

## ORIGINAL ARTICLE

# Increase in infected corneal ulcerations in dogs during the northern Colorado's 2020 wildfire season

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## Abstract

**Objective:** In the fall of 2020, Colorado experienced the two largest wildfires in state history. The smoke blanketed the college town of Fort Collins, Colorado, the location of the Veterinary Teaching Hospital at Colorado State University (CSU-VTH). The objective for this cross-sectional observational study was to evaluate how these wildfires and the corresponding elevated air quality index (AQI) was associated with infected corneal ulcerations in dogs when compared to the two previous years.

**Animals:** Seventeen dogs were included in this study.

**Procedures:** Medical records from dogs presented to the CSU-VTH ophthalmology service with infected corneal ulcerations in August, September, and October of 2020, 2019, and 2018 were evaluated. Only corneal ulcerations with growth on their microbial cultures were included in this study.

**Results:** The study revealed a significant increase in prevalence of infected corneal ulcerations in dogs presented to the CSU-VTH during the three wildfire months of 2020 that is, 3.5% (9/255) when compared with the two previous years, 2019: 1.0% (4/383,  $p = 0.04$ ), and 2018: 0.9% (4/457) ( $p = .01$ ). The AQI (mean  $\pm$  standard error) was also significantly elevated for dogs that presented with infected corneal ulcerations in 2020 ( $70.2 \pm 5.8$ ) compared with 2019 ( $19.7 \pm 8.7$ ) and 2018 ( $45.6 \pm 8.7$ ) ( $p < .01$ ).

**Conclusions and clinical relevance:** Elevation of AQI from wildfires seems to be correlated with an increased prevalence of infected corneal ulceration in dogs. As the duration and frequency of wildfires continues to rise globally, the effects of these wildfires on animal health should be investigated further.

## KEYWORDS

air quality index, culture swab, intraocular pressure, microbiology, schirmer tear test, wildfire

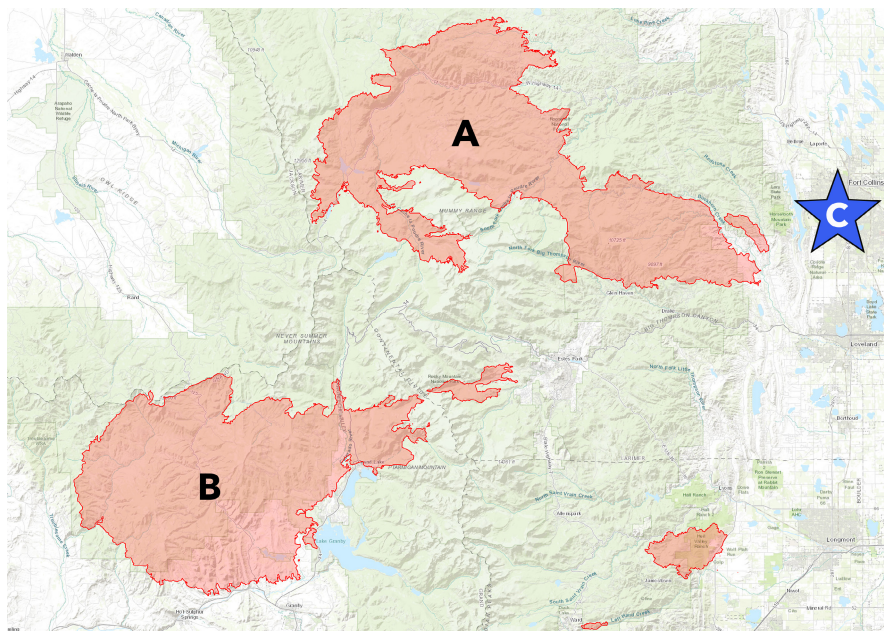
## 1 | INTRODUCTION

In the last half century, several variables have contributed to the increased incidence and severity of wildfires in the Western United States.<sup>1</sup> Wildfire smoke has been demonstrated to be a source of bioaerosols that includes aerosolized bacteria, fungi, and their metabolic byproducts.<sup>2</sup> Moore and colleagues demonstrated that even during small, prescribed fires, the number of microbial cells in the air was five times higher than at baseline levels.<sup>3</sup> A separate study in California attributed the increased incidence of coccidioidomycosis, caused by the soil inhabiting fungus *Coccidioides immitis*, with the increased incidence of wildfires.<sup>4</sup> These findings combined with potential for exacerbated inflammatory responses from direct irritation may increase the likelihood of infections, especially of body surfaces directly exposed to the environment like the respiratory passages and eyes.<sup>2,5</sup>

