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Establishing the relationship between wildfire smoke and performance metrics on finished beef cattle in Western Rangelands

Arturo Macias Franco,[†] Aghata Elins Moreira da Silva,[†,‡] Graham Holton,[†] Tio Brody,[†] and Mozart Alves Fonseca[†,1]

[†]Department of Agriculture, Veterinary & Rangeland Sciences, University of Nevada, Reno, Reno, NV 89557, USA
[‡]Department of Animal Sciences, Auburn University, Auburn, AL 36849, USA
[1]Corresponding author: mfonseca@unr.edu

Abstract

Identifying causal relationships is complicated. Researchers usually overlook causality behind relationships which can generate misleading associations. Herein, we carefully examine the parametric relationship and causality between wildfire smoke exposure and animal performance and behavior metrics over a period of 2 yr in Reno, Nevada. The animals in the 2020 smoke season were grain-finished (n = 12) and grass-finished (n = 12), whereas the animals during the 2021 season were fed under the same diet but finished with either a hormonal implant (n = 9), or without (n = 9). The dataset included daily records of feed intake (**FI**), body weight (**BW**), water intake (**WI**), average daily gain (**ADG**), and WI behavior (time spent drinking [**TSD**]; water intake events [**WIE**]; no-WIE [**NWIE]**). Variable tree length Bayesian additive regression trees (**BART**) were utilized to investigate the relationships between air quality index (**AQI**), particulate matter 2.5 µm (**$PM_{2.5}$**) and 10 µm (**PM_{10}**), NO_2, SO_2, Ozone, and CO levels in the air (sensors < 1.6 km from animals) with the animal data. Additionally, linear mixed models with a 7-d lag were used to evaluate parametric relationships among the same variables. All statistical analyses were performed on R Statistical Software (R Core Team 2023). Under the linear mixed model with a 7-d lag, significant positive and negative associations were found for all parameters examined ($P < 0.05$). Negative associations were found between FI, WI, ADG, BW, WIE, NWIE, TSD, and $PM_{2.5}$ ($P < 0.05$) for at least one animal group. Positive linear associations between wildfire smoke parameters and the metrics evaluated were more variable and dependent on year, treatment, and smoke parameters. When examining the credible intervals and the variable importance in the BART, relationships were more difficult to identify. However, some associations were found for Ozone, AQI, NO_2, CO, and PM_{10} ($P < 0.05$). Overall, our results carefully examine the relationship between smoke parameters and cattle performance and present interesting pathways previously unexplored that could guide early culling/finishing of animals to avoid economic losses associated with performance decrease in response to wildfire smoke exposure. Though interesting associations are found under linear mixed models, causality is difficult to establish, which highlights the need for controlled exposure experiments.

Lay Summary

The increase in wildfire severity and frequency is of global concern. As temperatures continue to warm, and water scarcity increases, the incidence of wildfires is also expected to increase. This research aims to clearly identify causal relationships between wildfire smoke exposure and cattle performance. The results herein highlight the inconsistencies identified in currently published literature regarding cause–effect relationships when parametric statistics are utilized alone. Performance metrics related to body weight gain and feed intake are both positively and negatively linearly associated with wildfire smoke exposure; however, causal relations are not clear. These results help quantify profit losses in response to wildfire smoke exposure that could be used to determine optimal slaughter and sale points for livestock producers and emphasize the need for controlled exposure experiments.

Keywords: Beef cattle, body weight gain, causality, feed intake, performance, wildfire smoke

Introduction

As drought and temperatures increase across rangelands, there has been a shift in the natural fire cycle, resulting in an increase in wildfire frequency and intensity, which is only expected to be further exacerbated when considering anthropogenic influences and population growth (Carnicer et al., 2022). Wildfire smoke exposure in the western US has increased over the last decade and is expected to continue increasing (Li and Banerjee, 2021; O'Hara et al., 2021). Further, there is an expected significant increase of "very large fires" mid-century (2021 to 2070) compared to what we saw from 1971 to 2000 (Barbera et al., 2015). Though most of the US cattle are held in central states (APHIS USDA, 2017), wildfire smoke exposure to western rangeland backgrounded beef steers and dairy animals is concerning due to potential carryover effects when these animals are transported for finishing. This is particularly true for the Great Basin which has recently experienced increased frequency and severity in wildfires which are often associated with cheatgrass expansion which covers more than 400,000 km^2 (Williamson et al., 2020). With over two million animal

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unit months allocated to Nevada alone each year (Bureau of Land Management), the potential for animals to be exposed to wildfire will continue to increase. Therefore, as wildfires become a seasonal occurrence in many regions of the world, the exposure of livestock to wildfire smoke raises interest in both the acute and long-term consequences of exposure. Though research has extensively investigated the effects of wildfire smoke on humans (Son et al., 2015; Kiser et al., 2021; Nguyen et al., 2023), studies on livestock have been limited. Therefore, evaluation of the effects of this exposure on livestock is necessary to help guide management decisions such as early culling, and late sale of backgrounding/finishing animals based on health, performance, welfare, and profitability in response to wildfire smoke exposure. Additionally, expected insurance costs, payoffs, and premiums will likely be tailored behind the early publications documenting the health and performance effects of wildfire smoke exposure, which highlights the need for more scientific information and guidance.

Though it can be expected that exposure to wildfire smoke affects the respiratory system (i.e., lungs), several other studies have investigated a variety of biomarkers that could help enlighten potential pathways and mechanisms. Wildfire smoke exposure has previously been associated with myocardial thickening and thrombi formation (Sharpe et al., 2020), edema, hemorrhagic infarctions, degeneration of hepatocytes, and hemorrhages (Wohlsein et al., 2016). Few studies on livestock investigate the effects on health, pulmonary lesions, milk production, meat quality, and metabolic markers (Anderson et al., 2022; Hillman et al., 2022; Pace et al., 2023). To the knowledge of the authors, the effects on beef cattle specifically finished steers, have not been reported hitherto. The need to quantify the effects of wildfire smoke on performance is essential in determining the costs, as well as the consequences associated with wildfire smoke exposure.

To generate these results, the data type, quality, and inferences made from the data are of critical importance to ensure accurate recommendations are made. The structure and origin of the data as well as the way that data are analyzed and reported are of extreme importance. To adequately assess the effects of wildfire smoke, sufficient data before, during, and after smoke exposure is necessary to determine clear effect responses. Current literature published on the topic makes it difficult to identify causal effects (defined as "comparisons among values that would have been observed under all possible assignments of treatments to experimental units"; Rubin, 1978) associated with wildfire smoke exposure. Parametric statistics are often misunderstood, and inferences and extrapolations from these statistics are often misused; further, repeatability and biased effect sizes are often overlooked in many publications (Amrhein et al., 2019). In some instances, multicollinearity and causality have largely been overlooked in currently published data reporting on the effects that wildfire smoke has on livestock performance and health (Anderson et al., 2022; Hillman et al., 2022). Such inferences could have detrimental economic effects, as these misleading associations would inaccurately influence policy, and misguide livestock producers as well as industry professionals. Overcoming these limitations can be explored through both parametric (Wellek, 2017; Amrhein et al., 2019) and nonparametric modeling techniques (Hill, 2011) by not only focusing on parametric *p* values but also investigating the causality behind those associations.

The goals herein involve the investigation of the effects of pre-during-post wildfire smoke exposure of finishing steers on performance and behavior parameters. We explore the causality of the relationships currently explored in literature and highlight the gap in research and knowledge currently necessary to address these through currently utilized and reported parametric models and present a nonparametric model often utilized to assess causality. We hypothesize that the comparison of linear mixed models and nonparametric Bayesian models will differ in variable and effect importance towards the parameters examined. Further, we hypothesize that negative effects between wildfire smoke and the parameters evaluated will be detected.

