	–
			Samples analyzed by PCM	Ranger	–	–	–	0.4
				Stationary	–	–	–	0.2
Ecology and Environment Inc. (2005)	El Dorado Hills, CA	Amphibole/ultramafic rocks						
			Personal samples were collected from five bicycle riders during a 2 hr period	Pair A				PCMe (f/cc)
					Leader			0.007
			Collection filters worn at low height to represent breathing zone of child		Follower			0.067
				Pair B				
			Four bicyclists rode in pairs (1&2, 3&5); rider 4 rode unaccompanied		Leader			0.001
					Leader (duplicate)			0.014
			Pairs of riders passed one another during sampling period—relative position within each pair (lead/follow) did not change		Follower			0.031
				Solo Rider			0.018	
			Stationary samples taken at 7 positions along trail	Stationary (range)			0.001–0.006	
California EPA (2005)	Garden Valley, CA	Chrysotile/ultramafic rocks			10 mph / 10 vph		25 mph / 30 vph	
				Distance from road (feet)	Initial (s/cc)	Post (s/cc)	Initial (s/cc)	Post (s/cc)
				5	0.755	0.016	6.300	0.065
			Sampling conducted under different vehicle speeds and frequency of vehicles:	10	0.225	–	2.275	–
				30	0.330	<0.014	1.535	0.022
			Scenario 1: 10 miles per hour (mph) at a rate of 25 vehicles per hour (vph)	50	–	–	0.910	–
				80	0.212	0.025	0.710	0.008
			Scenario 2: 25 mph at a rate of 30 vph	100	–	–	0.427	0.013
				130	0.048	–	0.505	–

Table 1 (*Continued*)

Reference	Location	Fiber Type/Geology	Study Design/Methods	Results				
			Stationary sites were located perpendicular to road at varying distances (5–190 ft)	160	–	–	0.350	<0.005
				190	–	–	0.187	0.009
			Fiber concentrations measured as PCMe	300	–	0.036	–	<0.043
EPA (2008a)	San Benito County, CA	Chrysotile/ultramafic rocks				PCMe		
				Adult		Min (f/cc)	Max (f/cc)	Mean (f/cc)
					ATV	0.0044	2.0392	0.3174
					Motorcycle	0.0099	1.2822	0.3071
					SUV	0.0099	0.6724	0.1841
			Personal samples were taken during ORV travel on unpaved trails	Child				
					ATV	0.0091	1.2765	0.4404
					Motorcycle	0.0099	1.2277	0.3671
					SUV	0.0050	0.9788	0.2605
			'Child' samples were taken lower on the body of riders during activities to represent closer proximity of a child's breathing zone to dust source	All Vehicles				
					Lead	–	–	0.07
					First Trialing	–	–	0.25
					Second Trailing	–	–	0.56
EPA (2008b)	Zion, IL	Chrysotile, ultramafic rock sources; Libby amphibole/alkali intrusive rocks		Sample #42232 (stationary)		PCMe		TEM (s/cc)
					Libby Amphibole	ND		ND
					Total Amphibole	ND		ND
					Total Asbestos	ND		0.00198
			Two ATV riders driving at one time—personal samples taken from 'lead' and 'tail' riders		Total Chrysotile	ND		0.00198
				Sample #42381 (stationary)				
					Libby Amphibole	0.000884		0.000884
			Stationary (15) and personal (4) samples were taken during ATV activities on two occasions		Total Amphibole	0.000884		0.000884
					Total Asbestos	0.000884		0.000884
					Total Chrysotile	ND		ND
				*Personal and remaining stationary samples ND				

Table 1 (*Continued*)