The effects of smoke inhalation on the cardiovascular and pulmonary systems in humans has been relatively well studied.<sup>5,6</sup> A recent study revealed that PM<sub>2.5</sub> specifically from wildfires is up to 10 times more harmful on human health than PM<sub>2.5</sub> from other sources.<sup>7</sup> Additional common symptoms reported in humans exposed to smoke from wildfires is, besides respiratory infections, ocular irritation.<sup>8,9</sup> This is likely due to the ocular surface coming in direct contact with substances contained in wildfire smoke leading to interference with the stability of the tear film.<sup>9</sup> This results in the ocular symptoms of itching, burning, a foreign body sensation and conjunctival hyperemia. These ocular symptoms are either caused by direct irritation or a result of ocular dryness.<sup>9</sup>

In 2020, Colorado experienced the two largest wildfires in state history, the Cameron Peak fire, burning a total of 208 913 acres, and the East Troublesome fire, burning a total of 193 812 acres.<sup>10</sup> These fires were first reported on August 13th and October 14th, respectively, and were not declared 100% contained until December 2nd and November 30th, respectively.<sup>10</sup> The northern Colorado university town, Fort Collins, was substantially impacted by the Cameron Peak and East Troublesome wildfires in 2020 with the air quality index (AQI) used by the United States Environmental Protection Agency elevated above 100 on multiple days.<sup>11</sup> Based on EPA guidelines an AQI of 0–50 is rated “good,” 51–100 is rated “moderate,” 101–150 is “unhealthy for sensitive groups,” and 151–200 is “unhealthy for the general public.” The Cameron peak fire was reported to only be eight miles west of Fort Collins city limits and an evacuation of the peripheral neighborhoods were in place for October 2020 (Figure 1).<sup>12</sup> Fort Collins is the hometown of Colorado State University (CSU) and the College of Veterinary Medicine and Biomedical Sciences. The ophthalmology service at the Veterinary Teaching Hospital at CSU (CSU-VTH) noted a potential increase in the number of infected canine corneal ulcerations during the time of the two 2020 wildfires compared with previous years which prompted the design of this study. The specific aims for this repeated cross-sectional study were to report the microbial culture results from infected corneal ulcerations in dogs and to evaluate for any differences in microbial growth, antimicrobial susceptibility, intraocular pressure (IOP), tear production (measured with Schirmer tear test—STT), and AQI among the two years prior to the two wildfires (August, September, and October—2018,

**FIGURE 1** The figure shows a map of northern Colorado. (A) The red delineates the acreage burned by the Cameron Peak wildfire. (B) The red delineates the acreage burned by the East Troublesome wildfire. (C) Fort Collins, Colorado, the location of the CSU-VTH. The Cameron Peak fire (A) was reported to only be eight miles away from Fort Collins city limits (Image used with permission from Colorado Public Radio)



2019) and for the year with the two wildfires near Fort Collins (August, September, and October—2020).

## 2 | MATERIALS AND METHODS

This study was designed as a repeated cross-sectional study evaluating dogs with infected corneal ulcerations presented to the ophthalmology service at the CSU-VTH from the months of August, September, and October from 2020 (test), 2019 (control), and 2018 (control). Electronic records were searched to include dogs with an infected corneal ulceration and had materials collected from the corneal ulceration for performance of aerobic and anaerobic bacterial culture and aerobic bacteria antibiotic susceptibility testing. Only dogs with positive bacterial growth for one or more bacteria were included in this study. Data gathered included signalment, history of ocular disease, result of culture and susceptibility testing, time until healed, if disease was managed medically or surgically, and the presence of other ocular or systemic diseases.

### 2.1 | Ophthalmic examination

All dogs in the study had a complete ophthalmic examination performed by a board-certified veterinary ophthalmologist and a veterinary ophthalmology resident. The ophthalmology examination included a neuro-ophthalmic examination (menace response, dazzle reflex, pupillary light reflex (direct and indirect), palpebral reflex), an examination of the adnexa and anterior segment with a transilluminator (Welch Allyn, NY, USA), slit-lamp biomicroscopy (KOWA-17; Japan), and a fundic examination performed with indirect binocular ophthalmoscopy using a headset (Keeler Inc., Malvern, PA, USA) and a 28-diopter condensing lens (Volk; Mentor, OH, USA). If possible, a Schirmer tear test-1 (STT; Merck Animal Health, NJ, USA) was performed and was recorded as how many seconds it takes until tears reached 15 mm on the tear strip (15 mm per “fill in” seconds). If possible, tonometry to determine the intraocular pressure (IOP; mmHg) of both eyes was performed (TonoVet: Icare, Finland Oy, or TonoPen AVIA: Reichert, Depew, NY, USA). Tonometry and STT may not have been performed in some dogs due to the risk of perforation if a deep corneal ulceration or a descemetocoele were present. Fluorescein stain of both eyes was performed (Fluorescein strip; Bio-Glo; HUB Pharmaceuticals, Scottsdale, AZ, USA). A gross photograph (NIKON Inc; Melville, NY, USA) of both eyes was taken at the end of the examination and uploaded in the medical record. All dogs included in this study had

material collected from the corneal ulceration by use of a microbial culture swab (BBL Culture Swab Plus; Becton, Dickinson and Company, Franklin Lakes, NJ, USA). The swab was submitted to the Veterinary Diagnostic Laboratory at CSU for aerobic and anaerobic microbiology growth and antimicrobial susceptibility for aerobic bacteria.

