

DISSERTATION

ENVIRONMENTAL DETERMINANTS OF THE EQUINE ATHLETE:
AIR POLLUTION EXPOSURE, PERFORMANCE IMPACTS, AND MANAGEMENT
RECOMMENDATIONS ACROSS EQUESTRIAN DISCIPLINES

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ABSTRACT

ENVIRONMENTAL DETERMINANTS OF THE EQUINE ATHLETE: AIR POLLUTION EXPOSURE, PERFORMANCE IMPACTS, AND MANAGEMENT RECOMMENDATIONS ACROSS EQUESTRIAN DISCIPLINES

Ambient air pollution represents the single greatest environmental health threat worldwide and is a leading contributor to human morbidity and mortality. Although policy has significantly improved air quality in the United States (U.S.), climate change is reversing these trends. Warmer and drier conditions promote more frequent and intense wildfires throughout western U.S. and Canada, resulting in fine particulate matter (PM_{2.5}) emissions that travel far from the source of smoke. Additionally, hotter climates promote ground-level ozone (O₃) formation, a secondary pollutant that forms in the presence of heat and sunlight. O₃ remains a persistent concern in many regions of the U.S., including the Colorado Front Range. While much is known about how air pollution impacts human health, little is known about its effects on domesticated animals. Athletes, especially those who exercise outdoors, have been identified as a particularly vulnerable group. Therefore, we identified equine athletes as a promising model, given decades of existing performance data and their primarily outdoor lifestyle. Our objective was to characterize the risk of air pollution exposure, explore the relationship between exposure and equine athletic performance, and develop evidence-informed management recommendations for horses during periods of poor air quality. Spatiotemporal analysis of air quality at U.S. Thoroughbred racetracks identified that all racetracks experienced levels of pollutants exceeding the National Ambient Air Quality Standards (NAAQS), and that PM_{2.5} and O₃, remain key

pollutants of concern with clear seasonal patterns and heterogeneous spatial distribution. We then explored air quality exposure during pre-competition training, applying a distributed lag non-linear model (DLNM) in a retrospective observational study to describe the relationship between training air quality and winning speed on race day, and how that relationship unfolds over time. Horses exposed to higher pollutant levels during training had slower winning speeds when compared to those exposed to lower levels, equating to approximately one horse-length slower. We then extended investigation into the sport of eventing to explore the relationship between event-level air quality and performance across the phases of dressage, cross-country, and show jumping. Our results suggested that worse air quality is associated with performance declines in dressage and show jumping. However, worsening air quality appears to benefit cross-country time penalties, with no discernible effect on cross-country jump penalties. These findings supported the development of expert-driven guidance on managing horses during periods of poor air quality. Through an iterative modified Delphi process engaging leading equine veterinarians around the world, we collated recommendations for the general management of all horses, including guidance for training and competition days. By using existing data, we established equine athletes as a promising sentinel model and filled a critical gap in the knowledge of how air pollution affects horses, emphasizing the need to incorporate air quality monitoring into equine sports. Future work must investigate mechanistic pathways underlying performance decline and equine-specific pollutant thresholds at which adverse health impacts are observed. Through the continued use of the equine athlete as a sentinel model or by applying this methodology to other animal species, this work can continue supporting efforts to best safeguard the health and welfare of all animals living under a rapidly changing climate.

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CSU LAND ACKNOWLEDGEMENT

Colorado State University acknowledges, with respect, that the land we are on today is the traditional and ancestral homelands of the Arapaho, Cheyenne, and Ute Nations and peoples. This was also a site of trade, gathering, and healing for numerous other Native tribes. We recognize the Indigenous peoples as original stewards of this land and all the relatives within it. As these words of acknowledgment are spoken and heard, the ties Nations have to their traditional homelands are renewed and reaffirmed.

CSU is founded as a land-grant institution, and we accept that our mission must encompass access to education and inclusion. And, significantly, that our founding came at a dire cost to Native Nations and peoples whose land this University was built upon. This acknowledgment is the education and inclusion we must practice in recognizing our institutional history, responsibility, and commitment.

DEDICATION

This dissertation is dedicated to my husband, Matthew Scott, who has been my peace and my anchor through ten years of graduate school and three degrees. I love you. And to my late father, Ralph Storz, who was undoubtedly the smartest and most generous person I have ever known. I hope I make you proud.

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CHAPTER 1: INTRODUCTION

Access to clean air is a critical determinant of health, yet 99% of the world's population is exposed to concentrations of air pollution that exceed the World Health Organization (WHO) guidelines.¹ Significant air pollution events, including Donora, Pennsylvania in 1948 and New York City in 1966, resulted in excessive death and illness prompting the signing of the Clean Air Act of 1970, which became a major public health success.^{2,3} However, climate change has emerged as a major driver that is stagnating, and even reversing, improvements in pollutant concentrations, particularly for fine particulate matter (PM_{2.5}) and ground-level ozone (O₃).⁴⁻⁶ PM_{2.5} is the main component of wildfire smoke and changing environmental conditions have influenced the prevalence, frequency, and intensity of wildfires globally,⁷ leading to associated wildfire smoke plumes that travel far from the source. In addition to PM_{2.5}, O₃ is a secondary pollutant that forms from precursor compounds, i.e., nitrogen oxides and volatile organic compounds, in the presence of heat and sunlight. Wildfire smoke plumes contain these precursor pollutants leading to the enhancement of ozone levels in urban areas.^{8,9} Additionally, O₃ is a standalone concern, especially in urban areas and heat islands, as many areas in the United States (U.S.) are in non-compliance with current regulatory standards.¹⁰ Despite overall improvements in air quality in the U.S., PM_{2.5} and O₃ remain critical concerns.

The scale of health impacts from exposure to air pollution is substantial; the 2021 Global Burden of Disease study identified particulate matter air pollution as the leading contributor to disease burden and estimated that it accounted for 8% of the total disability adjusted life years worldwide.¹¹ Similar to PM_{2.5}, O₃ is also consistently identified as a pollutant responsible for significant air pollution-related premature mortality and morbidity.^{11,12} Importantly, health

impacts from air pollution are not evenly distributed. Vulnerable populations include elderly, children, those with underlying illnesses, pregnant women, and lower socioeconomic communities.¹³ Athletes, especially those who exercise outdoors, are another vulnerable group; during exertion higher ventilation rates significantly enhance exposure through increased inhalation of pollutants.¹⁴ PM_{2.5}, measuring 2.5 microns or smaller, penetrates deep into the lungs and enters systemic circulation, while O₃, a highly reactive gas, causes significant oxidative stress at the airway surface, both ultimately driving multi-organ health impacts. Causal relationships have been established for respiratory and cardiovascular effects, with additional health effects extending to nearly every organ system implicated across the broader literature.^{12,15}

Given the significant detriment air pollution poses on health, the U.S. Environmental Protection Agency (EPA) developed the Air Quality Index (AQI) to communicate daily air quality and associated health risks to the public. The AQI provides a composite index value from 0 to 500, where higher values represent worse air quality, derived from six criteria pollutants: O₃, PM_{2.5}, coarse particulate matter (PM₁₀), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and carbon monoxide (CO), with the pollutant at the highest concentration in a region setting the index value. The AQI is further divided into six color-coded categories, each paired with public health messaging as pollutant levels increase (Table 1). In the U.S., PM_{2.5} and O₃ are most commonly the driving pollutants behind AQI values.¹⁶

Despite the well-documented impacts of air pollution on human health, leading to the development of the AQI, comparatively little is known about its effects on animal health. A recently published scoping review sought to synthesize existing evidence on the associations between ambient air pollution and health outcomes in domestic animals. Only 29 studies met the inclusion criteria and included studies in dogs (n=9), horses (n=8), and livestock (n=12).

Table 1: The U.S. Environmental Protection Agency's Air Quality Index categories, corresponding index values, color designations, and associated public health guidance.

Air Quality Index		
AQI Category and Color	Index Value	Description of Air Quality
Good / Green	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk.
Moderate / Yellow	51 to 100	Air quality is acceptable. However, there may be risk for some people, particularly those who are unusually sensitive to air pollution.
Unhealthy for sensitive groups / Orange	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.
Unhealthy / Red	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects.
Very unhealthy / Purple	201 to 300	Health alert: The risk of health effects is increased for everyone.
Hazardous / Maroon	301 and higher	Health warning of emergency conditions; everyone is more likely to be affected.

Although the animal-related literature was drastically underrepresented, the reported health outcomes paralleled those described in human health and spanned multiple body systems, including respiratory, neurologic, ophthalmologic, cardiovascular, immunologic, and metabolic effects, as well as neoplastic processes.¹⁷ As noted, athletes who exercise outdoors represent a particularly vulnerable group. The scoping review identified two studies in racehorses that evaluated performance impacts, both reporting a statistically significant correlation between pollutant exposure and winning times and running speeds.¹⁷⁻¹⁹ The review noted a study that was found through back citation, which evaluated stakes races in the U.S. and found that under the most hazardous O₃ levels, race times were markedly slower.²⁰ Finally, a study of Thoroughbred racehorses competing in California evaluated air quality on race day and findings suggest increasing PM_{2.5} levels were associated with a small, but statistically significant, decrease in winning speeds.²¹ Together, these findings suggest that equine athletes represent a promising model for advancing our understanding of air pollution impacts in domesticated animals.

The present dissertation seeks to expand this evidence base with the objective of characterizing the risk of air pollution exposure, exploring the relationship between exposure and equine athletic performance, and developing evidence-informed management recommendations

for horses during periods of poor air quality. In Chapter 2, we establish the foundation for this work by characterizing spatiotemporal patterns of criteria air pollutants surrounding U.S. Thoroughbred racetracks. Chapter 3 explores air quality during the pre-competition training period and uses advanced epidemiological modeling techniques to evaluate the relationship of air quality within the 20-day period preceding a race and race day winning speed. Chapter 4 extends investigation into the sport of equestrian eventing and explores the relationship between air quality at eventing competitions and performance, as measured by scores and penalties across the phases of dressage, cross country, and show jumping, as well as the overall final score. Finally, with a more comprehensive understanding of the risks air pollution poses on equine athletic performance, Chapter 5 applies a modified Delphi method to collate equine veterinary expert consensus on managing horses during increasing levels of air pollution. Together, this body of work establishes air quality as a measurable determinant of equine athletic performance and provides the first expert-informed framework for managing horses during periods of poor air quality to equip horse owners, trainers and riders with the tools needed to make informed decisions when faced with changing environmental conditions.

CHAPTER 2: AIR POLLUTION EXCEEDANCES ROUTINELY OCCUR AT THOROUGHBRED RACETRACKS IN THE CONTIGUOUS UNITED STATES¹

1. Introduction

Air pollution is the largest modifiable risk factor for adverse human health outcomes globally.²² Given the variability of pollution composition and concentration over both space and time, an understanding of local conditions is critical to inform efforts to protect health and welfare. In the United States, the Environmental Protection Agency (EPA) monitors and regulates six pollutants, referred to as ‘criteria pollutants’: ozone (O₃), particulate matter (PM_{2.5} and PM₁₀), carbon monoxide (CO), lead (Pb), sulfur dioxide (SO₂), and nitrogen dioxide (NO₂).²³ For each of these criteria pollutants, the National Ambient Air Quality Standards (NAAQS) were established based on evidence of human health impacts.^{15,24} There are two types of NAAQS standards: primary standards focused on direct public health protection, while secondary standards protect public welfare, including visibility and preventing damage to animals, crops, vegetation, and buildings.²⁵ Ambient air pollutants demonstrate temporal variability, with fluctuations occurring hourly and weekly based on traffic patterns, e.g., rush hour, and weekday commuting,²⁶ as well as seasonally due to combustible fuel sources used for heating²⁷ and meteorological conditions that influence the formation of pollutants (e.g., photochemical reactions that require heat and light for ozone formation).²⁸ The topographical features of the United States, in addition to features of the built environment, specifically relating to population density (e.g., housing, public facilities, roadways), industry, and energy extraction and production result in different levels of sources and levels of air and water contaminants within an airshed or watershed, and require distinct source controls or policy levers to reduce levels of pollution. Across the United States, the EPA has ten

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geographically based regions reflecting these broad differences in environmental conditions, pollution sources, and regulatory contexts.

Biological and social vulnerability to the health effects of air pollution is similarly heterogeneous. Recognized at-risk populations include the elderly, children, those with underlying cardiovascular or respiratory disease, pregnant women, and those of low socioeconomic status.¹³ Athletes are another group of concern, as higher ventilation rates significantly increase exposure and deposition of particulate matter within the lungs.¹⁴ Multiple pollutants, but most commonly ozone (O₃) and fine particulate matter (PM_{2.5}), are known to negatively influence human athletic performance, particularly in sports with high or protracted cardiovascular output.²⁹⁻³¹ The pathogenesis of these impacts is complex and nuanced but is largely due to the direct and indirect effects on the cardiovascular and pulmonary systems.^{32,33} While many studies focus on the impedance of athletic performance from pollution at high profile events like the Olympics^{34,35} or heavily polluted environments,³² there is growing recognition of the adverse performance impacts of training and competing under moderately elevated air quality conditions typical of many urban areas.³⁶

Although much less is known about how air pollution impacts animal athletes, extreme air pollution events, such as smoke from wildfires, have resulted in the cancellation of races out of health concerns for both horses and spectators.^{37,38} Epidemiologic studies in the USA (California)³⁹ and Chile⁴⁰ have identified associations between air pollution and performance, as measured by winning speed and race times, in Thoroughbred racehorses. As with human athletes, these effects can be seen at levels that would be classified as ‘good’ according to the EPA Air Quality Index.³⁹ Collectively, this work highlights the importance of understanding air pollution exposure trends that have implications for the health and welfare of equine athletes. However, existing evidence is

geographically limited, and little is known about air pollution exposure at racetracks in other regions of the U.S. or how these exposures have changed over time. The objective of this study is to evaluate the spatial and temporal dynamics of criteria air pollutants at Thoroughbred racetracks in the United States.

2. Methods

2.1 Racetracks

We identified currently operating Thoroughbred racetracks in the United States from the Bloodhorse website,⁴¹ as of October 10, 2025. We cross-checked that each racetrack had at least one race within the study period from 2011 to 2024, using historical data from Equibase.⁴² Each racetrack's physical address was recorded and verified using Google maps, then geocoded with the 'tidygeocoder' package⁴³ in R to obtain latitude and longitude coordinates. Missing coordinates were retrieved from Google Maps and entered manually.

2.2 Pollutants

We used the RAQSAPI package in R (v4.2.3) to obtain ambient air quality data from the US Environmental Protection Agency (EPA) Air Quality System.⁴⁴ We evaluated all criteria air pollutants over a 14-year period (2011 – 2024): PM_{2.5} and PM₁₀, O₃, NO₂, CO, SO₂, and Pb. Chemical analysis methods for each criteria pollutant are defined in 40 CFR Part 50, specifically Appendices A-1 and A-2 (SO₂), C (CO), D (O₃), F (NO₂), G (Pb), J (PM₁₀), and L (PM_{2.5}).⁴⁵ A 50 km bounding box was created around each racetrack to define the geographic area used to identify monitors representative of local air quality. Data from monitors were included if they reported at least 75% of the year; this completeness criterion was not applied to airborne Pb, which is measured intermittently with variable sampling frequency across sites and time. Daily pollutant concentrations at each racetrack were calculated as the mean of all monitors within the 50 km

bounding box for that pollutant and annual mean concentrations were derived from the daily averages. Because monitoring stations were identified using bounding coordinates derived from the 50 km buffer, some stations may have been located slightly beyond 50 km from the racetrack. Racetracks without any monitors within the defined bounding box were excluded from analysis. Each racetrack was subsequently assigned to its corresponding US EPA region for regional analyses.

2.3 Exceedances

We used the NAAQS primary thresholds, based on health effects in human populations and corresponding averaging time, as reported in 2025²⁵ to determine the exceedances by pollutant for each racetrack, EPA region, month, and year. An exceedance was defined as any observation in which the pollutant concentration met or exceeded its respective NAAQS threshold. Specifically, we compared (i) daily CO concentrations to 9 ppm; (ii) daily Pb concentrations to 0.15 $\mu\text{g}/\text{m}^3$; (iii) daily NO₂ concentrations to 100 ppb; (iv) O₃ to 0.070 ppm; (v) PM_{2.5} to 35 $\mu\text{g}/\text{m}^3$; (vi) PM₁₀ to 150 $\mu\text{g}/\text{m}^3$; and (vii) SO₂ to 75 ppb. For pollutants with an annual primary NAAQS standard, i.e., NO₂ and PM_{2.5}, we averaged daily pollutant concentrations within each year at each racetrack to calculate the annual mean. Annual exceedances were defined as annual averages ≥ 53 ppb for NO₂ or ≥ 9 $\mu\text{g}/\text{m}^3$ for PM_{2.5} (Supplemental Table S1, Appendix 1). The term “exceedance” used in this study refers solely to whether the pollutant levels surpassed the respective NAAQS and is not equivalent to an official EPA exceedance determination, which accounts only for human-origin sources (e.g., vehicle emissions) rather than natural events such as wildfire smoke. Beyond quantifying exceedances, we also assessed the proportion of PM_{2.5} observations ≥ 11 $\mu\text{g}/\text{m}^3$, a concentration previously associated with significantly slower winning speeds in Thoroughbred racehorses.³⁹

2.4 Spatiotemporal Analysis

For spatial patterns, we evaluated daily NAAQS threshold exceedances for all pollutants and annual exceedances for PM_{2.5} and NO₂ across EPA regions. EPA Region 1 (New England) was omitted due to the absence of active racetracks in those states. To assess temporal patterns, we examined monthly trends to characterize seasonal variation and annual trends to evaluate long-term changes in mean pollutant concentrations and exceedance counts throughout the study period.

2.5 Statistical Analysis

We performed descriptive statistics to summarize daily and annual pollutant concentrations, with mean (standard deviation) reported for normally distributed pollutants, and median (range) for skewed distributions. Exceedance counts were calculated by racetrack, region, month, and year.

To formally assess differences in exceedance counts across time and space, we used a negative binomial generalized linear model with EPA region, year, and pollutant as predictors, appropriate for over-dispersed count data. Model results were used to determine whether exceedance frequencies differed significantly by pollutant across EPA regions and over time. Values of $p < 0.05$ were considered significant.

3. Results

3.1 Racetracks

We identified 57 Thoroughbred racetracks in the contiguous United States that conducted at least one race between January 1, 2011, to December 31, 2024. One racetrack, Ruidoso Downs in New Mexico, did not have any air quality monitors within 50 km and was excluded from analysis for a total of 56 racetracks analyzed.

3.2 Pollutants

There was a total of 1,105 unique monitoring stations identified across the 56 racetracks. The number of monitors per track ranged from 1 to 52 (median 20.5). The median distance between monitoring stations and racetrack was 30.2 km (range 0.95 – 69.0 km).

After removing negative pollutant values and averaging multiple daily observations of the same pollutant at each racetrack, the final dataset included 1,434,429 observations across all pollutants. Of the pollutants, PM_{2.5} had complete racetrack coverage, with data available for 100% of the racetracks, whereas Pb had the lowest coverage, with data available for 66.1% of racetracks (Table 2).

Table 2: Distribution of air quality observations and racetrack coverage by pollutant. Values represent the total number of daily observations, and the number and percentage of Thoroughbred racetracks with at least one monitoring station reporting data within a 50 km radius.

Pollutant	Number of observations (n)	Racetracks with data (n)	Racetracks with data (%)
CO	214,960	46	82.1
Pb	39,762	37	66.1
NO ₂	239,403	48	85.7
O ₃	268,131	54	96.4
PM ₁₀	185,586	52	92.9
PM _{2.5}	247,574	56	100.0
SO ₂	239,013	49	87.5

Daily air pollutant concentrations across all locations during the study period were not normally distributed, with the exception of O₃, which followed an approximately normal distribution. We report median (range) values for all pollutants in Supplemental Table S2 (Appendix 1). The percentage of days with available observations for each pollutant is provided to indicate data completeness across regions. Notably, the median concentrations of all pollutants were below their respective daily NAAQS standards across all EPA regions.

Annual mean concentrations were approximately normally distributed for PM_{2.5}, PM₁₀, and O₃, and distributions were right-skewed for CO, Pb, NO₂, and SO₂; therefore, we report

median (range) to describe the annual summary statistics for all pollutants for consistency (Supplemental Table S3, Appendix 1). EPA Regions 5 (the Great Lake States) and 9 (California, Arizona, and Nevada) had annual average $\text{PM}_{2.5}$ concentrations exceeding the NAAQS threshold of $9 \mu\text{g}/\text{m}^3$ ($9.22 \mu\text{g}/\text{m}^3$ and $9.77 \mu\text{g}/\text{m}^3$, respectively), while no regions exceeded the annual NAAQS threshold for NO_2 . Figure 1 displays the annual mean concentration of each pollutant across the study period. Substantial declines were observed in CO, Pb, NO_2 , and SO_2 , reflecting notable improvements in air quality over time. In contrast, O_3 and PM_{10} initially decreased but began to increase again around 2020. $\text{PM}_{2.5}$ concentrations generally declined across the study period, although greater inter-annual variability was observed in more recent years.

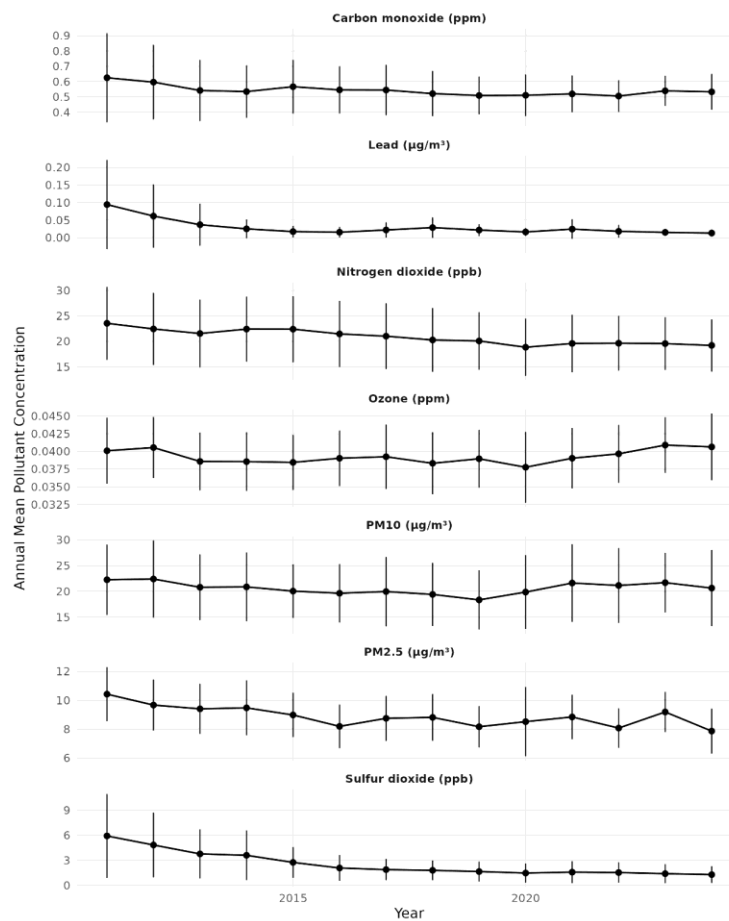


Figure 1: Annual mean (dots) with standard deviation (vertical lines) of concentrations for criteria air pollutants across the study period (2011 – 2022).

3.3 Exceedances

Every racetrack included in this study experienced at least one pollutant exceedance during the study period. Most racetracks exceeded the daily NAAQS at least once for O₃ (n = 54, 96.4%) and PM_{2.5} (n = 53, 94.6%), followed by PM₁₀ (n = 24, 43%), Pb (n = 20, 35.7%), SO₂ (n = 13, 23%), and NO₂ (n = 1, 2%). No CO exceedances were observed. Across all racetracks, Pb accounted for the highest total number of exceedances (n = 2,507), followed by O₃ (n = 2343), PM_{2.5} (n = 675), PM₁₀ (n = 160), SO₂ (n = 88), and NO₂ (n = 1) (Supplemental Table S4, Appendix 1). EPA region 9 had the greatest number of daily exceedances (n = 2105), followed by region 5 (n = 1492) and region 6 (n = 815). The remaining regions ranged from 70 to 437 exceedances (Table 3).

No region exceeded the annual NAAQS threshold for NO₂. EPA Region 8 (Mountain West) did not experience any annual exceedances for any pollutant, whereas the remaining regions collectively recorded 336 annual PM_{2.5} exceedances. Regions 6 and 9 had the highest number of exceedances (n = 74, each), followed by Region 5 (n = 70), Region 3 (n = 55), and Region 4 (n = 35). Regions 2, 7, and 10 had the fewest annual PM_{2.5} exceedances, with n = 13, n = 8, and n = 7, respectively.

Among all racetrack observations, 25.2% (62,410 of 247,607) of PM_{2.5} measurements met or exceeded 11 µg/m³, ranging from 13.4% to 33% amongst the EPA regions. Region 9 had the highest percentage of observations at or above this threshold (33%), followed by Region 5 (30.6%) and Region 6 (25.1%) (Table 4).

3.4 Spatiotemporal patterns

Figure 2 presents the annual count of daily pollutant exceedances by EPA region throughout the study period. Although Pb exhibited the highest number of exceedances overall,

Table 3: The number of exceedances above the daily NAAQS thresholds for each criteria pollutant over the study period.

EPA Region	Pollutant	Number of exceedances (n)	Total number of exceedances (n)
2	O ₃	167	205
	PM _{2.5}	38	
3	Pb	36	437
	O ₃	305	
	PM ₁₀	9	
	PM _{2.5}	86	
	SO ₂	1	
4	Pb	115	333
	O ₃	188	
	PM ₁₀	1	
	PM _{2.5}	23	
	SO ₂	6	
5	Pb	1100	1492
	O ₃	277	
	PM ₁₀	5	
	PM _{2.5}	93	
	SO ₂	17	
6	Pb	58	815
	O ₃	497	
	PM ₁₀	118	
	PM _{2.5}	78	
	SO ₂	64	
7	Pb	104	167
	O ₃	35	
	PM _{2.5}	28	
8	NO ₂	1	150
	O ₃	131	
	PM _{2.5}	18	
9	Pb	1093	2105
	O ₃	741	
	PM ₁₀	27	
	PM _{2.5}	244	
10	Pb	1	70
	O ₃	2	
	PM _{2.5}	67	

Table 4: Number and percentage of days during the study period (2011–2024) in which daily PM_{2.5} concentrations at Thoroughbred racetracks met or exceeded 11 µg/m³, relative to the total number of days with available observations, summarized by EPA region.

EPA region	Number of Days ≥ 11 µg/m ³ (n)	Total Number of Days (n)	Percent above 11 µg/m ³ (%)
2	4458	23800	18.7
3	11009	45353	24.3
4	6460	30343	21.3
5	12296	40184	30.6
6	10816	43077	25.1
7	2334	12810	18.2
8	679	5055	13.4
9	13326	40372	33.0
10	1032	6613	15.6

EPA Regions

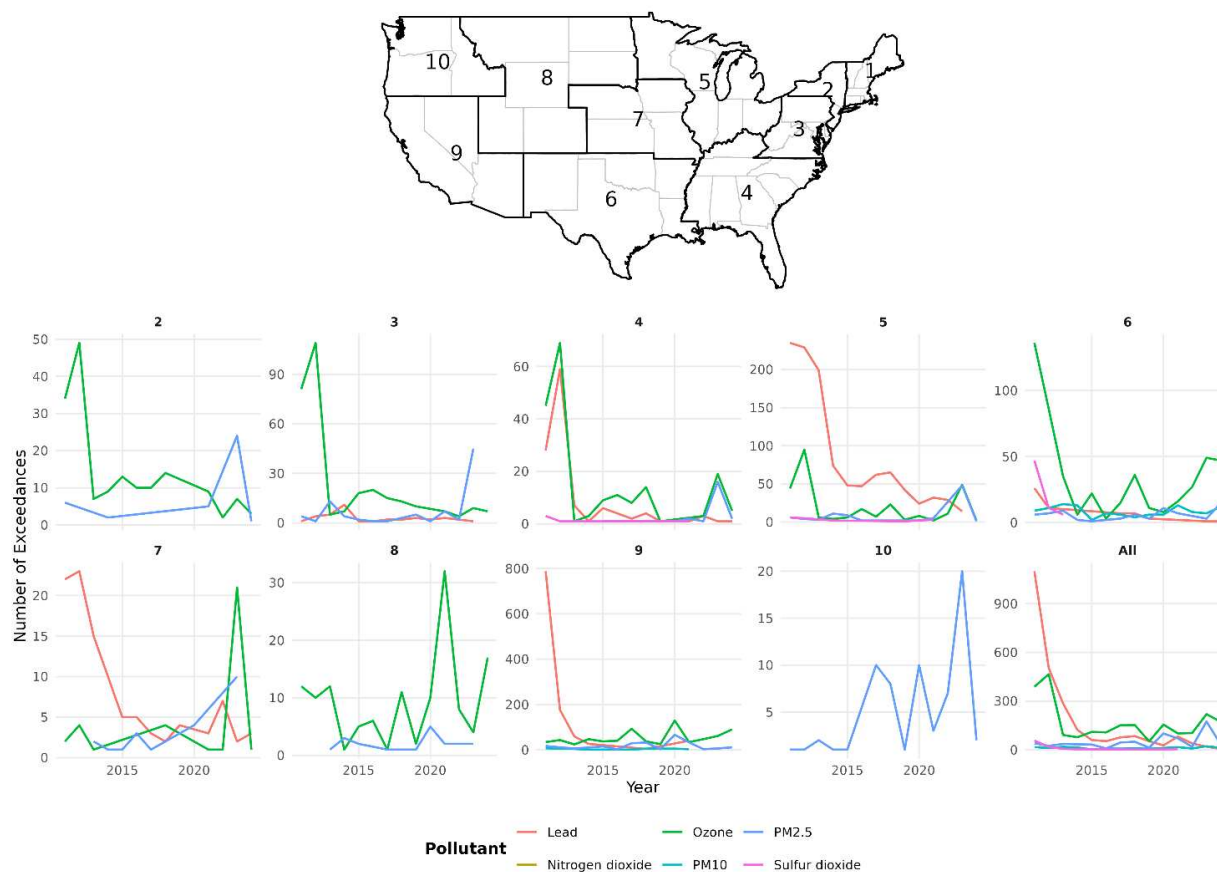


Figure 2: Annual counts of daily pollutant exceedances by EPA region from 2011–2024. Each panel corresponds to one EPA region (numbered as shown on the U.S. map), with 'All' compiling the number of exceedances per pollutants across the EPA regions. The number of exceedances varies significantly by the year ($\chi^2 = 11.6$, $p < 0.001$), pollutant type ($\chi^2 = 65.0$, $p < 0.001$), and EPA region ($\chi^2 = 102.6$, $p < 0.001$).

particularly in Regions 4, 5, 7, and 9, these declined sharply over time and remained low in recent years. In contrast, O₃ exceedances decreased markedly during the early years but increased again in Regions 6, 7, 8, and 9 after approximately 2020, showing greater interannual variability. PM_{2.5} followed a similar pattern, with notable year-to-year fluctuations and a pronounced upward trend, most evident in region 10 during the latter part of the study period.

Most criteria air pollutants demonstrate clear seasonal patterns across all racetracks, with the exception of Pb and SO₂ (Supplemental Figure S1, Appendix 1). CO and NO₂ concentrations peaked during winter months and declined during summer months. In contrast, O₃ and PM₁₀

peaked during summer months. $PM_{2.5}$ displayed a bimodal distribution across seasons, with peaks in both winter and summer months, and lower concentrations in spring and fall. When evaluating the median number of exceedances per month, similar seasonal patterns were observed for O_3 and $PM_{2.5}$; however, PM_{10} showed more exceedances in the first half of the year than in the second half (Figure 3). Monthly median Pb exceedances did not follow a clear seasonal pattern.

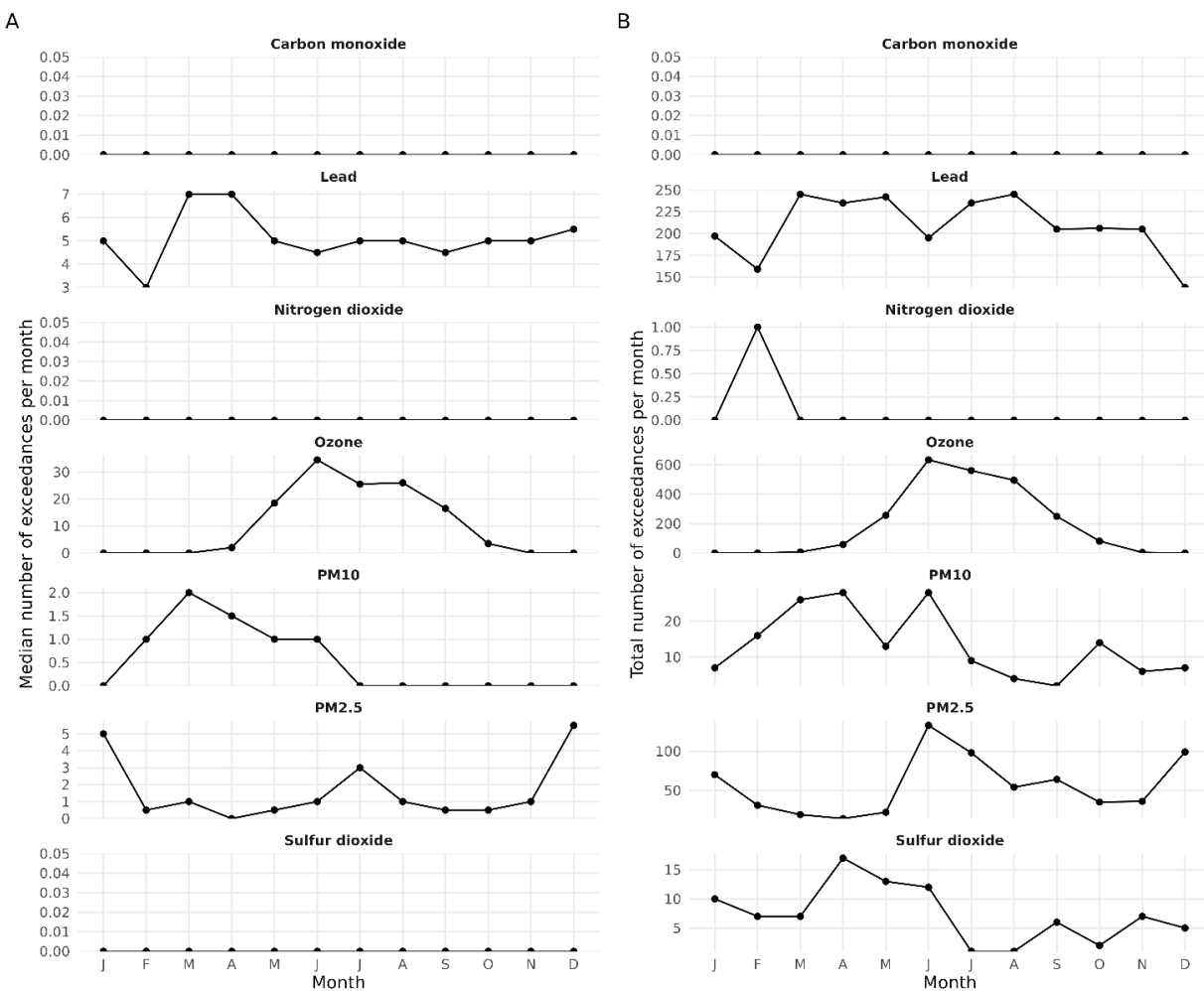


Figure 3: Monthly distribution of daily exceedances across all racetracks, with panel A showing the median number of exceedances per month and panel B showing the total number of exceedances per month across all racetracks.

