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Changes in lung function and fractional exhaled nitric oxide across wildfire seasons in the wildland firefighter exposure and health effect (WFFEHE) study

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A R T I C L E I N F O

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A B S T R A C T

Introduction: Long-term pulmonary effects of wildland firefighting are unclear even though lung function declines have been observed following wildfire season and firefighting shift.
Methods: Spirometry and airway inflammation indicated as fractional exhaled nitric oxide (FeNO) were measured among 152 wildland firefighters (WFFs) at the beginning (pre-season, April & May) and end (post-season, September & October) of the 2018 and/or 2019 wildfire seasons and among 19 WFFs at across 3 days of firefighting during a 2019 mid-season wildfire deployment.
Results: Overall peak expiratory flow (PEF) and percent of predicted PEF (PEF%) significantly decreased across fire season when 2018 and 2019 measurements were combined (-0.15 ± 0.07 L/s, $p = 0.04$; $-1.87 \pm 0.71\%$, $p = 0.01$; respectively), more so due to 2018 declines. PEF% and percent of predicted forced vital capacity (FVC%) significantly improved between 2018 post-season and 2019 pre-season (i.e., off-season) ($3.08 \pm 1.26\%$, $p = 0.02$; $0.99 \pm 0.41\%$, $p = 0.02$; respectively). FVC and FVC% significantly decreased across a firefighting shift on the first day of wildfire deployment (-0.12 ± 0.03 L, $p < 0.01$; $-2.35 \pm 0.64\%$, $p < 0.01$). FeNO significantly decreased across the 2018 and 2019 fire seasons ($p < 0.01$) and significantly increased during the off-season ($p < 0.01$). FeNO also showed statistically significant cross-shift decreases on the second day of wildfire deployment (-3.50 ± 0.95 ppm, $p < 0.01$).
Conclusions: Seasonal wildland firefighting were associated with decreases in lung function and FeNO as well as increases in respiratory symptom score in this cohort. While lung function recovered during the off-season among the WFFs, the results suggest a need for longer-term studies to determine the impact of chronic wildland firefighting on pulmonary health.

1. Introduction

Interest in wildland firefighter (WFF) pulmonary health has been driven by this group's repeated exposures to wildland fire smoke during fire suppression and prescribed burn activities. At large wildfires, WFFs can work shifts that are between 14-16 hours in remote areas for up to two weeks (Navarro et al., 2021). This prolonged and uninterrupted exposure to a smoke-filled environment could greatly affect their health. In addition, WFFs conduct prescribed burn operations, which are fires applied to pre-defined forest areas to remove combustible vegetation and debris and reduce the risk of unwanted wildfires. Exposure concentrations of smoke constituents, such as particulate matter and carbon monoxide, are similar or can even be higher at prescribed burns than in wildland fires (Navarro, 2020). The repeated occupational exposure to

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smoke is further worsened by WFF's increased breathing rate due to strenuous work and lack of suitable respiratory protection for wildland firefighting (Nakayasu et al., 2023).

Air pollutants derived from wildland fire smoke, especially respirable particulate matter, can have adverse impacts on the respiratory system (Adetona et al., 2016). Previous population-based studies identified wildfire events as a significant contributor to increased hospital admissions due to respiratory diseases (Delfino et al., 2009; Alman et al., 2016; Gan et al., 2017). The intensity, frequency, proximity, and duration of smoke exposure for WFFs are typically greater than they are for the general population. WFFs report respiratory symptoms (e.g., cough, wheezing, and sputum production) after firefighting shifts (Gianniou et al., 2018; Swiston et al., 2008; Rothman et al., 1991; Gaughan et al., 2008) and wildfire seasons (Gaughan et al., 2008). Increased airway inflammation post firefighting was also observed in this occupational group (Gaughan et al., 2008; Swiston et al., 2008; Gianniou et al., 2018).

Spirometry is a standard and non-invasive measurement that is used to evaluate integrated pulmonary function by checking the volume and flow rate of exhaled air. This measurement has been used to assess pulmonary response to wildfire smoke exposure. Decreased lung function among residents of wildfire smoke-impacted communities was observed one year after wildfire smoke exposure (Orr et al., 2020; Blando et al., 2022) and was sustained until two years after exposure (Orr et al., 2020). Longer-term pulmonary effects of wildfire smoke exposure were suggested by the observation of lower lung capacity among men and elderly people who had experienced large forest fires ten years prior (Kim et al., 2017).

Similarly, acute lung function declines have been observed among WFFs across prescribed burn shifts (Betchley et al., 1997). A dose-response relationship between acute smoke particulate matter exposure during the work shift and lung function impairment was documented in a previous study (Slaughter et al., 2004). Lung function declines across a single wildfire season (Betchley et al., 1997; Liu et al., 1992; Rothman et al., 1991) with impairment persisting for up to three months after the end of the season (Jacquin et al., 2011) have also been reported. Relatedly, an association between the number of firefighting days during the prescribed burn season and a decline in pulmonary function among WFFs has been reported (Adetona et al., 2011). However, other studies did not observe cross-shift changes in the lung function of WFFs after firefighting or across the fire season (Gaughan et al., 2008; Swiston et al., 2008), and a recent pilot study reported that WFFs' pulmonary function significantly improved during high pollution periods compared to low pollution periods (Niyatiwatchanchai et al., 2022).