### 2.2 | Microbiology and corneal ulceration data

The following data were recorded from each corneal ulceration case: bacterial growth, how many bacterial isolates grown per culture swab, and antibiotic susceptibility pattern. Outcome for the infected corneal ulceration was also recorded and classified as follows: healed with medical treatment (medical treatment plan was recorded with focus on topical antibiotic(s)); healed with surgical treatment (conjunctival graft, biomaterial graft); or failed to heal and enucleated. Time from when infected corneal ulceration was diagnosed until complete resolution (medical, surgical or enucleation) was determined based on a negative fluorescein stain and topical antibiotic was discontinued.

### 2.3 | Air quality data

Archived air quality data were obtained from the United States Environmental Protection Agency (EPA) AirNow online database.<sup>11</sup> Air quality index (AQI) data were recorded from the months of August through October from the years 2020, 2019, and 2018, using the particulate matter AQI measurement from Colorado State University facilities Fort Collins, CO site ID: 080690009.

### 2.4 | Data analysis

Age, sex, breed, microbiology result, STT, IOP, and AQI data were recorded, and descriptive statistics were performed. The Student's *t*-test was used for a pairwise comparison of the mean of STT and IOP for ulcerated and non-ulcerated eyes. Prior to the analyses, a Shapiro–Wilk test was used to assess if the data were normally distributed. Because the STT was only normally distributed following a log-transformation, this was used. The Fisher's Exact test was used to compare the prevalence of “infected corneal ulceration dogs” among all dogs presented to CSU-VTH ophthalmology service in each of the three years. A one-way analysis of variance (ANOVA) was used to evaluate for differences between mean AQI per year. All

statistical analyses were carried out in the statistical software R v. 4.1.2 (R Core Team, 2021) and a  $p$ -value  $< 0.05$  was considered significant.

### 3 | RESULTS

#### 3.1 | Included dogs

A total of 17 canine eyes with infected corneal ulcerations (from 17 different dogs) were included in this study: 2020;  $n = 9$  eyes, 2019;  $n = 4$  eyes, 2018;  $n = 4$  eyes.

In 2020, there were 255 dogs presented to the CSU-VTH ophthalmology service during the months of August, September, and October; 3.5% (9/255) of these patients were diagnosed with infected corneal ulcerations. The age of dogs from 2020 had a median and interquartile range (IQR) of 7.0 years of age (IQR: 6–11) [range: 1–11 years of age]. There were four spayed females and five castrated males included. Right eye (OD) was affected in five dogs and left eye (OS) was affected in four dogs. There were eight breeds represented. Most common was the Shih tzu ( $n = 2$ ), followed by English bulldog ( $n = 1$ ), mixed breed ( $n = 1$ ), Boston terrier ( $n = 1$ ), Chihuahua ( $n = 1$ ), Cavalier King Charles spaniel ( $n = 1$ ), Cairn terrier ( $n = 1$ ), and Maltese ( $n = 1$ ).

In 2019, there were 383 dogs presented to the CSU-VTH ophthalmology service during the months of August, September, and October; 1.0% (4/383) of these patients were dogs with infected corneal ulcerations. The dogs from 2019 had a median age of 10.0 and IQR: 7.3–11 years of age [range: 2–11 years of age]. There were two spayed females and two castrated males. OD was affected in three dogs, and OS was affected in one dog. There were four breeds represented: mixed breed ( $n = 1$ ), French bulldog ( $n = 1$ ), shih tzu ( $n = 1$ ) and Boston terrier ( $n = 1$ ).

In 2018, there were 457 dogs presented to the CSU-VTH ophthalmology service during the months of August, September, and October; 0.9% (4/457) of these patients were dogs with infected corneal ulcerations. The dogs from 2018 had a median age of 6.0 and IQR: 1.3–10 years of age [range: 0.33–10 years of age]. There were two intact females and two castrated males included. OD was affected in all four dogs. There were four different breeds represented: Shih tzu ( $n = 1$ ), Chihuahua ( $n = 1$ ), toy poodle ( $n = 1$ ), and mixed breed ( $n = 1$ ).

The prevalence of infected corneal ulcerations in dogs presented in 2020 (3.5%), 2019 (1.0%), and 2018 (0.9%) among all dogs presented to the ophthalmology service at the CSU-VTH in the three-month period differed between 2020 and 2019 ( $p = 0.04$ ) and between 2020 and 2019 ( $p = 0.02$ ), while no difference was observed between 2018 and 2019 ( $p = 1.0$ ).