When comparing the total number of exceedances per month across racetracks and years, patterns were similar to those observed in the monthly medians. Notably, NO_2 had only one

exceedance across all racetracks during the study period, which occurred in February 2014. Although monthly median exceedances for SO₂ were zero, the total number of SO₂ exceedances ranged from 1 to 17 per month, occurring primarily early in the study period. Across years, Pb exceedances declined substantially over time, while PM₁₀ and PM_{2.5} showed greater inter-annual variability, with the highest number recorded in 2023. O₃ exceedances decreased sharply between 2012 and 2013 and remained relatively consistent thereafter, although 2023 and 2024 had the highest and second-highest exceedance counts since 2012 (Figure 2 [“All”] and Supplemental Figure S2, Appendix 1). The negative binomial regression formally assessed these described differences, revealing significant effects of year ($\chi^2 = 11.6$, $p < 0.001$), pollutant type ($\chi^2 = 65.0$, $p < 0.001$), and EPA region ($\chi^2 = 102.6$, $p < 0.001$) on the number of exceedances, confirming that exceedance frequency varied significantly among pollutants and across both time and space.

4. Discussion

Results of this study highlight important spatial and temporal patterns in criteria air pollutants near US Thoroughbred racetracks. Pb exhibited the highest number of exceedances ($n = 2,507$), though both annual mean concentrations and exceedance frequency declined markedly over time, reflecting improvements in air quality. O₃ had the second highest number of exceedances ($n = 2343$); unlike Pb, O₃ concentrations peaked in 2023, which also recorded the greatest number of exceedances since 2012. Particulate matter (PM_{2.5} and PM₁₀) exceedances also increased over the study period, with 2023 showing the highest counts for both pollutants, a pattern consistent with increasing wildfire-related emissions across North America.⁴⁶ Additionally, pollutant burden varied across EPA regions, indicating a heterogenous spatial distribution of air quality across the U.S. that is further explored in subsequent sections.

Collectively, these findings highlight O₃ and particulate matter as key pollutants of concern that warrant focused management, particularly during periods of high equine physical activity, such as race and training days, when increased exertion and ventilation rates can expose horses to higher pollutant doses delivered to the lungs.²⁹ Although this analysis did not directly evaluate health outcomes, the identified spatial and temporal patterns have implications for equine and human health, emphasizing the importance of continued monitoring and mitigation.

Veterinarians and trainers can use this information to inform region-specific, health-protective management practices and to guide ongoing surveillance of air quality threats.

A surprising finding was the number of Pb exceedances observed during the study period. Pb had the highest number of exceedances (n = 2,507) affecting just over one-third of the racetracks. Although this figure appears concerning, airborne Pb concentrations have improved substantially over the study period, with exceedances declining sharply in more recent years. Nonetheless, certain EPA regions (3, 4, 5, 6, 7, and 9) representing the East Coast, Midwest, South-Central, and Western U.S. continue to experience exceedances each year. Pb is considered as legacy pollutant, as it can persist in the environment long after primary sources, such as Pb gasoline and smelting operations, have ceased.⁴⁷ Resuspension of Pb from contaminated soil can be a dominant source of airborne lead, as was shown to be the case in major cities including Birmingham, Chicago, Detroit, and Pittsburgh.⁴⁸ The continued presence of airborne Pb near some racetracks may reflect Pb resuspension due to proximity to decommissioned Pb smelters, legacy industrial sites, or areas with historically high traffic volumes. This is likely the case for Fairmont Park in Collinsville, IL, which had the highest number of Pb exceedances (n = 942). This area has documented history of Pb smelting activity and ongoing environmental contamination.⁴⁹ Atmospheric Pb can deposit into surrounding soils, introducing ingestion as an

additional potential exposure pathway. The effects of Pb exposure on equine health have primarily been studied in the context of ingestion rather than inhalation. Pb poisoning in horses can result in gastrointestinal disease, e.g., weight loss, colic, diarrhea, and neurologic dysfunction, including laryngeal or pharyngeal paralysis and dysphagia that may lead to aspiration pneumonia.⁵⁰ Racetracks located near former industrial or processing sites should consider soil testing, as Pb can deposit into water and soil environments, and contamination can persist for decades.

Although Pb had the most exceedances across racetracks ($n = 2,507$), O₃ followed closely behind with 2,343 exceedances across all but two racetracks. Notably, the annual mean concentration of O₃ has increased markedly since 2020, reaching the highest levels of the study period in 2023 and 2024. These two years also recorded the first and second highest numbers of O₃ exceedances since 2012. This upward trend in O₃ exceedances, particularly across the southern U.S. (Southeast, South-Central, and Southwest), as well as parts of the Midwest and West, underscores the importance of regulating training and racing schedules during high O₃ periods. These regions are especially prone to O₃ formation due to high solar radiation and warmer summer temperatures, when O₃ levels tend to peak, as it is a secondary pollutant formed through photochemical reactions between NO₂ and volatile organic compounds (VOCs) in the presence of heat and sunlight. Urban centers within these regions further amplify this risk through elevated emissions of NO₂ and VOCs. The strong association O₃ has with temperature and solar radiation explains the observed summer increase and characteristic diurnal cycle, with levels peaking in the afternoon, making early-morning training and racing sessions preferable to minimize exposure. During exercise, O₃ exposure disrupts breathing patterns and minute ventilation, impairs lung function, induces pulmonary inflammation, and causes respiratory

symptoms such as chest tightness, wheezing, and shortness of breath.³² Research on the effects of O₃ on equine athletes is limited, though one study demonstrated that Grade I Stakes Thoroughbred racing under ‘hazardous’ ozone conditions was significantly slower than horses competing under cleaner air quality categories.²⁰ A recent study further suggests that horses training under O₃ concentrations consistent with the “moderate” air quality index (AQI) category during the 14-28 days preceding a race exhibit slower winning speeds compared to those training under “good” AQI categories.⁵¹ Together, these findings emphasize that rising O₃ levels, particularly in the southern and western regions, represent an emerging environmental risk for equine performance that warrants targeted management and monitoring.

Particulate matter, particularly PM_{2.5}, was also identified as a pollutant of concern for racetracks, with every U.S. region experiencing an increasing number of exceedances and greater inter-annual variability, which can be attributed to wildfire smoke. Although the EPA excludes PM_{2.5} from natural sources, including wildfire smoke, when determining official exceedances, our analysis did not differentiate between anthropogenic and natural sources. As a result, the exceedance estimates presented here include contributions from wildfire smoke, which likely explains the observed trend.⁴⁶ Wildfire smoke is a major contributor to PM_{2.5} concentrations across the U.S., especially in the West and Great Lake states, reflected in EPA Regions 5 and 9, both of which exceeded the annual NAAQS threshold of 9 µg/m³. Owing to their small aerodynamic diameter, PM_{2.5} particles can penetrate deep into lung tissue and can enter systemic circulation, with well-established links to respiratory disease (e.g., asthma, COPD), cardiovascular disease (e.g., hypertension, heart failure), cognitive impairment, and various cancers.¹⁵ A recent study found that PM_{2.5} concentrations as low as 4 µg/m³ on race day were associated with slower winning speeds in Thoroughbred racehorses.³⁹ The same study referenced

above reported that horses training at a PM_{2.5} level of 13.6 µg/m³ during the 14-28 days preceding a race ran significantly slower than those training at 5.5 µg/m³.⁵¹ In addition to performance effects, PM_{2.5}, along with NO₂, has been associated with an increased likelihood of inflammatory cells detected in bronchoalveolar lavage fluid.⁵² Like O₃, particulate matter displays clear seasonality. In addition to summer peaks driven by wildfire activity, PM_{2.5} levels also rise during winter months due to increased heating demands and reduced atmospheric dispersion.⁵³ Recognizing the seasonal patterns of these pollutants can guide schedule adjustments and event planning to minimize exposure during peak periods. This will become increasingly important as wildfire smoke events continue to rise in frequency and intensity across the U.S.⁵⁴ Further, in addition to the increasing exceedance of PM_{2.5}, as well as O₃, co-occurrence of these two pollutants is increasing in both frequency and temporal persistence due to shared meteorological conditions and wildfire activity.⁶ Because many air pollutant levels fluctuate in response to climatic conditions, simultaneous exposure to multiple pollutants, even at concentrations individually considered acceptable, represents an area for future direction to assess additive or synergistic biological effects that influence equine health and performance.

Several limitations should be considered when interpreting these findings. First, we included only Thoroughbred racetracks, yet numerous other equestrian events and disciplines occur throughout the U.S. Although these results cannot be generalized to other equestrian centers, the broader message of air quality awareness, including regional trends and seasonality, applies widely. Second, the air pollution concentrations reported here represent only an approximation of the true conditions at each racetrack. By selecting monitors within 50 km of each track, we may not have fully captured local variation in pollutant levels, particularly for sites located in complex terrain or near localized emission sources. This limitation is likely

pollutant-specific, as spatial variability is generally lower for PM_x and O₃ at the airshed scale, but can be substantial for traffic-related pollutants, such as NO₂. Equestrian centers could improve the accuracy of future assessments by installing low-cost air quality sensors on site. This is particularly relevant for locations with sparse monitoring coverage, such as New Mexico, or in regions that lack representation. For instance, EPA Region 8 (Mountain West states) was represented by a single racetrack, yet this region, along with New Mexico, is known to experience frequent ozone and particulate matter pollution events,⁵⁵⁻⁵⁷ suggesting that the limited spatial representation may underestimate true pollutant burden. Third, we assessed air quality across the entire study period (January 1, 2011, to December 31, 2024) rather than isolating pollutant concentrations to specific training or race days. As a result, we cannot directly determine whether horses, riders, or spectators were exposed to poor air quality during actual training or competition events. Additionally, analyses were based on daily summary data; therefore, we were unable to determine the specific time of day when exceedances occurred or whether exceedances coincided with race events. However, racetracks host a variety of activities and often house horses on site year-round, supporting the decision to evaluate air quality across the broader temporal context. Nevertheless, the presence of exceedances at every racetrack underscores the importance of racetrack-level air quality monitoring to support decisions regarding training modification, event postponement, or cancellation of events during periods of poor air quality. This is critical given the documented negative effects of air pollution on both human and equine health, particularly during exertion. Finally, Pb is not measured daily and is inconsistently monitored across both time and sites, meaning that true exceedances may be underreported.

Results of this study demonstrate that Thoroughbred racetracks across the contiguous U.S. routinely experience periods of elevated air pollution that exceed EPA health-based standards. Importantly, pollutant concentrations and exceedances varied both seasonally and regionally, underscoring the need for localized air quality monitoring. Particulate matter and O₃ emerged as the primary pollutants of concern, which often co-occur on hot, smoky summer days, creating a heightened exposure risk for horses, jockeys, and spectators. The daily PM_{2.5} NAAQS threshold (35 µg/m³) is substantially higher than levels associated with documented performance declines in Thoroughbred racehorses, with adverse effects reported at concentrations as low as 4 to 13.6 µg/m³.^{39,51} Our findings also highlighted the need to further evaluate environmental Pb as a legacy pollutant that may continue to pose risk near certain tracks. In contrast, SO₂, NO₂, and CO showed marked improvements in annual concentration levels, with few exceedances during the study period, suggesting these pollutants are less of a risk for human and potentially animal health. At present, no air quality policies specific to Thoroughbred racing exist. The U.S. Equestrian Federation recommends considering suspension or cancellation of competitions when the AQI reaches 151 (Unhealthy),⁵⁸ a threshold that may not fully protect equine athletes given their elevated ventilation and susceptibility during exertion. Future investigations should identify pollutant concentrations at which performance decrements occur using normalized performance outcomes such as finish position with respect to post position or speed ratings. As research continues to clarify the impacts of air pollution on equine performance and health, racetracks should implement on-site air quality monitoring, and veterinarians and trainers should promote awareness of local pollution patterns. Integrating real-time air data into training and competition decisions will help safeguard both equine and human participants while promoting a safer racing environment.

CHAPTER 3: AIR POLLUTION EXPOSURE DURING TRAINING IMPAIRS PERFORMANCE IN THOROUGHBRED RACEHORSES²

1. Introduction

Ambient air pollution has long been recognized as a major environmental exposure that contributes to human morbidity and mortality. Fine particulate matter (PM_{2.5}), a combustion by-product, is considered to be responsible for approximately 90% of the health effects of air pollution.³ Wildfires have become an increasing source of PM_{2.5}, contributing to the stagnation and even reversal of air quality improvements in the western United States, with broader regional impacts observed across the U.S.^{4,59,60} In addition, ground-level ozone (O₃), a secondary pollutant, remains a persistent concern in certain regions of the United States, including California.¹⁰ The adverse health effects of PM_{2.5} and O₃ exposure in humans are well-documented.^{12,15} To communicate health risk linked to these air pollutants, the U.S. Environmental Protection Agency (EPA) created the Air Quality Index (AQI) tool, which aggregates pollutant levels into a standardized, color-coded scale to inform the public about local air pollution levels and the associated health impacts.

Athletes are particularly vulnerable to ambient air pollution exposure due to increased ventilation rates during exertion, thereby increasing the pollutant dose delivered to the lungs and distributed to other organ systems through systemic circulation.^{36,61,62} This can be especially true for athletes who primarily exercise outdoors.⁶³ However, few studies have evaluated the impact of air pollution on performance outcomes in animal athlete models. Racehorses are exceptional athletes and, therefore, may represent a vulnerable species requiring investigation into the health

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and performance consequences of air pollution. Two studies conducted at a racetrack in Santiago, Chile, reported associations between pollutant concentrations, including PM_{2.5}, coarse particulate matter (PM₁₀), nitrogen oxides (NO_x), sulfur dioxide (SO₂), and carbon monoxide (CO), and slower winning times and average speeds.^{18,19} A study assessing Grade 1 Stakes races around the U.S. demonstrated that horses racing under the most hazardous ozone conditions ran significantly slower race times.²⁰ More recently, a large-scale analysis of over 30,000 races in California found that horses exposed to PM_{2.5} concentrations as low as 4-11 µg/m³ ran significantly slower than those racing below those thresholds.²¹ These studies all focused on the competition-day air quality to evaluate the acute effects of exposure. However, studies in humans suggest that air pollution exposure the days prior to competition may also impair performance.^{36,61,64} Specifically, one study used a distributed lag non-linear model (DLNM), a statistical approach that estimates time-varying and non-linear effects of a defined exposure in the days preceding an outcome, to evaluate air pollution influences on collegiate athletic performance. The study demonstrated that track and field athletes experience significantly slower race times when exposed to higher pollutant levels in the 21 days preceding competition.³⁶⁸ To our knowledge, no studies have examined this lagged exposure effect in horses, that is, how the effects of air pollution exposure unfold over time. To explore this relationship in animal athletes, we performed a retrospective longitudinal study utilizing a DLNM to estimate the relationship between exposure to PM_{2.5} and O₃ during the pre-competition training period and race day performance among thoroughbred racehorses that competed on California racetracks.

2. Methods

2.1 Study Area

Twelve equine racetracks located across northern, central, and southern California were included in our study (Table 5). The map of track locations can be found in Kim et al. (2024).²¹

2.2 Outcome Data

We obtained study data for all horse races from January 1, 2011, to December 27, 2021, as well as training data, from The Jockey Club Information Systems (Table 5).²¹ These data included

Table 5: Locations of racetracks included in the study and the number of races evaluated at each site.

Name	City	Racetrack Code	Number of races
Golden Gate Fields	Albany	GG	10444
Santa Anita Park	Arcadia	SA	6130
Del Mar	Del Mar	DMR	2352
Los Alamitos	Los Alamitos	LA	508
Hollywood Park	Inglewood	HOL	369
Pleasanton	Pleasanton	PLN	49
Ferndale	Ferndale	FER	47
Fairplex Park	Pomona	FPX	41
Fresno	Fresno	FNO	32
Santa Rosa	Santa Rosa	SR	30
Sacramento	Sacramento	SAC	24
Stockton	Stockton	STK	11

information on winning horses, winning horse time, signalment, race date, and track conditions. Training data included information on the horse, the date of training sessions, and the track location at which they trained. We assumed that horses lived and trained at the track at which they raced during the pre-competition training period, therefore we restricted the analysis to include horses that had at least one recorded training session at the same racetrack where they subsequently competed within the 28 days preceding a race. This 28-day window was selected to ensure alignment with the longest exposure period evaluated in the sensitivity analysis (section 2.7), while the primary exposure window for the main analysis was defined as the 21 days preceding the race. We calculated the winning horses' speed in meters per second (m/s) as our outcome variable by using the length of the race over the winning time.

2.3 Exposure Data

We obtained air pollution data from the United States Environmental Protection Agency (EPA) Air Quality System Data Mart.⁶⁵ We included PM_{2.5} and O₃ as these are the two primary pollutants of concern.⁶⁶ Specifically, we collected the daily average concentration (ug/m³) for PM_{2.5} and the daily maximum 8-h average (MDA8) concentration of O₃ (ppb). The selection of pollution monitors is described in detail in Kim *et al.* (2024);²¹ briefly, we selected the closest monitor with the most complete data that was within 100km from the racetrack and that did not have geographical barriers (e.g., mountain ranges). Distances between each racetrack and the assigned pollution monitor are provided in Table S2 of Kim *et al.* (2024).²¹

We developed a 21-day air pollutant exposure profile for each winning horse, consisting of 20 training days prior to a race and the day of the race, aligned with previous research conducted in collegiate athletes.³⁶ We assigned PM_{2.5} and O₃ concentrations for every horse at the location of the racetrack at which they trained, competed, and won. The exposure profile for each horse used the threshold AQI, consistent with how the EPA assigns an index value, i.e., when multiple pollutants are present, the AQI is the highest index among the present pollutants. Since we were evaluating PM_{2.5} and O₃, we assigned the AQI as the higher of the two pollutant-specific index values.

2.4 Covariate Data

We included several covariates related to horse descriptors, race descriptors, as well as temporal and temperature data, that could be considered confounders or precision variables.²¹ Age (continuous) and sex (binary) were included as horse covariates. The race-related covariates included race distance (ordinal), the type of race (categorical), and track surface (i.e., dirt or turf). Temporal covariates included the time of the race (i.e., morning, afternoon, or evening),

race day occurring during the week or on the weekend (binary), month (categorical), and the year (continuous). Finally, we included the mean 24-hour temperature on race day.

2.5 Data Analysis

After removing any observations with incomplete or missing data, we completed descriptive statistics for all dependent and independent variables to assess normality and identify outliers (Table 6). We implemented the `dlnm` package in R Statistical Software (v 4.4.1) to

Table 6: Summary of race-related and horse-related information

Race-related variables	Original dataset (n = 41,208)	Analytical dataset (n = 20,037)
Race type		
Claiming handicap (CLM)	16,574 (40.2%)	7,236 (36.1%)
Claiming (MCL)	8,737 (21.2%)	4,129 (20.6%)
Maiden special weight (MSW)	4,757 (11.5%)	2,626 (13.1%)
Allowance or optional claiming (AOC)	3,845 (9.3%)	2,160 (10.8%)
Stakes (STK)	2,663 (6.5%)	1,262 (6.3%)
Starter allowance (STR)	2,360 (5.7%)	1,327 (6.6%)
Other	2,272 (5.5%)	1,297 (6.5%)
Furlong length		
≤4	401 (1.0%)	64 (0.3%)
Between 4 and 6	12,798 (31.1%)	4,801 (24%)
=6	8,490 (20.6%)	4,625 (23.1%)
Between 6 and 8	4,331 (10.5%)	2,029 (10.1%)
=8	9,837 (23.9%)	5,825 (29.1%)
Between 8 and 9	4,021 (9.8%)	1,980 (9.9%)
≥9	1,330 (3.2%)	713 (3.6%)
Weekend		
Weekend	23,026 (55.9%)	11,099 (55.4%)
Weekday	18,182 (44.1%)	8,938 (44.6%)
Time of day		
Morning (10am to 1pm)	2,669 (6.48%)	1,653 (8.3%)
Afternoon (1pm to 5pm)	29,743 (72.2%)	15,816 (78.9%)
Evening (5pm to 9pm)	8,794 (21.3%)	2,568 (12.8%)
NA	2 (0.005%)	----
Track surface		
Dirt	32,961 (80.0%)	15,505 (77.4%)
Turf	8,247 (20.0%)	4,532 (22.6%)
Horse-related factors		
Sex		
Male	22,906 (55.6%)	11,046 (55.1%)
Female	18,300 (44.4%)	8,991 (44.9%)
NA	2 (0.005%)	----
Age (years)		
Median (Range)	4 (2 – 11)	4 (2 – 10)
Speed (meters per second)		
Median (Range)	16.9 (14.5 – 19.3)	16.9 (14.8 – 18.9)

perform a distributed-lag non-linear model (DLNM).^{36,67,68} Within this package, we can transform the exposure data into a two-dimensional matrix, permitting simultaneous estimation of the exposure-response relationship and the lag-response relationships. Specifically, this estimates how increasing levels of air pollution relate to winning speed, and how these effects unfold across the days preceding a race. The shape of the relationships between the exposure and the outcome, as well as the lag-effect on the outcome, are determined by the degrees of freedom; higher degrees of freedom allow the model to fit more complex, curved relationships, i.e., there is more flexibility in the relationship. For AQI and the individual pollutants (PM_{2.5} and O₃) we varied the degrees of freedom between 3 to 7 for both the exposure-response effect and lag effect, individually and in combination. We report results with the form of the relationship as determined by the lowest Akaike Information Criterion (AIC), indicating the best-fitting model.

We estimated the difference in winning speeds for the lag-response relationship and the cumulative effect estimates when comparing horses that trained under poorer air quality conditions, defined at the 80th percentile of the exposure distribution, with horses that trained under less polluted air conditions, defined at the 20th percentile, during the pre-competition training period (Figure 4).³⁶ These contrasts represent point comparisons between the respective percentile values. Effect estimates are reported with corresponding 95% confidence intervals and two-sided p-values derived from model-based standard errors.

2.6 Final Model

Our final model to assess the association between air pollutant exposure and winning speed is represented by the equation:

$$E[O_{tij}] = \sum_{l=1}^{21} \beta_l T_l + \beta_2 X2_{tij} + \beta_3 X3_{tij} + \delta_i + \gamma_j + \epsilon_{tij}$$

Where $E[O_{tij}]$ is the expected winning speed for the i th horse on the t th day at the j th racetrack. $\sum_{l=1}^{21} \beta_l T_l$ denotes the DLNM component, where T_l is the air pollution exposure matrix for AQI, and β_l represents the estimated coefficients for the lagged air pollution exposure matrix T_l differentiated by lag day (l), ranging from the day of the race (day 0) through the 20 days before race day (a total period of 21 days). β_2 represents the coefficients related to the horses (i.e., age and sex) and the races (i.e., distance, type of race, track surface, racetrack). β_3 represents the 24-hour average temperature for the day of the race, as well as the temporal indicators including time of day (i.e., morning, afternoon, or evening), weekday/weekend, month, and year. The final terms, δ_i , represent the random intercept for each horse, γ_j represents the random intercept for each racetrack, and ϵ_{tij} accounts for the model residuals for each horse-specific race at a racetrack.

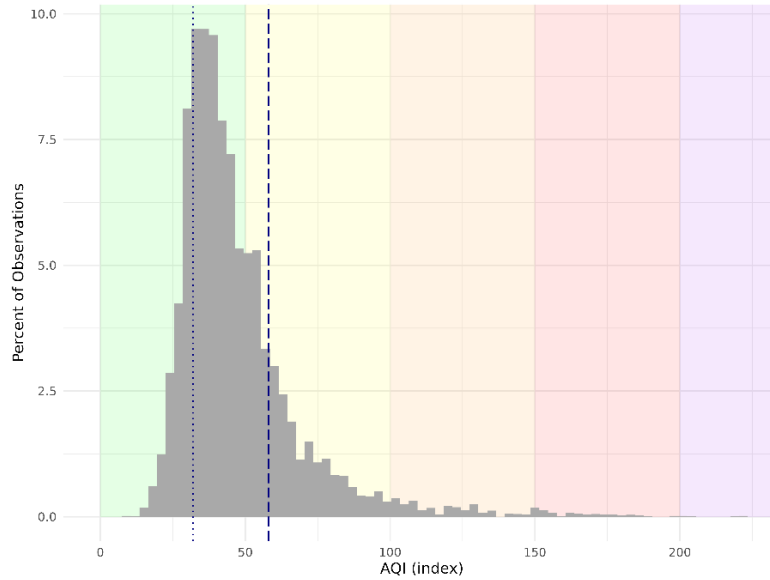


Figure 4: Distribution of the AQI exposure profile. The blue dotted line indicates the 20th percentile, and the blue dashed line indicates the 80th percentile. The background shading corresponds with the Air Quality Index (AQI) categories as follows: Green = Good; Yellow = Moderate; Orange = Unhealthy for sensitive groups; Red = Unhealthy; Purple = Very unhealthy.

As our dataset has multiple observations from the same winning horse, we fit the mixed-effects linear model to account for the expectation that observations within the same horse will have less variation than observations across horses. Additionally, we included the racetrack as a random intercept to account for track-level differences that might influence outcomes.⁶⁹

Our model inputs were largely aligned with the approach used by Kim et al.,²¹ however, we excluded track surface and retained track condition as a binary covariate, categorized as either “dirt” or “turf”. This change was made after we identified collinearity between track surface and track condition based on a chi-square test, then confirmed by examining variance inflation factors (VIFs) in a linear model approximation.

2.7 Sensitivity Analysis

We conducted sensitivity analyses to test whether our findings were robust to different model assumptions. These included varying the exposure lag period, testing alternative exposure percentile comparisons, and assessing the impact of track surface classification, including exclusion of races with ambiguous “good” track conditions. Full description of the sensitivity analysis and corresponding results are provided in the Supplementary Materials (Appendix 2).

3. Results

Our original dataset had 41,208 observations of winning horses that competed from January 1, 2011 to December 27, 2021. After excluding observations that had improbable or invalid values, i.e., invalid post time ($n = 2$), unidentifiable male or female horse ($n = 2$), negative air pollutant values ($n = 94$), all missing data ($n = 10,605$), and horses without a recorded workout in the 28 days prior to the race ($n = 10,468$) our analytic dataset included 20,037 observations over the 10-year study period. Descriptive statistics (Table 6) are presented with the median (range) as no continuous variable was normally distributed. Of the races, 77.4%

were run on a dirt track. Racing in the afternoon between 1 and 5 pm was the most common time races occurred (78.9%), and 55.4% of races happened on the weekend.

3.1 Winning Horses

The study population had 10,722 winning racehorses, with 4,634 horses (43.2%) winning more than once. The median age of racehorses was 4 years (range 2-10 years) and 55.1% were male. The median winning speed was 16.9 m/s (range 14.8-18.9 m/s) (Table 6).

3.2 Air Pollutant Concentrations and AQI

The median reported AQI was 42 (range 10 – 222) and 67.9% of observations were within the *good* AQI category (AQI = 0 – 50). Figure 4 illustrates the distribution of the observed AQI exposure profile.

When assessing the individual pollutants, the median PM_{2.5} concentration was 9 ug/m³ (range 0 – 172.1 ug/m³), and 50.1% of observations were within the *good* AQI category for PM_{2.5} (0 – 9 ug/m³). The median O₃ concentration was 36 ppb (range 0 - 115 ppb) and 91.4% of the observations were within the *good* AQI category for ozone (0 – 54 ppb). Figure 5 provides the distribution of both the PM_{2.5} and O₃ exposure profiles.

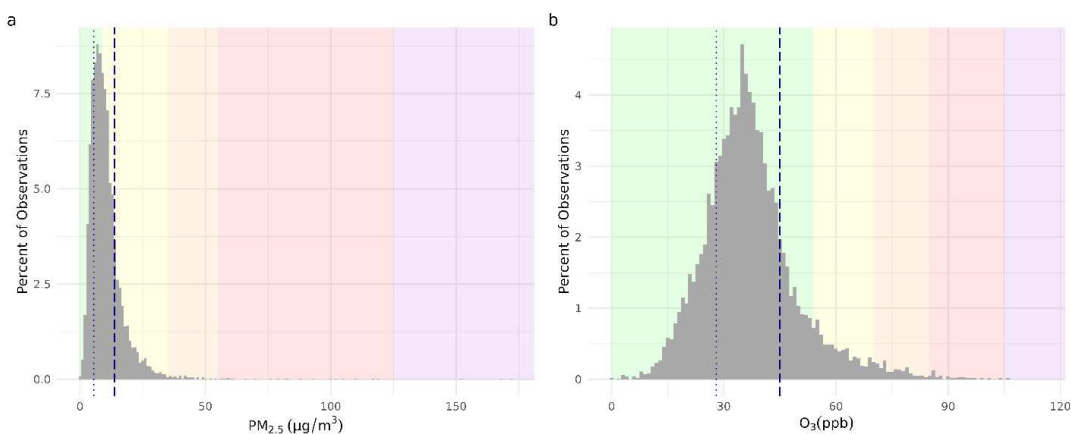


Figure 5: Distributions of each pollutant exposure profile: (a) PM_{2.5}; and (b) O₃. The blue dotted line indicates the 20th percentile, and the blue dashed line indicates the 80th percentile. The background shading corresponds with the Air Quality Index (AQI) categories as follows: Green = Good; Yellow = Moderate; Orange = Unhealthy for sensitive groups; Red = Unhealthy; Purple = Very unhealthy.

3.3 Associations Between Speed and AQI

After accounting for horse descriptors (age and sex), race distance, the type of race, and track surface, as well as the temporal covariates described and the mean-24 hour temperature on race day, the AQI exposure-lag relationship revealed that horses exposed to higher pollutant levels (80th percentile, AQI = 58) compared to lower pollutant levels (20th percentile, AQI = 32) had, on average, slower winning speeds across all lag days. The difference in speed was statistically significant when this exposure occurred between 2 to 17 days before a competition as observed by the confidence intervals (Figure 6a). The exposure-response curve, representing the cumulative effect of all 21 days for each AQI, indicates a nonlinear, negative relationship. As the AQI approaches 50 (i.e., the cut point in the air quality changes from “good” to “moderate”) horses exposed to worse air quality in the 21 days prior to the race will, on average, run slower (Figure 6b). Horses exposed to the 80th percentile (AQI = 58) across the 21-day pre-competition training period had a statistically significant cumulative decrease in speed of 0.044 m/s (95% CI -0.056, -0.032; $p < 0.001$) when compared with those exposed to the 20th percentile (AQI = 32).

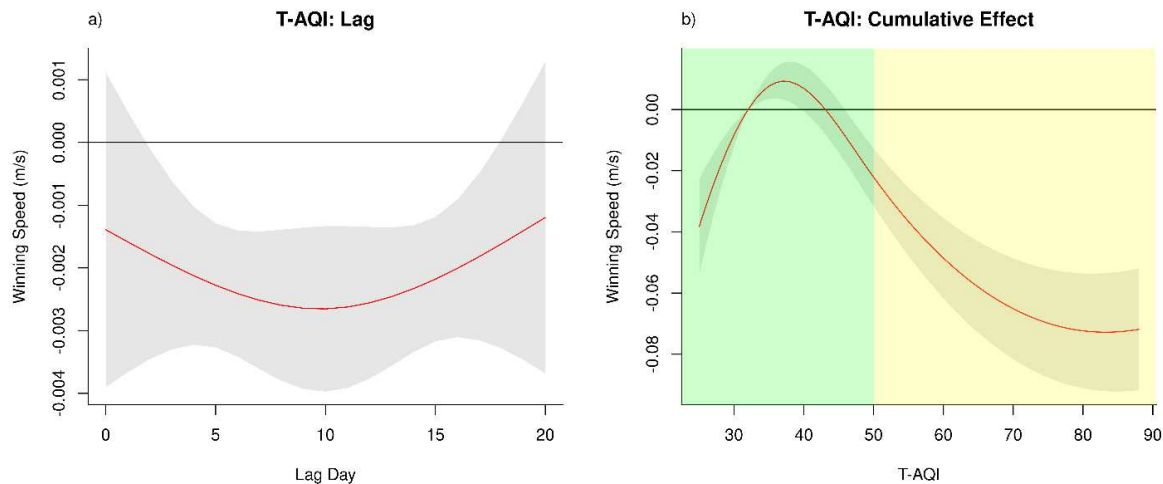


Figure 6: (a) AQI lag response relationship (red line) with 95% confidence interval (grey) when comparing the 80th percentile exposure (i.e., higher exposure) to the 20th percentile (i.e., lower exposure) over the 21-day exposure window that includes the day of the race (day 0) and the 20 days before race day. (b) The overall cumulative effect of AQI on winning speed (m/s) over the 21-day study period (red line) with 95% confidence intervals (shading). Background shading represents the AQI categories: green = Good and yellow = Moderate.