Fractional exhaled nitric oxide (FeNO) is a non-invasive biomarker for assessing airway inflammation, and it has been used to determine the respiratory effect of wood and wildfire smoke exposure. Results from controlled human exposure studies suggest short-term exposure to woodsmoke is associated with FeNO increase among healthy persons (Barregard et al., 2008; Stockfelt et al., 2012). A recent case-control study concluded individuals who frequently engaged in residential wood burning had higher FeNO levels (White et al., 2022). Increased levels of FeNO due to wildfire smoke exposure were also observed among individuals in smoke-affected communities in Australia (O'Dwyer et al., 2021). However, WFFs in Portugal had a significantly lower level of exhaled nitric oxide (FeNO) after firefighting shifts (Miranda et al., 2012). To date, no other study has examined the impact of occupational wildland fire smoke exposure on FeNO among WFFs.

To further clarify the cumulative pulmonary effect of occupational wildland fire smoke exposure, we investigated changes in lung function across two consecutive wildfire seasons among an open cohort of WFFs in the Western United States. This research is part of the Wildland Firefighter Exposure and Health Effects (WFFEHE) Study conducted by the Centers for Disease Control and Prevention (CDC) National Institute for Occupational Safety and Health (NIOSH), in 2018 and 2019 (Navarro et al., 2021). The overall goal of the WFFEHE study was to comprehensively evaluate the health risks of occupational exposure (e.g., fire smoke, noise, and heat stress) among WFFs. The present study primarily focuses on lung function and airway inflammation among WFFs across two consecutive wildfire seasons.

2. Material and methods

2.1. Study population

Details of the study population and recruitment timeline were previously reported (Navarro et al., 2021; Scott et al., 2024). Briefly, the study participants consisted of 152 professional WFFs who participated in at least one respiratory test (spirometry or FeNO) during the two-year testing period from three Interagency Hotshot Crews (IHCs) in Colorado, and two IHCs and a Type 2 Initial Attack (T2IA) crew in Idaho. These fire crews were selected based on their crew type and land management duties (i.e., potentially less turnover and more wildfire deployments) and logistic considerations for the WFFs and research personnel (i.e., proximity for field sample collection and measurement). WFFs must have completed a work capacity test and safety training annually before participating in the WFFEHE study. The recruitment of this two-year study started in March 2018, and participation at any time point was voluntary. Thus, this was an open cohort, and not all participants present at initial study recruitment completed the two pre-season and two post-season sampling periods. The number of WFFs who provided measurements at each time point is summarized in Fig. 1.

Furthermore, nineteen WFFs from one of the fire crews provided additional spirometry and FeNO tests before and after three firefighting shifts during a deployment to a wildfire incident in August 2019. The study protocol was reviewed and approved by the NIOSH Institutional Review Board (18-WSD-01) and was relied upon by The Ohio State University (2022X0122). All WFFs provided signed informed consent at the beginning of the participation.

2.2. Questionnaires

Questionnaires were administrated to WFFs before (pre-season) and after (post-season) wildfire season of 2018 and 2019. The pre-season questionnaire was used to collect information about demographics, occupational history, pre-season fire smoke exposure, tobacco use, current and past health status, symptoms during the previous two weeks, and medication and dietary supplement use. The post-season questionnaire was used to obtain information about job duties in the current fire season, fire suppression, and prescribed burn activities during the fire season, changes in health status since the last time point, symptoms over the previous two weeks, and medication and dietary supplement use (Scott et al., 2024).

WFFs rated their respiratory symptom severity in the last two weeks in pre- and post-season questionnaires. A Likert scale (0 = none, 1 = trivial, 2 = mild, 3 = moderate, and 4 = severe) (Gaughan et al., 2008) was used to estimate respiratory symptom severity scores for the eyes (summing responses of itching, swelling, and tearing), nose (summing responses of itching, congestion, sneezing, and runny nose), sinus (summing responses of headache, thick mucus, postnasal drip, and throat clearing), cough, wheezing, sputum production, shortness of breath (summing responses to questions about "shortness of breath or chest tightness" and "shortness of breath while walking").