#### 3.2 | Clinical case data

The dogs from 2020 had clinical signs associated with infected corneal ulcerations (blepharospasm, ocular discharge, and ocular pain) for a median of 8.5 (IQR: 2–15) days [range 1–21 days] prior to presentation. The median duration of infected corneal ulcerations was 23 (IQR: 14–27) days to heal [range 2–40 days] (two cases did not come back for a follow-up visit at CSU). Sixty-seven percent (6/9 eyes) had an unrelated ocular disease in the past or present, and 44% (4/9 cases) had a systemic disease (see Table 1). Of the eyes involved, 11% (1/9 eyes) of the infected corneal ulcerations resolved with surgical intervention; conjunctival graft was performed on the one eye that required surgical intervention, and 89% (8/9 eyes) of the infected corneal ulcerations resolved with medical treatment alone.

The cases from 2019 had clinical signs associated with infected corneal ulceration for a median of 3.5 (IQR: 1–6) days [range 1–7 days] prior to presentation. The median duration of healing of the infected corneal ulcerations was 26 (IQR: 24–32) days [range 22–45 days]. Seventy-five percent (3/4 eyes) had an unrelated ocular disease in the past or present, and 75% (3/4 patients) had a systemic disease (see Table 1). Of the eyes involved, 50% (2/4 eyes) of the infected corneal ulcerations resolved with surgical intervention; conjunctival graft was performed in both eyes. The two other involved eyes (2/4, 50%) resolved with medical intervention alone.

Based on owner reports, the cases from 2018 had clinical signs associated with infected corneal ulcerations for a median of 2 (IQR: 2–5) days [range 2–14 days] prior to presentation. The median healing of the infected corneal ulcerations was 19 (IQR: 10–34) days [range 2–62 days] to heal. Of these corneal ulceration patients, 50% (2/4 patients) had an unrelated ocular disease in the past or present, and none of the cases (0%, 0/4) had a systemic disease (see Table 1). No STT-1 was measured from any of the four dogs in 2018 at their initial examination. Fifty percent (2/4 eyes) of the eyes resolved with surgical intervention; enucleation was performed in one eye (25%, 1/4 eyes), and conjunctival graft in one eye (25%, 1/4 eyes). The two other eyes (50%, 2/4) resolved with medical intervention alone.

The medians and IQRs for STT and IOP for “ulcerated eye” versus “non-ulcerated eye” were STT 15 mm/23 (median) and 20–45 (IQR) seconds versus 15 mm/21 (median) and 20–60 s (IQR), and IOP 12 (median) and 10–15 (IQR) mmHg vs. 16 (median) and 13–21 (IQR) mmHg. No difference was observed for STT between eyes with and without ulcers ( $p = 0.32$ ), but the IOP was 3.3 mmHg (95% confidence interval: 1.8 to  $\infty$ ) lower in the ulcerated eyes ( $p < .01$ ).

TABLE 1 The table shows historical clinical data from dogs included in the present study

No	Eye	Sex	Age	Breed	Presented Month, Year	Time until healed (days)	Healed medical (M) or surgical (S)	Surgical treatment	Other ocular diseases	Other systemic diseases
1	OD	MC	5 yo	Boston Terrier	Aug, 2020	2	M	N/A	None	None
2	OS	FS	11 yo	Shih Tzu	Aug, 2020	10	M	N/A	None	None
3	OD	MC	7 yo	Chihuahua	Aug, 2020	40	M	N/A	None	None
4	OS	FS	6 yo	CKCS	Sep, 2020	LTFU	M	N/A	KCS OU	Caudal malformation syndrome
5	OD	MC	9 yo	English Bulldog	Aug, 2020	30	S	Conjunctival graft	KCS OU	None
6	OD	MC	11 yo	Cairn Terrier	Oct, 2020	27	M	N/A	Phacoemulsification OU	Diabetes mellitus
7	OS	FS	7 yo	Maltese	Oct, 2020	14	M	N/A	Phacoemulsification OU	Diabetes mellitus
8	OS	MC	1 yo	Shih Tzu	Oct, 2020	LTFU	M	N/A	None	None
9	OD	FS	11 yo	Mixed breed	Oct, 2020	26	M	N/A	Immune mediated keratitis OU	Erythema multiforme
10	OD	FS	11 yo	Shih Tzu	Aug, 2019	45	S	Conjunctival graft	Optic neuritis OU	Intermittent colitis with hematochezia, extra-hepatic biliary duct obstruction, urolithiasis
11	OD	MC	9 yo	Boston Terrier	Aug, 2019	28	M	N/A	None	None
12	OD	MC	2 yo	French Bulldog	Aug, 2019	22	S	Conjunctival graft	Conformational exophthalmos OU	Brachycephalic airway syndrome, Ventricular septal defect, aortic valve insufficiency, IBD
13	OS	FS	11 yo	Mixed Breed	Sep, 2019	24	M	N/A	Glaucoma OS Phacoemulsification OU	Mass left cranial thorax
14	OD	FI	4 mo,	Mixed breed	Aug, 2018	13	M	N/A	None	None
15	OD	MC	2 yo,	Shih Tzu	Aug, 2018	24	S	Conjunctival graft	Distichiasis	None
16	OD	MC	10 yo	Chihuahua	Sep, 2018	2	S	Enucleation	None	None
17	OD	FI	10 yo	Toy Poodle	Oct, 2018	62	M	N/A	Enucleation OS ICLE OD	None