Materials and Methods

All animal procedures were approved by the University of Nevada, Reno Institutional Animal Care and Use Committee (protocols 00845 and 00827). The experiments were conducted at the University of Nevada, Reno, Main Station Field Laboratory (39.513010, −119.741808), a semi-arid high desert climate averaging 190 mm yearly precipitation, 1,370 m elevation, with annual temperature of 21.72 °C (±9.19 °C) over the 2020 to 2021 years experimental periods.

Animal data

The animal data were composited over a period of 2 yr for 2020 (24 animals, 105 d; 495.18 ± 13.83 kg, 17 mo ± 3) and 2021 (18 animals, 135 d; 491.13 kg ± 25.78, 16 mo ± 2) wildfire smoke events in Reno, Nevada. All animals were sourced from the university research Angus × Hereford herd and fed to finish. The parameters were examined daily over a period of 105 and 135 d for the 2020 and 2021 seasons, respectively. Daily feed intake (**FI**; fed individually utilizing Calan Broadbent feed troughs [American Calan, Northwood, NH]), body weight (**BW**), average daily gain (**ADG**), water intake (**WI**), water intake events (**WIE**; represented the instances where animals visited the water troughs and consumed water), no-WIE (**NWIE**; represented the periods when animals visited the water through without actually consuming water), and time spent drinking (**TSD**; represented as the minutes spent on a day drinking water) were utilized as metrics to assess the effects of wildfire exposure on cattle behavior and performance. All other data were collected via an automated radio frequency identification (**RFID**) individual tag continuous monitoring system (Intergado, Ltda., Contagem, Minas Gerais, Brazil). The parameters collected were monitored individually for assessment of animal performance, efficiency, and behavior.

For the 2020 experiment, finished steers were split into grass ($n = 12$; crude protein (**CP**): 21.3%, net energy for maintenance (**NEm**): 0.32 Mcal/kg; net energy for gain (**NEg**): 0.20 Mcal/kg) and grain ($n = 12$; CP: 10.8%, NEm: 0.40 Mcal/kg; NEg: 0.30 Mcal/kg) finishing diets. For the 2021 experiment, finished steers were split into implanted ($n = 9$) and non-implanted ($n = 9$) treatments with all animals receiving one diet (CP = 14.79%, NEm = 0.39 Mcal/kg, NEg = 0.26 Mcal/kg). The treatments administered were chosen to originally investigate the effects of grain and grass diets and hormonal implants on animal water requirements and water footprint.

Air quality data

Air quality data were obtained from the United States Environmental Protection Agency (EPA, 2020) with sensors located at the Reno-Tahoe International Airport within a mile from the Main Station Field Laboratory experimental station for the University of Nevada, Reno. The parameters consisted of carbon monoxide (**CO**), sulfur dioxide (**SO_2**), Ozone, nitrogen dioxide (**NO_2**), and particulate matter under 2.5 µm (**$PM_{2.5}$**) and under 10 µm (**PM_{10}**), and the average air quality index (**AQI**; EPA, 2023a). The wildfire smoke exposure occurred during the last 50 d of the 2020 experiment and during the last 80 d of the 2021 experiment.

2020 season Wildfire exposure in Reno from August to October for the 2020 year from the Beckwourth Complex Fire, totaling 43 d of unhealthy air (Kiser et al., 2021). A more detailed map tracking the smoke exposure in the area can be found in Kiser et al. (2021).

2021 season For the 2021 smoke season, the Dixie fire was the biggest contributor to our smoke season during the experiment. This fire represented 71 d of smoke from July to October in Reno Nevada (Cal Fire, 2022).

Figures 1–4 are fit with a simple linear regression to show the overall behavior (increasing or decreasing), and the weighted least squares loess regression is fitted to investigate specific nonlinearities detected through time (Cleveland et al., 1992). The observed air quality parameters are reported in Figures 3 and 4.

Statistical analyses

Statistical analyses were performed on R Statistical Software (R Core Team, 2023). Linear mixed models with a 7-d lag (Anderson et al., 2022) were utilized to assess the effects of wildfire smoke exposure and environmental parameters on performance metrics collected intensively. In brief:

$$Y_{ijk} = \beta_1 + X_i\beta_i + T_j\beta_j + A_k + \epsilon_{ijk}$$

Where Y_{ij} represents the response effect modeled as the animal parameters affected by the X_i environmental air quality parameters (CO, NO_2, SO_2, $PM_{2.5}$, PM_{10}, AQI, OZ) among the different T_j treatments over the 2-yr period, A_k represents the animal random effect, and ϵ_{ijk} is the random error. The lag models are explained in Anderson et al. (2022) and Pace et al. (2023), only 7-d lag models are reported (for consistency with previously published results).

In addition to linear lag models, Bayesian additive regression trees (**BART**) were utilized, and credible intervals were generated for all predictors to determine if causality could be associated with the linear patterns (Hill, 2011). The bartMachine package in R was utilized to generate the BART models. Individual BART models were generated per treatment and year. In brief, the BART models were as follows:

$$\begin{aligned} Y = f(X) + \Sigma \approx \mathrm{T}_1^{\mathrm{M}}(X) + \mathrm{T}_2^{\mathrm{M}}(X) + \ldots \\ + \mathrm{T}_m^{\mathrm{M}}(X) + \Sigma, \quad \Sigma \sim \mathrm{N}_n(0, \sigma^2 I_n), \end{aligned}$$

Where Y is the $n \times 1$ vector of responses, X is the $n \times p$ design matrix, and Σ is the $n \times 1$ vector of noise with m distinct regression trees, with tree structure T and parameters at the terminal nodes or leaves denoted by M, and the two, T^{M} representing an entire tree with structure and a set of leaf parameters (Kapelner and Bleich, 2016). Unlike other ensemble methods, a set of priors is utilized to provide regularization which prevents any single tree from dominating the total fit; for a more complete description see (Chipman et al., 2010). Statistics reported were all fitted independent samples of the data kept from model fitting (out-of-bag; 30% of the data), data utilized for fitting the models (in-bag 70% of the data).

Variable importance and effects To assess individual response with all other parameters constant, we employed the covariate importance test from the bartMachine package, which employs analyses analogous to one-sided t test, F-test, or omnibus F-test from ordinary least squares (Kapelner and Bleich, 2016). For the linear models, the strength of

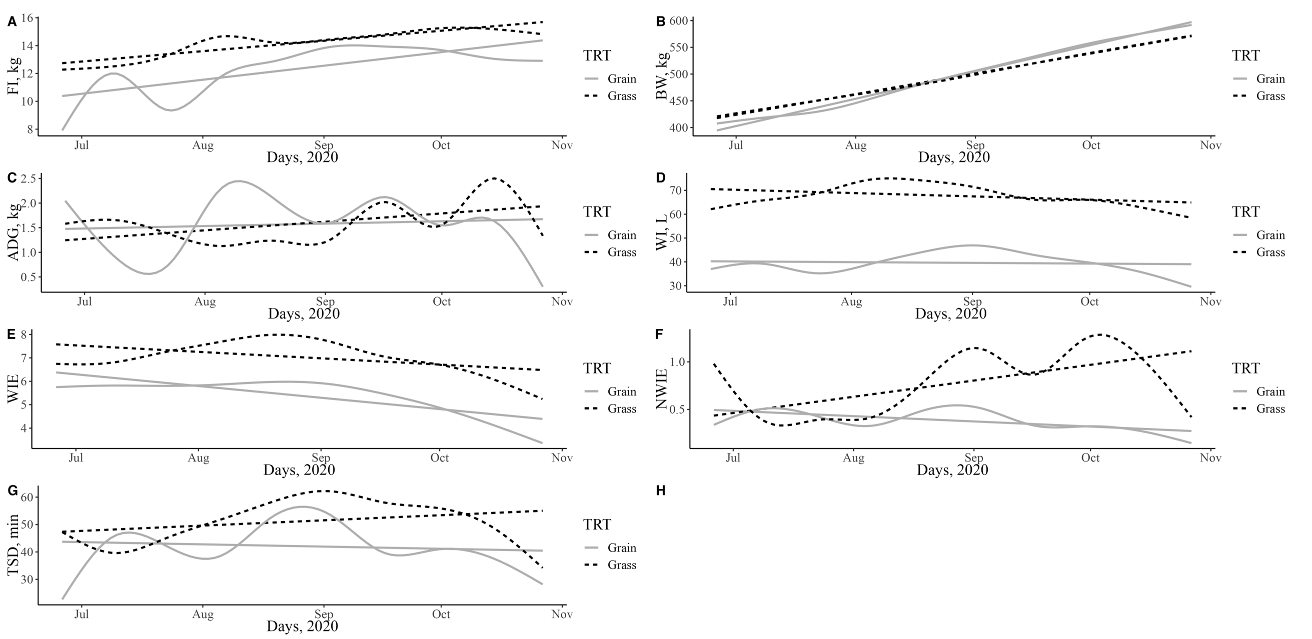

Figure 1. Performance and behavior parameters for finishing steers under smoke exposure during the 2020 season.