2.3. Spirometry and FeNO

WFFs performed spirometry and FeNO testing at the start (April and May, pre-season) and end (September and October, post-season) of each wildfire season in 2018 and 2019. WFFs from the same fire crew completed the lung function and FeNO tests on the same date for each set of pre- and post-season measurements and the post-season measurements were collected within five days since the last wildland fire

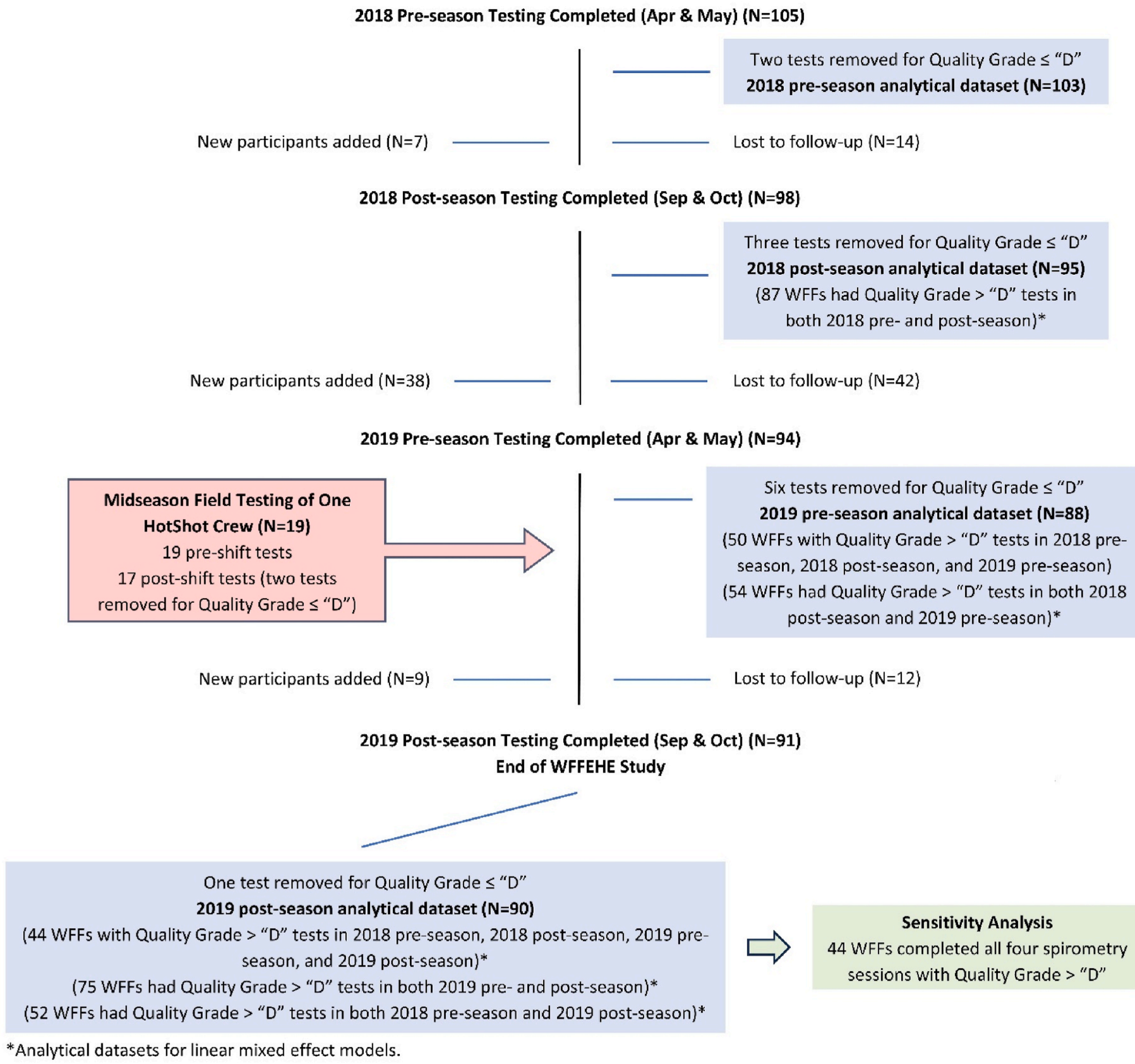

Fig. 1. Wildland firefighter cohort spirometry flow testing in the Wildland Firefighter Exposure and Health Effect study.
Acronyms: WFFEHE = the Wildland Firefighter Exposure and Health Effect study; WFFs = wildland firefighters.

suppression work. Fewer than 35% of participating firefighters reported information about when the last wildland firefighting prior to the pre-season measurements occurred for either year. Lung function was measured using an Easy-On PC Spirometry System (ndd Medical Technologies Inc., Andover, MA) according to the American Thoracic Society/European Respiratory Society (ATS/ERS) guidelines (Graham et al., 2019; Miller et al., 2005). Each WFF was instructed by NIOSH spirometry-trained technicians or registered respiratory therapists on how to properly perform a maximal, forced expiratory maneuver. At least two acceptable and two repeatable forced vital capacities were obtained from the WFFs in a standing position while wearing nose clips. A maximum of eight spirometry maneuvers were performed. The National Health and Nutrition Examination Survey (NHANES) III reference equations were used to determine expected parameter volumes based on height (cm), age (years), sex (male, female), and race (African American, Caucasian, Hispanic, Other/Mixed) (Hankinson et al., 1999).