Note: Data was taken from the electronic medical records and includes signalment, history of ocular disease, time until healed, if disease was managed medically (M) or surgically (S) and any other ocular or systemic diseases.

Abbreviations: Aug, August; CKCS, Cavalier King Charles Spaniel; FI, Female intact; FS, Female spayed; IBD, Inflammatory bowel disease; ICLE, Intracapsular lens extraction; KCS, Keratoconjunctivitis sicca (dry eye); LTFU, Lost to follow-up; MC, Male castrated; N/A, not available; Oct, October; OD, Ocular dexter (right eye); OS, Ocular sinister (left eye); OU, Oculi unitas (both eyes); Sep, September; YO, Years of age.

### 3.3 | Microbiology

In 2020, 16 bacterial isolates were cultured from the nine eyes with infected corneal ulceration:  $\beta$ -hemolytic *Streptococcus* sp. ( $n = 2$ ), *Staphylococcus pseudintermedius* ( $n = 2$ ), *Pasteurellaceae* sp. ( $n = 2$ ), *Enterobacter* sp. ( $n = 1$ ), *Neisseria* sp. ( $n = 1$ ), coagulase-negative *Staphylococcus* sp. ( $n = 1$ ), *Corynebacterium* sp. ( $n = 1$ ), unspciated gram-negative non-fermenter ( $n = 1$ ), unspciated coryneform organism ( $n = 1$ ), *Streptococcus agalactiae* ( $n = 1$ ), *Escherichia coli* ( $n = 1$ ), *Capnocytophaga* sp. ( $n = 1$ ), and *Mycobacterium fortuitum* complex ( $n = 1$ ) (Table 2).

In 2019, eight bacterial isolates were cultured from the four eyes with infected corneal ulcerations. The most common organism was  $\beta$ -hemolytic *Streptococcus* sp. ( $n = 2$ ). The following were represented equally: *Staphylococcus pseudintermedius* ( $n = 1$ ), *Pseudomonas aeruginosa* ( $n = 1$ ), *Pasteurella canis* ( $n = 1$ ), *Lactobacillus* sp. ( $n = 1$ ), *Peptostreptococcus* sp. ( $n = 1$ ), and *Bacteroides* sp. ( $n = 1$ ) (Table 2).

In 2018, 11 organisms were isolated from the four eyes with infected corneal ulcerations. The most common

bacterium cultured was  $\alpha$ -hemolytic *Streptococcus* sp. ( $n = 3$ ), the two second most common bacteria were *Neisseria species* ( $n = 2$ ) and *Pasteurella species* ( $n = 2$ ). The last four cultured bacteria were all represented equally and were as follows: *Staphylococcus pseudintermedius* ( $n = 1$ ), *Corynebacterium* sp. ( $n = 1$ ), *Moraxella* sp. ( $n = 1$ ), *Pantoea agglomerans* ( $n = 1$ ) (Table 2).

### 3.4 | Antimicrobial susceptibility

Some bacterial isolates are not routinely tested for antimicrobial susceptibility, including: *Capnocytophaga* sp. ( $n = 1$ , 2020), *Bacteroides* sp. ( $n = 1$ , 2019), *Lactobacillus* sp. ( $n = 1$ , 2019), *Peptostreptococcus* sp. ( $n = 1$ , 2019), *Corynebacterium* sp. ( $n = 1$ ; 2018),  $\alpha$ -hemolytic *Streptococcus* sp. ( $n = 3$ ; 2018). The three agents to which the most isolates were susceptible for in 2020 were ciprofloxacin with 80% (12/15) total susceptibility, as well as gentamicin and moxifloxacin with both 60% total susceptibility (9/15). The three agents to which the most isolates were susceptible for in 2019 were cefazolin, chloramphenicol, and moxifloxacin all with 60% (3/5) total

TABLE 2 The bacterial isolates that were cultured from the infected corneal ulcerations in 2020, 2019 and 2018 (# = number)