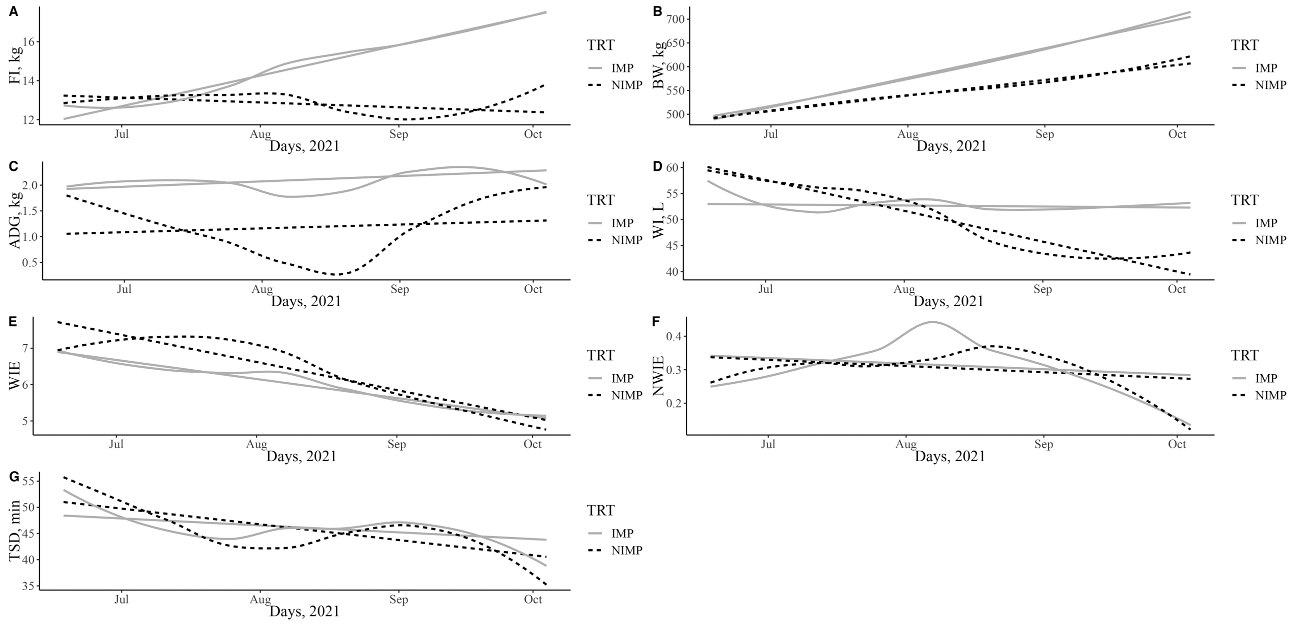

Figure 2. Performance and behavior parameters for finishing steers under smoke exposure during the 2021 season.

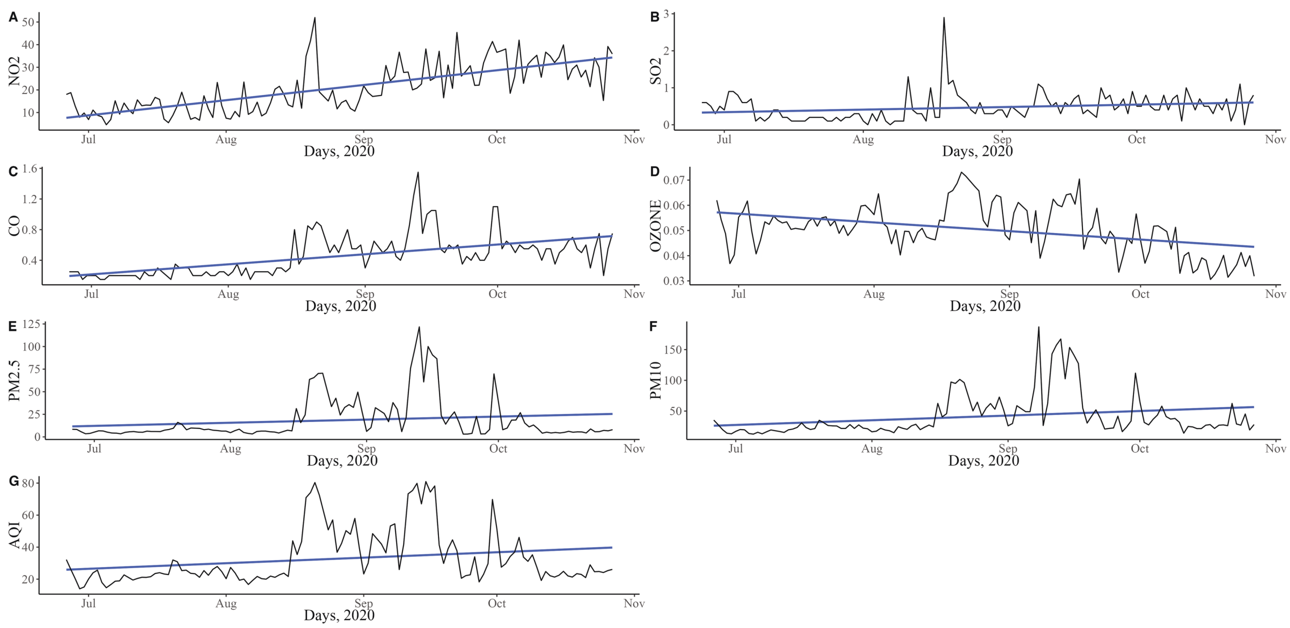

Figure 3. Environmental parameter quality for the 2020 smoke season, straight (blue) line represents a linear model fit on the data to assess the overall behavior of the data.

associations was examined through the default *t* test statistics reported in association with the response.

Results

The results presented below represent the 7-d lag models like those reported by Anderson et al., (2022). The linear mixed models with a 7-d lag are reported first followed by a paragraph with the BART at the end of each subsection.

Feed intake

FI was consistently higher for grain-finished steers compared to grass-finished steers, but both linearly increased for the 2020 season (Figure 1). During the 2021 season, implanted steers linearly increased their FI without much change, whereas non-implanted steers appeared to decrease their FI slightly overtime, showing a quadratic decrease with a minimum intake in FI around the fire season in September (Figure 2).