Age, race, and sex were self-reported measures by the participants. Weight and stocking-feet standing height (to the nearest 0.1 cm) was measured at the time of testing. Before the final interpretation of test results, each flow-volume maneuver graphic was reviewed by a respiratory epidemiologist for acceptability and repeatability criteria before it was determined to be a valid, reportable spirometry test. Tests with a quality grading score of C or better were used for the main analysis. Pulmonary function metrics included peak expiratory flow (PEF) (L/sec), percent of predicted PEF (PEF%), forced expiratory volume in one second (FEV_1) (L), percent of predicted FEV_1 (FEV_1%), forced vital capacity (FVC) (L), percent of predicted FVC (FVC%), and FEV_1/FVC test parameters. Percent of predicted lung function metric is a person's lung function values as a percentage of the predicted values for a person of the same age, sex, height, and race using the NHANES III reference equations.

FeNO testing was performed in accordance with ATS/ERS FeNO clinical guidelines at a flow rate of 50 ml/s using the NIOX VERO® Airway Monitor (Aerocrine AB, Sweden) (Dweik et al., 2011). WFFs were asked to refrain from consuming foods rich in nitrates (e.g., bacon, leafy green vegetables, lunch meats) prior to testing. Any WFF that self-reported smoking within one hour or eating nitrate rich foods within two hours were prohibited from testing.

Each WFF was instructed to inhale deeply to total lung capacity and exhale slowly into a chemiluminescence analyzer for 10 s, while receiving verbal coaching by NIOSH personnel and visual observation of real-time screen graphics during each maneuver. A minimum of two measurements were performed with the WFF seated and noseclips applied. The average value of the two measurements was reported. If FeNO results differed by >5% in parts per billion (ppb), then a third measurement was performed, and their average value reported.

Eosinophilic inflammation was considered when individual averaged results were ≥50 ppb (See and Christiani, 2013).

For the WFFs participating in the mid-season deployment (August) to a wildfire incident in 2019, spirometry testing was administered before (pre-shift) and after (post-shift) firefighting shift on the first day. On the second and third days, the FeNO test was administered pre- and post-shift.

2.4. Statistics

2.4.1. 2018 and 2019 wildfire seasons

Linear mixed model (LMM) using SAS MIXED with autoregressive 1 (AR1) variance-covariance matrix was used to determine lung function and FeNO changes among firefighters with paired samples across pairs of measurement time points, including: 1) overall cross-seasonal changes (combined 2018 and 2019, difference between pre- and post-season, hitherto referred to as the overall group change); 2) single cross-seasonal changes (either 2018 or 2019, changes from pre-to post-season); 3) off-season changes from 2018 post-season and 2019 pre-season; and 4) two-year follow-up changes (changes from 2018 pre-season to 2019 post-season). Residual plots were used to check the homoscedasticity and normality assumptions.

Lung function metrics and log-transformed FeNO were included as dependent variable and sampling time points (i.e., 2018 pre-season, 2018 post-season, 2019 pre-season, 2019 post-season) were used as dummy variable in the model to determine whether differences between measurement time-points (e.g., pre-season vs. post-season) were significant. Age, sex, race, height, weight, smoking status, the total number of responses to wildland and prescribed fire incidents during the season, and work as a volunteer structural/municipal firefighter before the wildland fire season were controlled for in the model when analyzing for changes in PEF, FEV_1, FVC, FEV_1/FVC, and FeNO. The model was adjusted for smoking status, the total number of responses to wildland and prescribed fire incidents and work as a volunteer structural/municipal firefighter before the wildland fire season when analyzing for changes in PEF%, FEV_1%, and FVC%. Sensitivity analyses were conducted for all cross-season changes by including WFFs who completed all four sampling sessions (44 and 40 WFFs for spirometry and FeNO tests, respectively). For respiratory symptom scores, Wilcoxon signed-rank test was used to determine if cross-seasonal changes (changes from pre-to post-season) in 2018 and 2019 were significant.

2.4.2. Mid-season fire incident deployment

LMM was used to determine cross-shift changes (changes from pre-to post-shift) in lung function on the first day and FeNO on the second and third days of three days when firefighting activity was monitored. The model was adjusted for age and height for PEF, FEV_1, FVC, FEV_1/FVC, and FeNO. Firefighters who had both pre- and post-shift tests were included in the analysis. Residual plots were used to check the homoscedasticity and normality assumptions, and no transformation was needed for any of the measures to satisfy the assumptions. All the analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, NC), and a *p*-value <0.05 was considered statistically significant.

3. Results

3.1. WFF participants

Overall, this WFF cohort was young (mean age of 28.8 years), fit (mean BMI = 25.2 kg/m^2), and most were males (91%), who self-identified as White (89%). Each year, the average WFF was deployed to at least twelve wildfire incidents and participated in fewer than three prescribed burns during each fire season (Table 1). The number of WFFs who provided spirometry measurements, including those who were added and dropped at each research time point, is shown in Fig. 1. Approximately, 78% of the WFFs that participated in 2018 completed both pre- and post-season spirometry testing whereas about 73% of the WFFs that participated in 2019 completed both testing periods. However, only 43% (N = 44) of the original WFF participants completed spirometry for all four research time points (Fig. 1).