3.4 Associations Between Speed and Individual Pollutants (PM_{2.5} and O₃)

We modeled the exposure-lag relationship, which revealed that the association between PM_{2.5} exposure and winning speed, when comparing the 80th percentile (13.8 µg/m³) to the 20th percentile (5.5 µg/m³), was most pronounced around lag day 10 (Figure 7a). The overall shape of the exposure-response curve, which represents the cumulative effect of all 21 days leading up to a race for each level of PM_{2.5} (Figure 7c), indicates a nonlinear relationship. This curve suggests a performance decline, characterized by decreasing winning speeds, with increasing PM_{2.5} concentrations above the 20th percentile (5.5 µg/m³). Specifically, horses ran significantly slower

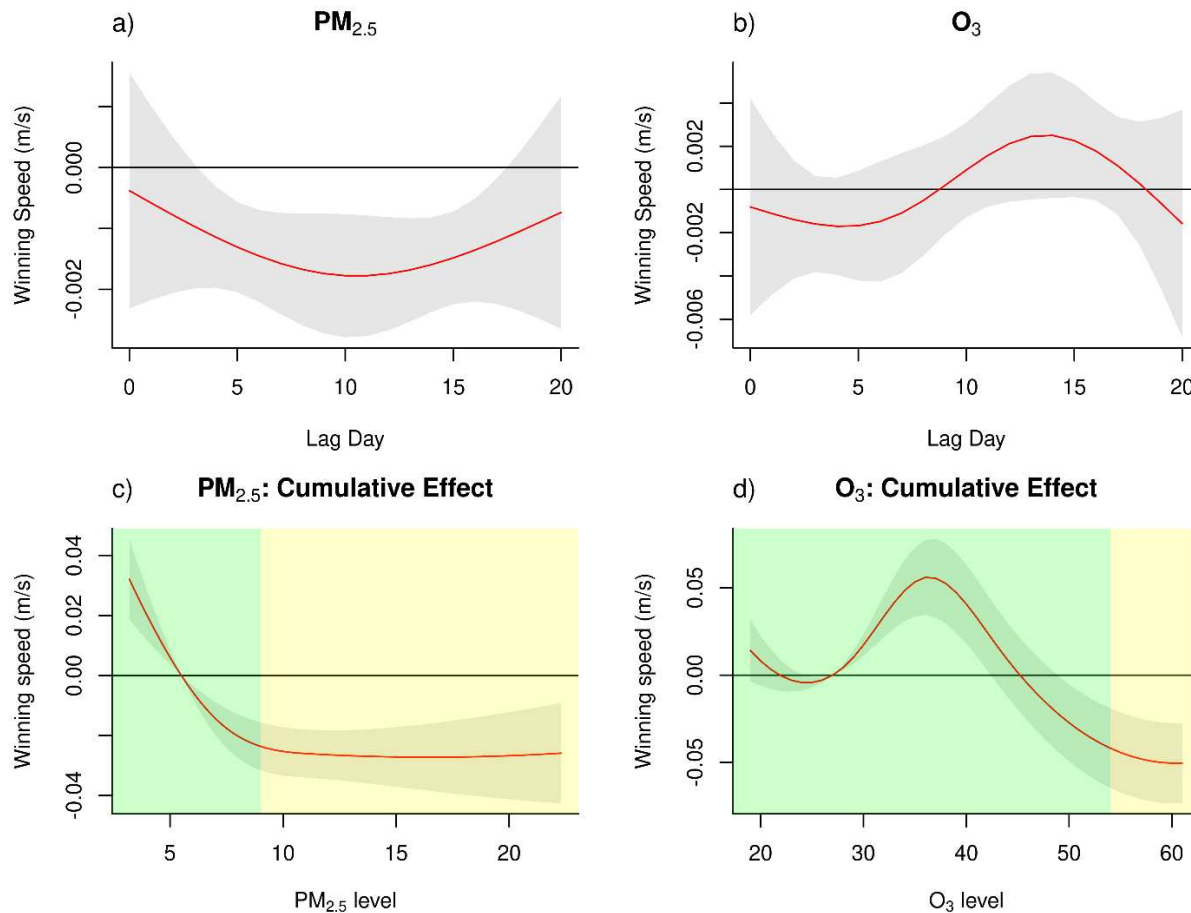


Figure 7: PM_{2.5} (a) and O₃ (b) lag response relationship (red line) with 95% confidence interval (grey) when comparing the 80th percentile exposure (i.e., higher exposure) to the 20th percentile (i.e., lower exposure) over the 21-day exposure window that includes the day of the race (day 0) and the 20 days before race day. The overall cumulative effect of PM_{2.5} (c) and O₃ (d) on winning speed (m/s) over the 21-day study period (red line) with 95% confidence intervals (grey). Background shading represents the AQI categories: green = Good and yellow = Moderate.

at PM_{2.5} levels above 5.5 µg/m³. Horses exposed to the 80th percentile (13.8 µg/m³) across the 21-day pre-competition training period had a statistically significant cumulative decrease in speed of 0.027 m/s (95% CI -0.036, -0.019; $p < 0.001$) when compared with those exposed to the 20th percentile (5.5 µg/m³).

The O₃ exposure-lag relationship revealed no statistically significant association with winning speed when comparing the 80th percentile (45 ppb) to the 20th percentile (27 ppb) across all lag days (Figure 7b). The overall shape of the exposure-response curve, representing the cumulative effect of all 21 days leading up to a race for each level of O₃, indicated a nonlinear relationship (Figure 7d). Horses exposed to the 80th percentile of O₃ (45 ppb) across the 21-day pre-competition training period had a small, non-significant cumulative increase in winning speed of 0.002 m/s (95% CI -0.020, 0.023, $p = 0.88$) compared with those exposed to the 20th percentile (27ppb). At lower O₃ concentrations above the 20th percentile (27 ppb), winning speeds initially increase before declining at higher O₃ levels, with horses running significantly slower at O₃ concentrations approaching and exceeding the threshold associated with the “moderate” AQI category, i.e., O₃ concentration of 55 ppb (Figure 7d).

4. Discussion

We identified a statistically significant relationship between air pollution exposure during training and race-day performance in Thoroughbred racehorses. We developed pollutant profiles designed to assess the cumulative impact of pollutant exposure during the pre-competition training period. Across the primary and sensitivity analyses, we found consistent evidence that exposure to poor air quality during the pre-competition training period was associated with slower winning speeds. This finding is consistent with previous research on exercise-induced pollutant uptake in human studies.^{36,61,62} In horses, previous research has demonstrated that air

quality on the day of a competition can affect performance.¹⁸⁻²¹ However, opportunities to reduce exposure on race day are limited. In contrast, the pre-competition training period offers a more feasible window for modifying training regimens to mitigate exposure. Our findings highlight the importance of air quality during training and offer a critical opportunity for intervention to protect equine health and optimize performance.

Intervention begins with knowledge of the local air quality. The AQI is a readily available and accessible tool that informs the public of the local air quality, and the risks associated with increasing levels of pollutants. Our study demonstrated that winning horses that trained at the 80th percentile of AQI (58), a value reflecting the *moderate* air quality category, consistently ran slower during races than a horse that trained at the 20th percentile (AQI = 32), reflecting *good* air quality. Although the magnitude of the change in speed is small (0.044 m/s), it's important to note that this analysis only included 1st-place finishers. To demonstrate the meaningfulness of this decrease in speed, this would equate to a time loss of approximately 0.18 seconds in a 6-furlong race, equivalent to a 3-meter loss of distance or approximately one length, a margin large enough to substantially affect finishing position in competitive events. Additionally, given that this analysis was conducted on the most elite athletes, i.e., first-place finishers, this effect may be more pronounced in horses competing for 2nd and 3rd place, or in horses that may have underlying conditions, such as asthma, a condition for which exposure to air pollutants, particularly PM_{2.5}, represents a major risk factor for both the onset and exacerbation of asthma in humans, including athletes.^{15,70} These results support the idea that recurrent training in anything worse than the *good* air quality category (AQI ≤ 50) can have a negative impact on performance. Referencing the daily AQI can be the first step to improving training decisions.

Notably, air pollutants are unevenly distributed across geographic regions. People living in the western United States may be more attentive to air quality monitoring because of frequent wildfire smoke events, but awareness is equally important in regions with generally good air quality. Weather patterns can transport smoke long distances, impacting air quality far from the source.⁶⁰ This was the experience of those living on the East Coast in June 2023 as wildfire smoke from Canada caused major disruptions.^{71,72} Our PM_{2.5} model demonstrated that higher exposure to PM_{2.5} throughout the training period was associated with slower winning speeds, supporting the premise that minimizing PM_{2.5} exposure during training may be advantageous to performance outcomes. However, evidence-based recommendations to guide training and exercise decisions during periods of poor air quality are currently lacking, highlighting the need for systematic development of such guidance. In the interim, risk-mitigation strategies aimed at reducing unnecessary pollutant exposure may be reasonable. For example, reducing outdoor exertion during wildfire smoke events can limit exposure. When training is imperative, consider moving horses to a location with better air quality. If relocation is not possible, trainers can limit the duration of training sessions with increased respiratory rate while still aiming to maintain fitness. During exertion, horses inhale greater volumes of air, thereby increasing the dose of inhaled pollutants that can reach systemic circulation.

Additionally, understanding which primary pollutant is present can conveniently guide pre-competition training decision-making. In addition to evaluating the AQI, which reflects the worst pollutant in an area for the day, we also evaluated specific pollution profiles, including ozone. Although we did not observe a statistically significant decrease in speed when comparing higher exposure (i.e., the 80th percentile of O₃ = 46 ppb) to lower exposure (i.e., the 20th percentile of O₃ = 27 ppb), it is important to note that both values are within the *Good* AQI

category. However, our model revealed that as O₃ levels entered the *Moderate* AQI category, horse performance declined, warranting caution surrounding increased O₃ exposure. Understanding patterns in O₃ can guide training decisions. Specifically, because O₃ is a secondary pollutant that forms in the presence of heat and sunlight, its levels peak in the afternoon, especially during summer months when warmer temperatures and longer daylight hours accelerate O₃ formation. Therefore, concerning O₃, prioritizing training in the morning is a simple method to avoid unnecessary and potentially harmful exposure.

This study did not directly investigate specific interventions or management strategies, however, there are practical steps that can reduce air pollution exposure, which may be particularly important during periods of poor ambient air quality. Such interventions represent best management practices in general and include having clean, dust-free surfaces, choosing low-dust bedding and feed, and feeding from the ground while avoiding the use of hay nets.⁷³ Additionally, avoid high-dust activities, such as sweeping or the use of power tools that stir up dust. It is also important to control ammonia and moisture levels in the barn. Even during good air quality periods, horses should be turned out during cleaning to minimize unnecessary exposure to dust and mold. Consider investing in a low-cost air quality monitor, such as PurpleAir sensors that provide real time, publicly accessible particulate data,⁷⁴ to empower trainers and owners to make location-specific, data-driven training decisions. This may be particularly important in areas without nearby regulatory monitors. Importantly, when considering opening new performance athletic facilities, assess air quality risks and hazards in choosing a location. Tools exist to provide climate risk information, including flooding, fire, wind, air, and heat factors, for any property throughout the United States.⁷⁵

While this study provides important considerations into air pollution exposure during the equine training environment, several limitations must be considered in the interpretation of these findings. First, this study was limited to racetracks located throughout California, a region disproportionately affected by wildfires and wildfire smoke compared with much of the U.S.⁷⁶ Evidence from toxicological studies suggest that PM_{2.5} originating from wildfire smoke may exert greater adverse health effects than PM_{2.5} from anthropogenic sources.⁷⁷ If source-specific differences in toxicity exists for equine athletes, associations observed here may have limited generalizability in regions where PM_{2.5} composition differs. However, wildfire emissions are the most likely driver of higher PM_{2.5} levels throughout the U.S.,⁵⁹ and elevated PM_{2.5} concentrations, regardless of the source, are consistently associated with adverse health effects. As such, the observed associations may be more broadly applicable to other states. To address potential regional and climatic variation, we included the racetrack as a random intercept to account for site-specific differences and controlled for average daily temperature. Other meteorological factors, such as humidity and wind, were not included in the analysis and may influence both air pollution exposure and performance outcomes, representing potential unmeasured confounding. Although an initial investigation in California was an appropriate first step given its temperate climate and year-round operation of most Thoroughbred racetracks,²¹ expansion into additional geographic regions and inclusion of additional environmental factors are required to confirm if these associations are consistent elsewhere. Because race counts were unbalanced across racetracks, ranging from more than 10,000 at Golden Gate Fields to only 11 races at Stockton, the mixed-effect model approach accounts for within-track clustering and site-specific differences. Nevertheless, tracks with few observations have less precise track-specific estimates, and the primary findings are driven largely by tracks with greater representation.

While geographic scope was limited to California racetracks, another limitation involves the reliability of the air quality data reflecting true horse exposure. We relied on the EPA's air quality monitoring data, and although we specifically sourced monitors within 100km and those without geographical barriers, e.g., mountain ranges, we can assume some exposure misclassification resulting from distance of the monitoring sites and air quality at the racetracks. Deployment of air monitors at competition sites and training facilities could eliminate this inaccuracy. Future studies should more accurately describe the air quality in the horses' breathing zone.

Additionally, although we included training data to confirm that horses trained at the track where they later raced, it was unclear what constitutes logging a training session and whether *all* sessions are consistently recorded. Therefore, we were unable to assess whether the number of recorded training sessions at the racetrack influenced the results. Further, it is possible that horses could have trained at alternative locations during the pre-competition period, which could result in exposure misclassification if air pollution levels differed from those assigned based on racetrack location, potentially introducing bias in the estimated associations. More complete data on training location, frequency, and duration prior to a race would help refine these findings. Finally, we accounted for repeated performances by the same horse by utilizing mixed-effects models, which appropriately models correlation among observations within horses while estimating population-level associations between air pollution exposure and race performance. As such, we did not explicitly assess within-horse changes in performance across varying pollution exposure levels. Future studies leveraging within-horse contrasts may provide additional insight into individual-level vulnerability.

Our analysis of 20,037 Thoroughbred races in California found that horses exposed to air pollution during training had slower winning speeds. Knowledge of local air quality and primary

pollutants of concern, along with an understanding of how to modify training in response to environmental conditions, may foster health and support the performance of equine athletes. Future work should evaluate the long-term effects of air quality on performance, health, and longevity in equine athletes, as well as how air pollution monitoring can be integrated into training practices to safeguard equine health, performance, and welfare.

CHAPTER 4: AIR POLLUTION IMPACTS PERFORMANCE AT US EVENTING COMPETITIONS³

1. Introduction

Despite major improvements in air quality in the United States, changing environmental conditions, including heat, drought, and wildfires, are contributing to increasing levels of air pollutants, particularly fine particulate matter (PM_{2.5}) and ozone (O₃).^{78,79} Substantial evidence in people supports a “causal relationship” between both short- and long-term PM_{2.5} exposure and cardiovascular effects and nonaccidental mortality, as well as a “likely causal relationship” between respiratory effects. Long-term PM_{2.5} exposure has also been linked to nervous system effects and cancer.¹⁵ Similarly, evidence supports a “causal relationship” between short-term O₃ exposure and respiratory effects, while both short- and long-term O₃ exposure have been associated with cardiovascular and nervous system effects and nonaccidental mortality.¹² Given the substantial public health burden of air pollution, exposure risks are widely communicated through the Air Quality Index (AQI), the U.S. Environmental Protection Agency’s (US EPA) air quality reporting tool.

Beyond its established health impacts, air pollution exposure has also been associated with impairments in performance and a higher risk of errors in people. For example, higher air pollution levels are linked with longer times to task completion,⁸⁰ increases in motor vehicle accidents,⁸¹ increases in incorrect calls by professional baseball umpires,⁸² decreased productivity as measured by passes per match among professional soccer players,⁸³ and an increase in draws among competitive chess players.⁸⁴ Although the research evaluating the

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impacts of air pollution exposure in animals is growing,¹⁷ existing equine studies have largely been limited to the performance of Thoroughbred racehorses.^{18-21,51} To better understand how these exposures impact equine athletes more broadly, research involving other domains for equestrian athletes is needed. Eventing provides a unique opportunity to further examine the relationship between air pollution exposure and equine performance. In eventing, horse-rider pairs compete across three phases: dressage, cross country, and show jumping. Across all phases, lower scores indicate better performance and the pair with the lowest score wins the division. As penalties arise from both physical exertion and errors under time constraints, scores reflect both physical and mental performance of the horse-rider pair. The association between ambient air pollution and cognitive effects in humans, as well as impaired performance in both human athletes and racehorses, suggests potential implications for eventing competitions. The objective of this retrospective observational study was to estimate the association between air pollution exposure during equestrian events and horse-rider performance at United States Eventing Association (USEA) competitions.

2. Methods

2.1 Outcome Data

This study included data from rider-horse pairs competing in USEA-sanctioned Horse Trials and Three-Day Events between January 11, 2003, and December 4, 2022 (Figure 8). We obtained outcome data for all USEA-sanctioned competitions held during the study period. The dataset included event dates, event type, competition level, unique horse and rider identifiers, horse and rider age at the time of competition, and the rider's USEA area. We used performance outcomes from official competition results for each rider-horse team, including dressage score, cross-country (XC) jumping penalties, XC time penalties, show jumping (SJ) jumping penalties,

SJ time penalties, and the final competition score. Analyses were restricted to the Preliminary level and above, representing upper-tier national and international eventing competitions.

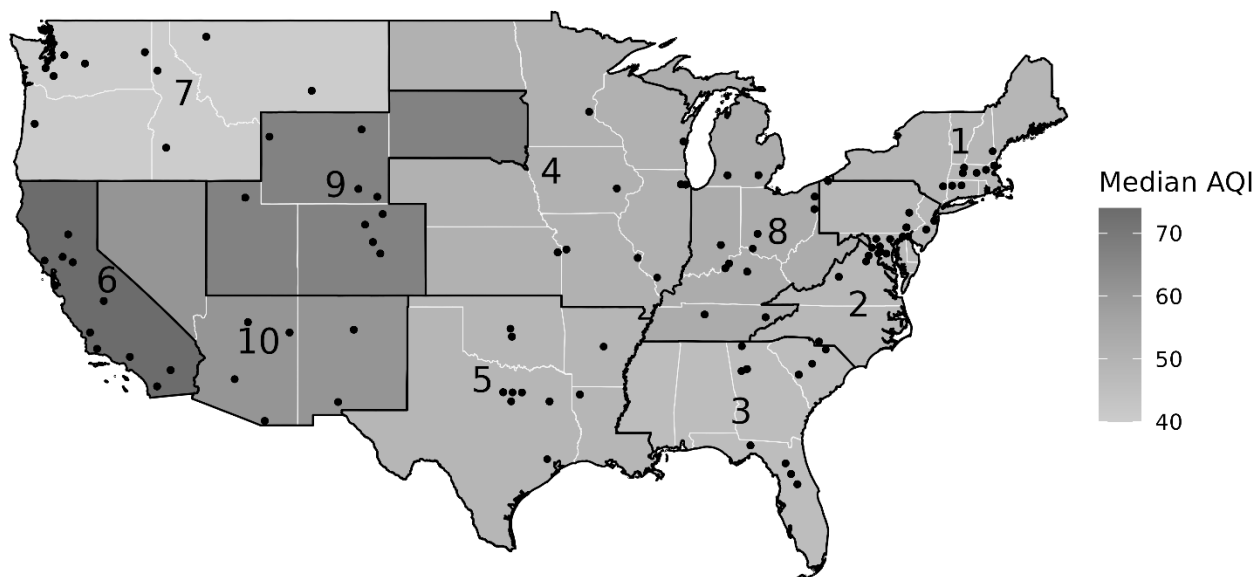


Figure 8: Geographic distribution of USEA-sanctioned event locations across the United States. Black dots indicate individual competition locations. State groupings outlined in black represent USEA regions, with numbers identifying each region. Shading indicates the median AQI-max within each region, with darker shades representing higher median AQI values.

2.2 Exposure Data

We obtained air quality data from the US EPA Air Quality System (AQS) database.⁸⁵ Our exposure of interest was the AQI, which is an index value ranging from 0 to 500. Sub-ranges of index values correspond to a level of concern and are assigned a color, for example 0-50 is green representing good air quality, 51-100 is yellow representing moderate air quality, and higher ranges indicate increasingly severe concern indicated by orange, red, purple and maroon, respectively. We extracted daily AQI values at the county level and matched observations to events using Federal Information Processing Standards (FIPS) codes and event dates. We used

county-level AQI because event location data were limited to the U.S. city and state. Because events often spanned multiple days, we assigned the corresponding daily AQI value to each event day. We then calculated event-level exposure metrics by averaging AQI (AQI-avg) values across event days and identifying the maximum AQI (AQI-max) observed during each event. Each rider-horse team was thus assigned an average AQI and a maximum AQI for each competition.

2.3 Covariate Data

We included several covariates related to the horse, the rider, event characteristics, temporal and spatial factors, and meteorological conditions, that could act as potential confounders or improve model precision. Event-level covariates included competition level (the national and international divisions of Preliminary, Intermediate and Advanced) and event type (Horse Trials or Three-Day Events). Rider-level covariates included rider age and their USEA geographic area of residence (rider area). Missing rider area values were partially resolved using the most frequently recorded rider area for each rider. Horse age was included as a horse-level covariate. Spatial covariates included the U.S. state in which the event was held. Temporal covariates included event year, event month, and event duration, defined as the number of days over which the event occurred.

Meteorological covariates included mean air temperature, mean relative humidity, and mean wind speed during each event, calculated by averaging daily values across the event duration. Data completeness was evaluated prior to analysis, revealing temporal and spatial heterogeneity in the meteorological data availability, with greater missingness in earlier study years and in specific event locations. Because meteorological variables were included as adjustment and precision covariates rather than primary exposure, we assessed their influence on

AQI effect estimates through sensitivity analyses. Specifically, we compared models to the full dataset without meteorological covariates to models including meteorological covariates restricted to observations with complete meteorological data.

2.4 Data Analysis

All observations that had missing data or improbable values, such as mismatched start to end dates and erroneous score metrics, were excluded from analysis. We excluded entries coded as “HC” (Hors concours), which indicate non-competitive participation. To reduce the potential impact of implausible or sparsely represented age groups, we restricted rider and horse age to the 1st-99th percentile range. We generated descriptive statistics for all outcomes and covariate variables to assess distributions, evaluate normality, and identify potential outliers. Outcome-specific analyses were restricted to events with available outcome data, as defined for each competition phase below.

Our primary exposure of interest was AQI-max. Consistent with models that truncated data to remove the influence of extreme values,²¹ we truncated AQI-max to observations within the 1st and 99th percentiles. We first evaluated the association between air quality and overall performance, using final score as the primary outcome. We included only numeric final scores and excluded observations with non-numeric outcomes, such as disqualification, withdrawal, elimination, and retirement, among others. We further restricted final scores to observations within the 1st and 99th percentiles. Because final score is a continuous outcome, we fit linear mixed effects regression models to estimate the change in final score per unit increase in AQI-max. Sensitivity analyses were conducted using the full, untruncated exposure distribution and evaluated: (1) the influence of extreme exposure values, (2) using AQI-avg as the exposure, (3)

the influence of outcome scale by modeling log-transformed final scores to address right-skewness, and (4) additional adjustment for meteorological conditions.

We next examined stage-specific performance outcomes, beginning with dressage. We treated dressage scores as a continuous outcome and restricted scores to numeric observations within the 1st and 99th percentiles to reflect plausible competitive results. We fit linear mixed effect regression models to assess associations with AQI-max, with sensitivity analyses paralleling those used for final scores.

XC jump and SJ jump penalties are not continuously distributed but are assigned in discrete increments for various jumping infractions negating the use of linear modeling. We therefore used generalized linear mixed effects logistic regression models to evaluate a binary outcome contrasting a perfect XC/SJ jumping score (0 penalties) versus any penalty or elimination. The latter category included numeric penalty scores, as well as outcomes indicating non-completion including withdrawals, eliminations, technical eliminations, retirements and mandatory retirement, and rider falls. Sensitivity analyses evaluated the influence of (1) extreme exposure values by using the full, untruncated exposure distribution, (2) using AQI-avg, and (3) additional adjustment for meteorological conditions.

XC time and SJ time penalties had a semi-discrete, right-skewed distributions with structural mass at zero. Accordingly, we followed the modeling structure of XC jump and SJ jump penalties, applying a generalized linear mixed effects logistic regression model to evaluate a binary outcome contrasting a perfect round (0 penalties) versus any penalty (scores greater than 0) or non-completion. Numeric scores were truncated at the 99th percentile. Sensitivity analyses were aligned with that of XC jump and SJ jump penalties.

We conducted all analyses in R Statistical Software (v 4.4.1)⁸⁶ using linear mixed-effects models implemented with the ``lme4`` package⁸⁷ and generalized linear mixed-effects model with a logistic link function implemented with the ``glmmTMB`` package.⁸⁸

2.5 Final Model

We specified a common mixed-effects modeling framework across outcomes, with identical fixed- and random-effects structures. For continuous outcomes, we fit linear mixed-effects models, whereas for binary outcomes we fit generalized linear mixed-effects logistic regression models. The general form of the model is represented as:

$$E[O_{ij}] = \beta_1 X1_{ij} + \beta_2 X2_{ij} + \beta_3 X3_{ij} + \beta_4 X4_{ij} + \beta_5 X5_{ij} + \delta_i + \gamma_j + \epsilon_{ij}$$

Where $E[O_{ij}]$ denotes the expected value of the performance outcome for the i th horse-rider pair and the j th rider. β_1 represents the estimated coefficients for the exposure metric (i.e., AQI-avg or AQI-max). β_2 represents event-level coefficients (competition level and event type). β_3 represents rider- and horse-level covariates (i.e., rider area, rider age, and horse age). β_4 represents temporospatial covariates (state, event year, event month, and event duration). State was included as a fixed effect in continuous models. However, in the binary mixed-effects models evaluating XC jump and time penalties, and SJ jump and time penalties, inclusion of state resulted in model non-convergence, likely due to sparse outcome variability within certain states. Therefore, state was excluded from these specific binary models to permit stable parameter estimation. β_5 represents meteorological data (average temperature, average humidity, and average wind speed across the competition). The terms, δ_i and γ_j represent the random intercepts for horse-rider pair and rider, respectively. These random intercepts account for reduced variability amongst multiple observations from the same horse-rider pair, as well as repeated observations from riders competing with different horses. For linear mixed-effects

models, ϵ_{ij} represents the residual error term, assumed to be normally distributed with mean zero. For generalized linear mixed-effects logistic regression models, residual variability is accounted for through the assumed outcome distribution. For the binary outcomes, results are reported as odds ratios obtained by exponentiating model coefficients. Finally, for clarity of interpretation, results are presented beginning with overall performance (final score) followed by phase-specific outcomes, grouped according to observed trends in the data.

3. Results

Our raw dataset had 577,712 observations across 3,244 unique events occurring between January 11, 2003, and December 4, 2022, that were paired with air quality data. We excluded observations with missing or invalid rider area, horse age, or rider age ($n = 20,136$); observations with missing or invalid performance metrics across competition phases ($n = 37,956$); observations coded “HC” ($n = 44$), and events with implausible start-end date ranges resulting in misclassified exposure windows (10 events; $n = 1,256$). We further restricted the dataset to events at the Preliminary, Intermediate and Advanced competition levels and retained observations with horse and rider ages within the 99th percentile. The final analytic dataset comprised 132,063 observations across 2,728 events. Additionally, we had a subset of 113,010 observations across 2,340 events that had complete meteorological data and were used in sensitivity analyses incorporating meteorological covariates (Table 7).

3.1 Study Population

The study population had 6,210 riders and 17,472 rider-horse pairs indicating that many riders rode multiple horses. The median rider age was 30 years old (range 15-61 years), and the

median horse age was 10 years old (range 6-19 years). Most observations occurred during Horse Trials (92.6%), with the remainder from Three-Day Events (Table 7).

Table 7: Summary of event-related and horse-rider pair related information. Values are reported at the observation level. The final analytic dataset comprised 132,063 observations across 2,728 events. Additionally, we had a subset of 113,010 observations across 2,340 events that had complete meteorological data and were used in sensitivity analyses incorporating.

Event-related variables	Full dataset (no meteorological restriction) (n = 132,063)	Restricted dataset (complete meteorological only) (n = 113,010)
Number of events	2,728	2,340
Event type		
Horse trial	122,273 (92.6%)	104,903 (92.8%)
Three-Day Event	9,790 (7.4%)	8,107 (7.2%)
Competition level		
Preliminary	88,415 (66.9%)	76,065 (67.3%)
Intermediate	32,933 (24.9%)	27,834 (24.6%)
Advanced	10,715 (8.1%)	9,111 (8.1%)
Event Duration (days)		
1	4,276 (3.2%)	3,274 (2.9%)
2	40,288 (30.5%)	30,358 (26.9%)
3	53,418 (40.4%)	47,300 (41.9%)
4	23,527 (17.8%)	22,947 (20.3%)
5	10,105 (7.7%)	8,682 (7.7%)
6	449 (0.3%)	449 (0.4%)
Horse-rider pair related factors		
Rider Area		
1: CT, ME, MA, NH, NY, RI, VT	8,642 (6.5%)	7,399 (6.5%)
2: NJ, PA, MD, DE, VA, NC	46,263 (35.0%)	35,463 (31.4%)
3: SC, MS, AL, GA, FL	23,501 (17.8%)	21,136 (18.7%)
4: IL, IA, KS, MO, MN, NE, ND, WI	4,266 (3.2%)	3,958 (3.5%)
5: AR, LA, TX, OK	6,823 (5.2%)	6,396 (5.7%)
6: CA, HI	17,619 (13.3%)	16,662 (14.7%)
7: OR, WA, ID, MT, AK	8,052 (6.1%)	7,071 (6.3%)
8: IN, KY, MI, OH, TN, WV	12,158 (9.2%)	10,588 (9.4%)
9: CO, WY, UT, SD	2,631 (2.0%)	2,350 (2.1%)
10: AZ, NM, NV	1,829 (1.4%)	1,724 (1.5%)
11: Other / Unknown	279 (0.2%)	263 (0.2%)
Rider Age (years)		
Median (Range)	30 (15 – 61)	30 (15 – 61)
Horse Age		
Median (Range)	10 (6 – 19)	10 (6 – 19)

3.2 Air Quality Exposure

Across observations, the median AQI-avg was 43.5 (range: 1.5 – 235). Most observations occurred under “good/green” conditions ($AQI \leq 50$; 67.4%, $n = 88,953$, with an additional 29.7%

classified as “moderate/yellow” (AQI 51-100; n = 39,239). A small proportion of observations occurred during poorer air quality, including “unhealthy for sensitive groups/orange” (AQI 101-150, 2.4%, n = 3,161), “unhealthy/red” (AQI 151-200, 0.5%, n = 708), and “very unhealthy/purple” (AQI 201-300; 0.002%, n = 2) categories (Figure 9a).

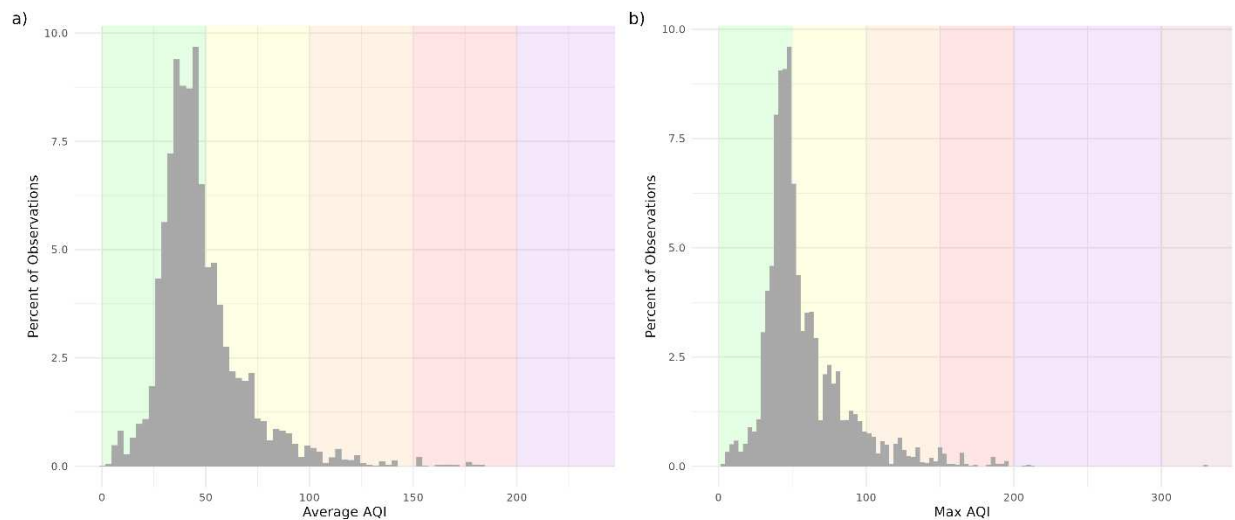


Figure 9: Distribution of the AQI exposure profiles with a) displaying the distribution of the average AQI (AQI-avg) across events, and b) displaying the distribution of the maximum AQI (AQI-max) at events. The background shading corresponds with the Air Quality Index (AQI) categories as follows: Green = Good; Yellow = Moderate; Orange = Unhealthy for sensitive groups; Red = Unhealthy; Purple = Very unhealthy.

The median AQI-max was 57.2 (range 3 – 331). Observations classified as “good/green” accounted for 55.4% (n = 73,200). While “moderate/yellow” air quality represented 37.0% (n = 48,843). Higher exposure categories were less common, with 6.1% of observations classified as “unhealthy for sensitive groups/orange” (n = 8,074). “Unhealthy/red”, “very unhealthy/purple” and “hazardous/maroon” (AQI 301+) conditions were rare, representing 1.4% (n = 1,838), 0.06% (n = 75), and 0.02% (n = 33) respectively (Figure 9b).

USEA Area 6 (California and Hawaii; events only occurred in California) had the highest median AQI-avg (61; range 8 – 182) and AQI-max (74; range 8-331) across events and accounted for the greatest number of events with AQI-avg (n = 9) and an AQI-max (n = 24)

values greater than 150 (Figure 8, Table 8). USEA Area 7 (Washington, Oregon, Idaho, and Montana) had the lowest median AQI-avg (34; range 2-96) and AQI-max (40; range 3 – 162).