SO_2, AQI, NO_2, CO, and $PM_{2.5}$, PM_{10}, all had significant linear effects on FI throughout the 2 yr ($P < 0.05$; Tables 1 and 2). Grain-finished steers appeared to display positive effects between FI and SO_2 levels and AQI ($P < 0.001$; Table 1), and significantly negative effects with $PM_{2.5}$ ($P < 0.001$; Table 1). For grass-finished steers, during that same season, significant positive effects on FI were detected for NO_2, SO_2, and AQI ($P < 0.008$), with negative effects

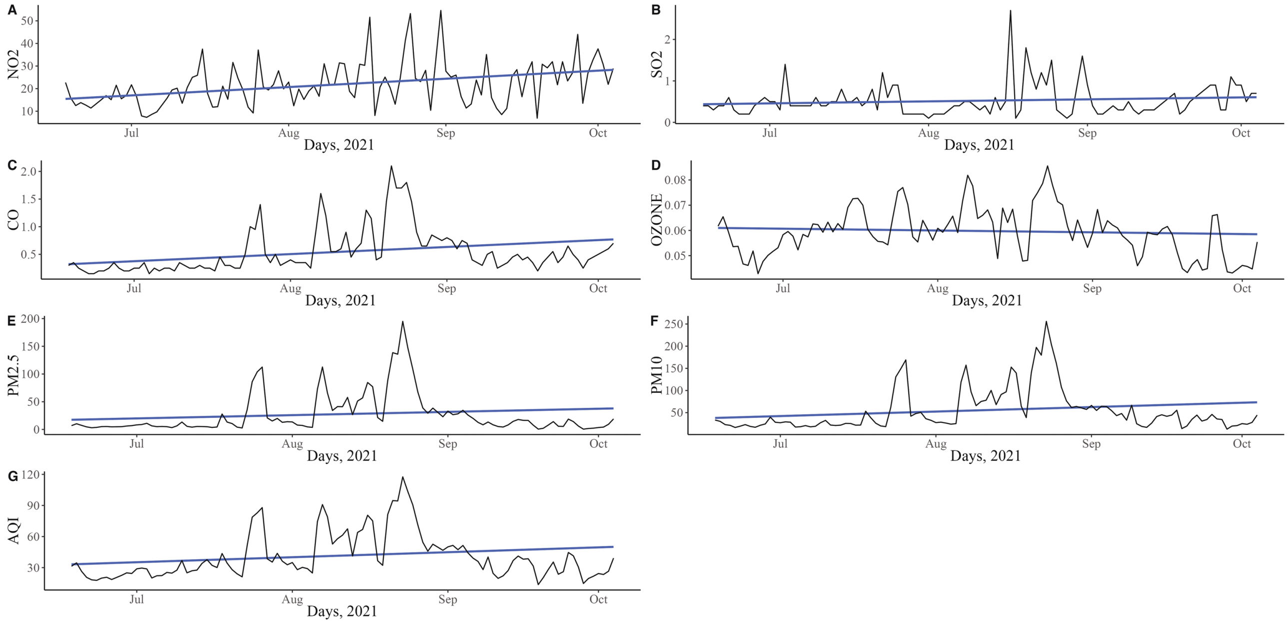

Figure 4. Environmental parameter quality for the 2021 smoke season, the straight (blue) line represents a linear model fit on the data to assess the overall behavior of the data.

Table 1. Effects of wildfire smoke exposure on FI, BW, and ADG for grain- and grass-finished steers in the 2020 smoke season

Parameters[1]	Estimate	Standard error	*P* value	Estimate	Standard error	*P* value
	Grain-finished steers			Grass-finished steers		
Feed intake						
Intercept	12.286	0.481	<0.001	14.189	0.156	<0.001
NO_2	−0.066	0.120	0.583	0.313	0.076	<0.001
SO_2	1.163	0.235	<0.001	0.611	0.150	<0.001
CO	0.131	0.083	0.116	−0.189	0.053	<0.001
Ozone	−0.097	0.175	0.578	−0.042	0.111	0.704
$PM_{2.5}$	−2.037	0.358	<0.001	−0.971	0.229	<0.001
PM_{10}	0.192	0.259	0.458	0.060	0.165	0.715
AQI	1.736	0.468	<0.001	0.799	0.301	0.008
Body weight						
Intercept	493.184	10.545	<0.001	492.116	10.519	<0.001
NO_2	14.829	1.481	<0.001	12.428	1.110	<0.001
SO_2	63.981	2.895	<0.001	49.500	2.179	<0.001
CO	−4.741	1.023	<0.001	−4.695	0.766	<0.001
Ozone	−14.030	2.154	<0.001	−8.543	1.621	<0.001
$PM_{2.5}$	−68.632	4.414	<0.001	−50.661	3.326	<0.001
PM_{10}	1.063	3.187	0.739	2.332	2.396	0.330
AQI	39.041	5.767	<0.001	23.760	4.374	<0.001
Average daily gain						
Intercept	1.558	0.131	<0.001	1.559	0.099	<0.001
NO_2	−0.063	0.083	0.449	0.026	0.056	0.639
SO_2	−0.036	0.162	0.824	0.225	0.109	0.040
CO	−0.094	0.057	0.101	0.096	0.038	0.013
Ozone	0.018	0.121	0.881	−0.152	0.081	0.062
$PM_{2.5}$	−0.106	0.248	0.668	−0.616	0.167	<0.001
PM_{10}	0.172	0.179	0.337	0.329	0.120	0.006
AQI	0.220	0.323	0.497	0.131	0.219	0.550

[1]Grain- and grass-finished steers exposed to the 2020 smoke season.

Table 2. Effects of wildfire smoke exposure on FI, BW, and average daily for implanted and non-implanted grain-finished steers in the 2021 smoke season

Parameters[1]	Estimate	Standard error	*P* value	Estimate	Standard error	*P* value
	Implanted steers			Non-implanted steers		
Feed intake						
Intercept	14.027	0.532	<0.001	12.870	0.436	<0.001
NO_2	−0.013	0.129	0.922	0.153	0.113	0.176
SO_2	0.443	0.201	0.028	−0.361	0.178	0.043
CO	−0.323	0.098	<0.001	0.130	0.087	0.135
Ozone	0.162	0.171	0.343	0.236	0.151	0.118
$PM_{2.5}$	−2.131	0.428	<0.001	0.509	0.379	0.180
PM_{10}	1.233	0.510	0.016	0.039	0.459	0.933
AQI	1.179	0.459	0.010	−0.727	0.408	0.075
Body weight						
Intercept	567.221	11.069	<0.001	535.598	7.493	<0.001
NO_2	−0.230	2.793	0.934	−0.924	1.759	0.600
SO_2	21.933	4.349	<0.001	9.339	2.768	<0.001
CO	−7.449	2.126	<0.001	−5.068	1.354	<0.001
Ozone	16.772	3.699	<0.001	11.004	2.342	<0.001
$PM_{2.5}$	−65.665	9.248	<0.001	−37.986	5.894	<0.001
PM_{10}	43.643	11.012	<0.001	30.594	7.127	<0.001
AQI	17.958	9.928	0.071	6.305	6.335	0.320
Average daily gain						
Intercept	2.081	0.124	<0.001	1.134	0.193	<0.001
NO_2	−0.219	0.109	0.045	−0.223	0.108	0.040
SO_2	0.434	0.169	0.010	0.594	0.170	<0.001
CO	0.150	0.083	0.070	0.157	0.083	0.060
Ozone	0.149	0.144	0.301	0.087	0.144	0.545
$PM_{2.5}$	−0.406	0.360	0.260	−1.095	0.363	0.003
PM_{10}	1.156	0.428	0.007	1.192	0.439	0.007
AQI	−1.227	0.386	0.002	−0.894	0.390	0.022

[1]Implanted and non-implanted steers exposed to the 2021 smoke season.

for CO and $PM_{2.5}$ ($P < 0.001$; Table 1). For the 2021 smoke season, implanted grain-finished steers appeared to have detrimental effects on FI for $PM_{2.5}$ due to a slight positive effect detected for SO_2, PM_{10}, and AQI ($P < 0.05$; Table 2). For the non-implanted steers during the 2021 smoke season, the effects of wildfire smoke exposure were detrimental for FI due to SO_2 ($P = 0.043$; Table 2) and AQI ($P = 0.075$; Table 2), with no significant positive effects detected.

When evaluated for causal effects through the BART algorithm and credible intervals, variable importance for grain-finished steers during the 2020 smoke season only appeared to show a trend on CO ($P = 0.069$; Table 3). For the grass-finished steers during the 2020 smoke season, no significant variables appeared to influence FI of the animals ($P > 0.05$; Table 3). For the 2021 smoke season, implanted grain-finished steers had no significant effects, and non-implanted grain-finished steers only showed a significant effect for CO ($P < 0.001$; Table 3). For both years, the models with all variables were significant.