Reference	Location	Fiber Type/Geology	Study Design/Methods	Results			
EPA (2008a)	Libby, MT	Amphibole/alkali intrusive rocks	Two ATV riders drove for a duration of 120 min—lead and following riders maintained position	Detection Frequency		PCMe (s/cc)	
			Two ATV riders drove for a duration of 120 min—lead and following riders maintained position	1/16		0.0028	
EPA (2008b)	Libby, MT	Amphibole/alkali intrusive rocks					
			Samples collected at personal breathing zone of two ATV riders during 20 min sampling periods—lead and trailing rider switch halfway	Miles from mine : 2–5	Location	Mean PCMe (s/cc)	Detection Frequency
					ABS – 06	0.0	0/7
					ABS – 07	0.0075	1/8
					ABS – 13	0.0	0/7
			Sampling conducted at varying distances from mine site	0–2			
					ABS -10	0.003	4/6
					ABS - 14	0.0	1/7
EPA (2014)	Libby, MT	Amphibole/alkali intrusive rocks				Mean PCMe (s/cc)	
				Bin A (Non detect soil)		0.0028	
			Two ATV riders drove for a duration of one hour—lead and trailing riders switch after 15 min, followed by 30 min of riding freely	Bin B (<0.2% soil)		0.0033	
ICF Technology (1994)	Diamond 20 Subdivision, Copperopolis, CA	Chrysotile/ultramafic rocks				PCMe (s/cc) 15 Vehicles / hr	PCMe (s/cc) 5 Vehicles / hr
				Distance from road (feet): Downwind			

Table 1 (*Continued*)

Reference	Location	Fiber Type/Geology	Study Design/Methods	Results			
			Stationary samples taken at varying distances from the roadway (25, 75, and 150 feet)		150	0.304	0.048
					75	0.396	0.065
			Vehicles were driven at a constant vehicle speed (30 mph) at varying frequencies of vehicles per hour—5 vs. 15 vph		25	1.400	0.191
				Upwind			
					150	0.002	0.003
Perkins, Hargesheimer et al. (2008)	Fairbanks, AK	Tremolite, actinolite/ultramafic rocks				Mean PCM (f/cc)	Detection Frequency
			Motorist exposures were simulated by driving a passenger car on an unpaved road behind a heavy construction vehicle—windows of the passenger car were kept open	Personal		0.049	9/9
			Roadside samples collected at multiple locations	Stationary (highest measurement)		0.064	6/6
Rohl, Langer et al. (1977)	Rockville, MD	Chrysotile/ultramafic rocks		Sampling Locations		PCM (f/cc)	
				1. 10 m from road intersection; light traffic		0.0	
				2. 10 m from road intersection; moderate traffic		0.05	
			Samples taken at 5 locations at varying distances from roadside and under differing traffic conditions				
				3. School parking lot; 100 m away from intersection		0.0	
				4. Residential area; 70 m away from intersection		0.01	
				5. 10 m roadside; moderate traffic		0.01	

PCM = phase contrast microscopy.
TEM = transition electron microscopy.
PCMe = phase contrast microscopy equivalents.
ND = non detect.