Table 8: Number of events occurring within each AQI category across each USEA Area based on the Average AQI (AQI-avg) and the Maximum AQI (AQI-max) recorded during the event.

USEA Area	Median (Range)	Average AQI					
		Green	Yellow	Orange	Red	Purple	Maroon
1	43 (9 – 178)	80	27	1	1	0	0
2	42 (6 – 154)	476	185	7	2	0	0
3	41 (4 – 98)	391	87	0	0	0	0
4	44 (17 – 155)	74	35	4	1	0	0
5	45 (13 – 235)	96	44	1	1	1	0
6	61 (8 – 182)	139	200	42	9	0	0
7	34 (2 – 96)	175	17	0	0	0	0
8	45 (10 – 136)	215	146	7	0	0	0
9	56 (28 – 154)	49	98	5	1	0	0
10	51 (8 – 94)	58	53	0	0	0	0
Total		1753	892	67	15	1	0
		Maximum AQI					
		Green	Yellow	Orange	Red	Purple	Maroon
1	49 (9 – 187)	66	36	5	2	0	0
2	48 (6 – 164)	402	242	22	4	0	0
3	46 (4 – 149)	342	125	11	0	0	0
4	51 (20 – 208)	60	43	7	3	1	0
5	49 (15 – 235)	84	49	8	0	2	0
6	74 (8 – 331)	112	186	68	22	1	1
7	40 (3 – 162)	157	31	2	2	0	0
8	53 (10 – 159)	169	173	25	1	0	0
9	67 (28 – 185)	36	102	12	3	0	0
10	61 (9 – 104)	50	59	2	0	0	0
Total		1478	1046	162	37	4	1

Overall, the percentage of events that had AQI-max values greater than 150 decreased from 5.3% in 2003 to 0.8% in 2022 (Figure 10). When assessing AQI across months, May and June have the highest percentage of events with an AQI-max greater than 150 with 3.5% and 2.7%, respectively. January and December have no events greater than 150 (Figure 11).

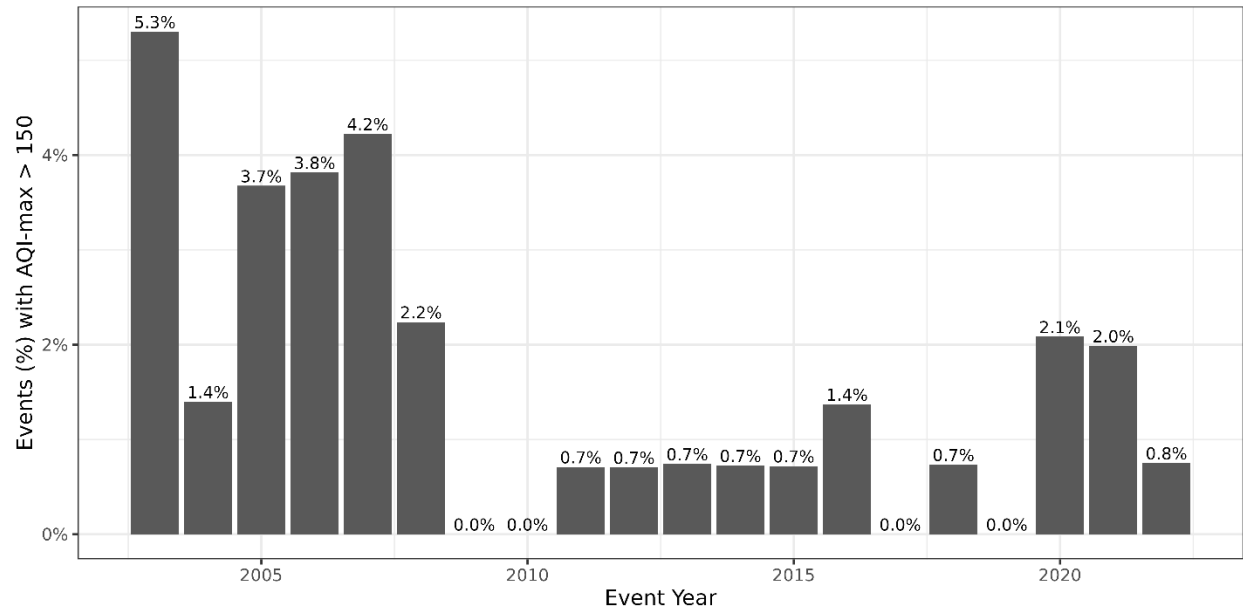


Figure 10: Percentage of USEA competitions with an AQI-max greater than 150 by year. Percent values are displayed above each bar.

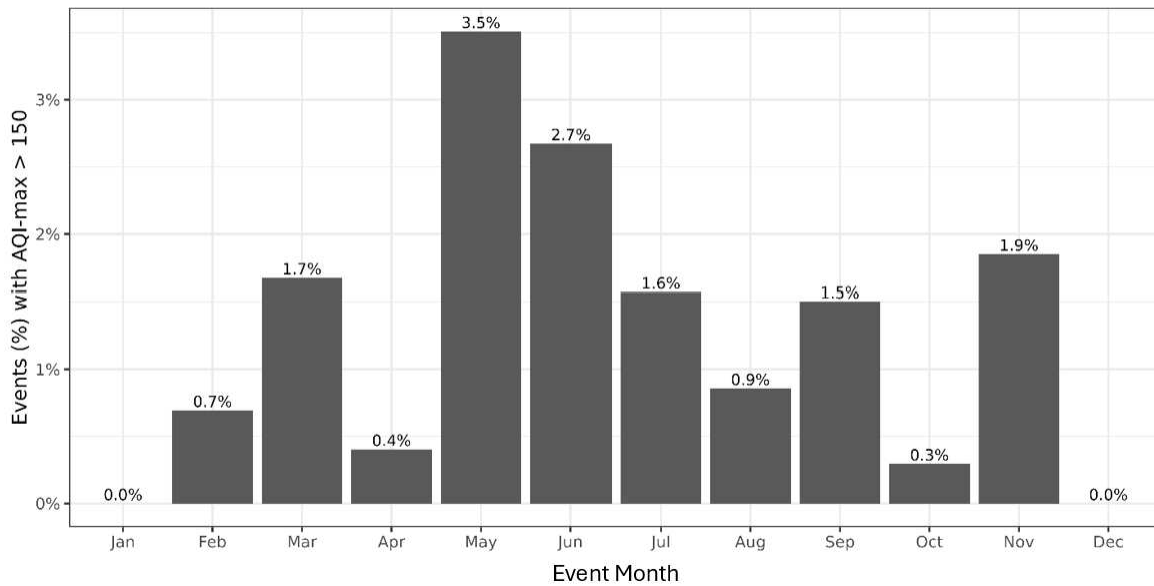


Figure 11: Percentage of USEA competitions with an AQI-max greater than 150 by month. Percent values are displayed above each bar.

3.3 Associations Between Air Quality and Final Score

The primary analysis included 117,694 observations, with a median score of 52.4 (range: 26.5 – 159.1) (Figure 12a). There was a positive association between AQI-max and final score in the primary model, however confidence intervals were wide and included the null ($\beta = 0.0027$, 95% CI -0.0026 – 0.0080, $p = 0.30$) (Figure 13). Sensitivity analysis yielded variable effect estimates; however, confidence intervals remained wide and consistently included the null value (Supplemental Figure 1a, Appendix 3).

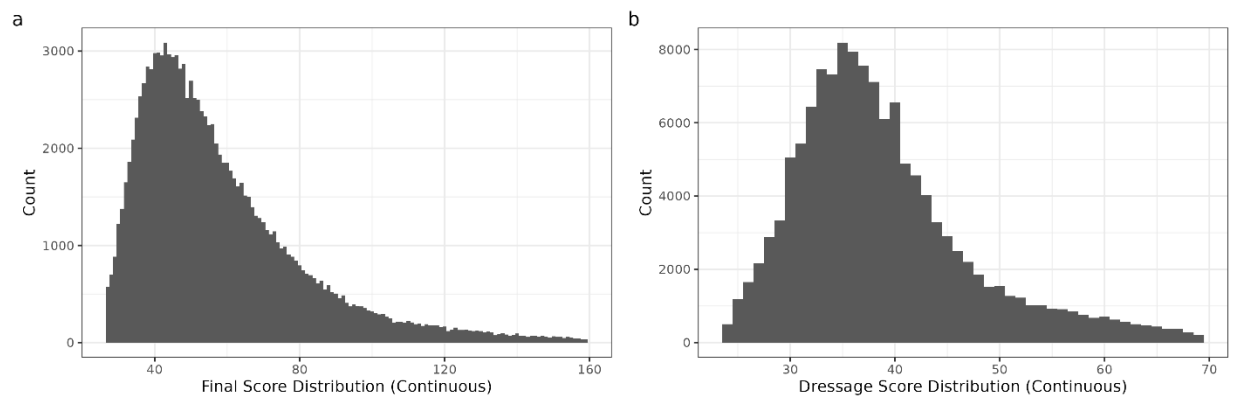


Figure 12: Distributions of the outcome scores for a) final scores and b) dressage scores, both on a continuous scale.

3.4 Associations Between Air Quality and Dressage Score

The association between air quality and dressage score included 127,225 observations, with a median score of 37.3 (range: 23.9 – 69.4) (Figure 12b). There was a positive statistically significant association between AQI-max and dressage score in the primary model; for a 10-unit increase in AQI-max, dressage score was estimated to increase by 0.052 (95% CI 0.037 – 0.068, $p < 0.001$) (Figure 13). Sensitivity analysis yielded variable effect estimates. Using the full AQI-max distribution and AQI-avg as exposure metrics resulted in increased uncertainty, with confidence intervals that included the null, while analyses restricted to the subset of observations

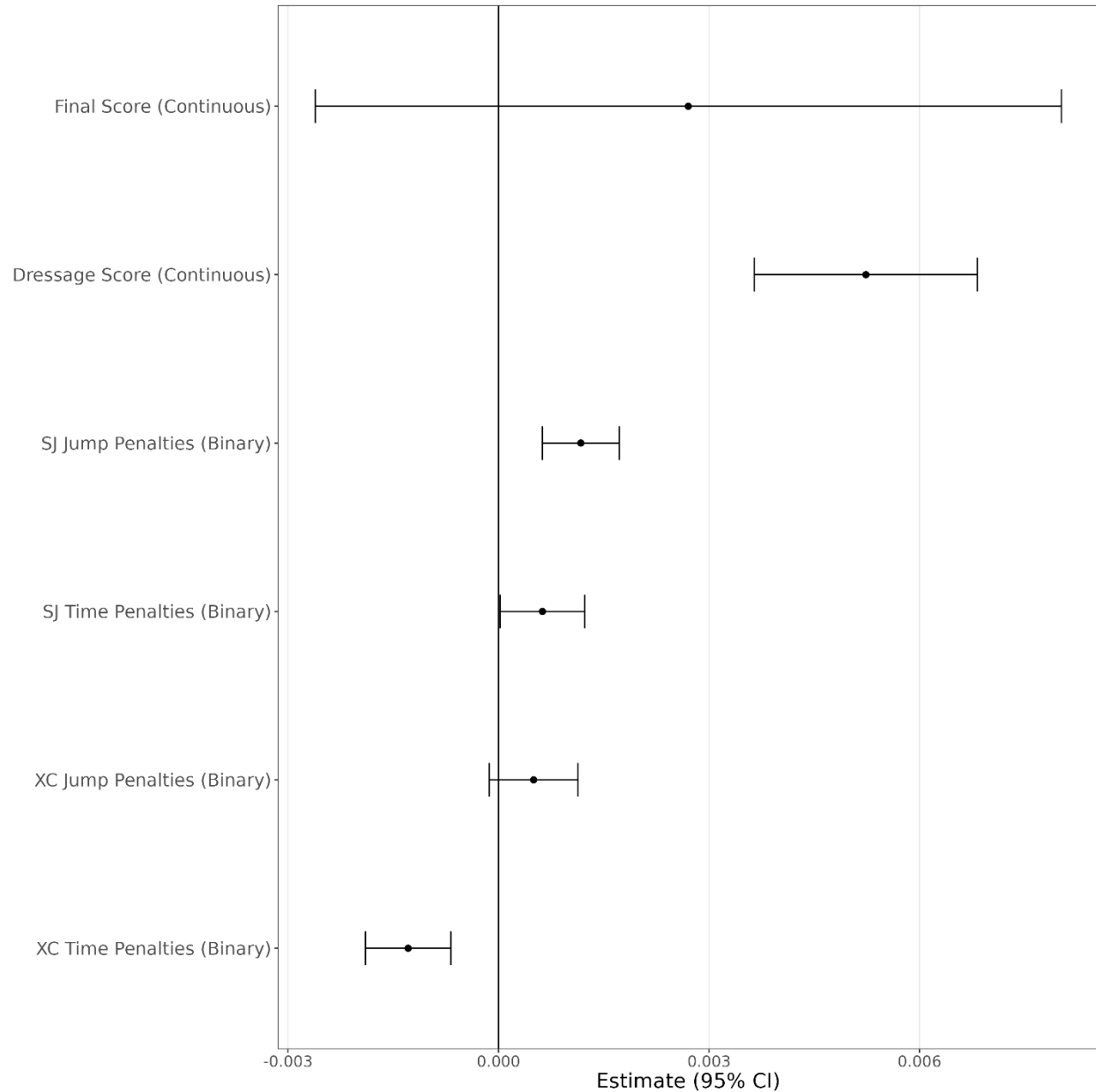


Figure 13: Estimated associations between a 1-unit increase AQI-max and performance outcomes across all eventing phases as estimated by primary models. Points represent the model estimates with horizontal bars denoting the 95% confidence intervals. Linear mixed-effects models were fit for continuous outcomes and generalized logistic mixed-effects models were fit for binary outcomes. The vertical line at zero indicates no association.

with complete meteorological showed a statistically significant negative effect between dressage score and AQI-max and AQI- avg. Finally, models using log-transformed dressage scores to assess robustness to outcome skewness demonstrated no association with AQI-max (Supplemental Figure 1b, Appendix 3).

3.5 Associations Between Air Quality and SJ Jump Penalties

We modeled SJ jump penalties as a binary outcome, with 55,825 observations reflecting no penalties and 73,527 observations reflecting any jump penalty or non-completion ($n = 129,352$). Higher AQI-max was associated with a statistically significant increase in the odds of incurring a SJ jump penalty. Specifically, a 10-unit increase in AQI-max was associated with a 1.2% increase in the odds of incurring a SJ jump penalty (OR = 1.012, 95% CI: 1.006 – 1.017, $p < 0.001$) (Figure 13). Truncation of AQI-max and substitution of AQI-avg as the exposure strengthened the observed association between air quality and SJ jump penalties. In contrast, adjustment for meteorological covariates attenuated the association, with confidence intervals including the null (Supplemental Figure 1c, Appendix 3).

3.6 Associations Between Air Quality and SJ Time Penalties

SJ time penalties were modeled as a binary outcome, with 97,946 observations reflecting no penalties and 30,374 observations reflecting any time penalty or non-completion ($n = 128,320$). Higher AQI-max was associated with a statistically significant increase in the odds of incurring a SJ time penalty or elimination. Specifically, a 10-unit increase in AQI-max was associated with a 0.63% increase in the odds of incurring a SJ time penalty (OR = 1.0063, 95% CI: 1.0003 – 1.0124, $p = 0.004$) (Figure 13). Sensitivity analysis yielded effect estimates that were consistent in the direction with the primary model. Confidence intervals from all alternative exposure definitions and model specifications excluded the null (Supplemental Figure 1d, Appendix 3).

3.7 Associations Between Air Quality and XC Jump Penalties

XC jump penalties were modeled as a binary outcome, with 102,608 observations reflecting no penalties and 26,498 observations reflecting any penalty, withdrawal, or elimination ($n = 129,106$). Analyses suggested a detrimental effect but was not statistically significant with confidence intervals including the null value (OR: 1.0005, 95% CI: 0.9999 - 1.0011, $p = 0.13$) (Figure 13). Sensitivity analysis yielded variable effect estimates, and all confidence intervals from sensitivity models included the null (Supplemental Figure 1e, Appendix 3).

3.8 Associations Between Air Quality and XC Time Penalties

XC time penalties were modeled as a binary outcome, with 32,638 observations reflecting no penalties and 95,697 observations reflecting any time penalty, withdrawal, or elimination ($n = 128,335$). Higher AQI-max was associated with a statistically significant decrease in the odds of incurring an XC time penalty. Specifically, each 10-unit increase in AQI-max was associated with a 1.3% decrease in the odds of incurring an XC time penalty or elimination (OR = 0.987, 95% CI: 0.981 – 0.993, $p < 0.001$) (Figure 13). Sensitivity analysis yielded effect estimates that were consistent in direction with the primary model, and confidence intervals from all alternative exposure definitions and model specifications excluded the null, suggesting robustness of this association between air quality and XC time penalties (Supplemental Figure 1f, Appendix 3).

4. Discussion

This study evaluated the association between air quality and performance during equestrian eventing competitions. Overall, we did not observe a statistical association between AQI and the final score, which we attribute to the heterogeneous patterns across the different event phases likely contributing to the large confidence intervals observed. Our phase-specific

analysis identified several significant associations and highlighted nuances in this multi-phase competition that should inform future research. Further, we identified geographical, seasonal, and long-term patterns that inform management interventions to safeguard equine health and welfare. Collectively this work provides a foundation for more refined exposure assessment and future research to clarify the physiological mechanisms underlying these associations.

Increasing AQI-max significantly and negatively influenced both arena-based phases (dressage and show jumping). Although effect sizes were small per 10-unit increase in AQI, translating estimates to a more meaningful scale aids interpretation. Specifically, a 50-unit increase in AQI, representing a shift between AQI categories, corresponds to approximately a 0.26-point increase in dressage scores and a 6.5% and 3.9% increase in the odds of incurring a SJ jump penalty or SJ time penalty, respectively. These findings align with prior research demonstrating small detrimental associations between same-day air pollution exposure and athletic performance. Thoroughbred racehorses in California ran 0.0008 m/s for every 1 $\mu\text{g}/\text{m}^3$ increase of $\text{PM}_{2.5}$.²¹ A similar pattern in professional soccer players exposed to increasing levels of air pollution had impaired sprint performance, slower change of direction times, and reduced speed and accuracy, though the observed decrements were on the scale of milliseconds.⁸⁹ One likely explanation is that the physiological impact of air pollution on performance is not acute but cumulative, with pre-competition exposure playing an equal or greater role than same-day conditions. Studies evaluating the air quality in the 21-day training period preceding a competition demonstrated that air pollution was associated with slower race times in collegiate athletes,³⁶ and slower winning speeds, equating to the loss of approximately one horse length, in Thoroughbred racehorses.⁵¹ These findings suggest that cumulative or antecedent exposure are likely more relevant to performance outcomes than exposure on the day of competition alone,

which may influence the magnitude of performance effects observed. In this study, we did not have information on where horses trained prior to a competition, which represents an important area for future research to better characterize the relationship between air quality and performance.

In addition to describing the performance outcomes, we identified important spatial and temporal trends across competitions in the U.S., highlighting opportunity for preventive intervention. Encouragingly, air quality appears to have improved across the study period, with a decreasing frequency of events where the AQI-max was greater than 150. Although it was not possible to determine if this reflects true improvements in air quality or increased awareness leading to cancellation of events during poor air quality conditions, it is nonetheless a promising finding. Yet despite overall improvement, interannual variability has increased in recent years (Figure 10), findings which align with a study that characterized air quality at U.S. Thoroughbred racetracks and attributed interannual variability to increased wildfire activity.⁹⁰ Within a calendar year, seasonal patterns were evident, with late spring and summer months demonstrating a higher frequency of events with an AQI-max greater than 150 (Figure 11). Additionally, USEA regions 6 (California only in this analysis) and 9 (Utah, Wyoming, Colorado, and South Dakota) exhibited the highest median AQI-max (Figure 8). Not only do these findings corroborate recent research,⁹⁰ they identify important timeframes and locations of greater concern that require increased awareness. For example, one may avoid hosting competitions in at-risk areas during summer months to ensure optimal conditions with low risk of cancellation. In general, increased vigilance of air quality in late spring and summer, can lead to identifying potentially harmful air quality. Overall, these findings underscore the importance of continued air quality monitoring and integration into equine sport.

A surprising finding was the inverse relationship seen with XC time penalties, which was directionally consistent across sensitivity analyses. Given that the XC phase requires sustained aerobic effort causing increased ventilation rates, we anticipated greater vulnerability to air pollution exposure during this phase. Cross country courses traverse terrain that substantially differs across events, introducing environmental heterogeneity and potential confounding variables that remain unaccounted for through our model adjustment. This is especially important to consider given this study employed an observational design using an existing competition dataset that was not originally constructed to evaluate environmental exposures. An alternative explanation may be the distribution, particularly the lack of exposure severity, influencing observed effect estimates. Dose-response relationships to air pollution are often non-linear, with more pronounced performance effects occurring at higher pollution concentrations.⁹¹ This has been demonstrated at stake races across the US where only the most hazardous O₃ levels were associated with markedly slower race times.²⁰ In the present study, the majority of observations occurred under an AQI $\leq$ 100. Higher AQI categories were underrepresented, with only 7.6% of AQI-max and 2.9% of AQI-avg observations exceeding an AQI of 100. While this is reassuring from a welfare perspective, the limited representation of higher exposure categories constrains our ability to evaluate potential threshold or non-linear effects at elevated pollutant levels. Therefore, the observed association warrants careful interpretation. Further investigation should include additional data capture, such as tree coverage, ground conditions, length of course, among other course- and environmental-level factors, as well as more refined performance metrics extending beyond dichotomized penalty outcomes, e.g., time over the optimum time allowed on a continuous scale. Additional data may allow for more nuanced characterization of these exposure-response relationships, including the exploration of non-linear associations.

A strength of this study is the large, multi-year dataset, which provided substantial statistical power to detect subtle performance differences across phases; however, several limitations warrant consideration. Exposure was summarized at the event level using maximum and average AQI, at the county level, across the competition window, as phase-specific timing was unavailable. This prevented precise alignment of site-specific air quality conditions within each phase and the ability to control for time of day and day of week, which prior studies have done due to their relationship with traffic-related air pollution.^{21,51} Additional ambiguity arose from the inability to determine whether events were postponed or rescheduled during periods of poor air quality or other weather events. Together, these limitations likely introduced non-differential exposure misclassification, biasing estimates toward the null and potentially underestimating true associations. Although analyses were restricted to Preliminary, Intermediate, and Advanced levels and adjusted for by competition level, substantial variability remained, including a wide range in horse and rider ages. This lack of temporal variables and the inherent heterogeneity across certain variables may partly explain the inconsistencies observed across dressage score sensitivity analysis. Finally, because AQI represents a composite index driven by the highest pollutant concentration, it limits the ability to distinguish pollutant-specific effects. Incorporating event-level air quality monitoring, pollutant-specific metrics, and refined temporal data in future research would enhance exposure precision and improve estimation of air quality-performance relationships. Additionally, future studies focusing on more homogenous subgroups, such as elite-level athletes, may reduce unmeasured confounding, as demonstrated in prior studies evaluating only first-place finishers or stratifying by handicap classifications.^{19,21,51}

Our findings demonstrate that ambient air pollution is associated with small but measurable, phase-specific changes in equestrian eventing performance. The observed spatial

and temporal variability in AQI at competitions indicate that risk is not uniformly distributed across competitions. Importantly, the predominance of relatively low AQI conditions and the use of available event-level metrics likely attenuated effect estimates and limited the ability to capture delayed or cumulative effects of exposure. Evidence from both human and equine athletes suggests that lagged and antecedent exposure may be more relevant to performance than same-day conditions.^{36,51} Future research incorporating phase-specific, longitudinal, and lagged exposure metrics will be critical to more fully characterize exposure-response relationships and inform competition management strategies.

CHAPTER 5: EXPERT INFORMED RECOMMENDATIONS FOR MANAGING HORSES DURING POOR AIR QUALITY⁴

1. Introduction

After decades of improvements in ambient air quality in the United States, exposure to unhealthy levels of air pollution is on the rise again.^{59,79} Fine particulate matter (PM_{2.5}), the main component of wildfire smoke, is a primary concern. As regions, such as the western United States (U.S) and Canada, are experiencing hotter and drier climates, more frequent and intense wildfires with resulting smoke events are occurring.⁵⁹ Over a decade ago, fewer than half a million people in the contiguous U.S. experienced a single day with smoke-related PM_{2.5} concentrations exceeding 100ug/m³; in recent years, that number has expanded to over 8 million⁴⁶ and is projected to continue to increase.⁵⁴ In addition to wildfire smoke, poor air quality also stems from ground-level ozone (O₃), a pollutant for which many areas in the U.S. are in non-compliance with current regulatory standards.^{90,92,93} O₃, which forms when nitrogen oxides (NO_x) and volatile organic compounds (VOCs) react in the presence of heat and sunlight, is a respiratory irritant known to induce inflammation and decreased lung function.¹² Without strong policies to reduce carbon emissions, both PM_{2.5} and O₃ levels are expected to increase throughout much of the U.S.^{54,94}

The Air Quality Index (AQI) is the U.S. Environmental Protection Agency's (EPA) standardized tool for reporting air quality and the associated public health risks as pollutant levels increase. Each category of the AQI is depicted by a color (green, yellow, orange, red, purple, and maroon), a corresponding level of health concern (good, moderate, unhealthy for

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sensitive groups, unhealthy, very unhealthy, and hazardous), and respective index values representing increasing severity. This informative tool communicates the health risks associated with rising AQI values,⁹⁵ and is based on decades of robust research demonstrating adverse health outcomes associated with exposure to ambient air pollution. The measured AQI is a composite measure of six key air pollutants, including particulate matter, both PM_{2.5} and coarse particulate matter (PM₁₀), O₃, carbon monoxide (CO), nitrogen dioxide (NO₂), and sulfur dioxide (SO₂). The AQI is determined by the pollutant with the highest concentration in a region, most commonly PM_{2.5} or O₃,¹⁶ yet this framework was developed exclusively around human health endpoints.

As communities across the U.S. are increasingly exposed to poor ambient air quality, horses may have substantially greater exposure through primarily outdoor living. However, owners and veterinarians lack evidence-based guidance for horse management, including physical activity and other forms of exertion, during periods of poor air quality. PM_{2.5} and O₃ have been shown to detrimentally impact equine athletes,^{20,21,51} who have increased vulnerability to air pollution due to increased ventilation rates during exertion permitting a higher pollutant dose delivered to their lungs and entering systemic circulation.^{36,61} The need for guidance intensified following the record-breaking air pollution event in 2023, where long distant transport of smoke from wildfires in Canada reached the east coast, resulting in hazardous levels of air pollution.⁹⁶ As a result, veterinarians have increasingly been called upon to provide guidance on protecting animal health.⁹⁷ Yet, common human-centric recommendations, such as limiting time outdoors, closing windows, and using air conditioning and filtration, are often impractical for horse owners. Therefore, there is a clear need for expert-informed, equine-specific guidelines to support management during periods of poor air quality. The objective of

this study is to adapt the existing AQI framework to communicate equine health risk and to develop practical recommendations for horse care, training, and competitions across increasing levels of air pollution.

2. Methods

2.1 Study Design

This study used a modified Delphi approach to collate expert agreement through a series of three questionnaires. This technique has been widely used in a variety of situations including health sciences and equine welfare.⁹⁸⁻¹⁰¹ Those on the expert panel who completed all three questionnaires were compensated for their time. This study was reviewed by the Colorado State University Institutional Review Board and determined to be exempt from full review.

2.2 Recruitment of Experts

Our research team, with expertise in veterinary medicine, epidemiology, and equine sports medicine, identified an international panel of participants through a literature review targeting experts in equine respiratory and cardiovascular pathology, as well as exercise physiology, or those who have conducted equine and air pollution-related research. Veterinarians who had achieved board certification and/or Diplomate status in their respective countries for equine internal medicine, emergency and critical care, and/or sports medicine and rehabilitation were of particular interest. Additional qualifications included a PhD with a focus in exercise physiology, cardiovascular disease, and/or respiratory disease. We also identified potential panel participants at the American College of Veterinary Internal Medicine (ACVIM) 2023 Forum, where multiple experts in equine respiratory physiology and the horse racing industry presented on various relevant topics. Finally, we employed the Peer Esteem Snowball Technique in which

individuals who were contacted were asked to refer additional experts. This technique enhanced the heterogeneity of our expert panel by expanding network boundaries and reducing selection bias.¹⁰²

2.3 Questionnaires

Questionnaires were delivered electronically via email. Respondents returned questionnaires via email to one of the investigators who de-identified each questionnaire prior to analysis and development of subsequent iterations. Each questionnaire is provided in the Supplemental Materials.

The initial questionnaire (supplemental material 1) contained eleven open-ended questions delivered in four sections. The first section examined air pollution impacts on horse health, identified affected body systems, associated health conditions, and the short-term versus long-term health implications of exposure. The second section sought to adapt AQI public health messaging for horse health and evaluated current AQI cut points and existing United States Equestrian Federation (USEF) recommendations for canceling or suspending competitions (i.e., AQI of 151 or above).¹⁰³ The third section formed management interventions at varying pollutant cut points. The final section asked respondents to make recommendations for post-exposure management and provided the opportunity for concluding remarks on the topic or the questionnaire. Objective measures of expert opinion utilized levels of importance and agreement (1 = not at all important / completely disagree, 5 = neutral, 9 = extremely important / completely agree) and provided opportunity for expansion. For items requiring a less refined but directional response, a 5-point scale of levels of concern or agreement (1 = not at all concerned / strongly disagree, 3 = moderately concerned / neither agree nor disagree, 5 = extremely concerned / strongly agree) was used.

We collected and synthesized responses from the first questionnaire to develop the second questionnaire (supplemental material 2). This iteration had four multiple-part questions in three sections. The first section revisited AQI adaptation for horse health and compiled management recommendations, defining horses that would be considered *sensitive* and *unusually sensitive* to air pollution exposure. The second section redistributed questions from the first round and requested additional input. The final section summarized results from questions that did not require follow-up, offering an optional opportunity for comments. Results from this iteration informed the final questionnaire (supplemental material 3), which had two sections and two multiple-part questions. The first section presented items that did not achieve consensus in round two and required further commentary. The second section summarized the results where consensus had been achieved, providing an optional opportunity for additional comments. Expert consensus was defined a priori as a $\geq 80\%$ agreement threshold among the panel.

3. Results

We invited 23 potential contributors to the expert panel, and 17 expressed interest in participating and were sent the first questionnaire. All those who returned each questionnaire were sent the follow-up questionnaire. Fifteen panelists returned the first questionnaire, 13 panelists returned the second questionnaire, and 11 panelists returned the final questionnaire. Reasons for panelists not completing the process included illness ($n = 1$), voluntary withdrawal ($n = 1$), and loss to follow-up ($n = 4$).

3.1 AQI Interpretation for Horses

Panelists supported translating the existing public health messaging for each AQI category to communicate equine health risk (Table 9). Median level of agreement with PM2.5

Table 9: The U.S. Environmental Protection Agency Air Quality Index table with associated public health messaging. The far-right column provides the agreed-upon horse-centered messaging. Horses who may be considered unusually sensitive and sensitive, as indicated by the yellow and orange rows, respectively, are described below the table.

Air Quality Index			
AQI Category and Color	Index Value	Description of Air Quality HUMAN-CENTERED MESSAGING	Description of Air Quality HORSE-CENTERED MESSAGING (all horses)
Good	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk	Air quality is satisfactory, and air pollution poses little or no risk to horses
Moderate	51 to 100	Air quality is acceptable. However, there may be risk for some people, particularly those who are unusually sensitive to air pollution	Air quality is acceptable. However, there may be risk for some horses, particularly those who are unusually sensitive* to air pollution
Unhealthy for sensitive groups	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected	Horses in sensitive groups† may experience health effects. The general horse population is less likely to be affected
Unhealthy	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects	Some healthy horses may experience health effects; horses of sensitive† groups may experience more serious health effects.
Very unhealthy	201 to 300	Health alert: The risk of health effects is increased for everyone.	Health alert: The risk of health effects is increased for all horses
Hazardous	301 and higher	Health warning of emergency conditions; everyone is more likely to be affected	Health warning of emergency conditions: all horses are likely to be affected

***Unusually sensitive groups** include those with pre-existing, non-infectious respiratory conditions e.g., severe equine asthma, interstitial lung disease, upper airway obstruction, exercise-induced pulmonary hemorrhage, and those with active or recently recovered from infectious respiratory illness, e.g., viral, bacterial or fungal respiratory infection. Horses with cardiac disease and concurrent respiratory sequelae, e.g., congestive heart failure and pulmonary hypertension, are also included here.

†**Sensitive groups** are those included in “unusually sensitive,” as well as horses with mild to moderate equine asthma, horses that are immunocompromised, horses with active or recently recovered from systemic illness, e.g., uncontrolled PPID, anhidrosis. Excessively obese horses are also included here.

and the 8-hour and 1-hour average for ozone level cut points corresponding to each AQI category are presented in Supplementary Table 1, demonstrating that respondents either expressed neutrality or agreement with these cut points. Three respondents commented that there is a lack of data to support or oppose these cut-offs, with one panelist noting that established cut-points represent the best starting point.

3.2 Horse Management and Care at Each AQI Level

Tables 10-14 present the final recommendations for each AQI category developed through the expert consensus process. Each AQI category provides recommendations for general management of *all* horses, training, and competition. Recommendations span a range of equine management including exercise, housing, feeding, and barn maintenance activity.

Table 10: Horse management recommendations for the Good / Green AQI category. Recommendations are provided for the general management of horses, i.e., recommendations for ALL horses, training days, and competition day.

Good / Green (AQI 0 to 50)	
Horse activity	Management recommendations
General management	Continue routine as normal. Air quality is unlikely to impact horse health.
Training days	Strenuous exercise can be commenced and carried out as ambient air quality is unlikely to impact horse health
Competition day	Strenuous exercise can be commenced and carried out as ambient air quality is unlikely to impact horse health or performance

Table 11: Horse management recommendations for the Moderate/Yellow AQI category. Recommendations are provided for the general management of horses, i.e., recommendations for ALL horses, training days, and competition day.