Body weight

A linear increase in BW was observed throughout the 2020 smoke season (Figure 1B). For the 2021 smoke season, both implanted and non-implanted steers increased their weight linearly through time, however, the implanted steers did it at a higher rate (Figure 3B).

For BW, Significant linear effects were observed across the 2 yr for NO_2, SO_2, AQI, CO, Ozone, $PM_{2.5}$ ($P < 0.05$; Tables 1 and 2). When evaluating the effects of wildfire smoke on BW of grain-finished steers during the 2020 season, significant positive effects were detected for NO_2, SO_2, and AQI ($P < 0.001$; Table 1); while, negative effects were detected for CO, Ozone, and $PM_{2.5}$ ($P < 0.001$; Table 1). For grass-finished steers, positive relations were detected for NO_2, SO_2, and AQI ($P < 0.001$; Table 1), while negative effects were detected for CO, Ozone, and $PM_{2.5}$ ($P < 0.001$; Table 1). For the 2021 smoke season the implanted grain-finished steers, significant positive effects on BW were detected for SO_2 ($P = 0.028$), Ozone ($P < 0.001$), and a trend for AQI ($P = 0.071$; Table 2), while, negative effects were detected for CO, and $PM_{2.5}$ ($P < 0.001$; Table 2). For the non-implanted grain-finished steers, significant positive effects were detected for SO_2, Ozone, and PM_{10} ($P < 0.001$), while negative significant effects were found for CO, and $PM_{2.5}$ ($P < 0.001$; Table 2).

When evaluated through the BART algorithm, during the 2020 smoke season, grain-finished steers showed no

Table 3. Variable importance tests for wildfire smoke composition variables through BART on dry matter intake, BW, ADG, WI, WIE, NWIE, TSD on finished steers

Parameters[1]	*P* values[2]							
	$PM_{2.5}$	PM_{10}	CO	NO_2	AQI	SO_2	Ozone	All covariates
Feed intake								
FIN_Grain	0.139	0.485	0.069	0.168	0.416	0.287	0.178	<0.001
FIN_Grass	0.376	0.495	0.248	0.505	0.653	0.178	0.436	<0.001
FIN_IMP_TMR	0.822	0.861	0.129	0.733	0.713	0.416	0.545	<0.001
FIN_NIMP_TMR	0.782	0.782	<0.001	0.703	0.703	0.782	0.851	<0.001
Body weight								
FIN_Grain	0.535	0.525	0.356	0.366	0.188	0.980	0.158	<0.001
FIN_Grass	0.822	0.941	0.792	0.891	0.782	0.990	0.287	<0.001
FIN_IMP_TMR	0.594	0.584	0.762	0.465	0.703	0.386	0.168	<0.001
FIN_NIMP_TMR	0.644	0.901	0.604	0.119	0.782	0.327	0.168	<0.001
Average daily gain								
FIN_Grain	0.772	0.703	0.812	0.941	0.762	0.911	0.455	<0.001
FIN_Grass	0.980	0.990	0.960	0.693	0.990	0.881	0.960	<0.001
FIN_IMP_TMR	0.871	0.713	0.574	0.762	0.644	0.762	0.089	<0.001
FIN_NIMP_TMR	0.980	0.990	0.931	0.950	0.990	0.970	0.921	<0.001
Water intake								
FIN_Grain	0.970	0.980	0.931	0.901	0.881	0.911	0.683	<0.001
FIN_Grass	0.931	0.841	0.871	0.881	0.921	0.911	0.832	<0.001
FIN_IMP_TMR	0.158	0.238	0.099	0.020	0.129	0.911	0.030	<0.001
FIN_NIMP_TMR	0.238	0.020	0.495	0.069	0.010	0.911	<0.001	<0.001
Water intake events								
FIN_Grain	0.792	0.545	0.554	0.752	0.693	0.950	0.267	<0.001
FIN_Grass	0.871	0.990	0.941	0.822	0.950	0.990	0.574	<0.001
FIN_IMP_TMR	0.594	0.594	0.139	0.515	0.733	0.703	0.683	<0.001
FIN_NIMP_TMR	0.574	0.545	0.842	0.683	0.475	0.149	0.436	<0.001
No water intake events								
FIN_Grain	0.990	0.990	0.990	0.990	0.990	0.990	0.990	<0.001
FIN_Grass	0.842	0.881	0.881	0.584	0.762	0.901	0.446	<0.001
FIN_IMP_TMR	0.822	0.881	0.713	0.663	0.881	0.911	0.901	<0.001
FIN_NIMP_TMR	0.792	0.891	0.426	0.842	0.990	0.960	0.990	<0.001
Time spent drinking								
FIN_Grain	0.752	0.594	0.960	0.297	0.772	0.842	0.178	<0.001
FIN_Grass	0.673	0.881	0.921	0.752	0.970	0.832	0.772	<0.001
FIN_IMP_TMR	0.535	0.594	0.327	0.634	0.574	0.812	0.584	<0.001
FIN_NIMP_TMR	0.752	0.475	0.950	0.980	0.812	0.842	0.591	<0.001

[1]Grain- and grass-finished steers exposed to the 2020 smoke season, and implanted and non-implanted steers exposed to the 2021 smoke season. FIN_Grain, grain-finished steers during the 2020 season; FIN_Grass, grass-finished steers during the 2020 season; FIN_IMP_TMR, implanted finished steers during the 2021 season; FIN_NIMP_TMR, non-implanted finished steers during the 2021 season.
[2]*P* values for variable importance from bayesian additive regression trees

significant effects on BW ($P > 0.05$; Table 3), the same was true for grass-finished steers during this season ($P > 0.05$; Table 3), and for both implanted and non-implanted grain-finished steers during the 2021 season ($P > 0.05$; Table 3). For both years, the models with all variables were significant ($P < 0.05$; Table 3).

Average daily gain

ADG increased linearly for both years of data. A shift in grain/grass ADG was observed for finished steers in September 2020 during the fire season where grain-finished steers ADG increased less gradually than that of grass-finished steers (Figure 1C), and with the implanted steers having higher rates than non-implanted steers during the 2021 season (Figure 2C).

Significant effects were detected between ADG and SO_2, NO_2, CO, AQI, PM_{10}, for 2020 and 2021, and $NO_{2.5}$ and Ozone for 2021 alone ($P < 0.05$; Tables 1 and 2). The 2020 smoke season appeared to have positive effects on ADG for SO_2 ($P = 0.010$) and PM_{10} ($P = 0.007$), and a trend in CO ($P = 0.083$), while negative effects on ADG were detected for NO_2 ($P = 0.045$), and AQI ($P = 0.002$; Table 1). For grass-finished steers during this season, positive effects on ADG were detected for SO_2 ($P = 0.040$), CO ($P = 0.013$), and PM_{10} ($P = 0.006$), while negative effects were detected with a trend for Ozone ($P = 0.062$), and a significant decrease on ADG for $PM_{2.5}$ ($P < 0.001$). For the 2021 smoke season, the effects of smoke exposure on ADG of grain-finished implanted steers appeared to show positive relations for SO_2 ($P = 0.010$), and PM_{10} ($P = 0.007$), with a trend for CO ($P = 0.083$), while negative effects were detected for NO_2 ($P = 0.045$), and AQI (0.002; Table 2). For non-implanted steers, positive effects were also detected for SO_2, PM_{10} ($P = 0.007$). While negative effects were detected for NO_2 ($P = 0.040$), $PM_{2.5}$ ($P = 0.003$), and for AQI, ($P = 0.022$).

No significant covariates were detected for any of the experiments throughout the smoke seasons for the BART algorithm. A trend was found during the 2021 season for the grain-finished implanted steers for the Ozone ($P = 0.089$; Table 3). For both years, the models with all variables were significant.