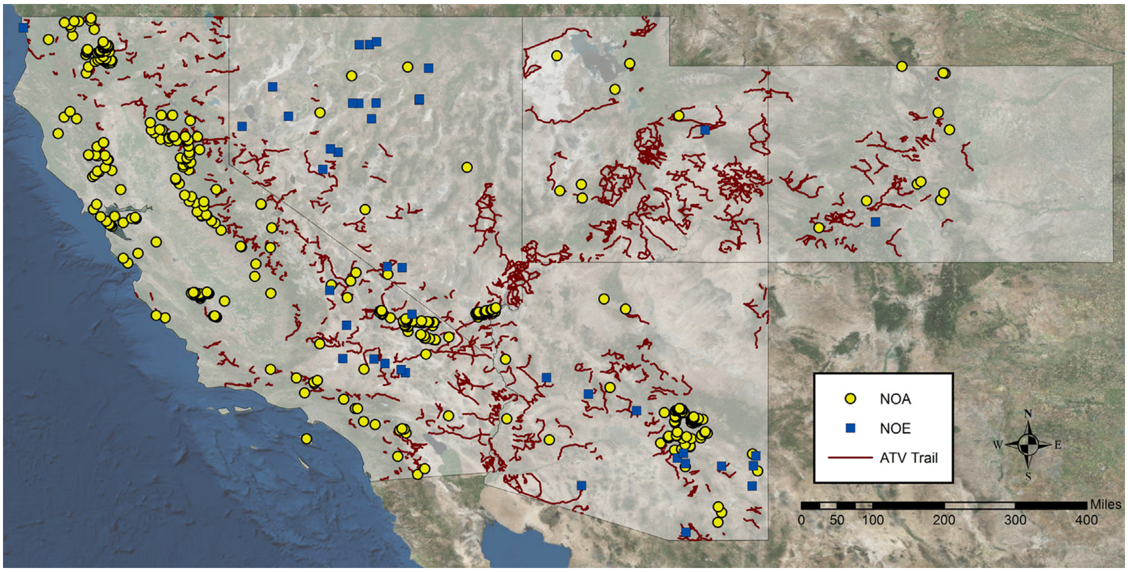

Fig. 2. Off-road vehicle trails and distribution of known NOA and NOE occurrences in five state study area. Trails represent user data from personal excursions while operating an off-road vehicle (ATV, motorcycle, etc.). A total of 655 occurrences (NOA: n = 614; NOE: n = 41) fell within the study region (AZ, CA, CO, NV, and UT).

Table 2
Length (miles) of ORV trails within varying buffer distances of NOA occurrences.

Fiber Type	Number of Occurrences	5 mi	10 mi	15 mi	20 mi
NOA	614	3746	13,649	33,384	59,995
NOE	41	150	714	1855	3170
All Fibers	655	3896	14,363	35,239	63,165

road surface as evidenced by sampling done in North Dakota and El Dorado Hills, CA (Ecology and Environment Inc., 2005). In Dunn County, ND, trailers were mounted to bicycles that contained sampling devices, and cyclists rode on gravel roads, including a community parking lot (mean NOE = 0.05 f/cc; PCMe) (Carbone et al., 2011; Miller, 2016). Similar results were measured in El Dorado Hills, where activity based sampling was conducted on an unpaved nature trail. Activities were carried out by adults who wore sampling devices at a lower height to reflect the breathing zone of a child. The results show that children may experience airborne chrysotile fiber concentrations up to 0.067 f/cc (PCMe) while biking (Ecology and Environment Inc., 2005). The results from El Dorado Hills also substantiate the findings in Clear Creek relating to rider position. Four bicyclists were divided into two groups. Each pair of riders was allowed to periodically pass the other, but the relative position of the two riders within each group was held constant. Trailing cyclists in each group had substantially higher exposures—0.067 vs. 0.007 f/cc and 0.031 vs 0.014 f/cc (PCMe). An exposure of 0.001 f/cc was recorded in a duplicate sample of a leading rider in the second group (Ecology and Environment Inc., 2005).

3.1.1. *Mineral fiber occurrences and ORV trails*

We identified a total of 1190 mineral fiber occurrences from available data resources (Buck et al., 2013; Metcalf and Buck, 2015; United States Geological Survey, 2014; Van Gosen et al., 2013). Of these, 655 occurrences (NOA = 614, NOE = 41) were located within our five state study region (AZ, CA, CO, NV, and UT). A total length of 39,784 miles of ORV trails were located in this region (Fig. 2). A total of 7 NOE locations were situated within 5 mile radius of an ORV trail, and over half of NOE locations (n = 26) were located within 20 miles, corresponding to a total length of 150 and 3170 miles of trail, respectively (Table 2). Of the NOA deposits, approximately 40% (n = 241) were located within a 5 mile radius of an ORV trail, corresponding to a total length of 3745 miles of trail. Nearly 80% of all NOA deposits were within a 20 mile radius (n = 515; 63,165 miles). Numerous NOA and NOE deposits were located substantially closer than 5 miles to an ORV trail. A total of 150 mineral fiber occurrences were located within one mile of an ORV trail, which includes 13 occurrences of fibrous amphiboles near Boulder City, NV (Fig. 3).