Table 1
Characteristics of wildland firefighters in the Wildland Firefighter Exposure and Health Effect Study (WFFEHE).

	Mean ± SD or N (%)		
	Overall (N = 152)	2018 (N = 112)	2019 (N = 105)
Age (years)	28.8 ± 5.9	29.4 ± 6.2	28.8 ± 5.7
Sex	Male: 139 (91%)	Male: 108 (96%)	Male: 96 (89%)
Race	White: 135 (89%)	White: 100 (88%)	White: 97 (90%)
Height (cm)	178.7 ± 6.6	178.5 ± 6.6	178.6 ± 6.9
Weight (kg)	80.5 ± 11.3	80.7 ± 11.5	79.3 ± 10.8
BMI (kg/m^2)	25.2 ± 2.9	25.3 ± 3.0	24.8 ± 2.8
Smoking ever	52 (34%)	52 (46%)	29 (27%)
Current smoker[a]	16 (11%)	16 (14%)	5 (5%)
Pre/Post-season allergic[b]	37 (24%)/9 (6%)	28 (25%)/6 (5%)	14 (13%)/5 (5%)
Pre/Post-season asthma[c]	8 (5%)/5 (3%)	4 (4%)/3 (3%)	4 (4%)/3 (3%)
Wildfire incidents	13.4 ± 4.3	12.8 ± 3.3	14.2 ± 5.7
Prescribed fires	1.9 ± 1.8	1.1 ± 2.0	2.6 ± 1.7

Acronyms: SD = standard deviation; BMI = body mass index.
[a] Wildland firefighter smokes cigarettes every day or some days.
[b] Wildland firefighter has ever been diagnosed with allergic or sensitivity reactions to poison ivy, poison oak, or poison sumac.
[c] Wildland firefighter has ever been diagnosed with asthma.

In total, we performed 388 pre-season/post-season spirometry tests for 152 WFF participants; with an additional 38 tests for 19 WFFs during a mid-season 'active fire' deployment (Fig. 1). We removed two spirometry tests in 2018 pre-season, three tests in 2018 post-season, six tests in 2019 pre-season, and one test in 2019 post-season due individual spirometry quality grading scores of D or lower. Thus, the analytical dataset resulted in 376 spirometry tests (i.e., 96.9% Quality Grades "C" or better) with an average 2.5 pre/post season repeated measures performed by each individual WFF participant. WFFs' spirometry tests and FeNO levels are summarized for pre- and post-season in 2018 and 2019 in Table 2. On average, WFF spirometry parameter results were above those of the general U.S. adult population (i.e. percent predicted >100%) (Table 2).

3.2. Cross wildfire season changes

The results of cross-seasonal comparisons and the number of WFFs with paired samples for the analyses are shown in Table 3. Overall, PEF and PEF% predicted significantly declined across the wildfire season when 2018 and 2019 measurements were combined (−0.15 ± 0.07 L/s, *p*-value = 0.04 and −1.87 ± 0.71%, *p*-value <0.01, respectively). Specific to singular seasons, PEF and PEF% significantly decreased following the 2018 fire season (−0.19 ± 0.09 L/s, *p*-value = 0.03 and −2.40 ± 0.86%, *p*-value = 0.01, respectively). On average, both PEF% predicted and FVC% predicted significantly improved during the post-2018 to pre-2019 off-season (3.08 ± 1.26%, *p*-value = 0.02 and 0.99 ± 0.41%, *p*-value = 0.02, respectively). We did not observe any significant lung function changes across the 2019 wildfire season or across the follow-up period from pre-season 2018 to post-season 2019 (Table 3). The parameter estimates of covariates in the model are summarized in Table A.1.

Results were similar for WFFs who completed spirometry testing across all four sampling time points. Overall, PEF% predicted, marginally decreased across the 2018 and 2019 combined season (−1.94 ± 0.98%, *p*-value = 0.06). PEF% predicted also marginally declined in the 2018 fire season (−2.42 ± 1.36%, *p*-value = 0.08), but FEV_1% increased

Table 2
Descriptive statistics for spirometry (quality grading score better than D) and FeNO (Mean ± SD) of wildland firefighters in pre- and post-season of 2018 and 2019.