Water intake

WI across both years appeared constant, except for non-implanted steers who had a linear decrease throughout the experiment (Figures 1D and 2D).

Significant effects were detected for CO, AQI, NO_2, SO_2, $PM_{2.5}$, PM_{10}, for the 2020 and 2021 year and Ozone for the 2021 year alone WI ($P < 0.05$; Tables 1 and 2). For the 2020 smoke season, the effects of wildfire smoke on WI for grain-finished steers showed positive relations for CO ($P = 0.023$), and for AQI ($P < 0.001$), while negative effects were found for NO_2 ($P < 0.001$), SO_2 ($P = 0.025$), and $PM_{2.5}$ ($P = 0.019$; Table 4). For grass-finished steers, positive effects were detected for Ozone ($P = 0.020$) and AQI ($P = 0.012$), while negative effects were found for NO_2 ($P = 0.036$), SO_2 ($P < 0.001$), and PM10 ($P = 0.019$; Table 4). WI from the 2021 smoke season for grain-fed implanted steers showed positive effects for SO_2 ($P = 0.004$), Ozone ($P = 0.057$), and PM_{10} ($P < 0.001$), while negative effects were detected for $PM_{2.5}$ ($P = 0.002$), and for AQI ($P = 0.006$; Table 5). For grain-fed non-implanted steers, positive relations were observed for CO ($P = 0.006$), and $PM_{2.5}$ ($P = 0.018$), while trends were identified for PM_{10} ($P = 0.100$) and AQI ($P = 0.100$; Table 5).

When evaluated through the BART algorithm, during the 2020 smoke season, no significant variables were detected (Table 3). For the 2021 smoke season, NO_2 ($P = 0.020$; Table 3) and Ozone ($P = 0.030$; Table 3) for grain-finished implanted steers were significant parameters for the models, and CO showed a trend ($P = 0.099$; Table 3). For non-implanted steers during the 2021 season PM_{10} ($P = 0.020$; Table 3), and AQI ($P = 0.010$; Table 3) were significant while a trend was observed for NO_2 ($P = 0.069$; Table 3). For both years, the models with all variables were significant.

Water intake events

WIE decreased linearly during both years but appeared to display a quadratic dynamic behavior with the maximum being achieved around September, which happens to match the smoke exposure season (Figures 1E and 2E).

For WIE, significant effects were detected for CO, SO_2, PM_{10}, AQI, $PM_{2.5}$, and Ozone over the 2 yr ($P < 0.05$; Tables 1 and 2). During the 2020 smoke season, positive relations between wildfire smoke and WIE for grain-finished steers for CO ($P = 0.006$) were observed, while negative associations were detected as trends for SO_2 ($P = 0.084$), and PM_{10} ($P = 0.053$; Table 4). For grass-finished steers, only AQI was detected to have a positive association ($P < 0.001$), while negative associations were detected as a slight trend for CO ($P = 0.069$) for Ozone ($P = 0.010$), $PM_{2.5}$ ($P < 0.001$), and PM_{10} ($P < 0.001$; Table 4). For the 2021 smoke season, finished implanted steers showed no positive associations with wildfire smoke, whereas negative associations were detected for PM_{10} ($P = 0.029$; Table 5). For finished non-implanted steers, positive associations were detected for CO ($P < 0.001$), and for AQI ($P = 0.055$), while negative associations were found for NO_2 ($P = 0.011$), Ozone ($P = 0.035$), and for PM_{10} ($P = 0.023$; Table 5).

WIE for the 2020 and 2021 smoke seasons showed no significant variable effects from the BART, but when all covariates were utilized, the model was significant (Table 3).

No-WIE

NWIE decreased for grain-finished animals in the 2020 smoke exposure, whereas the grass-finished animals had a linear increase throughout the experiment; dynamically, they appeared to vary through time but appeared to have a periodic increase and decrease (Figure 1F). During the 2020 smoke season, grass-finished steers also displayed a high increase in NWIE during September–November (Figure 1F), which appeared to match the smoke season this year.

For NWIE, significant effects were detected for NO_2, SO_2, AQI, CO, PM_{10}, and Ozone over the 2 yr ($P < 0.05$; Tables 1 and 2). Grain-finished steers in 2020 showed no positive associations, while negative associations were detected for NO_2 ($P = 0.003$), and SO_2 ($P < 0.001$; Table 4). For grass-finished steers during this season, a positive association was detected with AQI ($P = 0.043$), while negative associations were detected for SO_2 ($P = 0.005$; Table 5). For the 2021 smoke season, both implanted and non-implanted decreased NWIE through time. A positive trend was detected for finished implanted steers for SO_2 ($P = 0.058$), while only a negative effect was detected for AQI ($P = 0.042$; Table 5). For finished non-implanted steers, a positive effect was detected for CO ($P = 0.017$), while a negative trend was detected for PM_{10} ($P = 0.063$; Table 5).

NWIE for the 2020 and 2021 smoke seasons showed no significant variable effects from the BART, but when all covariates were utilized, the model was significant (Table 3).

Time spent drinking

During the 2020 smoke season, TSD increased linearly for grain-finished steers with a quadratic maximum around September and decreased linearly for grass-finished steers with a curvilinear local maximum around the same time (Figure 1G). For the 2021 smoke season, both implanted and non-implanted steers decreased TSD linearly through time, showing the same nonlinear patterns with decreases around August and increases around September (Figure 2G).

For TSD, significant effects were detected for CO, AQI, NO_2, NO_2, SO_2, $PM_{2.5}$, over the 2 yr ($P < 0.05$; Tables 1 and 2). During the 2020 smoke season, for the TSD on grain-finished steers, positive associations were detected for CO ($P = 0.022$), and for AQI ($P = 0.041$), while negative associations were observed trending for NO_2 ($P = 0.083$), and significant associations for SO_2 ($P = 0.032$; Table 4). For grass-finished steers, positive associations were detected for AQI ($P < 0.001$) alone, while negative associations were detected for $PM_{2.5}$ ($P < 0.001$; Table 4). For TSD during the 2021 smoke season, finished implanted steers had a positive association detected for NO_2 ($P = 0.009$), SO_2 ($P = 0.008$), and a trend was

Table 4. Effects of wildfire smoke exposure on WI, WIE, NWIE, and TSD for grain- and grass-finished steers in the 2020 smoke season

Parameters[1]	Estimate	Standard error	*P* value	Estimate	Standard error	*P* value
	Grain-finished steers			Grass-finished steers		
Water intake						
Intercept	39.385	2.416	<0.001	67.898	2.028	<0.001
NO_2	−1.491	0.394	<0.001	−0.945	0.451	0.036
SO_2	−1.722	0.770	0.025	−3.178	0.886	<0.001
CO	0.621	0.272	0.023	−0.246	0.311	0.429
Ozone	0.274	0.573	0.632	1.536	0.659	0.020
$PM_{2.5}$	−2.754	1.173	0.019	0.208	1.352	0.877
PM_{10}	0.096	0.847	0.910	−2.284	0.974	0.019
AQI	6.520	1.533	<0.001	4.482	1.778	0.012
Water intake events						
Intercept	−1.145	0.1688	<0.001	−0.458	0.1552	0.003
NO_2	−0.088	0.0735	0.232	0.061	0.0488	0.210
SO_2	−0.265	0.1530	0.084	−0.005	0.0991	0.963
CO	0.114	0.0413	0.006	−0.065	0.0355	0.069
Ozone	0.119	0.1101	0.281	−0.199	0.0770	0.010
$PM_{2.5}$	0.113	0.2648	0.671	−0.693	0.1738	<0.001
PM_{10}	−0.407	0.2103	0.053	−0.449	0.1172	<0.001
AQI	0.413	0.3024	0.172	1.260	0.2242	<0.001
No water intake events						
Intercept	1.657	0.0552	<0.001	1.940	0.0395	<0.001
NO_2	−0.060	0.0199	0.003	−0.027	0.0172	0.118
SO_2	−0.176	0.0395	<0.001	−0.095	0.0343	0.005
CO	0.018	0.0132	0.166	−0.001	0.0117	0.963
Ozone	0.025	0.0286	0.383	0.018	0.0252	0.473
$PM_{2.5}$	0.047	0.0584	0.424	−0.008	0.0523	0.884
PM_{10}	0.011	0.0411	0.796	−0.047	0.0375	0.213
AQI	0.097	0.0768	0.207	0.138	0.0681	0.043
Time spent drinking						
Intercept	41.837	4.275	<0.001	50.753	2.890	<0.001
NO_2	−2.242	1.292	0.083	−1.205	1.102	0.274
SO_2	−5.437	2.526	0.032	−1.889	2.163	0.383
CO	2.043	0.893	0.022	0.324	0.760	0.670
Ozone	0.327	1.879	0.862	−0.467	1.609	0.772
$PM_{2.5}$	−1.012	3.851	0.793	−11.851	3.301	<0.001
PM_{10}	−2.906	2.781	0.296	0.810	2.378	0.733
AQI	10.287	5.031	0.041	15.632	4.341	<0.001