4. Discussion

To our knowledge, this is the first comprehensive review of the literature related to ORV operation and exposure to naturally occurring mineral fibers. Operating an ORV on an unpaved surface produces fugitive dust emissions, and in areas where NOA and NOE are a component of the underlying terrain, these fibers can be liberated and produce measureable airborne concentrations. Most ORVs include vehicles without an enclosed cabin, which puts riders at greater risk for exposure to airborne fibers through inhalation. The dusty environments to which riders are exposed often occur outside of traditional occupational settings and beyond regulatory boundaries that would necessitate monitoring and guidance regarding the use of personal protective equipment. Thus, off-roading in areas with NOA and NOE presents a nontraditional route of exposure that has not been sufficiently explored.

At a fundamental level, 'environmental' refers to that which is of the natural world. The presence of mineral fibers in the environment may result from both natural phenomena and anthropogenic activity. Surfaces may contain mineral fibers due to: 1) Soils formed from the weathering of *in-situ* NOA/NOE-containing bedrock, 2) Soils formed in areas in which natural geological processes have transported and deposited NOA/NOE-containing sediment (e.g. alluvial and eolian deposits), 3) Humans have transported soil, gravel, or rock containing NOA/NOE, and lastly 4) Soils were contaminated with asbestos fibers as a result of current or past industrial processes such as mining, manufacturing of asbestos containing products, building construction and demolition, or other anthropogenic sources. ORV use in areas where NOA/NOE is a component of the underlying soil, regardless of source, may result in exposure to airborne fibers.

The data presented in our review suggests that exposures to mineral fibers among children during ORV use may be elevated