	2018		2019	
	Pre-season	Post-season	Pre-season	Post-season
All WFFs				
N	103	95	88	90
PEF (L/s)	11.67 ± 1.82	11.48 ± 1.75	11.52 ± 1.70	11.41 ± 1.98
PEF%[a]	114.67 ± 16.41	111.82 ± 15.76	113.50 ± 14.31	112.67 ± 16.35
FEV_1 (L)	4.61 ± 0.62	4.59 ± 0.59	4.62 ± 0.64	4.64 ± 0.69
FEV_1%[a]	102.77 ± 11.30	101.66 ± 10.87	103.00 ± 10.53	103.83 ± 11.91
FVC (L)	5.78 ± 0.72	5.81 ± 0.71	5.82 ± 0.78	5.82 ± 0.80
FVC%[a]	105.61 ± 9.88	105.12 ± 9.97	106.18 ± 9.86	106.26 ± 10.17
FEV_1/FVC	0.80 ± 0.06	0.79 ± 0.06	0.79 ± 0.05	0.80 ± 0.06
N	91	97	99	95
FeNO (ppb)	35.48 ± 35.88	22.56 ± 15.24	35.14 ± 35.09	25.92 ± 19.60
WFFs who completed all four tests				
N	44	44	44	44
PEF (L/s)	11.66 ± 1.82	11.47 ± 1.67	11.78 ± 1.62	11.64 ± 1.64
PEF%[a]	113.14 ± 17.10	110.45 ± 15.99	114.16 ± 15.23	112.73 ± 15.57
FEV_1 (L)	4.63 ± 0.54	4.62 ± 0.53	4.60 ± 0.50	4.64 ± 0.56
FEV_1%[a]	102.23 ± 10.63	101.25 ± 10.25	101.66 ± 10.02	102.80 ± 11.16
FVC (L)	5.89 ± 0.72	5.90 ± 0.74	5.91 ± 0.72	5.94 ± 0.72
FVC%[a]	105.98 ± 10.18	105.02 ± 10.31	106.07 ± 10.42	106.84 ± 10.33
FEV_1/FVC	0.79 ± 0.06	0.79 ± 0.06	0.78 ± 0.06	0.78 ± 0.07
N	40	40	40	40
FeNO (ppb)[b]	33.81 ± 37.67	21.73 ± 13.25	36.49 ± 41.03	25.87 ± 18.75

Acronyms: WFFs = wildland firefighters; PEF = peak expiratory flow; PEF% = percent of predicted PEF; FEV_1 = forced expiratory volume in one second; FEV_1% = percent of predicted FEV_1; FVC = forced vital capacity; FVC% = percent of predicted FVC; FeNO = fractional exhaled nitric oxide; ppb = part per billion.

[a] NHANESIII reference prediction equations used for parameter estimates (Hankinson et al., 1999).

[b] FeNO: <25 ppb = normal; 25 ≤ X < 50 ppb = equivocal; ≥50 ppb eosinophilic inflammation (Dweik et al., 2011).

across the 2019 season (1.05 ± 0.49%, *p*-value = 0.04). PEF% and FVC% significantly increased in the off-season (3.54 ± 1.39%, *p*-value = 0.01 and 1.08 ± 0.44%, *p*-value = 0.02, respectively). No other significant cross-season changes in lung function were found (Table 3). The parameter estimates of covariates for WFFs with complete sets of measurements are summarized in Table A.2.

FeNO significantly decreased when the results from both years were combined (*p*-value <0.01), also decreased across singular fire season (*p*-values <0.01) and across study period (2018 pre-season to 2019 post-season, *p*-value = 0.02), but significantly increased during the off-season (*p*-value <0.01). Sensitivity analysis for WFFs who provided all four tests yielded similar results for cross seasonal changes in FeNO (Table 3). The parameter estimates of covariates for the two sets of analyses for FeNO are shown in Tables A.1 and A.2.

The prevalence of respiratory symptoms at pre- and post-season in both years was highest for nose, sinus, and cough symptoms (Table 4). The prevalence of symptoms was higher in the post-season than in pre-season. Overall, cross-seasonal symptomology showed a relative increase in prevalence between 23.0-154.2%, and these increases were generally greater in 2018 than in 2019 (Table 4). WFFs had higher symptom scores for nose, sinuses, cough, wheezing, sputum production, and shortness of breath in the post-season than in the pre-season of 2018 as well as 2019 (*p*-values <0.05). The sensitivity analysis, which

Table 3
Cross-seasonal changes of spirometry and FeNO, estimate ± standard error (*p*-value). Bold font indicates statistical significance.