[1]Grain- and grass-finished steers exposed to the 2020 smoke season.

detected for Ozone ($P = 0.065$), while negative associations were detected for CO ($P = 0.013$) and a negative trend for AQI ($P = 0.075$; Table 5). For finished non-implanted steers, positive associations were detected for SO_2 ($P = 0.046$), while negative associations were not detected (Table 5).

The TSD for the 2020 and 2021 smoke seasons showed no significant variable effects from the BART, but when all covariates were utilized, the model was significant (Table 3).

Prediction and credible intervals

Tables 6 and 7 show the significant drop in coverage of variation when comparing prediction and credible intervals. The highest credible intervals were observed for non-implanted steers during the 2021 season, with some high credible intervals for feed and WI and their behaviors, but not as high for BW and ADG.

Discussion

Current literature seems to be fixed on the effects that $PM_{2.5}$ and PM_{10} have on health without considering the actual organic volatiles and other inorganic oxidant radicals in the smoke (Andersen et al., 2022; Pace et al., 2023). The effects from these variations have consistently been discussed in other studies, yet continue to be overlooked in cattle production (Nguyen, et al., 2023). Inconsistencies of effects in response to wildfire smoke have been evaluated for humans through causal models where they examined $PM_{2.5}$ effects on human

Table 5. Effects of wildfire smoke exposure on WI, WIE, NWIE, and TSD for implanted and non-implanted grain-finished steers in the 2021 smoke season

Parameters[1]	Estimate	Standard error	*P* value	Estimate	Standard error	*P* value
	Implanted steers			Non-implanted steers		
Water intake						
Intercept	52.169	1.981	<0.001	53.084	2.227	<0.001
NO_2	0.067	0.533	0.900	−0.754	0.615	0.221
SO_2	2.378	0.829	0.004	−0.760	0.967	0.433
CO	−0.591	0.405	0.145	1.313	0.473	0.006
Ozone	1.342	0.705	0.057	−0.070	0.819	0.932
$PM_{2.5}$	−5.455	1.763	0.002	4.865	2.060	0.018
PM_{10}	7.608	2.100	<0.001	−4.060	2.491	0.100
AQI	−5.176	1.893	0.006	−3.618	2.214	0.100
Water intake events						
Intercept	−1.363	0.2310	<0.001	−1.202	0.1727	<0.001
NO_2	0.054	0.0899	0.546	−0.246	0.0966	0.011
SO_2	0.150	0.1485	0.313	0.108	0.1459	0.460
CO	0.102	0.0666	0.127	0.227	0.0626	<0.001
Ozone	0.070	0.1228	0.566	−0.276	0.1308	0.035
$PM_{2.5}$	0.321	0.3409	0.346	0.287	0.3562	0.420
PM_{10}	−0.870	0.3993	0.029	−0.970	0.4255	0.023
AQI	0.239	0.3330	0.473	0.682	0.3560	0.055
No water intake events						
Intercept	1.807	0.0573	<0.001	1.902	0.0510	<0.001
NO_2	0.012	0.0215	0.592	−0.018	0.0215	0.416
SO_2	0.064	0.0336	0.058	−0.001	0.0346	0.988
CO	−0.012	0.0166	0.457	0.039	0.0163	0.017
Ozone	0.028	0.0279	0.308	0.005	0.0286	0.862
$PM_{2.5}$	0.025	0.0712	0.724	0.103	0.0745	0.166
PM_{10}	−0.001	0.0836	0.987	−0.167	0.0895	0.063
AQI	−0.156	0.0767	0.042	−0.016	0.0791	0.839
Time spent drinking						
Intercept	46.653	6.586	<0.001	48.027	3.558	<0.001
NO_2	3.245	1.245	0.009	−1.492	1.250	0.233
SO_2	5.168	1.939	0.008	3.923	1.967	0.046
CO	−2.368	0.948	0.013	0.846	0.962	0.379
Ozone	3.044	1.649	0.065	0.414	1.665	0.804
$PM_{2.5}$	3.842	4.123	0.352	−1.411	4.188	0.736
PM_{10}	−4.647	4.909	0.344	−7.457	5.065	0.141
AQI	−7.894	4.425	0.075	3.645	4.502	0.418

[1]Implanted and non-implanted steers exposed to the 2021 smoke season.

health (Cox, 2023). Herein we demonstrate that overlooking other parameters is misleading given the wide variation in response effect when evaluating animal performance.

Our results highlight that this omission is grave and that animals are affected differently by PM and by other volatiles associated with wildfire smoke. Furthermore, causality is often overlooked in most analyses reporting data on wildfire smoke which can be troublesome, especially when attempting to establish guidelines and recommendations related to animal health and the producer's response to wildfires. Given that these results are also expected to influence insurance premiums and subsidized government programs, great caution should be taken when examining the data to make well-informed decisions on these issues. Associations reported without considering biological significance or meaning are misleading, and when establishing new policy; *correlation and causation should not be considered one.*

Positive associations

FI has previously been utilized as a predictor of digestive disease (Macias Franco et al., 2023). For the 2020 year, both PM_{10} and $PM_{2.5}$ increased linearly through time (Figure 3E and F), only a negative effect was observed for $PM_{2.5}$ which would somewhat agree with the literature citing that smaller particulate matter is expected to pass further into the alveoli

Table 6. Prediction interval coverage for in-sample and out-of-sample predictions for the effect of wildfire smoke exposure on beef cattle performance and behavior

Parameters[1]	IS	OOS	IS	OOS	IS	OOS	IS	OOS
	Grain-finished steers		Grass-finished steers		Implanted steers		Non-implanted steers	
Feed intake, kg	96.49	96.61	96.92	97.60	96.86	95.11	96.62	95.93
Body weight, kg	97.00	96.95	95.03	96.92	97.95	93.48	98.38	95.93
Body weight gain, kg	95.21	96.27	95.80	94.86	95.90	94.02	95.45	92.44
Water intake, L	95.76	93.02	95.63	95.55	96.45	91.85	97.36	94.19
Water intake events	96.66	96.61	96.49	94.52	96.72	93.48	97.94	93.60
No water intake events	94.35	94.24	95.80	94.86	94.26	95.65	95.15	94.19
Time spent drinking, m	96.49	93.56	96.49	96.58	95.63	91.30	96.48	91.28

[1]Grain- and grass-finished steers were exposed to the 2020 smoke season, and implanted and non-implanted steers were exposed to the 2021 smoke season. Param, parametric models for; IS, in sample evaluation of predictions; OOS, out of sample evaluation of predictions.