Moderate / Yellow (AQI 51-100) <i>Horses who are unusually sensitive to air pollution may experience health effects</i>	
Horse activity	Management recommendations
General management	Most horses can carry on with their normal routine. Exercise should be limited in horses that are unusually sensitive* to air pollution.
Training days	Training, including strenuous exercise, can be undertaken by most horses. Horses that are unusually sensitive* to air pollution should be restricted to moderate exercise.
Competition day	Competition, including those involving strenuous exercise, can be undertaken by most horses. Horses that are unusually sensitive* to air pollution should be restricted to moderate exercise.

Table 12: Horse management recommendations for the Unhealthy for sensitive groups/Orange AQI category. Recommendations are provided for the general management of horses, i.e., recommendations for ALL horses, training days, and competition day.

Unhealthy for sensitive groups / Orange (AQI 101 – 150) <i>Horses in sensitive groups may experience health effects</i>	
Horse activity	Management recommendations
General management	Healthy horses: Adjust normal routine to light to moderate work Sensitive† horses: • Limit time outdoors if possible • Provide a low dust environment; avoid activities that increase dust exposure indoors, e.g., sweeping • Minimize additional dust exposure with low dust forage and bedding • Ensure fresh water is always available • Monitor for abnormalities: cough, changes in breathing rate or pattern, abnormal breathing noise
Training days	Healthy horses: • Light to moderate training outdoors • Normal training indoors may be acceptable • It is advisable to avoid or reduce moderate to strenuous exercise. High-intensity exercise should be avoided. Sensitive† horses: • Refrain from training outdoors • Light to moderate exercise may be appropriate in a low-dust indoor environment
Competition day	• Organizers should consider canceling racing/high-intensity exercise events • Owners of horses with known respiratory health issues should consider withdrawing • The following recommendations are for events that will continue at this level of AQI: ○ Adequate and constant watering of working surfaces to minimize dust ○ Provide access to areas with optimal ventilation and temperature ○ Minimize dust exposure with from hay and bedding ○ Increased biosecurity protocols to minimize infectious disease circulation and spread ○ Pay extra attention to cooling down horses if in hot conditions, if possible move indoors with air conditioning

Table 13: Horse management recommendations for the Unhealthy/Red AQI category. Recommendations are provided for the general management of horses, i.e., recommendations for ALL horses, training days, and competition day.

Unhealthy / Red (AQI 151 – 200) Some healthy horses may experience health effects; sensitive† horses may experience more serious health effects	
Horse activity	Management recommendations
General management	- Horses should not work - Horses may benefit from being kept indoors or in an area with less pollution - Maintain a low-dust environment: Avoid sweeping and dust-generating activities, use low-dust forage and bedding - Ensure fresh water is always available - Monitor for abnormalities: Cough, changes in breathing rate or pattern, abnormal breathing noise, eye irritation - Sensitive† or unusually sensitive* horses should remain inside in a low-dust environment - These horses should be monitored closely for signs of illness - Contact your veterinarian if any abnormalities are observed.
Training days	In addition to the <i>general management</i> recommendations, consider the following for training days: <u>Exercise:</u> - Avoid exercising horses - Limit outdoor activity to slow walks <u>If training <i>must</i> occur:</u> - Avoid exercising horses outdoors - Avoid increased levels of exertion that increase respiratory rate/effort - Select indoor/low-dust environments - Walking horses for rehab or to stretch limbs may be appropriate for some horses without underlying health conditions
Competition day	In addition to the <i>general management</i> recommendations, consider the following for competition days <u>Competitions and events should be suspended or canceled in accordance with USEF recommendations.</u> For horses that competed under these air quality conditions, the following are recommendations for management/intervention: - Consider a veterinary health exam before resuming training - Return to exercise should be gradual after the air quality improves with guidance from your veterinarian

When asked about specific cut-points for PM_{2.5} and O₃ for (a) when horses should avoid competition in ambient air, (b) when horses should avoid exercising/training in ambient air, and (c) when all horses should avoid exposure to ambient air, experts consistently indicated that scientific evidence to support horse-specific cut points was lacking, supporting the use of the current AQI cut points available.

Importantly, while over 80% of experts agreed with the adaptations for the green, yellow, red, purple, and maroon categories, the orange category reached only 69%, primarily due to concerns about the definitions of *sensitive* and *unusually sensitive* groups after round two. These

Table 14: Horse management recommendations for the Very unhealthy/Purple and Hazardous/Maroon AQI categories. Recommendations are provided for the general management of horses, i.e., recommendations for ALL horses, training days, and competition day.

Very unhealthy / Purple (AQI 201 – 300)		AND	Hazardous / Maroon (AQI 301 and higher)
These recommendations apply to both very unhealthy (AQI 201-300) and hazardous (AQI > 300) <i>All horses are at increased risk. AQI > 300 is considered an emergency condition</i>			
Horse activity	Management Recommendations		
General management	During air pollution event - Horses should not work - Move horses out of the exposure: Move indoors, keep indoors with doors and windows temporarily closed if possible, consider evacuating to an area with better air quality - Maintain a low-dust environment: Avoid sweeping and dust-generating activities, use low-dust forage and bedding, only essential activity should be considered under these conditions - Ensure fresh water is always available - Monitor for abnormalities: cough, changes in breathing rate or pattern, abnormal breathing noise, eye irritation - Sensitive^f or unusually sensitive* horses should remain inside in a low-dust environment <i>These horses should be monitored closely for signs of illness</i> - Contact your veterinarian if any abnormalities are observed. After air pollution event - Continue monitoring for abnormalities: cough, changes in breathing rate or pattern, abnormal breathing noise, eye irritation, nasal discharge, prolonged recovery from exercise, behavioral abnormalities - Contact your veterinarian if your horse develops any abnormal signs - Optimize the air quality in the horses' breathing zone: provide adequate ventilation once the ambient pollution levels have resolved, use low-dust forage and bedding - Ensure adequate hydration		
Training days	In addition to the <i>general management</i> recommendations, consider the following for training days: <u>Suspend all training/exercise during the air pollution event</u> After the air pollution event: - Check for signs of abnormal breathing or coughing before returning to exercise - Consider a veterinary health exam before resuming training - Return to exercise should be gradual after the air quality improves with guidance from your veterinarian		
Competition day	In addition to the <i>general management</i> recommendations, consider the following for competition days: <u>All competitions and events should be suspended or canceled in accordance with USEF recommendations. This includes both indoor and outdoor events.</u> For horses that competed under these air quality conditions, the following are recommendations for management/intervention: - Consider a veterinary health exam before resuming training - Return to exercise should be gradual after the air quality improves with guidance from your veterinarian		

definitions were revised based on feedback and redistributed; however, agreement declined slightly to 64% after the concluding round. Dissenting experts requested the removal of vague or non-specific conditions, e.g., “lung disease” and “shipping fever.” There was also debate about including exercised induced pulmonary hemorrhage (EIPH) in the *unusually sensitive* group. While some experts supported its inclusion, one contributor opposed it, noting that most horses competing at high speed have exhibited EIPH, which is not currently linked to smoke inhalation

and may not represent increased sensitivity. Although two studies found no association between EIPH and air pollution,^{104,105} a recent study supports the association.¹⁰⁶ Ultimately, EIPH was included in the final definition. Finally, one expert raised a broader concern, arguing that the terms *sensitive* and *unusually sensitive* may not be appropriate for equine populations, given the comparatively limited evidence base relative to human health literature. Ultimately, the guidelines retained these groups given the general support to reflect some horses may be at increased risk to air pollution exposure.

3.3 Air Pollution and Equine Health

3.3.1 General Equine Health

All respondents (100%) agreed that air quality events, i.e., periods of elevated air pollution, are important, but one must also consider the average air quality for the individual horse, which can be influenced by hay quality, feeding method, and barn dust. The median level of importance in reference to exposure to air pollution when considering *equine health in general* was *somewhat important* (median = 6, IQR 6-8). Most respondents (92%) agreed with the following: (i) one must consider factors related to the pollutant, e.g., duration of exposure, composition of the pollutant, and the AQI; (ii) air pollution exposure is associated with respiratory impacts; and (iii) research to assess the relationship between air pollution and health outcomes in horses is lacking and needed. Lastly, 77% of respondents agreed that one must consider factors related to the horse, e.g., health/immune status, occupation, individual differences, and exercise intensity. Any statements receiving less than 60% agreement have been omitted from further consideration.

There was very strong agreement that horses *with underlying health conditions* exposed to air pollution may experience adverse health effects (median = 9, IQR 8-9). The most

significant health impacts (i.e., conditions, illnesses, injuries) indicated by panelists are summarized in Supplementary Table 2 and indicate the respiratory system to be the most impacted body system. Additional comments included that effects on the cardiovascular system, tumor development, and systemic inflammation are established in the human literature and can potentially be translated to equine health but thus far lack equine-specific evidence (n = 4). Experts also stated that there is existing evidence in the literature that air pollution can impact respiratory health and lead to poor performance in horses (n = 3).

There was strong agreement that *healthy* horses exposed to air pollution may experience adverse health effects (median = 8, IQR 7-9). Body systems primarily impacted by air pollution included the respiratory system (n = 14), cardiovascular system (n = 5), ocular tissues (n = 2), and the immune system (n = 1). Additionally, panelists indicated the top pollutants of concern included particulate matter (PM_{2.5} and PM₁₀) (n = 6), ozone (n = 4), NO₂ (n = 3), SO₂ (n = 3), CO (n = 2), and ammonia (n = 2). The categories of pollutants indicated to be of concern include smoke (n = 5), organic dust (n = 4), fungal spores (n = 2), and pollen (n = 2).

There was slight agreement that the *signalment* of a horse plays a key role in considering the health risks of exposure to air pollution (median = 6, IQR 5-7). Most respondents (77%) agreed that although the breed and use of a horse are associated, the *use* of the horse is more important when considering the health risks of air pollution exposure. Additionally, 62% agreed that age can be a risk factor in that young horses and older horses have greater health risks.

3.3.2 Short-term and long-term health impacts

There was strong agreement that horses exposed to elevated levels of air pollution may experience negative *short-term* health impacts (median = 8, IQR 7-9). Short-term health impacts

indicated include respiratory inflammation (n = 8), systemic inflammation (n = 2), cough (n = 2), and reduced athletic performance (n = 2). Additionally, two respondents noted that short-term health impacts depend on the source and severity of the pollutant. When this same question was asked with regard to *long-term* health impacts, there was moderate agreement (median = 7, IQR 7-8). Specified long-term health impacts included airway inflammation and disease (n = 11), the development and/or exacerbation of equine asthma (n = 4), and lung remodeling (n = 4).

3.3.3 Acute and chronic exposure

The level of concern for both acute and chronic exposure to increasing pollutant levels is summarized in Supplementary Table 3 and revealed that level of concern was dependent on whether exposure was acute or chronic. Specifically, for prolonged or chronic exposure, respondents expressed greater concern at yellow and orange categories compared to acute exposure scenarios, yet concern levels align at red, purple, and maroon categories regardless of whether exposure is acute or chronic.

To define acute and chronic exposure, we adapted the U.S. EPA's glossary of definitions for exposure based on the environment and community-based air pollution,¹⁰⁷ and 64% favored these definitions, with one respondent noting that in the "*Current lack of evidence in horses to support cutoff times / definitions...it is probably best to stick to those described for other species including humans.*" Those not in favor expressed that the cutoff for determining chronicity depends on multiple factors, e.g., the pollutant, the level of the pollutant, housing conditions, and horse factors (n = 4). Additionally, the provided cut points may not effectively capture adverse health outcomes associated with both acute vs chronic exposure (n = 3). For example, as stated by one respondent, "*a 23 hour exposure and a 25 hour exposure are unlikely to differ with regard to the induced detrimental health effects*", while other panelists commented "*the incidence of*

health problems stemming from <24 hour exposure to pollution is extremely low”, and “we need to consider a distinction between exposure that might last several days/weeks to exposures that are experienced for months or even years.” One panelist summarizes resolving the issue of defining acute versus chronic exposure as, “A more appropriate definition could therefore be formulated for exposure to air pollution in horses that is multifactorial, incorporating both duration and the degree of air pollution.”

4. Discussion

We adapted the AQI framework to communicate equine health risk, identified horses that may be considered *unusually sensitive* or *sensitive* to air pollution, and generated expert-informed management recommendations for each AQI category. These recommendations are intended to provide horse owners, barn managers, trainers, and riders with foundational strategies to minimize exposure risk. These recommendations do not replace veterinary examination and intervention when required but can prompt timely discussions with veterinarians when concerns arise. In turn, veterinarians can refer to this framework when advising clients on how to manage air pollution exposure. As the number of horses experiencing periods of poor air quality continues to rise,^{46,54,94} awareness of local conditions and exposure minimization is essential.

Notably, the expert panel supported retaining the existing pollutant cut points of the AQI, citing insufficient evidence to establish horse-specific thresholds. This retention of existing cut points enables use of the publicly available AQI with reference to the equine translation presented here (Figure 1). However, these thresholds are based primarily on human data, and the Delphi process reflects expert opinion rather than empirical measurement. Horse-specific data on air pollution exposure and health are limited, a major concern raised by almost every

contributing panelist, necessitating reliance on translational evidence from human and experimental animal models. While this extrapolation was considered reasonable, panelists emphasized the importance of clearly acknowledging these limitations particularly for outcomes beyond the respiratory system, such as the cardiovascular system. Future studies should prioritize objective, horse-specific performance and health metrics.

This equine-adapted AQI resource facilitates informed decision-making during periods of poor air quality, complementing and extending existing guidance. Presently, the only recommendation comes from USEF and applies to competition days, recommending suspension or cancellation of competitions when the AQI exceeds 151 (red; “unhealthy” air quality). USEF also advises that individual horses with underlying medical conditions consider withdrawing from competition when the AQI is in the range of 101-150 (orange; “unhealthy for sensitive groups”). However, evidence indicates that training and competitions still occur under unhealthy air quality conditions,^{20,21,51} highlighting a gap between existing guidance and practice. The recommendations from our study strongly suggest that at AQI levels of 101-150, organizers should consider canceling races or high-intensity exercise events, and at levels above 151, competitions and events should be suspended or canceled, reinforcing USEF guidance. Additionally, these recommendations extend to include training days, and the general management of all horses, providing a practical tool that owners, trainers, and event organizers can reference during poor air quality.

Central to increased vigilance is recognizing that not all horses carry equal risk. Identifying horses who may be *unusually sensitive* or *sensitive* to air pollution, as well as the conditions that may occur due to exposure, provides opportunity for earlier intervention for those at increased risk. There was less consensus surrounding which *specific* conditions should be

included, however horses with respiratory illness, cardiac disease, systemic illness, or compromised immune function were identified as individuals with increased risk at lower AQI categories. These results align with the findings of a recent scoping review concluding that air pollution exposure studies in horses were limited to respiratory, ophthalmologic, and performance outcomes, with cardiovascular and reproductive outcomes identified as a significant research gaps.¹⁷ There is robust evidence in humans demonstrating a causal relationship between short-term and long-term PM_{2.5} exposure and cardiovascular morbidity and mortality.^{15,108} Similarly, there are strong associations between air pollution exposure and preterm births, low birth weight, and stillbirth in humans.¹⁰⁸ These findings highlight that the adapted AQI and associated management recommendations represent an initial framework that must be iteratively updated as equine-specific research on air pollution exposure and health outcomes expands.

Having species-specific AQI resources can help to raise awareness of air pollution risks and protective actions. A survey of dog owners found that less than one-fifth of respondents reported they knew the AQI well and only one-quarter of respondents stated they check the AQI frequently, despite this information being readily available on weather forecasts.¹⁰⁹ Veterinary teams can address this gap by demonstrating how to access local air quality data and by sharing horse-adapted AQI guidance. Posting AQI charts in barns, training facilities, and event settings can extend engagement. These tools can empower owners, riders, and trainers to adjust training, reduce exposure, and question activities occurring under unhealthy conditions. Increased vigilance around air quality helps safeguard equine health while also reducing exposure risk for riders and spectators.

Experts emphasized both the importance and the complexity of environmental management during periods of poor air quality. This was particularly relevant to optimizing the

horse's breathing zone through management practices such as reducing airborne dust. While strategies such as wetting hay and bedding may be effective in some settings, they may be contraindicated in others, particularly in humid environments that can promote mold growth. Consistent with ACVIM guidance, reducing respirable dust and avoiding feeding hay from nets remain important considerations. Importantly, one expert emphasized that optimizing a horse's breathing zone should always be part of routine general management of sensitive horses, not just during periods of poor air quality. Finally, given that indoor air quality varies widely across facilities due to many lacking filtration systems, low-cost air quality monitors may provide useful site-specific data to guide management decisions. These monitors can be placed in barn aisles to monitor and compare the indoor air quality to outdoor. Applying these recommendations in the context of environmental complexities enables caretakers to tailor practices to diverse facility types and geographic conditions.

In addition to the previously addressed considerations regarding the lack of equine-specific data and reliance on translational models to inform the horse-adapted AQI and recommendations, there are additional limitations requiring acknowledgment. Importantly, some items in the final round did not meet the a priori $\geq 80\%$ consensus threshold. However, dissenting feedback was incorporated to improve clarity and relevance, which informed the final recommendations (Figures 1-6). Further, although we engaged an international expert panel to ensure a diverse perspective, the recommendations are anchored to the U.S. EPA's AQI tool. To address potential variation in air quality indices across countries, panelists were provided with the EPA's AQI framework with associated PM_{2.5} and O₃ cut points to ensure a standardized reference. Generalizability may therefore be limited in countries using different indices or

pollutant cut points; however, the methodology framework could serve as a translatable model for similar exercises in other regions.

Advancing this work necessitates open dialogue among researchers, practitioners, and national and international equine sport governing bodies to ensure that the recommendations are both feasible and practical across diverse equine settings. Collaborative efforts can help refine the guidelines, identify implementation barriers, and inform policies that prioritize equine health, welfare, and performance. Future research should prioritize empirical validation of these tools, with particular attention to identifying critical pollutant thresholds. Studies in Thoroughbred racehorses demonstrated performance detriments at PM_{2.5} concentrations consistent with “good” air quality,^{21,51} suggesting that current AQI thresholds may not adequately protect equine athletes. Further, at the time of expert engagement, there was no evidence of air pollution impacting EIPH, yet a recent publication identified greater risk and severity of EIPH in Thoroughbred racehorses when the AQI is greater than 100.¹⁰⁶ Compared to human health, the research examining air pollution and equine health is in its infancy. These emerging findings highlight the necessity for continued work on this topic.

As air pollution events become more frequent and severe, horses face increasing exposure risks. This study provides a practical, expert-informed framework to guide management decisions at increasing AQI levels. However, the reliance on translational data highlights a critical need for equine-specific research to define health impacts and pollutant thresholds. Future work should prioritize generating these data to support iterative refinement of AQI-based guidance and strengthen protection of equine health and performance.

CHAPTER 6: CONCLUSIONS

Wildfire smoke and O₃ formation are worsening air quality in much of the U.S.^{54,94} Understanding how air pollution impacts the health and welfare of domesticated animals is a critical gap of knowledge requiring dedicated research attention.¹⁷ We identified equine athletes as a promising research model given the extensive pre-existing data available and their primarily outdoor lifestyle. This concluding chapter will synthesize the findings across the four studies, discuss their contributions to the equine health and performance literature, suggest directions for future investigation, and identify overarching limitations.

This work identified air quality as a driver for equine athletic performance. Horses are elite athletes who primarily exercise and compete outdoors, yet prior to this work, the literature examining air quality and equine athletic performance was limited to a few studies. Four studies explored air pollution and athletic performance,¹⁸⁻²¹ and all investigated air quality on the day of a competition. Results varied, demonstrating no association between air quality and performance except when racing under hazardous ozone conditions,²⁰ to small, but significant, effects sizes with increasing PM_{2.5} concentrations.²¹ This dissertation builds on this foundation by first characterizing air quality at U.S. Thoroughbred racetracks, establishing that U.S. Thoroughbred racetracks experience periods of poor air quality with identifiable regional and seasonal patterns, providing key insight into exposure risk. Second, we expanded the exposure timeframes investigated to include the pre-competition training period to assess a delayed or lag effect. To our knowledge, this represents the first application of a DLNM model to assess air quality associated outcomes during training and race day performance in equine athletes. Importantly, the pre-competition training period represents a more actionable window for exposure mitigation

compared to race day, given the competitive and financial pressures inherent to Thoroughbred racing. Next, we extended investigation into an additional discipline (equestrian eventing) representing an initial exploration beyond the racing environment, providing support that air quality effects are not limited to Thoroughbred racehorses, though findings varied across eventing disciplines. Notably, spatiotemporal trends aligned with the regional and seasonal patterns identified at Thoroughbred racetracks in Chapter 2. Finally, we collated expert-informed recommendations for managing horses during periods of poor air quality, addressing a key translational need of merging research with clinical guidance. Cohesively, these findings establish a foundation that characterizes exposure risk, identifies performance impacts across disciplines, and translates those findings into actionable management recommendations. Further, we established the equine athlete as a valuable model for epidemiological investigation of environmental hazards using existing data.

Beyond exposure characterization and describing performance outcomes, future research should investigate the pathophysiological mechanisms underlying performance decline. In Chapter 5, experts emphasized the limited equine-specific evidence base underpinning current guidance, necessitating reliance on translational data from human health and experimental animal models. This, in conjunction with the reported findings, supports several priorities for future investigation. For instance, air pollution is known to have a causal relationship with cardiovascular outcomes in humans, including the occurrence of arrhythmia;¹⁵ however, a recent scoping review identified the cardiovascular system as a significant research gap in horses,¹⁷ despite the fact that arrhythmias are commonly reported in healthy equine athletes during exercise.¹¹⁰ This represents a critical mechanism requiring exploration as a potential explanation to the observed performance declines. Future work should also extend beyond the equine athlete

into other vulnerable populations such as breeding animals; negative reproductive and developmental outcomes have been described in humans,¹¹¹⁻¹¹⁴ yet remain underexplored in equine research.¹⁷ Given their seasonal breeding patterns, large geographic distribution, and existing records from breeding facilities and reproduction clinics, horses may be uniquely positioned to investigate reproductive outcomes. Through enhancing our understanding of the mechanistic factors underlying adverse health outcomes, the expert-informed recommendations must be updated to provide a more comprehensive overview of at-risk individuals and populations. Additionally, investigations should determine at which pollutant levels adverse health effects occur. The current recommendations are based on the AQI, whose tiered-risk structure is grounded in human health research. Identifying equine-specific thresholds and refining the associated risk structure is a critical area for future work.

While limitations specific to each study are addressed within their respective chapters, several overarching limitations warrant consideration. A primary limitation is that these epidemiological investigations utilized existing data representing convenience samples. As such, the data were not originally captured with the goal of investigating environmental exposures and therefore potentially introduced unmeasured confounding that we could not account for in the available covariates. Further, given the observational nature of these data we can only assess an association and not make any conclusions towards causation. Additionally, our reliance on open-access air quality data from EPA regional monitors may not accurately represent site-specific air quality at racetracks and competition venues and does not capture the air quality of barns and stables. Stables are known to have high concentrations of particulate matter and microorganisms from bedding and food material, which likely contributes to inflammatory airway disease in horses,¹¹⁵ yet we were unable to incorporate indoor air quality as a confounding factor in these

studies representing an important measurement gap. Finally, we studied associations between air quality and performance in equine athletes, which may limit generalizability to the general population of horses; however, athletes represent a sentinel population given their heightened ventilatory demand during exercise and the availability of detailed performance records, supporting that observed effects may broadly apply across the equine population where data is lacking. Despite these limitations, our results strongly support integration of air quality monitoring at equine facilities to guide management, training, and competition decisions.

From exposure quantification through performance impacts to caretaker guidance, this dissertation represents a comprehensive characterization of air quality as a determinant of equine athletic performance. This work fills a critical gap in the knowledge of how air pollution affects horses, while emphasizing the necessity of incorporating air quality monitoring in equine sports. Through using existing data on athletic performance, we demonstrated that equine athletes are a sentinel animal model for investigating environmental hazards, providing a foundation for continued investigation into equine-specific thresholds and mechanistic pathways underlying performance decline. As air quality worsens around much of the U.S., management practices can be immediately implemented to mitigate exposure, while guidance must continue to evolve as mechanistic knowledge advances. With concerted effort, we can better safeguard the health and welfare of all animals during changing environmental conditions.

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APPENDIX I

Supplemental Table S1: National Ambient Air Quality Standards (NAAQS) primary daily and annual threshold levels for criterial pollutants evaluated in this study.

**The primary annual standard for PM_{2.5} is based on the 3-year average of annual means; however, for the purpose of this study, annual means were assessed for each individual year. Chemical analysis methods for each criteria pollutant are defined in 40 CFR Part 50, specifically Appendices A-1 and A-2 (SO₂), C (CO), D (O₃), F (NO₂), G (Pb), J (PM₁₀), and L (PM_{2.5}).⁴⁵*

Pollutant	Daily Threshold Level	Yearly Threshold Level
CO	9 ppm	
Pb	0.15 µg/m ³	
NO ₂	100 ppb	53 ppb (annual mean)
O ₃	0.07 ppm	
PM _{2.5}	35 µg/m ³	9 µg/m ³ (annual mean) *
PM ₁₀	150 µg/m ³	
SO ₂	75 ppb	

Supplemental Table S2: Distribution of the average daily pollutant concentrations by EPA region. Values are reported as median (range). The third row in each cell presents the percentage of study days with available data for that pollutant in the given EPA region.

EPA region	CO (ppm)	Pb (µg/m ³)	NO ₂ (ppb)	SO ₂ (ppb)	PM ₁₀ (µg/m ³)	PM _{2.5} (µg/m ³)	O ₃ (ppm)
2	0.45 (0-5.4) 100%	0.01 (0-0.05) 1.2%	26.09 (0.3-94.45) 100%	0.94 (0-36.3) 100%	14 (0-84.5) 25.9%	6.7 (0.2-154.44) 100%	0.03 (0-0.09) 100%
3	0.4 (0-3.6) 100%	0 (0-0.8) 32.8%	17.63 (0-63.38) 100%	1.38 (0-96.5) 100%	14.59 (0-281.24) 100%	7.76 (0-191.67) 100%	0.04 (0-0.1) 100%
4	0.44 (0-8.8) 100%	0.02 (0-3.3) 20.7%	16 (0-69.8) 100%	1.7 (0-134.27) 100%	17.59 (0-183.59) 100%	7.55 (0.4-110.44) 100%	0.04 (0-0.1) 100%
5	0.48 (0-8.8) 100%	0.01 (0-8.58) 95.3%	19.76 (0-94) 100%	1.85 (0-550.06) 100%	19.27 (0-241.38) 100%	8.5 (0.2-162.45) 100%	0.04 (0-0.09) 100%
6	0.44 (0-8.02) 100%	0 (0-0.63) 16.8%	15.17 (0-77.5) 100%	1.1 (0-192.7) 100%	19.27 (0-2173.06) 100%	8.05 (0-130.4) 100%	0.04 (0-0.09) 100%
7	0.38 (0.1-3.46) 99.9%	0.02 (0-1.01) 24.1%	13.45 (1.8-53.1) 94.3%	0.8 (0-68.4) 99.9%	19.94 (1-121.64) 100%	6.7 (0-116.97) 100%	0.04 (0-0.09) 97.6%
8	0.65 (0.18-4.19) 100%	0.01 (0-0.11) 4.6%	35.5 (5-113.07) 99.9%	2.03 (0-39) 100%	25.17 (2-114.75) 99.8%	6.26 (1.05-88.59) 98.8%	0.05 (0.01-0.09) 100%
9	0.57 (0.1-2.87) 100%	0.02 (0-4.49) 76.2%	24.84 (2.42-67.67) 100%	0.93 (0-32.33) 100%	27.06 (1-218.87) 100%	8.97 (0-168.69) 100%	0.04 (0.01-0.1) 100%
10	0.43 (0.11-2.68) 96.4%	0.02 (0-0.17) 1.2%	25.4 (6-72.75) 81.5%	0.9 (0-30.3) 84.8%	10 (1-104) 27.9%	5.6 (0-395) 100%	0.03 (0-0.08) 98.6%

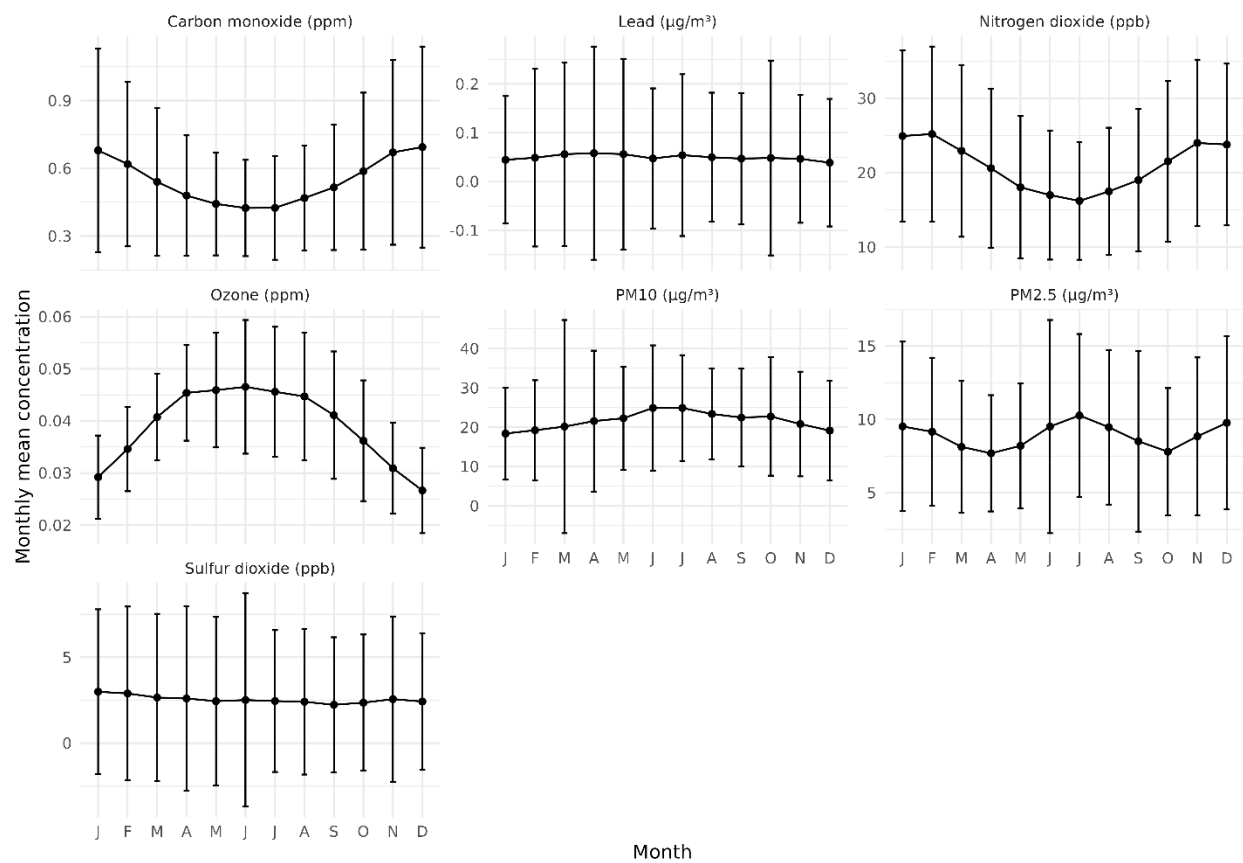
Supplemental Table S3: Distribution of the average yearly pollutant concentrations by EPA region. Values are reported as median (range). The third row in each cell presents the percentage of study years with available data for that pollutant in the given EPA region.