	Overall – 2018 & 2019 Pre to Post-season	2018 Pre to Post-season	2018 Post-season to 2019 Pre-season	2019 Pre to Post-season	2018 Pre-season to 2019 Post-season
All WFFs with paired tests across period					
N of paired samples	162	87	54	75	52
PEF (L/s)[a]	**−0.15 ± 0.07 (0.04)**	**−0.19 ± 0.09 (0.03)**	0.21 ± 0.13 (0.11)	−0.08 ± 0.11 (0.50)	−0.13 ± 0.15 (0.37)
PEF%[b]	**−1.87 ± 0.71 (0.01)**	**−2.40 ± 0.86 (0.01)**	**3.08 ± 1.26 (0.02)**	−1.25 ± 1.11 (0.26)	−0.89 ± 1.38 (0.52)
FEV_1 (L)[a]	0.01 ± 0.02 (0.65)	0.00 ± 0.02 (0.83)	−0.01 ± 0.03 (0.73)	0.02 ± 0.02 (0.38)	0.02 ± 0.03 (0.55)
FEV_1%[b]	0.09 ± 0.37 (0.81)	−0.45 ± 0.55 (0.41)	0.14 ± 0.54 (0.79)	0.73 ± 0.52 (0.17)	0.46 ± 0.66 (0.49)
FVC (L)[a]	0.02 ± 0.02 (0.14)	0.02 ± 0.02 (0.36)	0.03 ± 0.02 (0.21)	0.03 ± 0.02 (0.19)	0.06 ± 0.03 (0.08)
FVC%[b]	0.29 ± 0.32 (0.36)	−0.11 ± 0.47 (0.82)	**0.99 ± 0.41 (0.02)**	0.76 ± 0.39 (0.06)	1.23 ± 0.74 (0.11)
FEV_1/FVC[a]	0.00 ± 0.00 (0.32)	0.00 ± 0.00 (0.15)	−0.01 ± 0.00 (0.06)	0.00 ± 0.00 (0.96)	−0.01 ± 0.00 (0.18)
N of paired samples	162	77	60	86	44
Log FeNO (ppb)[a]	**−0.25 ± 0.04 (< 0.01)**	**−0.31 ± 0.06 (< 0.01)**	**0.29 ± 0.08 (<0.01)**	**−0.20 ± 0.05 (< 0.01)**	**−0.18 ± 0.07 (0.02)**
WFFs who completed all four tests					
N of paired samples	88	44	44	44	44
PEF (L/s)[a]	−0.16 ± 0.10 (0.11)	−0.20 ± 0.14 (0.16)	0.24 ± 0.14 (0.10)	−0.10 ± 0.12 (0.41)	−0.06 ± 0.17 (0.72)
PEF%[b]	−1.94 ± 0.98 (0.06)	−2.42 ± 1.36 (0.08)	**3.54 ± 1.39 (0.01)**	−1.45 ± 1.30 (0.27)	−0.12 ± 1.54 (0.94)
FEV_1 (L)[a]	0.01 ± 0.06 (0.85)	−0.01 ± 0.03 (0.79)	−0.01 ± 0.03 (0.65)	0.03 ± 0.02 (0.19)	0.03 ± 0.03 (0.34)
FEV_1%[b]	0.05 ± 0.44 (0.91)	−0.93 ± 0.68 (0.18)	0.30 ± 0.57 (0.57)	**1.05 ± 0.49 (0.04)**	0.45 ± 0.65 (0.48)
FVC (L)[a]	0.02 ± 0.07 (0.82)	−0.01 ± 0.03 (0.77)	0.03 ± 0.03 (0.27)	0.03 ± 0.02 (0.23)	0.05 ± 0.03 (0.11)
FVC%[b]	−0.07 ± 0.43 (0.87)	−0.91 ± 0.67 (0.18)	**1.08 ± 0.44 (0.02)**	0.79 ± 0.43 (0.08)	0.94 ± 0.76 (0.22)
FEV_1/FVC[a]	0.00 ± 0.00 (0.63)	0.00 ± 0.00 (0.98)	−0.01 ± 0.00 (0.06)	0.00 ± 0.00 (0.65)	0.00 ± 0.00 (0.54)
N of paired samples	80	40	40	40	40
Log FeNO (ppb)[a]	**−0.26 ± 0.06 (< 0.01)**	**−0.32 ± 0.09 (<0.01)**	**0.34 ± 0.10 (<0.01)**	**−0.20 ± 0.08 (<0.01)**	**−0.18 ± 0.07 (0.01)**

Acronyms: WFFs = wildland firefighters; PEF = peak expiratory flow; PEF% = percent of predicted PEF; FEV_1 = forced expiratory volume in one second; FEV_1% = percent of predicted FEV_1; FVC = forced vital capacity; FVC% = percent of predicted FVC; FeNO = fractional exhaled nitric oxide; ppb = part per billion.

[a] Adjusted for age, sex, race, height, weight, smoking status, the total number of responses to wildfire and prescribed fire incidents during the season, and

work as a volunteer structural/municipal firefighter before the wildland fire season.

[b] Adjusted for smoking status, the total number of responses to wildfire and prescribed fire incidents during the season, and work as a volunteer structural/municipal firefighter before the wildland fire season.

included WFFs who reported their symptom scores across all four time points, showed similar trends (Table A.3).

3.3. Mid-season fire incident deployment

The demographics of the WFF Hotshot crew (N = 19) that was followed during deployment on an active fire incident were similar to those of the other WFFs in the study (Table A.4, p-values >0.05). However, none of the WFF in this group identified as current smokers, whereas 12% of all WFF participants reported being current smokers (Table A.4). The spirometry tests (N = 2) with a grade of D were removed from the analyses of cross-shift changes in lung function. On the first day of testing, we observed an average 120 mL decline in cross-shift FVC volume; this represented an average 2.35% cross-shift decline in FVC% for each WFF (-0.12 ± 0.03 L, p-value <0.01 and -2.35 ± 0.64%, p-value <0.01, respectively). FeNO significantly decreased across the work shift on the second day (-3.50 ± 0.95 ppb, p-value <0.01) (Table 5).