Table 7. Credible interval coverage for in-sample and out-of-sample predictions for the effect of wildfire smoke exposure on beef cattle performance and behavior

Parameters[1]	IS	OOS	IS	OOS	IS	OOS	IS	OOS
	Grain-finished steers		Grass-finished Steers		Implanted steers		Non-implanted steers	
Feed intake, kg	47.7	52.20	59.90	58.90	60.52	50.54	60.06	61.05
Body weight, kg	41.52	38.31	45.42	47.60	49.04	44.57	42.73	47.67
Body weight gain, kg	45.89	42.03	54.24	54.45	51.78	52.17	64.32	69.19
Water intake, L	68.13	56.40	51.67	47.95	58.74	45.65	65.93	62.79
Water intake events	49.32	46.78	52.44	48.29	62.43	56.52	64.14	63.95
No water intake events	48.12	47.12	64.18	61.64	61.34	58.15	64.61	62.21
Time spent drinking, m	58.65	54.58	57.67	55.48	58.61	47.83	55.95	45.35

[1]Grain- and grass-finished steers exposed to the 2020 smoke season, and implanted and non-implanted steers exposed to the 2021 smoke season. Param, parametric models for; IS, in-sample evaluation of predictions; OOS, out of sample evaluation of predictions.

and can therefore be chemiosmotically transferred into the blood more easily (EPA, 2023b). Increasing FI in response to stressors, termed "stress-induced or emotional eating" (McMillan, 2013), could explain the significant positive associations with increased exposure to wildfire smoke. Similarly, hormonal/enzymatic imbalances in response to the smoke particulates could directly influence intake (i.e., insulin which would increase FI; Sharma et al., 2022). In laboratory mice, stressors have been shown to increase FI, signaling pathways of hyperphagia as a mechanism in response to stressors (Francois et al., 2022). An additional hormone stress-influenced hormone is leptin. Increases of leptin in response to acute stress are studied in humans and mice to predict increases of intake in comfort foods (Tomiyama et al., 2012); which could also be associated with stress associated with smoke exposure. However, these effects from acute and prolonged smoke exposure remain to be explored in cattle. Additional mechanisms altering hormonal regulation related to intake in response to stress should be investigated and utilized to develop thresholds for marketing points to delineate optimal trade-offs for profitability during wildfire smoke exposure; for instance, proteomic or metabolomic markers indicating nutritional or stress status could be utilized to develop culling or early slaughter thresholds after prolonged exposure optimizing for costs associated with feed and medication. Additionally, future studies should investigate if cattle exposed to wildfire smoke develop epigenetic or histologic modifications that could affect them at later stages (i.e., finishing/lactation/future progeny).

BW and ADG positive associations likely follow similar pathways as those mentioned for FI and could simply be co-factors of modifying FI. Mechanisms of extraordinary gain in response to stressors or deficiencies are common in cattle. Compensatory gain is often associated with abnormally high gains in BW following periods of stress (Keady et al., 2021; Moura et al., 2022), it could be sufficient to help explain the positive associations we observed in the fire exposure years.

Regarding WI, WIE, NWIE, and TSD, wildfire smoke exposure is known to affect animal behavior and health of wild animals (Sanderfoot et al., 2022). Positive associations on increasing behavioral visits without intake such as NWIE, have previously been utilized to demonstrate animals experiencing digestive disturbance visit water troughs more frequently without consuming water (Macias Franco et al., 2023). Positive associations for WI, WIE, and the TSD could be explained through phenomenon previously observed on mice where WI and water balance produce a better ability to respond to stressors in rats through mechanisms related to social aspects of waterers and through chemiosmotic balances that could also suppress fear and anxiety (Krause et al., 2011).

Negative associations

The negative associations observed for FI and $PM_{2.5}$ have not been reported in the literature but have previously been associated negatively with performance in milk production in dairy cows (Anderson et al., 2022), negatively in postmortem carcass cattle traits, and increased pneumonia and pleurisy in sheep (Hillman et al., 2022), and in heifers' metabolism and health (Pace et al., 2023). Our results indicate that smoke exposure negatively affects FI, WI, BW, ADG, and behavioral intake patterns of finishing cattle.

Feeding behavior has previously been explored to highlight the effects of stress in cattle. Nogues et al. (2020) showed that differential responses to social stress are observed in the behavior of dairy heifers, with negative effects on behavior reported for time feeding and resting, among others. Such effects on behavior would help explain the negative effects observed on FI and behaviors associated with intake. Decreased FI during digestive disturbances has previously been reported in our group (Macias Franco et al., 2023). A potential mechanism for this during wildfire smoke exposure could be the effects of the buffering ability of saliva. In a human saliva study, buffering ability and alkaline phosphatase activity were severely affected in smokers compared to nonsmokers (Ahmadi-Motamayel et al., 2016). Though these effects should be explored for ruminant animals in future studies, the potential effect of witnessing those buffering effects on fermentation is alarming. The effects of saliva on rumen pH have been associated wth inadequate salivary secretion which further complicated acidosis and subacute acidosis (Goad et al., 1998; Nagaraja and Titgemeyer, 2007); therefore, salivary buffering in response to wildfire smoke should be considered in intensively raised livestock (feedlots and dairies). The negative associations we observed could therefore be explained by inadequate saliva production in response to reduced intakes, also paired with the reduced buffering ability of the saliva produced.

The negative effects associated with BW and ADG could be associated with histological respiratory damage, however, these remain to be studied in cattle. The effects of respiratory disease and pulmonary lesions have previously been explored and associated with decreased weight gain in feedlot cattle (Wittum et al., 1996). A potential mechanism for these effects could be through pulmonary lesions that manifest as reduced intakes and overall performance.

Lastly, a likely mechanism for all negative associations could be explained by the buffering effects on blood pigment. Increased partial atmospheric pressures and concentrations of oxidants from wildfire smoke would alter the binding ability of O_2 in blood pigments which would alter the buffering ability, respiratory and enzymatic activity, and the potential regulation of mitochondrial respiration (Hill et al., 2012). All of which would have detrimental effects on the animal. Given that wildfire smoke exposure could affect the blood pigment's buffering ability, livestock studies should investigate the effects associated with this altered buffering ability. Acid balance in blood is essential in ruminants for most of the energy is supplied through volatile fatty acid absorption. Blood and salivary pH alterations occur when animals are acidotic (Nagaraja and Titgemeyer, 2007); therefore, potential disturbances in blood pH due to wildfire smoke exposure could alter animal energetics and health through impaired blood buffering ability.

Causal inferences and BART

The statistically significant numerical associations (parametric) found in all datasets should be interpreted carefully. As animals grow, their BW will increase, their FI will increase, and the WI will also increase. Therefore, when paired with linearly increasing data, we can expect significant effects to be captured by many regression models based solely on the fact that both performance parameters and smoke parameters during wildfires increase. Regarding credible intervals, the lack of effects on BW as long-term metrics appear to signal that the effect exposure to animals is short-lived and that acclimation to fire allows the animals, to some extent, to continue performing adequately. The effects observed on intake and intake behaviors highlight potential causal relations that should further be explored in future controlled exposure trials.

The lack of high-performing credible intervals, as well as their significant lower values when compared to prediction intervals suggest that better-controlled experiments are necessary to explore relationships between wildfire smoke and cattle. Evaluation of controlled exposure studies will allow for a better examination of the decision boundaries behind these algorithms and data. Further, future studies should examine histological damage and draw focus on the potential of delayed epigenetic generational modifications (Moura et al., 2022) and later-in-life modifications that could hinder performance (i.e., how does early exposure affect lung capacity of finishing/dairy animals during lactation/finishing).

Conclusion

Our results are the first to highlight the causality of effects currently being overlooked in wildfire smoke effects on cattle. We present potential mechanisms for positive and negative effects on FI, WI, BW, and ADG, as well as in intake behaviors under linear lag mechanisms. Our findings demonstrate the significance behind linear and nonlinear modeling techniques and prove that even with multi-year pre-during-post smoke exposure, causal relations between performance and wildfire smoke are difficult to establish. These results highlight the need for controlled exposure experiments with dose–response titrations to assess the effects of wildfire smoke exposure on cattle performance and health.

Supplementary Data

Supplementary data are available at *Translational Animal Science* online.

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Conflict of interest statement

The authors declare no perceived conflicts of interest.

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