Bacterial isolates	2018 Percentage ( $n =$ no. of isolates)	2019 Percentage ( $n =$ no. of isolates)	2020 Percentage ( $n =$ no. of isolates)
<i>Streptococcus species, alpha hemolytic</i>	27% ( $n = 3$ )	-	-
<i>Streptococcus species, beta hemolytic</i>	-	25% ( $n = 2$ )	13% ( $n = 2$ )
<i>Pasteurellaceae species</i>	18% ( $n = 2$ )	-	13% ( $n = 2$ )
<i>Neisseria species</i>	18% ( $n = 2$ )	-	6% ( $n = 1$ )
<i>Staphylococcus pseudintermedius</i>	9% ( $n = 1$ )	12.5% ( $n = 1$ )	13% ( $n = 2$ )
<i>Bacteroides species</i>	-	12.5% ( $n = 1$ )	-
<i>Lactobacillus species</i>	-	12.5% ( $n = 1$ )	-
<i>Pasteurella canis</i>	-	12.5% ( $n = 1$ )	-
<i>Peptostreptococcus species</i>	-	12.5% ( $n = 1$ )	-
<i>Pseudomonas aeruginosa</i>	-	12.5% ( $n = 1$ )	-
<i>Corynebacterium species</i>	9% ( $n = 1$ )	-	6% ( $n = 1$ )
<i>Moraxella species</i>	9% ( $n = 1$ )	-	-
<i>Pantoea agglomerans</i>	9% ( $n = 1$ )	-	-
<i>Capnocytophaga species</i>	-	-	6% ( $n = 1$ )
<i>Coryneform bacteria</i>	-	-	6% ( $n = 1$ )
<i>Enterobacter species</i>	-	-	6% ( $n = 1$ )
<i>Escherichia coli</i>	-	-	6% ( $n = 1$ )
Gram negative non-fermenter	-	-	6% ( $n = 1$ )
<i>Mycobacterium fortuitum complex</i>	-	-	6% ( $n = 1$ )
<i>Staphylococcus coagulase negative</i>	-	-	6% ( $n = 1$ )
<i>Streptococcus agalactiae</i>	-	-	6% ( $n = 1$ )

susceptibility. The three agents to which the most isolates were susceptible for in 2018 were chloramphenicol and ciprofloxacin, both with 71% total susceptibility (5/7). The agents that the least number of isolates were susceptible for in all three years was the topical triple antibiotic which is a combination of three antibiotics: neomycin, polymyxin-B, and bacitracin. Both bacitracin and polymyxin-B had a 0% total susceptibility for all three years, whereas neomycin had a total susceptibility of 40% (6/15) in 2020, 20% (1/5) in 2019, and 57% (4/7) in 2018.

### 3.5 | Air quality

Figure 2 displays the AQI data for each day of the months of August, September, and October for the three years involved in this study (2020, 2019, and 2018). Points are marked on days where a patient presented with an infected corneal ulceration. The AQI mean  $\pm$  standard error seven days prior to the presentation of a dog with an infected corneal ulceration in 2020 for the months of August, September, and October was  $70.2 \pm 5.8$  AQI. In 2019, the AQI was  $19.7 \pm 8.7$ , and in 2018 the AQI was  $45.6 \pm 8.7$ . The AQI was significantly elevated for dogs that presented with infected corneal ulceration in 2020 compared with 2019 and 2018 ( $p < .01$ ).

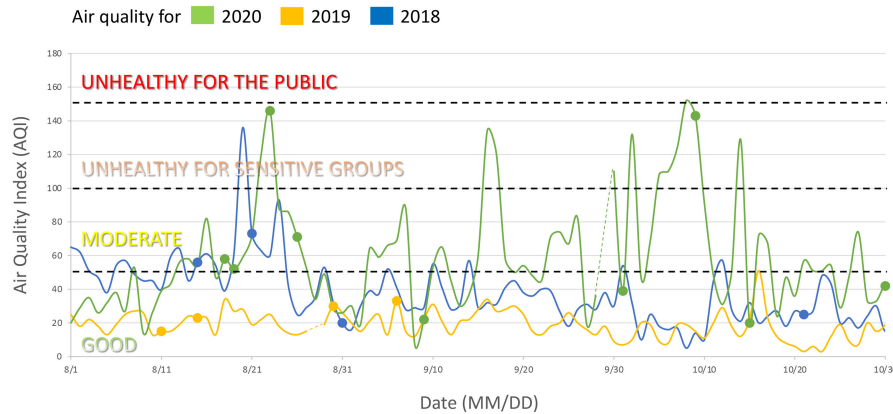
## 4 | DISCUSSION

Literature is lacking in the field of wildfire smoke exposure and the effects seen in domestic pets. In conjunction, there has been minimal research done on the impacts of wildfire smoke especially regarding infected corneal ulcerations in humans and animals. As the duration and frequency of wildfires globally continues to rise this present study highlights the importance of culture and susceptibility in relation to corneal ulcerations in dogs during times of increased AQI due to wildfires. The present study demonstrated an increase in dogs with infected corneal ulcerations presented to the CSU-VTH ophthalmology service during the months of the 2020 Cameron Peak and East Troublesome fires (3.5%) compared with the two years prior to 2020 with limited wildfires in the area (1.0% and 0.9%, respectively, for 2019 and 2018). Notably, the overall number of dogs presented to the ophthalmology service at CSU-VTH in 2020 was less than the previous two years (255 dogs in 2020, 383 dogs in 2019, 457 dogs in 2018). This decrease in overall case numbers for 2020 was due to the COVID-19 pandemic that had placed CSU-VTH on lockdown for multiple months prior to the wildfires and continued to influence the case number during the wildfire months.