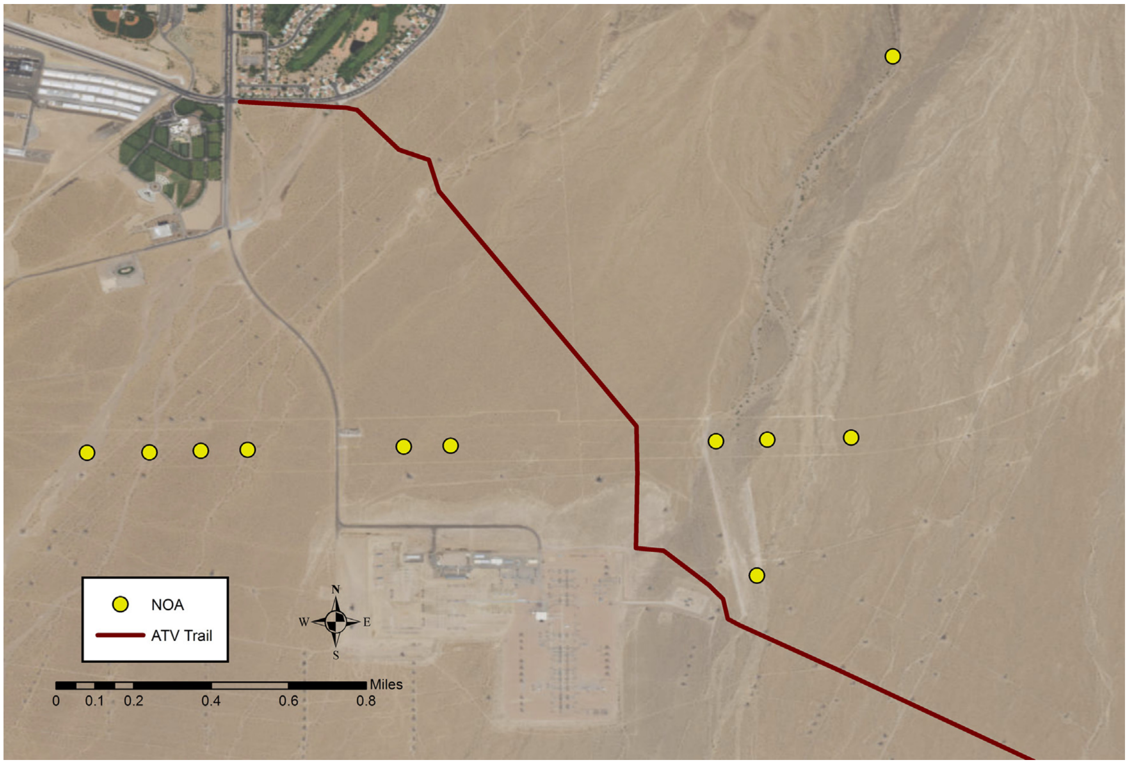

Fig. 3. Off-road vehicle trail and NOA locations near Boulder City, NV. Primarily actinolite, the pictured NOA locations lie in very close proximity to a GPS-recorded ORV trail from a personal excursion (nearest occurrence ~490 feet).

when compared to adults. Exposure during childhood is of particular concern as the growth and development of the lung is not complete until early adulthood. In addition, 20–30 years of latency are typically observed between initial exposure to asbestos and disease onset. Therefore, not only are children likely to experience higher doses of mineral fibers during ORV use, but exposures as children may increase the risk of disease onset within their lifetime (Reid et al., 2013; Vinikoor et al., 2010). ORV use in areas containing NOA may also result in bystander or take home exposures. After driving an SUV and walking on a dirt road in Boulder City, NV, amphibole asbestos was found in settled dust on the vehicle that was used and on the driver's clothes and shoes (Buck et al., 2013). Handling of clothes loaded with asbestos may re-suspend fibers into the air (Sahmel et al., 2014), and asbestos related diseases among household contacts of asbestos workers have been reported (Kilburn et al., 1986; Miller, 2005). The same potential for exposure and disease exists for individuals who handle dusty clothes or otherwise share a household of an ORV participant. Likewise, a rider may also transfer NOA or NOE fibers to the upholstery and surfaces of a personal vehicle, and individuals who enter the vehicle thereafter may disturb and re-suspend embedded fibers.

Decades of epidemiologic studies have demonstrated that inhalation exposure to asbestos and asbestos-like fibers can induce a range of malignant and nonmalignant pulmonary diseases—most of which examined exposures sustained in an occupational setting. To date, no epidemiologic studies have explicitly assessed the relationship between exposure to mineral fibers via ORV use and pulmonary disease. Exposures experienced by ORV riders, under most circumstances, likely occur less frequently and are of lesser duration compared to those experienced in an occupational setting. Yet, asbestos-related disease has been shown to occur at low levels of lifetime cumulative exposure (EPA, 2014b; Lockey et al., 2015; Rohs et al., 2008). This has been documented in a cohort of workers in Marysville, OH that were exposed occupationally to Libby amphibole asbestos. In workers with lifetime cumulative exposures between 0.29 and 0.85 f/cc-years, 25% (17/72) had pleural changes based on chest radiograph (Rohs et al., 2008). In a subsequent analysis, the same cohort of workers were shown to have a higher rate of pleural changes based on chest high resolution computed tomography. Within the group with lifetime cumulative exposures of 0.15–<0.45 f/cc-years, 44% (22/50) had pleural changes (Lockey et al., 2015). The data presented in Lockey et al. and Rohs et al. were critical studies used in the determination of the US EPA Integrated Risk Information System Reference Concentration (RfC) for Libby amphibole asbestos (LAA). The RfC, which represents än estimate of a continuous inhalation exposure that is likely to be without an appreciable risk of deleterious effects during a lifetime,̈ for Libby amphibole was determined to be 9×10^{-5} fiber/mL (PCM) based on the critical effect of localized pleural thickening (EPA, 2014b). The composition of LAA is diverse and includes a blend of winchite, richterite, tremolite, magnesioriebeckite, and low levels of magnesio-arfvedsonite and edenite (Meeker et al., 2003). Meeker et al. (2003) also note that LAA displays a unique variety of morphologies. Thus, the RfC for LAA may not be congruently applied in risk calculations for other amphiboles or mineral fibers.