EPA Region	CO (ppm)	PB ($\mu\text{g}/\text{m}^3$)	NO ₂ (ppb)	SO ₂ (ppb)	PM ₁₀ ($\mu\text{g}/\text{m}^3$)	PM _{2.5} ($\mu\text{g}/\text{m}^3$)	O ₃ (ppm)
2	0.51 (0.46-0.59) 100%	0.01 (0.01-0.01) 14.3%	26.29 (23.39-31.55) 100%	0.97 (0.75-5.02) 100%	14.81 (12.45-29.67) 100%	7.63 (6.67-10.09) 100%	0.036 (0.035-0.036) 100%
3	0.45 (0.39-0.49) 100%	0.01 (0.01-0.02) 100%	18.37 (16.53-23.18) 100%	1.67 (1.11-5.08) 100%	15.95 (13.83-17.92) 100%	8.53 (6.8-11.08) 100%	0.039 (0.036-0.04) 100%
4	0.49 (0.42-0.89) 100%	0.03 (0.02-0.29) 100%	17.18 (15.99-19.17) 100%	2.19 (1.93-6.32) 100%	18.72 (17.29-21.14) 100%	8.55 (7.25-12.08) 100%	0.038 (0.036-0.041) 100%
5	0.56 (0.45-0.6) 100%	0.04 (0.01-0.23) 100%	20.97 (19.05-23.32) 100%	2.1 (1.34-10.04) 100%	21.5 (19.59-23.74) 100%	9.22 (7.81-11.82) 100%	0.037 (0.036-0.04) 100%
6	0.53 (0.4-0.59) 100%	0.01 (0-0.06) 100%	16.78 (15.64-18.97) 100%	2.4 (1.28-7.66) 100%	23.88 (20.83-26.04) 100%	8.84 (8.26-10.59) 100%	0.039 (0.037-0.042) 100%
7	0.42 (0.36-0.52) 100%	0.04 (0.03-0.09) 100%	14.88 (11.76-18.25) 100%	2.61 (1.36-4.08) 100%	22.06 (17-33.25) 100%	7.85 (5.98-9.46) 100%	0.038 (0.034-0.043) 100%
8	0.77 (0.68-0.86) 100%	0.02 (0.01-0.02) 28.6%	38.16 (28.89-41.75) 100%	2.29 (1.31-7.86) 100%	28.1 (21.98-35.98) 100%	7.73 (6.16-8.51) 100%	0.046 (0.044-0.049) 100%
9	0.68 (0.59-0.79) 100%	0.02 (0.01-0.28) 100%	25.65 (22.65-29.51) 100%	1.31 (0.67-1.89) 100%	28.5 (23.69-30.64) 100%	9.77 (8.93-11.7) 100%	0.044 (0.042-0.048) 100%
10	0.45 (0.32-0.68) 100%	0.03 (0.03-0.04) 14.3%	25.36 (22.92-33.17) 85.7%	1.22 (0.46-3.74) 100%	10.39 (7.47-13.25) 85.7%	7.59 (6.11-9.43) 100%	0.029 (0.026-0.031) 100%

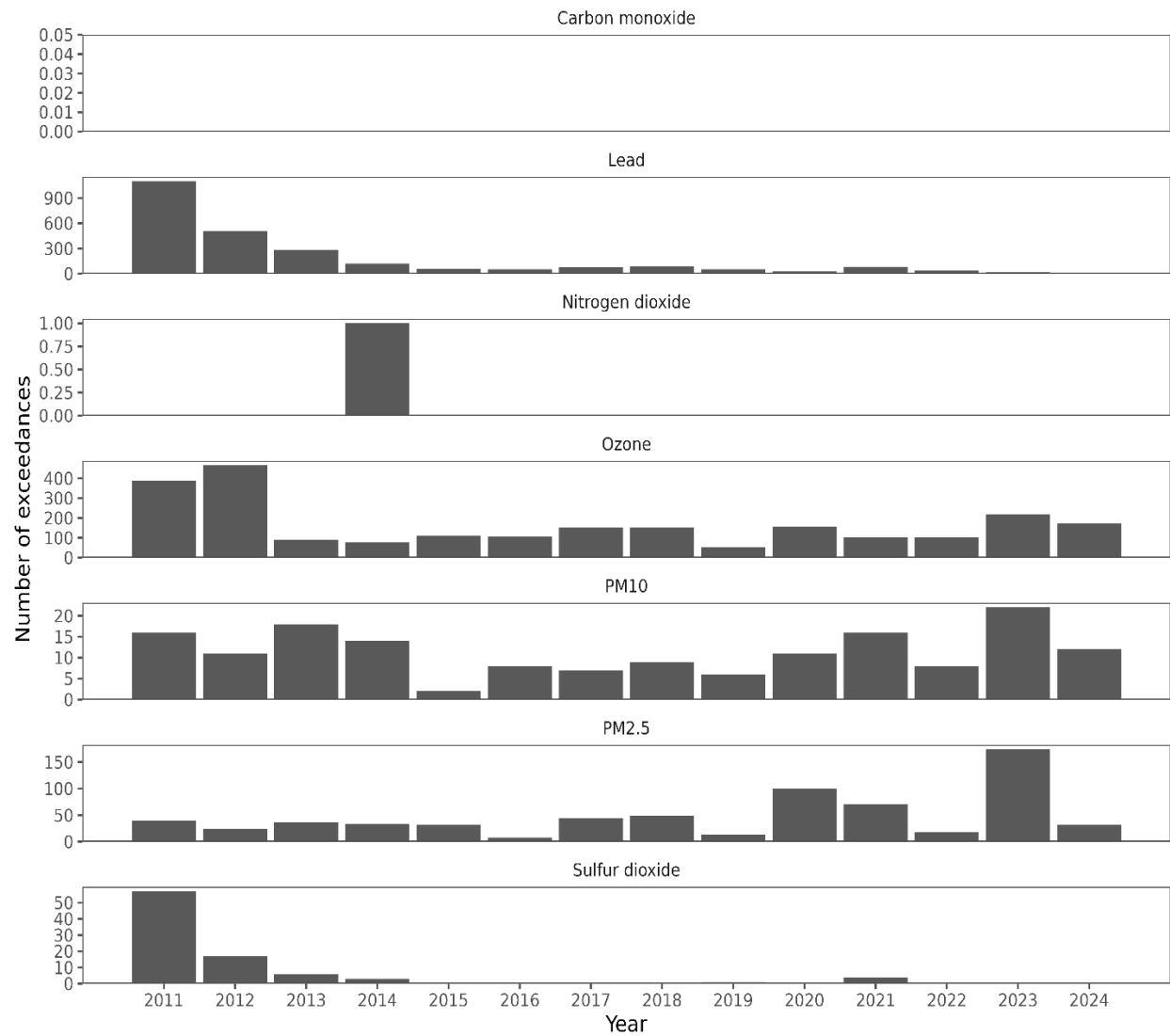
Supplemental Table S4: Number of exceedances above the daily National Ambient Air Quality Standards (NAAQS) for each pollutant measured at racetracks across the study period. Daily standards correspond to 1-hour (NO₂, SO₂), 8-hour (O₃, CO), 24-hour (PM_{2.5}, PM₁₀), and rolling 3-month (Pb) averaging times.

EPA Region States	Racetrack	PM _{2.5} (n)	PM ₁₀ (n)	O ₃ (n)	NO ₂ (n)	SO ₂ (n)	Pb (n)
2 NJ, NY	Aqueduct Racetrack	9		45			
	Belmont Park	9		46			
	Finger Lakes	4		24			
	Monmouth Park	7		43			
	Saratoga Race Course	9		9			
3 DE, DC, MD, PA, VA, WV	Colonial Downs	5		19			
	Delaware Park	10	2	48			
	Hollywood Casino At Charles Town Races	12	1	13			
	Laurel Park	4	1	45			
	Mountaineer Casino Racetrack & Resort	5	2	17			4
	Parx Racing	12	2	52			
	Penn National Race Course	28		28		1	32
	Pimlico Race Course	4	1	50			
4 AL, FL, GA, KY, MS, NC, SC, TN	Presque Isle Downs	6		33			
	Churchill Downs	3		42			
	Ellis Park	4		35			
	Gulfstream Park	1		3			
	Keeneland	3		23			38
	Kentucky Downs	4		22		1	
	Tampa Bay Downs	2		6		1	77
5 IL, IN, MI, MN, OH, WI	Turfway Park	6	1	57		4	
	Belterra Park Gaming & Entertainment Center	6	1	56		3	
	Canterbury Park	17		13		1	7
	Fairmount Park	9		69		3	942
	Hawthorne Race Course	15		53			26
	Hollywood Gaming at Mahoning Valley Racecourse	5	1	19		3	84
	Hoosier Park	16	1	24		5	39
	Horseshoe Indianapolis	17	1	17		1	
6 AR, LA, NM, OK, TX	Thistledown	8	1	26		1	2
	Delta Downs Racetrack	3		15		1	
	Evangeline Downs	2		13			
	Fair Grounds Race Course & Slots	2		16		63	19
	Lone Star Park	6		87			39
	Louisiana Downs	5	1	36			
	Oaklawn Park			2			
	Remington Park	3	1	75			
	Retama Park	10		71			
	Sam Houston Race Park	6	3	61			
	Sunland Park	29	112	29			
7 IA, KS, MO, NE	Will Rogers Downs	4	1	56			
	Zia Park	8		36			
	Fonner Park	5					
8 CO, MT, ND, SD, UT, WY	Horsemen's Park	13		26			104
	Prairie Meadows	10		9			
9 AZ, CA, HI, NV	Arapahoe Park	18		131	1		
	Arizona Downs			28			
	Barretts Race Meet at Fairplex	50	3	317			260
	Betfair Hollywood Park	22	1	69			259
	Del Mar	13		10			6
	Golden Gate Fields	37	1	1			50
	Los Alamitos Race Course	48	1	103			259
	Rillito Park Race Track		5	15			
	Santa Anita Park	52	1	127			259
10 AK, ID, OR, WA	Turf Paradise	22	15	71			
	Emerald Downs	33		2			1
	Grants Pass Downs	34					
	TOTAL	675	160	2343	1	88	2507

Supplemental Figure S1: Monthly mean concentrations of each pollutant across the study period. Points represent monthly mean concentrations and vertical lines indicate the standard deviation.



Supplemental Figure S2: Annual counts of exceedances by pollutant across the study period. Bars represent the total number of exceedances observed in each year for each pollutant.



APPENDIX 2

Sensitivity Analysis

Methods

We conducted sensitivity analyses to test whether our findings were robust to different model assumptions. First, to see whether the associations between exposure and winning speed changed depending on how long we allowed the exposure effects to accumulate, we varied the number of lag days by applying the model with 14- and 28-day lags, in addition to the original 21-day lag.³⁶ In our primary analysis, we compared race performance when horses were exposed to air pollution levels at the 80th percentile (higher exposure) versus the 20th percentile (lower exposure). To test the robustness of our findings, we performed alternative comparisons, which included the 85th vs 15th percentile and the 90th vs 10th percentile exposures. Track surface was determined based on the reported track condition. Because the condition “good” can apply to both dirt and turf surfaces, and no additional information was available to distinguish between them, “good” was classified as “dirt” in the primary analysis, as the majority of thoroughbred races in California occur on dirt tracks. Finally, to assess the impact of classifying all “good” track conditions as “dirt”, a sensitivity analysis was conducted excluding all races with a “good” track condition.

Results

We started our sensitivity analyses by varying the number of lag days by applying the model with 14- and 28-day lags to assess if the associations between exposure and winning speed changed depending on how long we allowed the exposure effects to accumulate. Across all lag periods, horses exposed to higher levels of pollutants (the 80th percentile) compared to lower

pollutant levels (the 20th percentile) had, on average, slower winning speeds, regardless of how long the lag period is (Figure S1). Additionally, there was minor variability across the cumulative effect with significant overlap across the three lag periods (Figure S2).

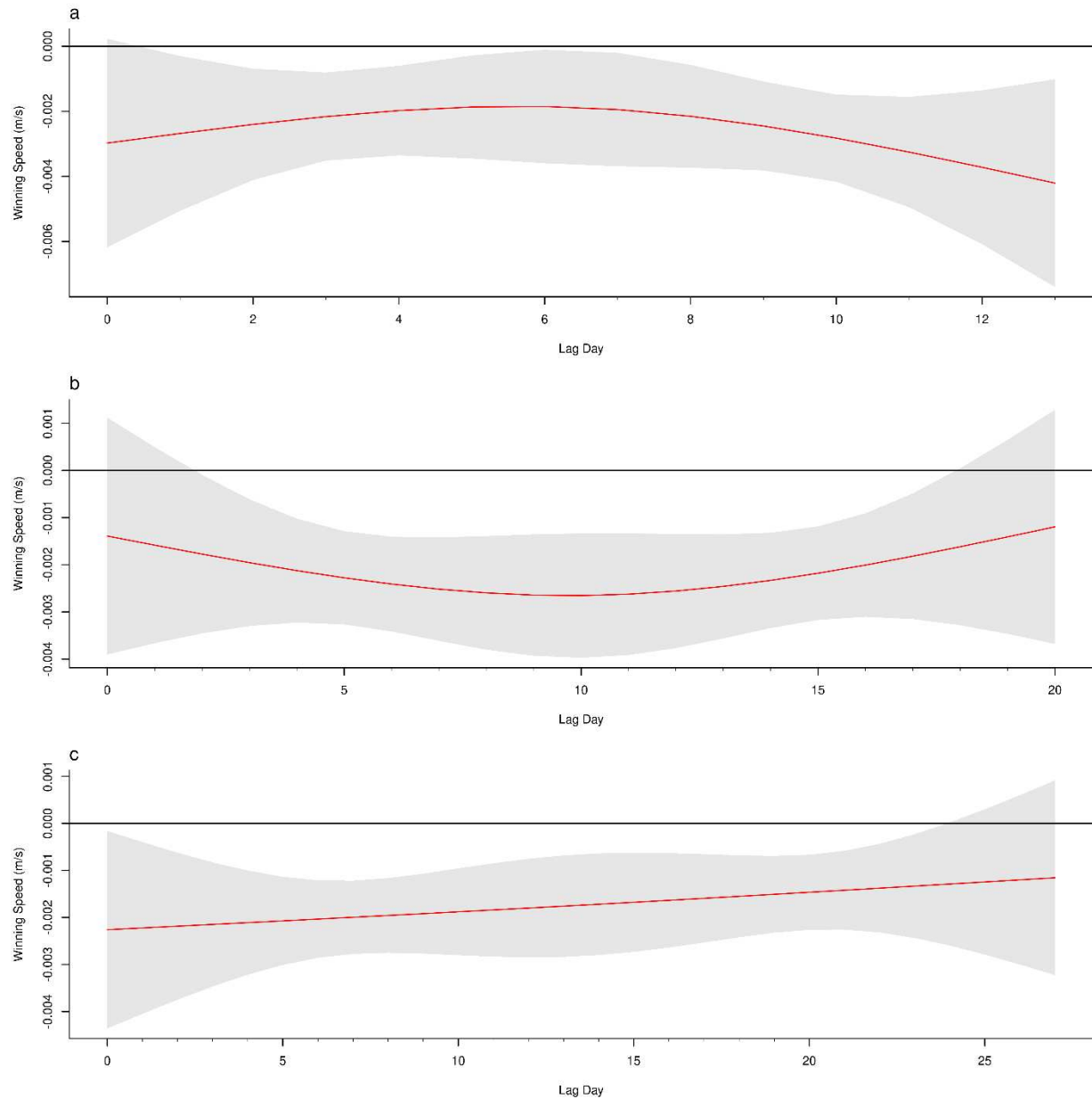


Figure S1: Model outputs for the sensitivity analysis when varying lag times in the 14- and 28- day period before a race. The lag response relationship (red line) with 95% confidence intervals (grey) for 14-day lag (a), 21-day lag (original) (b), and 28-day lag (c), when comparing the 80th percentile exposure (i.e., higher exposure) to the 20th percentile (i.e., lower exposure).

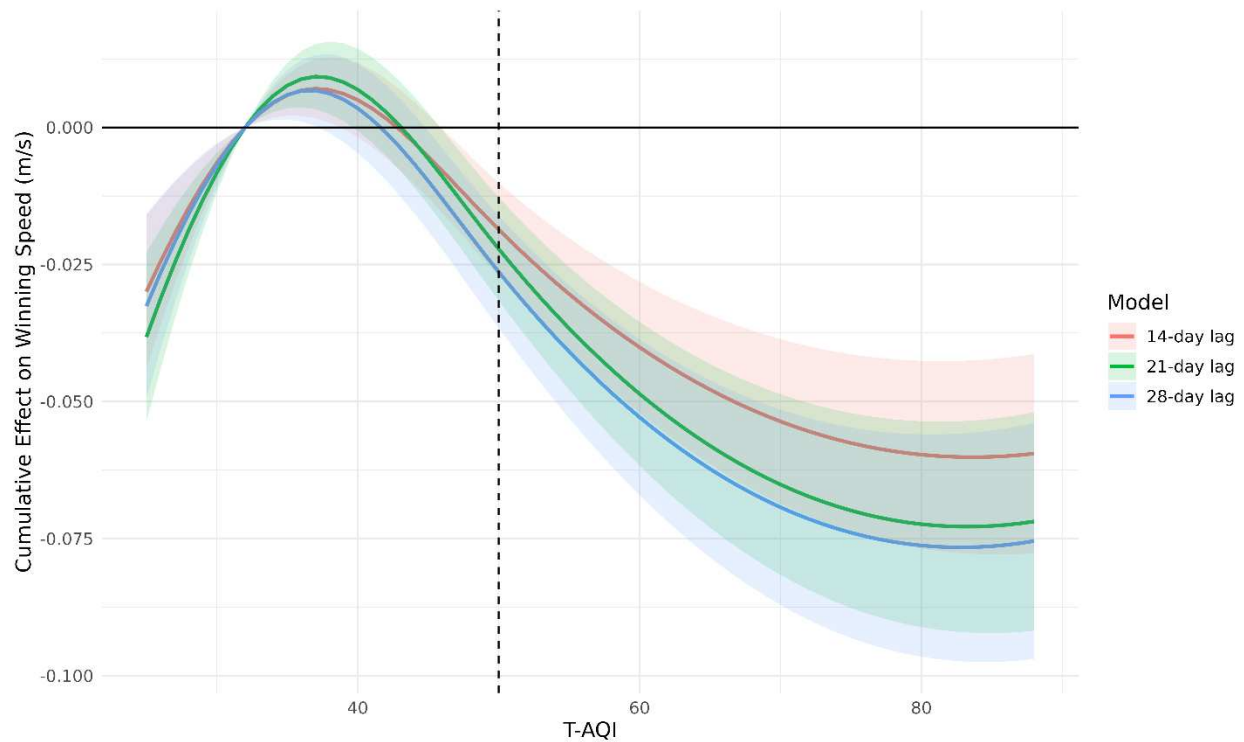


Figure S2 Cumulative effect curve for T-AQI when varying the lag-response length from the original model of a 21-day exposure period (green line with 95% confidence interval in green shade) to a 14-day exposure period (red line with 95% confidence interval in red shade) and a 28-day exposure period (blue line with 95% confidence interval in blue shade). The dashed line represents the AQI of 50, which is when the air quality transitions from “good” to “moderate”.

Our primary analysis compared the 80th percentile of exposure, representing higher pollutant exposure, with the 20th percentile (lower exposure) to estimate the change in winning speed. Alternative comparisons of the 85th versus the 15th percentile of exposure and the 90th versus the 10th percentile of exposure yielded no statistically significant differences amongst comparisons, supporting the robustness of our findings (Figure S3). Finally, there were 492 races classified with the track condition “good.” Excluding these observations did not meaningfully alter the estimated lag-response relationships or the overall exposure-response form (Figure S4).

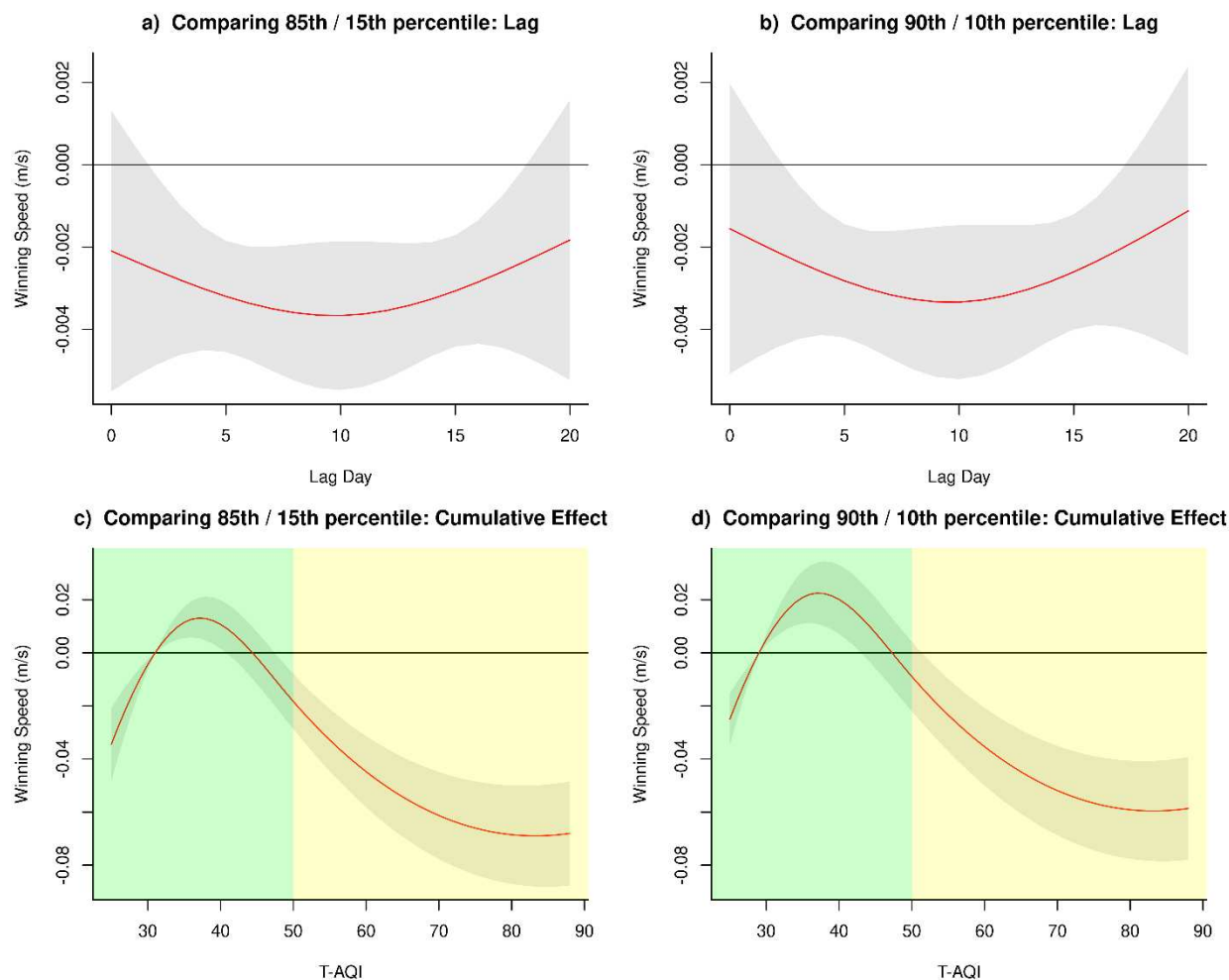


Figure S3: Model outputs for the sensitivity analysis when performing the alternative comparisons of the 85th percentile of exposure to the 15th percentile of exposure (a, c), and the 90th percentile of exposure compared to the 10th percentile of exposure (b, d). Panels (a–b) show lag-specific effects; panels (c–d) show cumulative effects across 21 days. Results were consistent across comparisons.

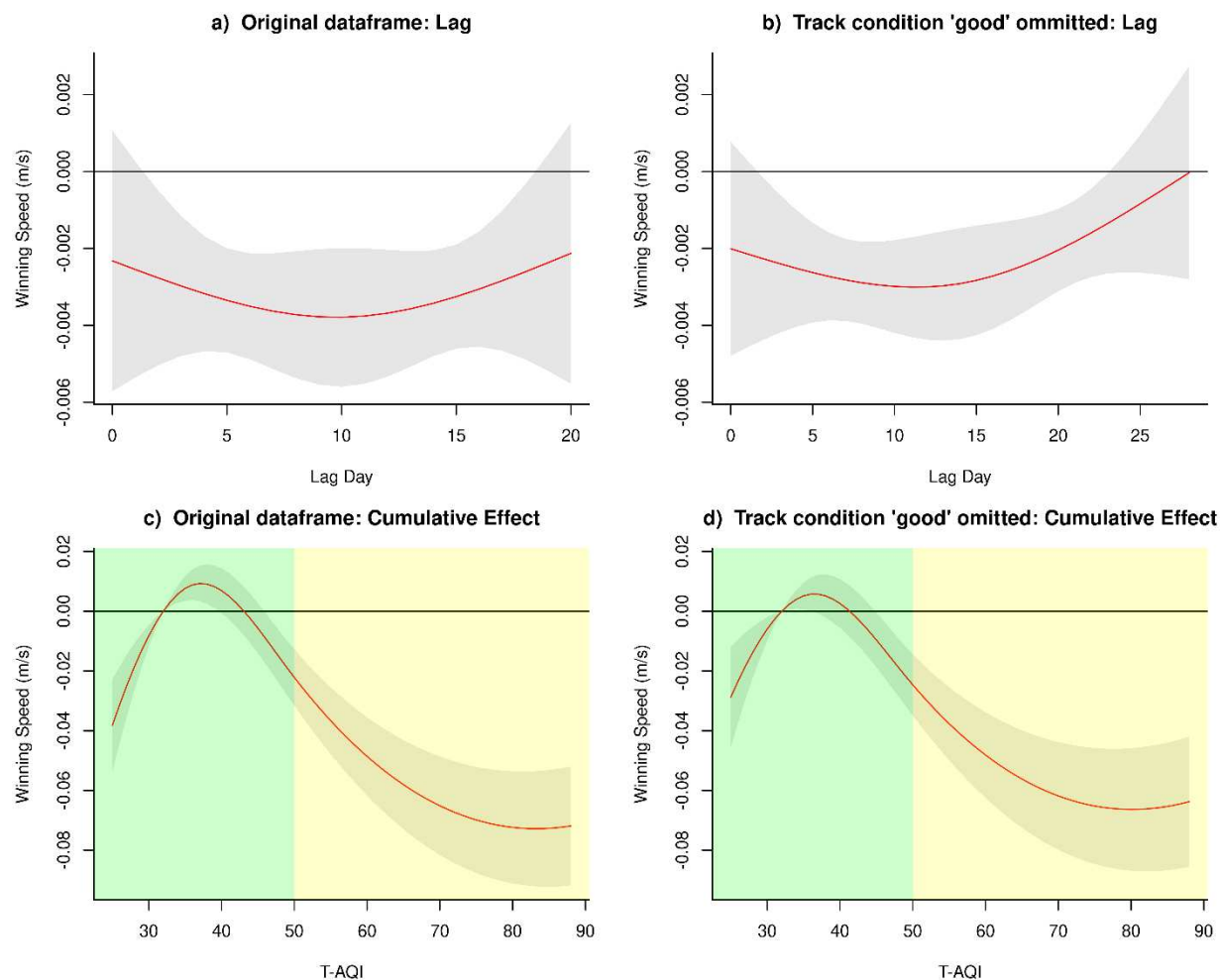


Figure S4: Model outputs for the sensitivity analysis excluding races with track condition classified as “good.” Panels (a, c) show results from the original dataset; panels (b, d) show results after excluding these races. Panels (a–b) display lag-specific effects, while panels (c–d) display cumulative effects across 21 days. Results were consistent across analyses.

APPENDIX 3

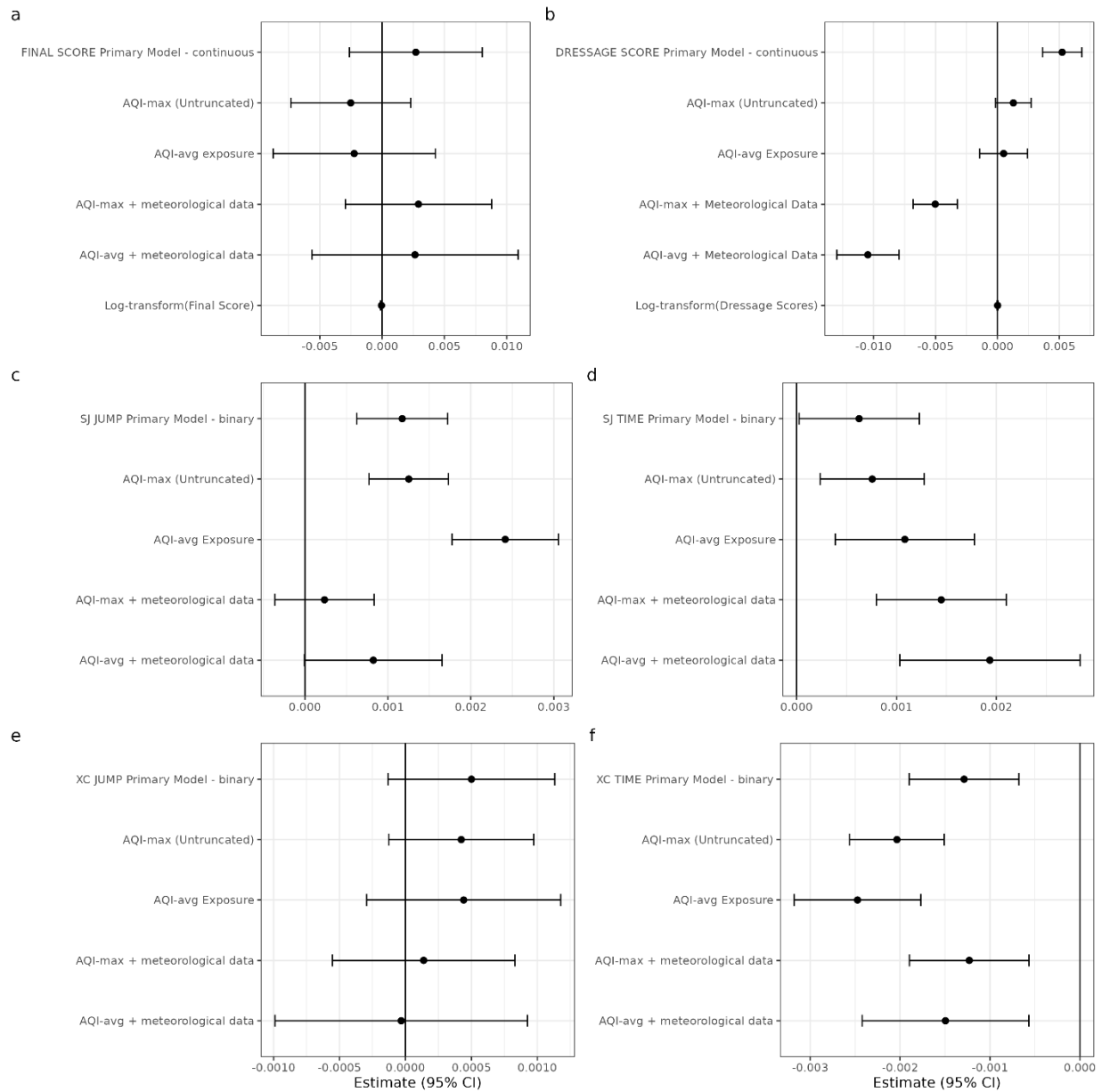


Figure S1: Estimated associations between air quality and performance outcomes for primary and sensitivity analyses across all eventing phases. Points represent the model estimates for a 1-unit increase in index value, with horizontal bars denoting the 95% confidence intervals. Linear mixed-effects models were fit for continuous outcomes using the final score (a) and dressage score (b) and generalized logistic mixed-effects models were fit for binary outcomes for SJ jump penalties (c), SJ time penalties (d), XC jump penalties (e), and XC time penalties (f). The vertical line at zero indicates no association.

APPENDIX 4

Supplementary Table 1: Panelists were asked to provide the top five most significant health impacts (i.e., conditions, illnesses, injuries) horses exposed to air pollution may experience. Conditions are reported here organized by body system. The number of respondents who indicated each reported impact is included in parenthesis.

Respiratory System
Lower airway inflammation/compromised function, e.g., asthma, IAD, RAO, heaves (n = 14)
Upper airway inflammation, e.g., rhinitis, pharyngitis, laryngitis, tracheitis (n = 9)
EIPH (n = 5)
Respiratory infection/illness (n = 3)
Bronchospasm (n = 1)
Cough (n = 1)
Increased mucus production (n = 1)
Pleuropneumonia (n = 1)
Cardiovascular System
Cardiovascular disease (n = 4)
Cardiac arrhythmia (n = 2)
Ocular System
Conjunctivitis (n = 2)
Other/unspecified ocular inflammation and irritation (n = 2)
Unspecified ocular disease and disorders (n = 2)
Performance
Poor performance (n = 2)
Exercise intolerance (n = 2)
Other
Other systemic illness (unspecified) (n = 3)
Immunologic challenge (n = 2)
Head shaking due to exacerbated response of the trigeminal nerve firing secondary to neuritis and upper airway inflammation (n = 1)
Integument via contact (n = 1)

Supplementary Table 2: Panelists' level of concern for equine health risks associated with chronic and acute exposure across increasing AQI categories, reported as the number (percentage) of respondents.

Exposure	Not at all concerned	Slightly concerned	Moderately concerned	Very concerned	Extremely concerned	Please provide comments (if any)
PROLONGED or CHRONIC EXPOSURE as defined by exposure that is more than 24 hours						
Exposure to very low (AQI = green) levels of air pollution	10 (71.4%)	3 (21.4%)	0	1 (7.1%)	0	Median = <i>Not at all concerned</i> Mode = <i>Not at all concerned</i>
Exposure to low to moderate (AQI = yellow) levels of air pollution	4 (28.6%)	8 (57.1%)	1 (7.1%)	0	1 (7.1%)	Median = <i>Slightly concerned</i> Mode = <i>Slightly concerned</i>
Exposure to moderate to high (AQI = orange) levels of air pollution	0	3 (21.4%)	7 (50%)	3 (21.4%)	1 (7.1%)	Median = <i>Moderately concerned</i> Mode = <i>Moderately concerned</i>
Exposure to unhealthy (AQI = red) levels of air pollution	0	0	4 (28.6%)	7 (50%)	3 (21.4%)	Median = <i>Very concerned</i> Mode = <i>Very concerned</i>
Exposure to very unhealthy (AQI = Purple) levels of air pollution	0	0	1 (7.1%)	8 (57.1%)	5 (35.7%)	Median = <i>Very concerned</i> Mode = <i>Very concerned</i>
Exposure to hazardous (AQI = Maroon) levels of air pollution	0	0	0	3 (21.4%)	11 (78.6%)	Median = <i>Extremely concerned</i> Mode = <i>Extremely concerned</i>
ACUTE EXPOSURE as defined by an exposure that lasts 24 hours or less						
Exposure to very low (AQI = green) levels of air pollution	12 (85.7%)	1 (7.1%)	1 (7.1%)	0	0	Median = <i>Not at all concerned</i> Mode = <i>Not at all concerned</i>
Exposure to low to moderate (AQI = yellow) levels of air pollution	8 (57.1%)	5 (35.7%)	1 (7.1%)	0	0	Median = <i>Not at all concerned</i> Mode = <i>Not at all concerned</i>
Exposure to moderate to high (AQI = orange) levels of air pollution	2 (14.3%)	5 (35.7%)	4 (28.6%)	3 (21.4%)	0	Median = <i>Slightly concerned</i> Mode = <i>Slightly concerned</i>
Exposure to unhealthy (AQI = red) levels of air pollution	0	4 (28.6%)	2 (14.3%)	7 (50%)	1 (7.1%)	Median = <i>Very concerned</i> Mode = <i>Very concerned</i>
Exposure to very unhealthy (AQI = Purple) levels of air pollution	0	2 (14.3%)	2 (14.3%)	4 (28.6%)	6 (42.9%)	Median = <i>Very concerned</i> Mode = <i>Extremely concerned</i>
Exposure to hazardous (AQI = Maroon) levels of air pollution	0	0	2 (14.3%)	4 (28.6%)	8 (57.1%)	Median = <i>Extremely concerned</i> Mode = <i>Extremely concerned</i>

Supplementary Table 3: Panel level of agreement with PM_{2.5} and ozone cut points corresponding to each AQI category, assessed using a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). Median response, interquartile range (IQR), and response rates are provided in the lightly shaded columns.