Trends toward increased wildfire season length globally indicate that the population of humans and domestic pets exposed to wildfire smoke is expected to continue to increase.<sup>13</sup> Smoke from wildfires contains several compounds correlated with adverse health effects in humans. Compounds including carbon monoxide [CO], polycyclic aromatic hydrocarbons, ozone precursors, benzenes, aldehydes, and particulate matter.<sup>5</sup> Many of these are compounds measured and reported to the public using the United States Environmental Protection Agency's AQI. The fine particulate matter [PM<sub>2.5</sub>] related to the smoke has been described in the literature as the most detrimental to the human lung. The human health side effects observed can be attributed to the corresponding inflammatory response and oxidative stress caused by the particulate matter.<sup>14</sup> Additionally, the PM<sub>2.5</sub> from wildfire smoke was found to be more detrimental to human respiratory health than PM<sub>2.5</sub> from other sources.<sup>7</sup>

Colorado is a mountain state, and Fort Collins is located 5000 feet above sea level. The climate in Fort Collins for the three evaluated months (August, September, and October) is described as dry and warm.<sup>15</sup> The ophthalmology service at the CSU-VTH is not accustomed to seeing a high number of infected corneal ulcerations in any species which is likely related to the local climate. The low number of infected corneal ulcerations was reasonably described in a study evaluating the prevalence for fungal keratitis in horses from northern Colorado presented to CSU. This equine study revealed that northern Colorado had less cases with fungal keratitis (16.4%, 10/61) when compared to other veterinary teaching hospitals such as the University of Florida (84.6%, 33/39) or the University of Pennsylvania (24%, 10/41).<sup>16</sup> Normal corneal flora in the healthy dog varies slightly based on geographic location with the most common genera being the gram-positive bacteria *Staphylococcus* and *Streptococcus*.<sup>17</sup> Common bacterial species involved in infected corneal ulcerations have been identified as, but are not limited to, *Staphylococcus* sp., *Streptococcus* sp., *Pseudomonas aeruginosa*, *Corynebacterium* sp., *Neisseria* sp., and *Escherichia coli*.<sup>18-21</sup> All these bacterial isolates were found in the present study among the three years that were evaluated. The present study also supports the theory that infected corneal ulcerations in northern Colorado are generally uncommon with only four cases in each year of August, September, and October in 2019 and 2018.

All three years had bacterial isolates from less common ocular bacterial inhabitants including *Peptostreptococcus* sp. in 2019, and *Pantoea agglomerans* from a dog in 2018. Although these species are less commonly identified, they have previously both been described in the literature regarding canine infected corneal ulcerations.<sup>22,23</sup> *Mycobacterium fortuitum* complex was found



**FIGURE 2** The figure shows a graph of the archived air quality index (AQI) from the months of August, September, and October from the years of 2020 (green), 2019 (orange), and 2018 (blue). The x-axis shows the date (month/day) and the y-axis shows the AQI. The year 2020 is represented by the green graph with the enlarged data points representing the dates of dogs presented to the CSU-VTH with corneal ulcerations. The year 2019 is represented by the orange graph and the enlarged data points correspond to the dates of the corneal ulcerations in dogs. The year 2018 is represented by the blue graph with the enlarged data points representing the dates of canine corneal ulcerations. Dashed lines in the years of 2019 and 2020 represent archived dates that did not have an AQI score reported (8/28/19 and 9/29/20). Based on EPA guidelines an AQI of 0–50 is rated good, 51–100 is rated moderate, 101–150 is unhealthy for sensitive groups, and 151–200 is unhealthy for the general public<sup>11</sup>

in one of the infected corneal ulcerations in the year of the wildfires (2020). Non-tuberculous mycobacterium (NTM), such as *Mycobacterium fortuitum* complex, are typically found in the environment in soil and water sources.<sup>24</sup> They have been described in corneal ulcerations in human patients after corneal trauma, surgery or after prolonged contact lens use, but have yet to be implicated in canine infected corneal ulcerations.<sup>25</sup> The current literature available demonstrates an increase in viable aerosolized organisms during wildfires and the potential for spread of pathogenic organisms via this transmission method.<sup>3</sup> Further studies are needed to characterize the organisms commonly found in wildfire smoke.