The risks associated with ORV use in areas of NOA have been recognized by US regulatory bodies, and previous efforts have been implemented to limit human exposures to mineral fibers during ORV use. In 2008, the Bureau of Land Management issued an emergency closure of a portion of the Clear Creek Recreation Area known as the Serpentine Area of Critical Environmental Concern. As of March 2014, this area was reopened to the public, but the use of ATVs and motorcycles remains prohibited. Still, there continues to be strong support, including federal congressional legislation. The U.S. House of Representatives passed the Clear Creek National Recreation Area and Conservation Act in July 2015 and is currently awaiting approval by the U.S. Senate (U.S House of Representatives, 2015). If passed into law, this legislation would permit the reintroduction of ORVs into Clear Creek in spite of evidence that elevated asbestos exposures are associated with this activity.

Multiple factors such as inhalation dose, frequency and duration of exposure, personal risk factors like the use of tobacco products, as well as fiber morphology and mineralogy influence the development of asbestos-related diseases. Disentangling these factors and extrapolating risk estimates based on occupational exposures in order to ascertain the disease risk associated with ORV use is an exceedingly intricate undertaking and outside the scope of this manuscript. At minimum, the personal and airborne exposures reported by studies examined in this manuscript warrant future research to address this research gap.

There are some limitations to our review that should be noted. Given that the ORV tracks used in this study are self-reported and based on individual riders' GPS use, it is likely that these are an underestimate of the true length of all ORV trails. The existence of additional tracks shown in aerial photos suggests that additional ORV trails are utilized but were not captured by the user data examined in this review (Fig. 3). Additionally, a significant portion of ORV use can occur beyond designated trails, particularly in arid environments characterized by sand dunes, badlands, or flat desert regions. The sparseness of ORV trail data required us to restrict our analysis to a five state region. Off-roading is known to occur in other areas (Consumer Product Safety Commission, 2015; Cordell, 2008), and we located information regarding ORV trails for other states throughout the country. However, the data was presented in an unusable format (i.e. PDF maps). Similarly, the number of the mineral fiber occurrences used in this study is likely an underestimation. The distribution of NOA-bearing rocks has only been measured or predicted for a limited number of locations (Churchill et al., 2000; Metcalf and Buck, 2015; Solie and Athey, 2015), and recent research suggests at least some NOA-containing rocks have gone unrecognized (Metcalf and Buck, 2015). Additionally, only known, solitary GPS-identified sites were analyzed in this study, yet NOA and NOE occurrences are controlled by geologic processes that distribute the fibers widely across the landscape. Such areas can span several to hundreds of square miles (Buck et al., 2013; Van Gosen et al., 2013). Weathering, erosion, and wind/water transport can further distribute these mineral fibers across a wide geographic region (Goossens et al., 2012; Van Gosen et al., 2013). Thus, the actual mileage of ORV trails that falls within the NOA and NOE deposits is likely higher than what we have presented. These uncertainties could be better addressed by comparing the distribution of ORV trails to maps showing the distribution of rock types with high geologic potential to contain asbestos or erionite (Buck et al., 2013; Plumlee et al., 2015)

The references we present in this review demonstrate that ORV activity can generate quantifiable airborne concentrations of mineral fibers in areas where they are naturally occurring. Our review also shows that a substantial amount of ORV trails are located in close proximity to NOA/NOE sources, despite the restricted geographical scale of our study region. Future research should include detailed geological surveys to identify and predict the geographic extent of NOA and NOE occurrences. In addition, further activity based sampling studies are needed to better characterize airborne fiber exposures resulting from ORV use and the disturbance of NOA and NOE contaminated soils or gravels. Lastly, active surveillance and epidemiologic studies should be performed to help determine the risk of asbestos related disease among individuals who frequently engage in ORV use or may otherwise be exposed to hazardous mineral fibers in areas where they are naturally occurring. In the interim, public health measures are recommended to communicate the possible dangers associated with ORV use in areas that are known to contain NOA/NOE, which will enable ORV users to make informed decisions and take appropriate measures to limit their exposures where possible.

Declaration of interest

The authors listed on this manuscript claim no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijheh.2017.07.003.

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