Air Quality Index						
AQI Category and Color	Index Value	Associated PM _{2.5} levels	<u>Your level of agreement with the PM_{2.5} cut points?</u> <u>If not, what would be your suggested cut points?</u>	Associated Ozone levels		<u>Your level of agreement with the ozone cut points?</u> <u>If not, what would be your suggested cut points?</u>
				8-hour average	1-hour average	
Good / Green	0 to 50	0 – 9 ug/m ³	Median: 4 IQR: 3 – 4 Resp Rate: 73.3%	0 – 54 ppb	Na	Median: 3.5 IQR: 3 – 4.75 Resp Rate: 60%
Moderate / Yellow	51 to 100	9.1 – 35.4 ug/m ³	Median: 3 IQR: 3-4 Resp Rate: 73.3%	55 – 70 ppb	Na	Median: 3 IQR: 3 – 4.75 Resp Rate: 60%
Unhealthy for sensitive groups / Orange	101 to 150	35.5 – 55.4 ug/m ³	Median: 4 IQR: 3-4 Resp Rate: 73.3%	71 – 85 ppb	125 – 164 ppb	Median: 3 IQR: 3 – 4.75 Resp Rate: 60%
Unhealthy / Red	151 to 200	55.5 – 125.4 ug/m ³	Median: 3 IQR: 3-5 Resp Rate: 73.3%	86 – 105 ppb	165 – 204 ppb	Median: 3 IQR: 3 – 4.5 Resp Rate: 66.7%
Very unhealthy / Purple	201 to 300	125.5 – 225.4 ug/m ³	Median: 3 IQR: 3-5 Resp Rate: 73.3%	106 – 200 ppb	205 – 404 ppb	Median: 3 IQR: 3 – 4.5 Resp Rate: 66.7%
Hazardous / Maroon	301 and higher	225.5+ ug/m ³	Median: 3 IQR: 3-5 Resp Rate: 73.3%	na	405 – 604 ppb	Median: 3 IQR: 3 – 5 Resp Rate: 66.7%

Round 1 Questionnaire begins next page

My name is Danielle Scott and I am a researcher from Colorado State University in the Clinical Sciences department. I am the Principal Investigator and I want to thank you for your participation in ATHLETE: Air and Temperature for Health and Longevity in the Equine Training Environment, serving as part of my PhD work generously funded by the Morris Animal Foundation. This project's objective aims to develop recommendations for the exercise and management of horses during periods of poor ambient air quality, addressing three topics: (1) exercise and training practices; (2) the physical environment; and (3) medical management.

The Delphi method engages experts to arrive at the most reliable consensus. Through a series of questionnaires, we will systematically elicit and synthesize knowledge and opinions from a group of experts, i.e., yourselves. Results from the first questionnaire will be aggregated and summarized into group answers, which will then be redistributed to you to provide the opportunity for reconsideration, clarification, and revision while ensuring accurate representation of expert judgments. Subsequent questionnaires are structured to allow for the expansion and confirmation of results from the previous iteration. All responses and re-distributions will remain anonymous. We anticipate two to three rounds to reach a consensus but recognize that additional rounds may be required. All participants who complete the project will receive an honorarium.

We are fortunate to have an international representation of leading health experts in the equine field and the countries represented have respective tools for measuring air quality, although there are variations in how these indices are represented. For this reason, we are going to reference the following Air Quality Index (AQI) included below. We have included the respective PM_{2.5} and ground-level ozone levels associated with each category of AQI for your reference throughout the survey, as these pollutants are the focus of this study. *Please note on February 7, 2024, the US Environmental Protection Agency announced a final rule to strengthen the PM_{2.5} standards. The chart reflects the updated PM_{2.5} levels that will be implemented as a result of this ruling.*

Air Quality Index				
AQI Category and Color	Index Value	Associated PM _{2.5} levels	Associated Ozone levels	
			8-hour average	1-hour average
Good / Green	0 to 50	0 – 9 ug/m ³	0 – 54 ppb	Na
Moderate / Yellow	51 to 100	9.1 – 35.4 ug/m ³	55 – 70 ppb	Na
Unhealthy for sensitive groups / Orange	101 to 150	35.5 – 55.4 ug/m ³	71 – 85 ppb	125 – 164 ppb
Unhealthy / Red	151 to 200	55.5 – 125.4 ug/m ³	86 – 105 ppb	165 – 204 ppb
Very unhealthy / Purple	201 to 300	125.5 – 225.4 ug/m ³	106 – 200 ppb	205 – 404 ppb
Hazardous / Maroon	301 and higher	225.5 + ug/m ³	na	405 – 604 ppb

We would like you to fill out the following questionnaire. Participation can be completed at your convenience and returned to the PI by **April 1, 2024**. Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participation at any time without penalty. We will be collecting your name and your email address. When we report and share the data with others, we will combine the data from all participants. We will keep your data confidential; your name and your email will be kept separately on the PI's password-protected computer, only accessible to the PI. To indicate your consent to participate in this research and continue the survey, please click the box for "I consent": ☐ I consent ☐ I do not consent

SECTION 1 – IMPACTS

In this section, we are gauging how air pollution may impact horse health. We are looking for specific body systems that may be affected, as well as what health conditions may arise, and what existing health conditions may be exacerbated by exposure to air pollution. Please include this information where appropriate in open-ended questions. The scales are provided to objectively capture responses, but the greatest value in arriving at a consensus lies in your written responses.

Question 1: The goal of this series of questions is to understand how important it is to consider air pollution with regard to overall equine health.

1a:

On the scale below, please indicate how important it is to consider exposure to air pollution when considering *equine health in general* (highlight your selection in green).

Not at all important									Extremely Important	
1	2	3	4	5	6	7	8	9		

Please provide comments regarding your response to this question:

1b:

Please rate your level of agreement with the following statement: The *signalment* of a horse plays a key role in considering the health risks of exposure to air pollution (highlight your selection in green).

Completely disagree			Neutral			Completely agree		
1	2	3	4	5	6	7	8	9

Please provide comments regarding your response to this question. Are age/sex/breed factors to consider?

1c:

Please rate your level of agreement with the following statement: *Healthy* horses exposed to air pollution may experience adverse health effects (highlight your selection in green).

Completely disagree			Neutral			Completely agree		
1	2	3	4	5	6	7	8	9

Please provide comments regarding your response to this question. Specifics to include are which body systems may be impacted and/or disease processes initiated. Are there certain environmental/management risk factors to consider? Are there specific pollutants to consider?

1d:

Please rate your level of agreement with the following statement: Horses with underlying health conditions exposed to air pollution may experience adverse health effects (highlight your selection in green).

Completely disagree		Neutral		Completely agree				
1	2	3	4	5	6	7	8	9

Please provide comments regarding your response to this question. Specifics to include are what existing pathologies/underlying conditions may be exacerbated:

Question 2:

In your opinion, what may be the top five most significant health impacts (i.e., conditions, illnesses, injuries) horses exposed to air pollution may experience?

- 1.
- 2.
- 3.
- 4.
- 5.

Please briefly justify your responses.

Question 3: The goal of this series of questions is to assess the temporal effects of exposure to air pollution.

3a:

Please rate your level of agreement with the following statement: Horses exposed to elevated levels of air pollution may experience negative short-term health impacts (highlight your selection in green).

Completely disagree		Neutral		Completely agree				
1	2	3	4	5	6	7	8	9

Please provide comments regarding your response to this question. What, if any, short-term health impacts may occur?

3b:

Please rate your level of agreement with the following statement: Horses exposed to elevated levels of air pollution may experience negative long-term health impacts (highlight your selection in green).

Completely disagree Neutral Completely agree
1 2 3 4 5 6 7 8 9

Please provide comments regarding your response to this question. What, if any, long-term health impacts may occur?

3c:

The following table provides different levels of exposure.

- Please refer to the AQI chart above for exposure categories.
- Use the following definitions:
 - An acute exposure is one that lasts 24 hours or less
 - Prolonged/chronic exposure is more than 24 hours
- Please rate your level of concern by placing an “X” in the appropriate box and provide comments in the space provided as to why you chose your level of concern.

Exposure	Not at all concerned	Slightly concerned	Moderately concerned	Very concerned	Extremely concerned	Please provide comments (if any)
PROLONGED or CHRONIC EXPOSURE as defined by exposure that is more than 24 hours						
Exposure to very low (AQI = green) levels of air pollution						
Exposure to low to moderate (AQI = yellow) levels of air pollution						
Exposure to moderate to high (AQI = orange) levels of air pollution						
Exposure to unhealthy (AQI = red) levels of air pollution						
Exposure to very unhealthy (AQI = Purple) levels of air pollution						
Exposure to hazardous (AQI = Maroon) levels of air pollution						
ACUTE EXPOSURE as defined by an exposure that lasts 24 hours or less						
Exposure to very low (AQI = green) levels of air pollution						
Exposure to low to moderate (AQI = yellow) levels of air pollution						
Exposure to moderate to high (AQI = orange) levels of air pollution						
Exposure to unhealthy (AQI = red) levels of air pollution						
Exposure to very unhealthy (AQI = Purple) levels of air pollution						
Exposure to hazardous (AQI = Maroon) levels of air pollution						

3d:

Question 3c provided definitions for acute and chronic exposure adapted from the US Environmental Protection Agency's glossary of definitions for exposures based on the environment and community-based air pollution projects.

- An acute exposure is one that lasts 24 hours or less
- Prolonged/chronic exposure is more than 24 hours

Do you agree with these definitions for exposure to air pollution in horses? Yes____ No____

If no, please justify your answer and provide an improved definition:

SECTION 2 – CUT POINTS

This section explores pollutant cut points and when you would recommend interventions. In this round, we are exploring available human health resources and apply appropriate horse-focused messaging. Additionally, we seek to gauge if current cut points are adequate to capture health risks to horses. This section will not focus on recommended interventions or management strategies, which will be addressed in the following section.

Question 4:

Below is the Air Quality Index that the United States uses to advise public health on air quality and risk. As this is the tool publicly available, a goal of this project is to adapt current recommendations to be applicable to guiding horse owners and trainers.

4a: In the space provided, please translate the human public health interpretation to be appropriate/applicable messaging for managing horses.

Air Quality Index			
AQI Category and Color	Index Value	Description of Air Quality HUMAN-CENTERED MESSAGING	Description of Air Quality <u>HORSE-CENTERED MESSAGING</u>
Good / Green	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk	
Moderate / Yellow	51 to 100	Air quality is acceptable. However, there may be risk for some people, particularly those who are unusually sensitive to air pollution	
Unhealthy for sensitive groups / Orange	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected.	
Unhealthy / Red	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects	
Very unhealthy / Purple	201 to 300	Health alert: The risk of health effects is increased for everyone.	
Hazardous / Maroon	301 and higher	Health warning of emergency conditions; everyone is more likely to be affected	

4b: The chart below shows the same AQI with the associated cut points for PM_{2.5} and the 8-hour and 1-hour average for ozone levels. In the space provided, please indicate by filling in the two empty columns your level of agreement from 1 to 5 (**1 = Strongly disagree; 2 = disagree; 3 = Neither agree nor disagree; 4 = Agree; 5 = Strongly agree**). If you indicate *Strongly disagree* or *disagree*, please indicate what you believe to be better cut-point values.

Air Quality Index						
AQI Category and Color	Index Value	Associated PM _{2.5} levels	<u>Your level of agreement with the PM_{2.5} cut points?</u>	Associated Ozone levels		<u>Your level of agreement with the ozone cut points?</u>
			<u>If not, what would be your suggested cut points?</u>	8-hour average	1-hour average	<u>If not, what would be your suggested cut points?</u>
Good / Green	0 to 50	0 – 9 ug/m ³		0 – 54 ppb	Na	
Moderate / Yellow	51 to 100	9.1 – 35.4 ug/m ³		55 – 70 ppb	Na	
Unhealthy for sensitive groups / Orange	101 to 150	35.5 – 55.4 ug/m ³		71 – 85 ppb	125 – 164 ppb	
Unhealthy / Red	151 to 200	55.5 – 125.4 ug/m ³		86 – 105 ppb	165 – 204 ppb	
Very unhealthy / Purple	201 to 300	125.5 – 225.4 ug/m ³		106 – 200 ppb	205 – 404 ppb	
Hazardous / Maroon	301 and higher	225.5+ ug/m ³		na	405 – 604 ppb	

Question 5 – COMPETITION

The United States Equestrian Federation (USEF) recommends event organizers consider canceling or suspending competitions if the Air Quality Index (AQI) reaches 151 or above. Please rate your level of agreement that this is an appropriate cut-point for canceling or suspending competitions (highlight your selection in green).

Completely disagree Neutral Completely agree
 1 2 3 4 5 6 7 8 9

Please provide information for your chosen level of agreement. If you indicated a lower level of agreement, at which AQI would you recommend postponing a competition:

Question 6 – TRAINING

Please rate your level of agreement that an AQI of 151 or above is an appropriate cut-point for canceling or suspending training sessions for a horse in the pre-competition training period (highlight your selection in green).

Completely disagree		Neutral		Completely agree				
1	2	3	4	5	6	7	8	9

Please provide information for your chosen level of agreement. If you indicated a lower level of agreement, at which AQI would you recommend postponing a training session:

SECTION 3: IDENTIFYING CUT POINTS (cont'd) WITH INTERVENTIONS

This section explores more specifically what interventions should take place to minimize risk to horses during air pollution events. To increase specificity, this will focus on specific pollutant cut points regarding ozone and PM_{2.5}, as well as recommendations for intervention at these cut points.

Question 7: This question will ask about specific cut-offs for PM_{2.5} and the associated recommendations for the cutoff.

In the chart below, please fill in the PM_{2.5} level you believe should be the cut-off in the provided scenarios. In the comment box, please provide additional comments answering the specific questions provided, including any additional information you believe may be relevant.

Scenario	PM _{2.5} cut off (ug/m ³)	Provide comments here:
When horses should <u>avoid competition</u> in ambient air		<i>Specifically, what actions should be taken? What additional considerations may be important?</i>
When horses should <u>avoid exercising/training</u> in ambient air		<i>Specifically, what actions should be taken? What recommendations do you have for training if air quality is above your indicated answer?</i>
When horses should <u>avoid exposure</u> to ambient air		<i>At what level would you make recommendations and what recommendations would you make regarding husbandry, housing, etc.?</i>

Question 8: This question is similar to the above but now asks specifically about ozone. Please fill in the ozone level you believe should be the cut-off in the provided scenarios. In the comment box, please provide additional comments answering the specific questions provided, including any additional information you believe may be relevant.

Scenario	Ozone cut off (ppb)	Provide comments here:
When horses should <u>avoid competition</u> in ambient air		<i>Specifically, what actions should be taken? What additional considerations may be important?</i>
When horses should <u>avoid exercising/training</u> in ambient air		<i>Specifically, what actions should be taken? What recommendations do you have for training if air quality is above your indicated answer?</i>
When horses should <u>avoid exposure</u> to ambient air		<i>At what level would you make recommendations and what recommendations would you make regarding husbandry, housing, etc.?</i>

SECTION 4: CONCLUDING THOUGHTS

Question 9: The questions up to this point have addressed management strategies to prevent exposure, but we understand that exposure will occur. For this question, assume there was an air pollution event where the AQI was greater than 200 and many horses were exposed. What recommendations would you make for post-exposure management for the following horses:

9a:

A companion horse (no forced exercise):

9b:

An athletic horse whose training regimen is important:

9c:

A horse that competed during the air pollution event:

9d:

The above questions were based on an AQI > 200 (very unhealthy/purple). If you feel that you would make post-exposure recommendations at another AQI level (or with other conditions), please share those comments here:

Question 10: Sections 1 through 3 focused on horses in general. Is there anything additional that should be considered specifically for elite-level performance horses?

Question 11: Is there anything we did not ask in this survey that should be considered for the next round of this Delphi process?

**THIS IS THE END OF THE ROUND 1 SURVEY
THANK YOU SO MUCH FOR YOUR TIME AND MEANINGFUL CONTRIBUTIONS**

Round 2 Questionnaire

Fifteen expert veterinarians specializing in equine health from around the world contributed to the first round of this project, informing this subsequent questionnaire. This questionnaire has three sections:

- **Section A** will focus on adapting the available Air Quality Index to message toward horses and formulating consensus around recommendations for managing horses at different AQI levels. Results from multiple questions in Round 1 informed this section and the primary goal of this round is to establish clear-cut messaging and recommendations at different AQI levels.
- **Section B** will revisit questions from the first round that were not included in Section A. Results will be provided and a follow-up question will be asked.
- **Section C** is OPTIONAL and summarizes the results of questions that do not have a follow-up question but provide an opportunity for comment.

SECTION A – ADAPTING AIR QUALITY INDEX MESSAGING & FORMING RECOMMENDATIONS

Round 2, Question 1: Description of air quality.

In round 1 there was strong support for adapting the Air Quality Index messaging for public health to be appropriate for ALL horses. The table below was constructed from responses to *Round 1, Question 4* while conserving the original language. The messaging for public health is clear and concise and our goal is to do the same for horses; we would like to maintain the overall messaging of health risk and apply it to horses. We are **NOT** addressing management strategies in this question (to follow in Question 2).

***NEW* Round 2, Question 1:** This question has three parts:

- a) Please review the Air Quality Index table below, which includes the AQI category and associated color, the Index Value, and the messaging for public health. In the mid-right column, is the adapted messaging for horses. In the column to the far-right, please indicate if you agree or disagree with this adaptation by placing an 'X' in the appropriate box.
- b) If you indicate 'No' to the *horse-centered messaging*, we will ask you to include how you would alter that message to be more appropriate for horses. Make sure to include the category (color) of the text you wish to alter. This messaging should be clear and concise, and modeled off the current messaging for public health.
- c) Finally, to keep the *horse-centered messaging* consistent with the original text, we included an '*' and '+' in the text to direct users to the caption to clarify '*unusually sensitive*' and '*sensitive*' horses, respectively. From your responses in Round 1, Question 4 we have generated what could be considered '*unusually sensitive*' and '*sensitive*'. We will ask you for your agreement on the horses included in these groupings and provide an opportunity to make additions.

These instructions will be repeated with each part.

Intentionally blank so that the Air Quality Index table does not cross a page break

Question 1a: Please review the Air Quality Index table below, which includes the AQI category and associated color, the Index Value, and the messaging for public health. In the mid-right column, is the adapted messaging for horses. In the column to the far-right, please indicate if you agree or disagree with this adaptation by placing an 'X' in the appropriate box.

Table: Adaptation of the AQI to message to horses

Air Quality Index				Do you agree with the wording?	
AQI Category and Color	Index Value	Description of Air Quality HUMAN-CENTERED MESSAGING	Description of Air Quality HORSE-CENTERED MESSAGING (all horses)	Yes	No (Suggest changes below)
Good / Green	0 to 50	Air quality is satisfactory, and air pollution poses little or no risk	Air quality is satisfactory, and air pollution poses little or no risk to horses		
Moderate / Yellow	51 to 100	Air quality is acceptable. However, there may be risk for some people, particularly those who are unusually sensitive to air pollution	Air quality is acceptable. However, there may be risk for some horses, particularly those who are unusually sensitive* to air pollution		
Unhealthy for sensitive groups / Orange	101 to 150	Members of sensitive groups may experience health effects. The general public is less likely to be affected	Horses in sensitive groups† may experience health effects. The general horse population is less likely to be affected		
Unhealthy / Red	151 to 200	Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects	Some healthy horses may experience health effects; horses of sensitive† groups may experience more serious health effects.		
Very unhealthy / Purple	201 to 300	Health alert: The risk of health effects is increased for everyone.	Health alert: The risk of health effects is increased for all horses		
Hazardous / Maroon	301 and higher	Health warning of emergency conditions; everyone is more likely to be affected	Health warning of emergency conditions: all horses are likely to be affected		

***Unusually sensitive groups** include those with pre-existing respiratory conditions e.g., asthma, lower airway disease, upper airway restriction, etc., and those with active or recently recovered from respiratory illness

†**Sensitive groups** are those included in "unusually sensitive," as well as very young horses, geriatric horses, or horses with active or recently recovered from systemic illness.

Question 1b: If you indicated 'No' to the Horse-Centered Messaging, please include how you would alter that message to be more appropriate for horses. Make sure to include the category (color) of the text you wish to alter. This messaging should be clear and concise, and modeled off the current messaging for public health.

Question 1c: To keep the 'horse-centered messaging' consistent with the original text, we included an '*' and '+' in the text to direct users to the caption to clarify '*unusually sensitive*' and '*sensitive*' horses, respectively. From your responses in Round 1, Question 4 we have generated what could be considered '*unusually sensitive*' and '*sensitive*'. Please answer the following:

(i) '*Unusually sensitive*' groups include those with pre-existing respiratory conditions e.g., asthma, lower airway disease, upper airway restriction, etc., and those with active or recently recovered from respiratory illness.

Do you agree with the groups included as '*Unusually sensitive*' in the above statement? Please check the appropriate box.

- ☐ Yes – These horses would be considered '*unusually sensitive*'
- ☐ Yes – but there are additional groups that should be included. Please list additional groups to include here: _____
- ☐ No – These horses would not be considered '*unusually sensitive*'. Please justify your answer:

(ii) '*Sensitive*' groups include those included in "unusually sensitive," as well as very young horses, geriatric horses, or horses with active or recently recovered from systemic illness.

Do you agree with the groups included as '*sensitive*' in the above statement? Please check the appropriate box.

- ☐ Yes – These horses would be considered '*sensitive*'
- ☐ Yes – but there are additional groups that should be included. Please list additional groups to include here: _____
- ☐ No – These horses would not be considered '*sensitive*'. Please justify your answer:

Please use this space for any additional comments you wish to make about this question:

***NEW* Round 2, Question 2: Intervention and Management**

In round 1 there were many excellent suggestions for managing horses. The goal of this question is to formulate management recommendations for horses under each category of the Air Quality Index. We are interested in forming recommendations for the average horse, which falls under 'general management'. Additionally, we seek to provide recommendations for training days and competition days for the performance horse

Question 2a: The tables below are separated into each Air Quality Index category. You will see rows for Horse Activity, including *General Management*, *Training*, and *Competition*. Categories have text derived from *Round 1, Questions 4, 5, 6, 7, 8, and 9*. We will ask if you agree to the text and provide the opportunity to propose updates.

- (i) When the AQI is *Good*, please indicate if you agree with the text for *General Management*, *Training*, and *Competition*. If you have any additional interventions to add, please include them in the appropriate box labeled 'proposed changes'.

Good / Green (AQI 0 to 50)		
Horse activity	Agree Y/N	Management recommendations
General management		Continue routine as normal. Air quality is unlikely to impact horse health.
General management – proposed changes	---	
Training days		Strenuous exercise can be commenced and carried out as ambient air quality is unlikely to impact horse health
Training – proposed changes	---	
Competition day		Strenuous exercise can be commenced and carried out as ambient air quality is unlikely to impact horse health or performance
Competition – Proposed changes	---	

- (ii) When the AQI is Moderate, please indicate if you agree with the text for *General Management, Training, and Competition*. If you have any additional interventions to add, please include them in the appropriate box labeled 'proposed changes'.

Moderate / Yellow (AQI 51-100)		
Horse activity	Agree Y/N	Management recommendations
General management		Most horses can carry on with their normal routine. Horses that are unusually sensitive* to air pollution should limit exercise/exertion.
General management – proposed changes	---	
Training days		Strenuous exercise can be commenced and carried out. Horses that are unusually sensitive* to air pollution are restricted to moderate exercise.
Training – proposed changes	---	
Competition day		Strenuous exercise can be commenced and carried out. Horses that are unusually sensitive* to air pollution are restricted to moderate exercise.
Competition – Proposed changes	---	

***Unusually sensitive groups** include those with pre-existing respiratory conditions e.g., asthma, lower airway disease, upper airway restriction, etc., and those with active or recently recovered from respiratory illness

- (iii) When the AQI is *Unhealthy for sensitive groups*, please indicate if you agree with the text for *General Management, Training, and Competition*. If you have any additional interventions to add, please include them in the appropriate box labeled 'proposed changes'.

Unhealthy for sensitive groups / Orange (AQI 101 – 150)		
Horse activity	Agree Y/N	Management recommendations
General management		Healthy horses: • Adjust normal routine to light to moderate work Sensitive† horses: • Limit time outdoors if possible • Control indoor dust by wetting down hay and bedding • Provide fresh water • Monitor for respiratory signs
General management – proposed changes	---	
Training days		Healthy horses: • Light to moderate training outdoors • Normal training indoors may be acceptable • It is advisable to avoid or reduce moderate to strenuous exercise. High-intensity exercise should be avoided. Sensitive† horses: • Refrain from training outdoors • Light to moderate intensity exercise may be appropriate in a low-dust indoor environment
Training – proposed changes	---	
Competition day		• Organizers should consider canceling racing/high-intensity exercise events • Owners of horses with known respiratory health issues should consider withdrawing • The following recommendations are for events that will continue at this level of AQI: ○ Adequate and constant watering of working surfaces to minimize dust ○ Provide access to areas with optimal ventilation and temperature ○ Minimize dust exposure by wetting down hay and bedding ○ Increased biosecurity protocols to minimize infectious disease circulation and spread ○ Extra attention to cooling down horses if in hot conditions, place indoors with air conditioning whenever possible
Competition – Proposed changes	---	

†**Sensitive groups** are those included in “unusually sensitive,” as well as very young horses, geriatric horses, or horses with active or recently recovered from systemic illness.

- (iv) When the AQI is Unhealthy, please indicate if you agree with the text for *General Management, Training, and Competition*. If you have any additional interventions to add, please include them in the appropriate box labeled 'proposed changes'.

Unhealthy / Red (AQI 151 – 200)		
Horse activity	Agree Y/N	Management recommendations
General management		• Avoid riding outdoors • Do not exercise horses • Limit time outdoors / keep indoors if possible • Limit outdoor activity to slow walks
General management – proposed changes	---	
Training days		• Avoid exercising horses outdoors – increased levels of exertion should be avoided. A workout inducing high respiratory rates and large tidal volumes would be problematic. • Walking horses for rehab or to “stretch” limbs may be OK for some horses without underlying health conditions • Keep horses indoors if possible, or turn out in an area with less pollution • Light exercise can be performed indoors in a low dust environment. • Additional PM exposure associated with forages and beddings should be minimized as much as possible • Sensitive horses should not be exercised and should remain inside in a low dust environment
Training – proposed changes	---	
Competition day		Competitions should be suspended or canceled in accordance with USEF recommendations. Racing, eventing, and other competitions should be avoided.
Competition – Proposed changes	---	

- (v) When the AQI is *Very unhealthy*, please indicate if you agree with the text for *General Management, Training, and Competition*. If you have any additional interventions to add, please include them in the appropriate box labeled 'proposed changes'.

Very unhealthy / Purple (AQI 201 – 300)		
Horse activity	Agree Y/N	Management Recommendations
General management		- Avoid outdoor exercise. - Horses should be kept indoors whenever possible. - Exposed horses are at risk of developing respiratory issues, nasal discharge, and ocular discharge. - Only essential activity should be considered under these conditions. During air pollution event: - Move horse out of the exposure/move indoors/limit time outdoors/keep indoors with doors and windows temporarily closed until the AQI has improved After the air pollution event: - Monitor for clinical signs, e.g., cough, nasal discharge, neurologic signs, fever, post-exercise discharge, ophthalmic irritation, behavioral abnormalities, respiratory rate and pattern - Contact a veterinarian at the onset of clinical signs - Rest the horse for 3-5 days AFTER AQI has returned to below 200 - Management should be aimed at optimizing the breathing zone air quality of the horse, including providing adequate ventilation in the stable once the ambient pollution levels have resolved, low dust forage/wet hay and bedding - Ensure adequate hydration
General management–proposed changes	---	
Training days		During the air pollution event: - Owners/trainers should cease all exercise - Owners/trainers should limit the time horses are outside - House horses indoors if possible After the air pollution event: - Owners/trainers should monitor for clinical signs including respiratory effects, neurologic abnormalities, fever, post-exercise nasal discharge, and prolonged recovery - It is recommended to cease exercise for up to one week post exposure - It is recommended to rest horses for up to one week post exposure - Optimize the breathing zone air quality through adequate ventilation, low dust forage/steamed hay, and low dust bedding - Prior to returning to exercise, conduct a respiratory exam - Contact a veterinarian if onset of clinical signs - Ensure adequate hydration
Training – proposed changes	---	
Competition day		All competitions and events should be canceled. Both indoor and outdoor. For horses that competed under these air quality conditions, the following are recommendations for management/intervention: - Horses should be monitored for onset of clinical signs - Horses should be rested for at least one week up to two weeks - Seek veterinary care at the onset of clinical signs, e.g., respiratory signs, neurologic signs, fever, post-exercise discharge, prolonged recovery - A bronchoscopy with BAL should be performed if any clinical signs develop - A lung function test/respiratory exam should be performed prior to resuming training

		• Return to exercise should be gradual • The breathing zone air quality should be optimized by providing adequate ventilation and low dust forage and bedding • Provide immune system support
<i>Competition – Proposed changes</i>	---	

- (vi) When the AQI is *Hazardous*, please indicate if you agree with the text for *General Management, Training, and Competition*. If you have any additional interventions to add, please include them in the appropriate box labeled 'proposed changes'.

Hazardous / Maroon (AQI 301 and higher)		
Horse activity	Agree Y/N	Management Recommendations
General management		Avoid outdoor exercise. Horses may benefit from being kept indoors Management should be aimed at optimizing the breathing zone air quality of the horse, including providing adequate ventilation in the stable once the ambient pollution levels have resolved, low dust forage and bedding. After the air pollution event: • Owners/trainers should monitor for clinical signs including respiratory effects, neurologic abnormalities, fever, post-exercise nasal discharge, and prolonged recovery • It is recommended to cease exercise for up to one week post exposure • It is recommended to rest horses for up to one week post exposure • Optimize the breathing zone air quality through adequate ventilation, low dust forage/steamed hay, and low dust bedding • Prior to returning to exercise, conduct a respiratory exam/lung function test including bronchoscopy/BAL, and cytology • Contact a veterinarian if onset of clinical signs • Administer bronchodilators* for 1 week post exposure • Nebulize with ImmunoSan • Support the immune system • Ensure adequate hydration
General management – proposed changes	---	
Training days		During the air pollution event: • Owners/trainers should cease all exercise • Owners/trainers should house horses indoors if possible After the air pollution event: • Owners/trainers should monitor for clinical signs including respiratory effects, neurologic abnormalities, fever, post-exercise nasal discharge, and prolonged recovery • It is recommended to cease exercise for up to one week post exposure • It is recommended to rest horses for up to one week post exposure • Optimize the breathing zone air quality through adequate ventilation, low dust forage/steamed hay, and low dust bedding • Prior to returning to exercise, conduct a respiratory exam • Contact a veterinarian if onset of clinical signs • Ensure adequate hydration
Training – proposed changes	---	
Competition day		All competitions and events should be canceled. Both indoor and outdoor. For horses that competed under these air quality conditions, the following are recommendations for management/intervention: • Horses should be monitored for onset of clinical signs • Horses should be rested for at least one week up to two weeks • Seek veterinary care at the onset of clinical signs, e.g., respiratory signs, neurologic signs, fever, post-exercise discharge, prolonged recovery • A bronchoscopy with BAL should be performed if any clinical signs develop • A lung function test/respiratory exam should be performed prior to resuming training

		• Return to exercise should be gradual • The breathing zone air quality should be optimized by providing adequate ventilation and low dust forage and bedding • Provide immune system support
<i>Competition – Proposed changes</i>	---	

SECTION B – FOLLOW-UP QUESTIONS

In this section, we provide the results of questions from Round 1 that **did not** have a clear consensus and that were not captured in Section A. These questions will have a follow-up question requiring response.

From Round 1, Question 1a:

Please indicate how important it is to consider exposure to air pollution when considering equine health in general.

Summary of Round 1 Responses

Response rate: 100%

Scale: 1 = Not at all important; 9 = Extremely important

Range: 4 to 8 Mean: 6.47 SD: 1.25 Mode: 6 Median: 6

***NEW* Round 2, Question 1a:** 80% of respondents provided comments or justification to support their rating above. The comments are summarized in tabular format below, highlighting several themes related to exposure to air pollution when considering equine health in general. The number of experts addressing these themes is indicated in parentheses. In the table below, please indicate with an “X” the statements with which you agree.

	Air pollution exposure is associated with respiratory impacts (n = 7)
	One must consider factors related to the pollutant, (e.g., duration of exposure, composition of the pollutant, AQI) (n = 4)
	One must consider factors related to the horse (e.g., health/immune status, occupation, individual differences, exercise intensity) (n = 3)
	Air pollution is associated with poor athletic performance (n = 3)
	Research to assess the relationship between air pollution and health outcomes in horses is lacking and needed (n = 3)
	Air quality events are important, but we must also consider the average air quality for the individual horse which can be influenced by hay quality, feeding method, barn dust (n = 2)
	Horse exposure to poor ambient air quality is increasing through urbanization (more horses living in suburban/urban locations) (n = 2)
	Horse exposure to poor ambient air quality is increasing through more frequent wildfire smoke events (n = 1)
	Given horses’ shorter lifespan than humans, the health effects of ambient air pollution may not be as important to consider as it is in humans (n = 1)

Additional comments on exposure to air pollution and equine health *in general*:

From Round 1, question 1b:

Please rate your level of agreement with the following statement: The signalment of a horse plays a key role in considering the health risks of exposure to air.

Summary of Round 1 Responses:

Response rate: 100%

Scale: 1 = Completely disagree; 9 = Completely agree

Range: 1 to 8

Mean: 5.47

SD: 1.73

Mode: 5

Median: 6

***NEW* Round 2, Question 1b:** 100% of respondents provided comments addressing if there are age/sex/breed factors to consider regarding health risks of exposure to air pollution. The comments are summarized in tabular format below, highlighting several in response to the signalment playing a key role in considering the health risks of exposure to air pollution. The number of experts addressing these themes is indicated in parentheses. In the table below, please indicate with an "X" the statements with which you agree.

	Age (n = 8) can be a risk factor in that young horses (n = 3) and older horses (n = 4) have a greater health risk.
	Although breed and the use of a horse are associated, the use of the horse is more important when considering the health risks of air pollution exposure (n = 7)
	Signalment doesn't matter because <i>all</i> horses can be affected (n = 4)
	Body condition is an important factor to consider: Higher BCS affects respiratory health in horses with asthma therefore likely interactions between respiratory health, air pollution, and obesity (n = 1)
	The horse's origin, due to stable/boardings conditions that may be similar within countries/provinces but different across may be useful in considering the risk of exposure (n = 1)

Additional comments on the signalment of a horse playing a role in considering the health risks of exposure to air pollution:

SECTION C – Summary responses and results from remaining Round 1 questions.