The bacterial culture results show a relatively high diversity of bacterial taxa cultivated, demonstrating that the increased prevalence of infected corneal ulcerations was not an expansion of the bacterial taxa cultivated in the previous years. Due to the relatively small sample size, it is difficult to draw conclusions about trends in resistance. However, the susceptibility results did show increased diversity in resistance phenotypes, and illustrate the importance of performing bacterial culture and antibiotic susceptibility from any corneal ulcerations with a suspicion for an infection during periods of wildfire smoke exposure. An increase in resistance to ciprofloxacin and ofloxacin has been documented in the literature and it is important to monitor the susceptibility towards these drugs to make sure that patients are being treated with the most effective antibiotics.<sup>26,27</sup> This present study demonstrated that the first-line topical antibiotic containing neomycin, polymyxin-B, and bacitracin, also known as triple antibiotic or Neo-Poly-Bac ophthalmic ointment, has poor

effect on infected corneal ulcerations due to low susceptibility of most of the bacterial isolates cultured from all three years in this study. Topical Neo-Poly-Bac ophthalmic ointment should, therefore, not be used as a treatment for an infected corneal ulceration.

Infected corneal ulcerations were found to be associated with an increased mean AQI seven days prior to presentation to CSU-VTH ( $p < .01$ ). EPA guidelines state that if the AQI reaches above 100 the air quality is unhealthy for sensitive groups (those with heart and lung diseases, children, and the elderly), and if AQI reaches above 150 the air quality is unhealthy for those in the general public.<sup>11</sup> Figure 2 shows that during the three months included in this study, two cases in 2018 were presented to the CSU-VTH ophthalmology service in the “moderate” AQI (51–100) and no cases in 2019. The rest of the cases for 2018 and 2019 were found in the “good” AQI (AQI below 50). In 2020 three cases were presented to CSU-VTH in the “moderate” AQI (51–100), and two cases presented in the “unhealthy for sensitive groups” AQI (101–150), whereas the rest of the cases ( $n = 4$ ) were presented in the “good” AQI (below 50). Investigation of the wildfire history of Colorado revealed that 2018 had several fires and was categorized as one of the worst wildfire seasons of Colorado, whereas 2019 was categorized as a mild wildfire season with only one wildfire listed.<sup>28,29</sup> The smoke from the wildfires in 2018 and single wildfire in 2019 would have had an impact on AQI and potential case presentation despite the fact that a significant difference was found with 2020 having a significant higher AQI than 2019 and 2018. It is unfortunately not possible to find a previous year in



Colorado's history with no wildfires in the investigated period, and it would not give a correct picture of case presentation if other months were used for the control group as Colorado's cold weather causes low corneal infection risk.<sup>16</sup> The present study demonstrates an association between increased AQI and the development of infected corneal ulceration in dogs. Previous studies in human patients have demonstrated a trend of ocular irritation including ocular burning, dryness, foreign body sensation, and itching, related to smoke and air pollution exposure.<sup>8,9</sup> Berra and colleagues (2015) found that human patients exposed to an increased AQI in relation to wildfire smoke correlated with low tear film break-up times, and therefore, tear film instability.<sup>9</sup> Instability of the tear film increases the chance of developing dry eye, which corresponds to ocular irritation and inflammation and ultimately the formation of corneal ulcerations. No significant differences were found between STT-1 for "ulcerated eyes" versus "non-ulcerated eyes" ( $p = 0.32$ ). Future studies evaluating dogs tear film quality during wildfires and increased AQI could be useful for canine populations living in high-risk wildfire areas. The significantly decreased IOP ( $p < .01$ ) in the "ulcerated eye" compared to the "non-ulcerated eye" is not a surprising finding as complicated corneal ulcerations are known to cause reflex uveitis.<sup>30</sup>

This study may suffer from the limitations of a cross-sectional study, as compared to a longitudinal analysis, for instance, including decreased statistical power and the capability to estimate a smaller range of conditional probabilities, besides the presence of incomplete or nondescriptive medical records. Time of infection was difficult to surmise in most cases as the historical data available was often incomplete or absent. Due to this, seven days was used as the standard time for ulceration development and for the mean AQI calculation, although this likely varied per patient depending on the etiology of the ulceration. Additionally, some of the dogs did not return for re-evaluation appointments leading to incomplete data on length of healing of the ulceration. The ophthalmology service at the CSU-VTH does not see many infected corneal ulcerations, and the sample size especially for the years of 2018 and 2019 was small; therefore, making it difficult to determine statistical significance of the data presented, but the study still gives a thorough description of infected corneal ulcerations in the area of the CSU-VTH.

## 5 | SUMMARY

The present study reveals how wildfires potentially increase the risk of developing an infected corneal ulceration in dogs due to elevation of air quality index (AQI). As

the duration and frequency of wildfires continues to rise globally the effect of these wildfires on animal and human health should be investigated further.

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## CONFLICT OF INTEREST

The authors of this manuscript have no conflict of interest to declare.

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