Opportunity to comment **(OPTIONAL)**

In this section, we provide the results of questions that had a consensus and were not captured in Section A. These questions will provide an opportunity for comment to support the Delphi process. There is no specific question to answer. Providing comments is welcomed but optional.

From Round 1, question 1c:

Please rate your level of agreement with the following statement: Healthy horses exposed to air pollution may experience adverse health effects

Summary of Round 1 Responses:

Response rate: 100%

Scale: 1 = Completely disagree; 9 = Completely agree

Range: 5 to 9

Mean: 7.8

SD: 1.47

Mode: 9

Median: 8

93.3% of respondents provided comments regarding this question with specifics including body systems that may be impacted and/or disease processes initiated. Additionally, responses included certain environmental/management risk factors to consider, as well as specific pollutants to consider.

Summary of expert group comments of Round 1 responses to question 1c categorized by body systems affected and pollutants of concern. The number of experts indicating each comment is included in parentheses.

Body systems impacted by air pollution
Respiratory system (n = 14)
Cardiovascular system (n = 5)
Ocular tissues (n = 2)
The immune system (n = 1)
Other body systems (not specified) (n = 1)
Pollutants of concern include:
Particulate Matter (PM2.5, PM10) (n = 6)
Ozone (n = 4)
NO2 (n = 3)
SO2 (n = 3)
CO (n = 2)
Ammonia (n = 2)
NO (n = 1)
Mineral particles (n = 1)
Silica (n = 1)
Carbon (n = 1)
Endotoxin (n = 1)
Beta glucan (n = 1)
Categories of pollutants that are of concern include:

Smoke (n = 5)
Organic dust (n = 4)
Fungal spores (n = 2)
Pollens (n = 2)
Fumes (n = 1)
Chemicals (n = 1)
Bio-aerosols (n = 1)
Mold (n = 1)
Sources of pollutants that are of concern include:
Traffic (n = 3)
Industrial (n = 1)
Diesel fumes (n = 1)

If you have any comments regarding the results of Question 1c, please provide them here:

From Round 1, question 1d:

Please rate your level of agreement with the following statement: Horses with underlying health conditions exposed to air pollution may experience adverse health effects

Summary of Round 1 Responses:

Response rate: 93.3%

Scale: 1 = Completely disagree; 9 = Completely agree

Range: 7 to 9

Mean: 8.43

SD: 0.85

Mode: 9

Median: 9

100% of respondents provided comments regarding this question with specifics on which health conditions may be exacerbated by exposure to air pollution. Responses are summarized in tabular format below grouped by body system. The number of experts indicating each comment is included in parentheses.

Airway
Asthma (n = 7)
Unspecified airway inflammation (n = 5)
Upper airway inflammation/disease that increases work of breathing (e.g., DDSP, laryngeal hemiplegia) (n = 2)
Unspecified infectious respiratory disease (n = 2)
EIPH (n = 2)
Pneumonia (bacterial, viral, other) (n = 1)
Viral infection disrupting “normal” epithelial function (n = 1)
Recurrent airway obstruction/heaves (n = 1)
Pulmonary edema (n = 1)
Metabolic
EMS/PPID difficulties in thermoregulation (n = 1)
Horses with low immunity (e.g., PPID) predisposed to secondary infection (n = 1)
Cardiovascular
Cardiovascular compromise (n = 1)
Other
Any condition requiring systemic (especially long-term) antimicrobial treatment, which increases the risk of fungal colonization (n = 1)

If you have any comments regarding the results of Question 1d, please provide them here:

From Round 1, Question 2:

In your opinion, what may be the top five most significant health impacts (i.e., conditions, illnesses, injuries) horses exposed to air pollution may experience?

All respondents provided answers to this question. Indicated health impacts secondary to exposure to air pollution are organized by body system in tabular format below. The number of experts indicating each impact is included in parentheses.

Respiratory System
Lower airway inflammation/compromised function, e.g., asthma, IAD, RAO, heaves (n = 14)
Upper airway inflammation, e.g., rhinitis, pharyngitis, laryngitis, tracheitis (n = 9)
EIPH (n = 5)
Respiratory infection/illness (n = 3)
Bronchospasm (n = 1)
Cough (n = 1)
Increased mucus production (n = 1)
Pleuropneumonia (n = 1)
Cardiovascular System
Cardiovascular disease (n = 4)
Cardiac arrhythmia (n = 2)
Ocular System
Conjunctivitis (n = 2)
Other/unspecified ocular inflammation and irritation (n = 2)
Unspecified ocular disease and disorders (n = 2)
Performance
Poor performance (n = 2)
Exercise intolerance (n = 2)
Other
Other systemic illness (unspecified) (n = 3)
Immunologic challenge (n = 2)
Head shaking due to exacerbated response of the trigeminal nerve firing secondary to neuritis and upper airway inflammation (n = 1)
Integument via contact (n = 1)

Additional comments:

- Effects on CV system, tumor development, and systemic inflammation are established in the human literature and can potentially be translated to equine health but thus far lack equine-specific evidence (n = 4).
- Experts stated that there is existing evidence that air pollution can impact respiratory health and lead to poor performance in the literature (n = 3).

If you have any comments regarding the results of Question 2, please provide them here:

From Round 1, Question 3a:

Please rate your level of agreement with the following statement: Horses exposed to elevated levels of air pollution may experience negative short-term health impacts

Summary of Round 1 Responses:

Response rate: 100%

Scale: 1 = Completely disagree; 9 = Completely agree

Range: 3 to 9

Mean: 7.67

SD: 1.59

Mode: 8

Median: 8

86.7% of respondents provided comments on the *short-term* health impacts of air pollution exposure. The table below summarizes write-in *short-term* health impacts that may occur due to exposure to elevated levels of air pollution. The number of experts indicating each short-term health impact is included in parentheses.

Respiratory inflammation (n = 8)
Systemic inflammation (n = 2)
Cough (n = 2)
Reduced athletic performance (n = 2)
Depends on the source and severity (n = 2), definition of short-term (n = 2), level of concurrent exercise (n = 1)
No short-term effects, exposure to pollution requires a few weeks to induce inflammation (n = 1)
ALI/ARDS when exposed to high levels even for short periods of time, e.g., smoke exposure from fires) (n = 1)
Serous nasal discharge (n = 1)
Serous ocular discharge (n = 1)
Acute lung effects (n = 1)
Acute CV effects (n = 1)

If you have any comments regarding the results of Question 3a, please provide them here:

From Round 1, Question 3b:

Please rate your level of agreement with the following statement: Horses exposed to elevated levels of air pollution may experience negative long-term health impacts

Summary of Round 1 Responses:

Response rate: 100%

Scale: 1 = Completely disagree; 9 = Completely agree

Range: 6 to 9

Mean: 7.6

SD: 0.91

Mode: 7

Median: 7

86.7% of respondents provided comments on the *long-term* health impacts of air pollution exposure. The table below summarizes write-in *long-term* health impacts that may occur due to exposure to elevated levels of air pollution. The number of experts indicating each short-term health impact is included in parentheses.

Airway inflammation and disease (n = 11), including the development and/or exacerbation of equine asthma (n = 4), and lung remodeling (n = 4)
Alterations to immune response (n = 1)
Abnormal mucus production (n = 1)
Impacts to Cardiovascular health (n = 1)
Adverse effects dissipate when exposure to pollution is corrected/removed (n = 1)
It depends on the length and level of exposure (n = 1)
Data is lacking to conclude about long-term health impacts (n = 1)

If you have any comments regarding the results of Question 3b, please provide them here:

From Round 1, Question 3c:

The following table provides different levels of exposure.

- Please refer to the AQI chart above for exposure categories.
- Use the following definitions:
 - An acute exposure is one that lasts 24 hours or less
 - Prolonged/chronic exposure is more than 24 hours
- Please rate your level of concern by placing an “X” in the appropriate box and provide comments in the space provided as to why you chose your level of concern.

Response rate: 93.3%

The table below provides the results of this question. The number in each box indicates the number of experts who chose that level of concern for each category with the percentage of those responding included in parentheses.

Exposure	Not at all concerned	Slightly concerned	Moderately concerned	Very concerned	Extremely concerned	Please provide comments (if any)
PROLONGED or CHRONIC EXPOSURE as defined by exposure that is more than 24 hours						
Exposure to very low (AQI = green) levels of air pollution	10 (71.4%)	3 (21.4%)	0	1 (7.1%)	0	Median = <i>Not at all concerned</i> Mode = <i>Not at all concerned</i>
Exposure to low to moderate (AQI = yellow) levels of air pollution	4 (28.6%)	8 (57.1%)	1 (7.1%)	0	1 (7.1%)	Median = <i>Slightly concerned</i> Mode = <i>Slightly concerned</i>
Exposure to moderate to high (AQI = orange) levels of air pollution	0	3 (21.4%)	7 (50%)	3 (21.4%)	1 (7.1%)	Median = <i>Moderately concerned</i> Mode = <i>Moderately concerned</i>
Exposure to unhealthy (AQI = red) levels of air pollution	0	0	4 (28.6%)	7 (50%)	3 (21.4%)	Median = <i>Very concerned</i> Mode = <i>Very concerned</i>
Exposure to very unhealthy (AQI = Purple) levels of air pollution	0	0	1 (7.1%)	8 (57.1%)	5 (35.7%)	Median = <i>Very concerned</i> Mode = <i>Very concerned</i>
Exposure to hazardous (AQI = Maroon) levels of air pollution	0	0	0	3 (21.4%)	11 (78.6%)	Median = <i>Extremely concerned</i> Mode = <i>Extremely concerned</i>
ACUTE EXPOSURE as defined by an exposure that lasts 24 hours or less						
Exposure to very low (AQI = green) levels of air pollution	12 (85.7%)	1 (7.1%)	1 (7.1%)	0	0	Median = <i>Not at all concerned</i> Mode = <i>Not at all concerned</i>
Exposure to low to moderate (AQI = yellow) levels of air pollution	8 (57.1%)	5 (35.7%)	1 (7.1%)	0	0	Median = <i>Not at all concerned</i> Mode = <i>Not at all concerned</i>
Exposure to moderate to high (AQI = orange) levels of air pollution	2 (14.3%)	5 (35.7%)	4 (28.6%)	3 (21.4%)	0	Median = <i>Slightly concerned</i> Mode = <i>Slightly concerned</i>
Exposure to unhealthy (AQI = red) levels of air pollution	0	4 (28.6%)	2 (14.3%)	7 (50%)	1 (7.1%)	Median = <i>Very concerned</i> Mode = <i>Very concerned</i>
Exposure to very unhealthy (AQI = Purple) levels of air pollution	0	2 (14.3%)	2 (14.3%)	4 (28.6%)	6 (42.9%)	Median = <i>Very concerned</i> Mode = <i>Extremely concerned</i>
Exposure to hazardous (AQI = Maroon) levels of air pollution	0	0	2 (14.3%)	4 (28.6%)	8 (57.1%)	Median = <i>Extremely concerned</i> Mode = <i>Extremely concerned</i>

If you have any comments regarding the results of Question 3c, please provide them here:

Round 1, Question 3d:

Question 3c provided definitions for acute and chronic exposure adapted from the US Environmental Protection Agency's glossary of definitions for exposures based on the environment and community-based air pollution projects.

- An acute exposure is one that lasts 24 hours or less
- Prolonged/chronic exposure is more than 24 hours

Do you agree with these definitions for exposure to air pollution in horses? Yes 9 No 5

Response rate: 93.4%

64.3% in favor of these definitions

Experts not in agreement with these definitions expressed that the cutoff for determining chronicity depends on multiple factors (e.g., the pollutant, the level, housing conditions, horse factors, etc. (n = 4). Additionally, the provided cut-offs distinguishing acute vs chronic may not effectively capture adverse health outcomes associated with both acute vs chronic exposure (n = 3). For example, what is the expected difference in health outcomes between 23 and 25 hours of exposure? Furthermore, there may be a low incidence of adverse health outcomes with exposures less than 24 hours and these cut offs lack the ability to capture differences between days/weeks vs months/years. One person in favor of these definitions stated that in the lack of evidence it is best to stick with available definitions.

If you have any comments regarding the results of Question 3d, please provide them here:

From Round 1, Question 4b: The table below shows the same AQI with the associated cut points for PM_{2.5} and the 8-hour and 1-hour average for ozone levels. In the space provided, please indicate by filling in the two empty columns your level of agreement from 1 to 5 (**1 = Strongly disagree; 2 = disagree; 3 = Neither agree nor disagree; 4 = Agree; 5 = Strongly agree**). If you indicate *Strongly disagree* or *disagree*, please indicate what you believe to be better cut-point values.

The results for Question 4b are included in the table below in the lightly shaded boxes. Few experts provided write-in responses for this question, with three experts reporting there is a lack of data to support/oppose these cut-offs and one expert stating the use of these already established cut-points serves as the best starting point.

Air Quality Index						
AQI Category and Color	Index Value	Associated PM _{2.5} levels	<u>Your level of agreement with the PM_{2.5} cut points?</u> <u>If not, what would be your suggested cut points?</u>	Associated Ozone levels		<u>Your level of agreement with the ozone cut points?</u> <u>If not, what would be your suggested cut points?</u>
				8-hour average	1-hour average	
Good / Green	0 to 50	0 – 9 ug/m ³	Mean: 3.81 SD: 0.75 Median: 4 Mode: 4 Range: 3 – 5 Resp Rate: 73.3%	0 – 54 ppb	Na	Mean: 3.75 SD: 0.89 Median: 3.5 Mode: 3 Range: 3 – 5 Resp Rate: 60%
Moderate / Yellow	51 to 100	9.1 – 35.4 ug/m ³	Mean: 3.36 SD: 1.0 Median: 3 Mode: 3 Range: 2-5 Resp Rate: 73.3%	55 – 70 ppb	Na	Mean: 3.63 SD: 0.92 Median: 3 Mode: 3 Range: 3 – 5 Resp Rate: 60%
Unhealthy for sensitive groups / Orange	101 to 150	35.5 – 55.4 ug/m ³	Mean: 3.72 SD: 0.79 Median: 4 Mode: 3 Range: 3 – 5 Resp Rate: 73.3%	71 – 85 ppb	125 – 164 ppb	Mean: 3.63 SD: 0.92 Median: 3 Mode: 3 Range: 3 – 5 Resp Rate: 60%
Unhealthy / Red	151 to 200	55.5 – 125.4 ug/m ³	Mean: 3.72 SD: 0.91 Median: 3 Mode: 3 Range: 3-5 Resp Rate: 73.3%	86 – 105 ppb	165 – 204 ppb	Mean: 3.56 SD: 0.88 Median: 3 Mode: 3 Range: 3 – 5 Resp Rate: 66.7%
Very unhealthy / Purple	201 to 300	125.5 – 225.4 ug/m ³	Mean: 3.72 SD: 0.91 Median: 3 Mode: 3 Range: 3-5 Resp Rate: 73.3%	106 – 200 ppb	205 – 404 ppb	Mean: 3.67 SD: 0.87 Median: 3 Mode: 3 Range: 3 – 5 Resp Rate: 66.7%
Hazardous / Maroon	301 and higher	225.5+ ug/m ³	Mean: 3.72 SD: 0.91 Median: 3 Mode: 3 Range: 3-5 Resp Rate: 73.3%	na	405 – 604 ppb	Mean: 3.76 SD: 0.97 Median: 3 Mode: 3 Range: 3 – 5 Resp Rate: 66.7%

If you have any comments regarding the results of Question 4b, please provide them here:

Questions 10 and 11 were optional, open-ended questions where panelists could add additional thoughts on the topic. Feedback where appropriate has been integrated into this round.

Round 3 Questionnaire

Thirteen expert veterinarians specializing in equine health from around the world contributed to the second round of this project. This will be the final distribution to our expert contributors. This document has two sections:

- **Section A** presents final follow-up questions to **4 items**. The previous questionnaire resulted in much consensus around presented items, but few items had low agreement. Comments and suggestions resulted in updated language around specific items. These items will be presented to you in this section, inviting a final round of consideration and feedback.
- **Section B** summarizes the results of the round 2 questionnaire for which we had consensus. There is an opportunity for comment, but this is **OPTIONAL**. Your input has been invaluable leading to strong considerations and topics for discussion.

SECTION A – ITEMS REQUIRING ADDITIONAL FEEDBACK

Round 3, Question 1: Description of air quality

In round 2 there was strong consensus around the horse-adapted messaging of the Air Quality Index. The table is included below with the % of respondents answering this question and the % agreement of the adapted language. Over 80% of respondents agreed to the language for green, yellow, red, purple, and maroon categories. **The orange category only had a 69.2% agreement.** The disagreement was mostly about the conditions listed under “sensitive” and “unusually sensitive groups”. For the definitions of these groups, the original language is in grey italicized text directly under the table. The suggested changes are written below with the edits highlighted. **Please review the suggested changes for defining “Unusually sensitive groups” and “Sensitive groups” and answer the follow up questions on the next page.**

Description of Air Quality HUMAN-CENTERED MESSAGING	Description of Air Quality HORSE-CENTERED MESSAGING (all horses)	Yes % Responded % Agreement
Air quality is satisfactory, and air pollution poses little or no risk	Air quality is satisfactory, and air pollution poses little or no risk to horses	100%
Air quality is acceptable. However, there may be risk for some people, particularly those who are unusually sensitive to air pollution	Air quality is acceptable. However, there may be risk for some horses, particularly those who are unusually sensitive* to air pollution	100%
Members of sensitive groups may experience health effects. The general public is less likely to be affected	Horses in sensitive groups† may experience health effects. The general horse population is less likely to be affected	100%
Some members of the general public may experience health effects; members of sensitive groups may experience more serious health effects	Some healthy horses may experience health effects; horses of sensitive† groups may experience more serious health effects.	69.2%
Health alert: The risk of health effects is increased for everyone.	Health alert: The risk of health effects is increased for all horses	84.6%
Health warning of emergency conditions; everyone is more likely to be affected	Health warning of emergency conditions: all horses are likely to be affected	81.8%
		84.6%
		90.9%
		84.6%
		100%

****Unusually sensitive groups** include those with pre-existing respiratory conditions e.g., asthma, lower airway disease, upper airway restriction, etc., and those with active or recently recovered from respiratory illness*

*†**Sensitive groups** are those included in “unusually sensitive,” as well as very young horses, geriatric horses, or horses with active or recently recovered from systemic illness.*

Suggested changes:

****Unusually sensitive groups** include those with pre-existing respiratory conditions e.g., **severe equine asthma, lung disease, upper airway obstruction, EIPH, etc.,** and those with active or recently recovered from respiratory illness, e.g., **shipping fever.** Horses with cardiac disease, heart failure, and pulmonary hypertension are also included here.*

*†**Sensitive groups** are those included in “unusually sensitive,” as well as horses with **mild to moderate equine asthma, very young horses, geriatric horses,** or horses with active or recently recovered from **systemic illness** or suffer from metabolic disease, e.g., **uncontrolled PPID, EMS.***

Follow-up questions to Round 2, Question 1:

(i) The updated language defining 'Unusually sensitive groups' is as follows:

****Unusually sensitive groups** include those with pre-existing respiratory conditions e.g., severe equine asthma, lung disease, upper airway obstruction, EIPH, and those with active or recently recovered from respiratory illness, e.g., shipping fever. Horses with cardiac disease, heart failure, and pulmonary hypertension are also included here.*

Do you agree with this language defining 'Unusually sensitive groups'?

☐ Yes

☐ No – Please provide revised language:

(ii) The updated language defining 'Sensitive groups' is as follows:

***[†]Sensitive groups** are those included in "unusually sensitive," as well as horses with mild to moderate equine asthma, or horses with active or recently recovered from systemic illness or suffer from metabolic disease, e.g., uncontrolled PPID, EMS.*

Do you agree with this language defining 'Sensitive groups'?

☐ Yes

☐ No – Please provide revised language:

(iii) Additional comments you wish to make about this question:

Round 3, Question 2: Description of air quality

In round 2, we collated management recommendations under each air quality index level for (a) the general management of horses, (b) training days, and (c) competition days. There was high agreement for the recommendations for green, yellow, and orange categories, however red, purple, and maroon categories lacked consensus.

Comments and feedback led to the updated text for red, purple, and maroon and are included in the tables below. For each of these categories, we will ask you to review the updated language, indicate your agreement (Y/N), and if “No” provide your revised language.

Key points for these recommendations:

- These will be messaging to horse owners, trainers, and riders; therefore, recommendations should be presented in lay language.
- Standard language should be maintained throughout for clear messaging
- *General Management* recommendations apply to all horses at all times under the specified condition scenario. Actions listed under *Training Days* and *Competition Days* should not repeat what is under *General Management* but instead include additional recommendations specific to those days.

- (vii) When the AQI is *Unhealthy (Red)*, please indicate if you agree with the updated text for *General Management, Training, and Competition*. If you don't agree, please provide your revised language/edits in the space provided below each category.

Unhealthy / Red (AQI 151 – 200)		
Horse activity	Results from the previous round	Management recommendations
<i>General management</i>	Response rate: 92.3% Agreement: 75%	• Avoid riding outdoors • Do not exercise horses • Horses may benefit from being kept indoors, or turn out in an area with less pollution • Provide a low dust environment; avoid activities that increase dust exposure indoors, e.g., sweeping • Minimize additional dust exposure with low dust forage and bedding • Limit outdoor activity to slow walks • Ensure fresh water is always available • Monitor for changes in breathing rate, breathing rhythm, or abnormal noise associated with breathing • Sensitive or unusually sensitive horses should not be exercised and should remain inside in a low dust environment if possible
<i>General management – Provide your revised language</i>	Agree? Y / N	
<i>Training days</i>	Response rate: 84.6% Agreement: 72.7%	In addition to the <i>general management</i> recommendations above, the following should be considered for training days: If training must occur: • Avoid exercising horses outdoors • Avoid increased levels of exertion • Select indoor/low dust environments • Walking horses for rehab or to stretch limbs may be OK for some horses without underlying health conditions
<i>Training – Provide your revised language</i>	Agree? Y / N	
<i>Competition day</i>	Response rate: 84.6% Agreement: 90.9%	In addition to the <i>general management</i> recommendations above, the following should be considered for competition days: • Competitions and events should be suspended or canceled in accordance with USEF recommendations.
<i>Competition – Provide your revised language</i>	---	<i>Competition had >90% agreement; comments not required here</i>

- (viii) When the AQI is *Very unhealthy (Purple)*, please indicate if you agree with the updated text for *General Management, Training, and Competition*. If you don't agree, please provide your revised language/edits in the space provided below each category.

Very unhealthy / Purple (AQI 201 – 300)		
Horse activity	Results from the previous round	Management Recommendations
General management	Response rate: 100% Agreement: 69.2%	During air pollution event: - Do not ride outdoors - Do not exercise horses - Only essential activity should be considered under these conditions. - Move horses out of the exposure, e.g., move indoors, keep indoors with doors and windows temporarily closed if possible, consider evacuating to an area with better air quality - Provide a low dust environment; avoid activities that increase dust exposure indoors, e.g., sweeping - Minimize additional dust exposure with low dust forage and bedding - Ensure adequate hydration - For sensitive or unusually sensitive horses, they should remain inside in a low dust environment with air conditioning whenever possible After the air pollution event: - Monitor horses for abnormalities, e.g., cough, nasal discharge, post-exercise nasal discharge, prolonged recovery from exercise, eye irritation, behavioral abnormalities, changes in breathing - Contact a veterinarian if your horse develops any abnormal signs - Optimize the air quality in the horses' breathing zone, e.g., providing adequate ventilation in the stable once the ambient pollution levels have resolved, and low dust forage and bedding - Ensure adequate hydration
General management— Provide your revised language	Agree? Y / N	
Training days	Response rate: 92.3% Agreement: 66.7%	In addition to the <i>general management</i> recommendations above, the following should be considered for training days: During the air pollution event: - Owners/trainers should cease all training After the air pollution event: - It is recommended to rest horses for up to one week post-exposure and gradually increase exercise according to air quality improvement. - Check for signs of abnormal breathing or coughing before returning to exercise - Consider a veterinary health exam before returning to exercise
Training – Provide your revised language	Agree? Y / N	
Competition day	Response rate: 100% Agreement: 46.2%	In addition to the <i>general management</i> recommendations above, the following should be considered for competition days: All competitions and events should be canceled in accordance with USEF recommendations. This includes both indoor and outdoor events. For horses that competed under these air quality conditions, the following are recommendations for management/intervention:

		• Monitor horses for signs of illness (e.g. increased coughing, increased breathing rate, etc. • Horses should be rested for at least one week • Consider a veterinary health exam before resuming training • Return to exercise should be gradual after the air quality improves • Seek veterinary care at the onset of abnormal signs, e.g., cough, nasal discharge, post-exercise nasal discharge, prolonged recovery from exercise, eye irritation, behavioral abnormalities, abnormal breathing
Competition – Provide your revised language	Agree? Y / N	

- (i) When the AQI is *Hazardous (Maroon)*, please indicate if you agree with the updated text for *General Management, Training, and Competition*. If you don't agree, please provide your revised language/edits in the space provided below each category.

Hazardous / Maroon (AQI 301 and higher)		
Horse activity	Results from the previous round	Management Recommendations
General management	Response rate: 100% Agreement: 23.1%	During air pollution event - Do not ride horses - Do not exercise horses - Only essential activity should be considered under these conditions. - Move horses out of the exposure, e.g., move indoors, keep indoors with doors and windows temporarily closed if possible, consider evacuating to an area with better air quality - Provide a low dust environment; avoid activities that increase dust exposure indoors, e.g., sweeping - Minimize additional dust exposure with low dust forage and bedding - Ensure adequate hydration - For sensitive or unusually sensitive horses, should remain inside in a low dust environment with air conditioning whenever possible After the air pollution event: - Monitor horses for abnormalities, e.g., cough, nasal discharge, post-exercise nasal discharge, prolonged recovery from exercise, eye irritation, behavioral abnormalities, abnormal breathing - Contact a veterinarian if your horse develops any abnormal signs - Optimize the air quality in the horses' breathing zone, e.g., providing adequate ventilation in the stable once the ambient pollution levels have resolved, low dust forage and bedding - Ensure adequate hydration
General management – Provide your revised language	Agree? Y / N	
Training days	Response rate: 76.9% Agreement: 60%	In addition to the <i>general management</i> recommendations above, the following should be considered for training days: During the air pollution event: - Owners/trainers should cease all training (indoors and outdoors) After the air pollution event: - It is recommended to rest horses for up to one week post-exposure and gradually increase exercise according to air quality improvement. - Check for signs of abnormal breathing or coughing before returning to exercise - Consider a veterinary health exam before returning to exercise
Training – Provide your revised language	Agree? Y / N	
Competition day	Response rate: 92.3% Agreement: 25%	In addition to the <i>general management</i> recommendations above, the following should be considered for competition days: All competitions and events should be canceled in accordance with USEF recommendations. This includes both indoor and outdoor events. For horses that competed under these air quality conditions, the following are recommendations for management/intervention:

		• Closely monitor horses for signs of illness (e.g. increased coughing, increased breathing rate, etc. • Horses should be rested for <u>at least</u> one week • Consider a veterinary health exam before resuming training • Return to exercise should be gradual after the air quality improves • Seek veterinary care at the onset abnormal signs, e.g., cough, nasal discharge, post-exercise nasal discharge, prolonged recovery from exercise, eye irritation, behavioral abnormalities, abnormal breathing
Competition – Provide your revised language	Agree? Y / N	

SECTION B – Summary responses and results from remaining Round 2 questions.

Opportunity to comment
(OPTIONAL)

Round 2 Results:

In round 2, we presented tables separated into each Air Quality Index category and collated management recommendations under each air quality index level for (a) the general management of horses, (b) training days, and (c) competition days. Results for the red, purple, and maroon categories were presented in Section A for further discussion. Here we present the results for the green, yellow, and orange categories, which all achieved >80% consensus. Please note that minor wording adjustments may have been made to ensure consistent language across categories. However, these changes did not alter the meaning of the recommendations provided.

Good / Green (AQI 0 to 50)		
<i>Horse activity</i>	<i>Agree Y/N – Results from the previous round</i>	<i>Management recommendations</i>
<i>General management</i>	<i>Response rate: 92.3%</i> <i>Agreement: 100%</i>	Continue routine as normal. Air quality is unlikely to impact horse health.
<i>Training days</i>	<i>Response rate: 92.3%</i> <i>Agreement: 91.7%</i>	Strenuous exercise can be commenced and carried out as ambient air quality is unlikely to impact horse health
<i>Competition day</i>	<i>Response rate: 92.3%</i> <i>Agreement: 91.7%</i>	Strenuous exercise can be commenced and carried out as ambient air quality is unlikely to impact horse health or performance

Moderate / Yellow (AQI 51-100)		
<i>Horse activity</i>	<i>Agree Y/N – Results from the previous round</i>	<i>Management recommendations</i>
<i>General management</i>	<i>Response rate: 92.3%</i> <i>Agreement: 91.7%</i>	Most horses can carry on with their normal routine. Exercise should be limited in horses that are unusually sensitive* to air pollution.
<i>Training days</i>	<i>Response rate: 92.3%</i> <i>Agreement: 83.3%</i>	Training, including strenuous exercise, can be undertaken by most horses. Horses that are unusually sensitive* to air pollution should be restricted to moderate exercise.
<i>Competition day</i>	<i>Response rate: 92.3%</i> <i>Agreement: 83.3%</i>	Competition, including those involving strenuous exercise, can be undertaken by most horses. Horses that are unusually sensitive* to air pollution should be restricted to moderate exercise.

****Unusually sensitive groups** include those with pre-existing respiratory conditions e.g., asthma, lower airway disease, upper airway restriction, etc., and those with active or recently recovered from respiratory illness (note: final language of defining ***Unusually sensitive groups** TBD by round 3)*

Unhealthy for sensitive groups / Orange (AQI 101 – 150)		
Horse activity	Agree Y/N – Results from the previous round	Management recommendations
General management	Resp rate: 84.6% Agreement: 81.8%	Healthy horses: • Adjust normal routine to light to moderate work Sensitive† horses: • Limit time outdoors if possible • Provide a low dust environment; avoid activities that increase dust exposure indoors, e.g., sweeping • Minimize additional dust exposure with low dust forage and bedding • Ensure fresh water is always available • Monitor for changes in breathing rate, breathing rhythm, or abnormal noise associated with breathing
Training days	Resp rate: 84.6% Agreement: 90.9%	Healthy horses: • Light to moderate training outdoors • Normal training indoors may be acceptable • It is advisable to avoid or reduce moderate to strenuous exercise. High-intensity exercise should be avoided. Sensitive† horses: • Refrain from training outdoors • Light to moderate intensity exercise may be appropriate in a low-dust indoor environment
Competition day	Resp rate: 76.9% Agreement: 80%	• Organizers should consider canceling racing/high-intensity exercise events • Owners of horses with known respiratory health issues should consider withdrawing • The following recommendations are for events that will continue at this level of AQI: ○ Adequate and constant watering of working surfaces to minimize dust ○ Provide access to areas with optimal ventilation and temperature ○ Minimize dust exposure with from hay and bedding ○ Increased biosecurity protocols to minimize infectious disease circulation and spread ○ Pay extra attention to cooling down horses if in hot conditions, if possible move indoors with air conditioning

†Sensitive groups are those included in “unusually sensitive,” as well as very young horses, geriatric horses, or horses with active or recently recovered from systemic illness.

(note: final language of defining †Sensitive groups TBD by round 3)

If you have any comments regarding these tables, please provide them here:

In Round 1, you were asked to indicate how important it is to consider exposure to air pollution when considering *equine health in general*. 80% of respondents provided comments or justification for their response which we summarized and presented in Round 2, where you were asked to indicate with an “X” the statements in which you agree. The percentage agreement for each statement is included in the table below.

92.3%	Air pollution exposure is associated with respiratory impacts (n = 7)
92.3%	One must consider factors related to the pollutant, (e.g., duration of exposure, composition of the pollutant, AQI) (n = 4)
76.9%	One must consider factors related to the horse (e.g., health/immune status, occupation, individual differences, exercise intensity) (n = 3)
53.8%	Air pollution is associated with poor athletic performance (n = 3)
92.3%	Research to assess the relationship between air pollution and health outcomes in horses is lacking and needed (n = 3)
100%	Air quality events are important, but we must also consider the average air quality for the individual horse which can be influenced by hay quality, feeding method, barn dust (n = 2)
46.2%	Horse exposure to poor ambient air quality is increasing through urbanization (more horses living in suburban/urban locations) (n = 2)
53.8%	Horse exposure to poor ambient air quality is increasing through more frequent wildfire smoke events (n = 1)
15.4%	Given horses’ shorter lifespan than humans, the health effects of ambient air pollution may not be as important to consider as it is in humans (n = 1)

If you have any comments regarding the results presented in this table, please provide them here:

In Round 1, you were asked to indicate your level of agreement with the following statement: The signalment of a horse plays a key role in considering the health risks of exposure to air. All respondents provided comments addressing if there are age/sex/breed factors to consider regarding health risks of exposure to air pollution. We summarized these comments and presented them in Round 2, where you were asked to indicate with an “X” the statements in which you agree. The percentage agreement for each statement is included in the table below.

61.5%	Age (n = 8) can be a risk factor in that young horses (n = 3) and older horses (n = 4) have a greater health risk.
76.9%	Although breed and the use of a horse are associated, the use of the horse is more important when considering the health risks of air pollution exposure (n = 7)
30.8%	Signalment doesn't matter because <i>all</i> horses can be affected (n = 4)
15.4%	Body condition is an important factor to consider: Higher BCS affects respiratory health in horses with asthma therefore likely interactions between respiratory health, air pollution, and obesity (n = 1)
7.7%	The horse's origin, due to stable/boardings conditions that may be similar within countries/provinces but different across may be useful in considering the risk of exposure (n = 1)

If you have any comments regarding the results presented in this table, please provide them here:

**THIS IS THE END OF THE FINAL ROUND SURVEY.
THANK YOU SO MUCH FOR YOUR TIME AND MEANINGFUL CONTRIBUTIONS TO THIS PROJECT.**