4. Discussion

4.1. Cross-seasonal changes in lung function

The mean percent of predicted lung function values for WFFs were typically above 100% (Table 2). This observation is similar to previous reports for WFFs in Northern California and Montana (Liu et al., 1992; Rothman et al., 1991). Using lower limit of normal (LLN) of FEV_1/FVC to determine airway obstruction, most WFFs (N = 134, 88%) had normal spirometry (i.e., $FEV_1/FVC > FEV_1/FVC$ LLN). Among those who displayed some level of airway obstruction (N = 18), twelve WFFs presented with mild or borderline obstruction in both pre- and post-season measurements in either 2018 or 2019; the other six WFFs presented with mild obstruction for at least one test session.

The overall combined cross-seasonal declines in lung function measures were mainly driven by decreases across the 2018 wildfire season. In contrast, there were no significant cross-season changes in 2019. Interestingly, the number of responses to wildfire and prescribed fire incidents that the WFFs reported during the 2018 and 2019 fire seasons is comparable (Table 1) and was adjusted for in the linear mixed effect models. The difference in lung function declines between these two seasons could be due to differences in cumulative days on wildfire deployments and prescribed burns and possibly work tasks during these wildland firefighting assignments. In this study, IHC WFFs had 387 and 13 cumulative days of 2018 wildfire deployments and prescribed fire incidents, respectively across all crews. In 2019, they had 305 and 73 cumulative days, respectively. These results may indicate higher cumulative smoke exposure in 2018 and might explain the observation of cross-season lung function decline in 2018 but not in 2019. Information for the number of cumulative days working at wildfire and prescribed fire incidents was crew-level data and was not available for individual firefighters. Therefore, the number of cumulative days in fire incidents was not adjusted for in the statistical models. Moreover, controlling for fire crew in the models (Table A.5) did not change the results when compared to those presented in Table 3. The pulmonary impairment across the 2018 fire season tended to resolve during the off-season, as evidenced by significant increases in the percent predicted lung function measures (Table 3).

We did not investigate the association between the length of the off-season period away from wildland firefighting and the level of recovery in lung function because of incomplete data. While questions were asked about prior wildland firefighting and when the most recent wildland firefighting occurred in the 2019 pre-season questionnaire, the information was not sufficient to determine the length of the break away from firefighting since the previous season.

4.2. Cross-shift changes in lung function

WFFs' lung function trended towards a decrease across a fire suppression shift, with a statistically significant decline observed for FVC and FVC% (Table 5). FEV_1/FVC significantly increased after firefighting shifts, but the increase is not clinically significant (Table 5) (Pellegrino et al., 2005). Acute lung function impairment has also been observed among WFFs who worked at prescribed burns (Betchley et al., 1997; Nelson et al., 2020; Slaughter et al., 2004). Similarly, WFFs in Canada had a significant transient decline in FVC (approximately 0.3 L decrease) one week after fighting wildfires which was no longer evident during the second week following exposure (Dorman and Ritz, 2014).

We observed that 16 and 12 of the 19 WFFs had a reduced FEV_1 and

Table 4
Wildland firefighters self-reported symptom prevalence and severity scoring between pre- and post-season sampling periods. Eye symptoms include itching, swelling, and tearing; nose symptoms include itching, congestion, sneezing, and runny nose; sinus symptoms include headache, thick mucus, postnasal drip, and throat clearing. Shortness of breath symptoms include shortness of breath or chest tightness and shortness of breath while walking. p-values indicate significant changes in the prevalence. Symptom severity Likert scores (Mean ± SD): (0 = none, 1 = trivial, 2 = mild, 3 = moderate, and 4 = severe).

2018 fire season	N of paired samples	Pre-season		Post-season		p-value	Relative change in cross-season prevalence
		Prevalence %	Likert Score	Prevalence %	Likert Score		
Eyes	96	19.4 %	0.8 ± 1.6	26.0 %	1.3 ± 2.2	0.07	↑ 34.0 %
Nose	96	44.6 %	2.8 ± 3.1	56.9 %	3.9 ± 3.4	0.04*	↑ 27.6 %
Sinus	96	34.4 %	2.1 ± 2.6	50.7 %	3.8 ± 3.8	<0.01**	↑ 47.4 %
Cough	95	35.8 %	0.4 ± 0.6	60.4 %	1.0 ± 1.0	<0.01**	↑ 68.7 %
Wheezing	94	17.0 %	0.2 ± 0.6	38.0 %	0.6 ± 1.0	<0.01**	↑ 123.5 %
Sputum production	95	19.8 %	0.3 ± 0.6	42.6 %	0.8 ± 1.1	<0.01**	↑ 115.2 %
Shortness of breath	96	13.2 %	0.3 ± 0.8	28.2 %	0.8 ± 1.3	<0.01**	↑ 113.6 %
2019 fire season	N of paired samples	Prevalence %	Likert Score	Prevalence %	Likert Score	p-value	Relative change in cross-season prevalence
Eyes	90	17.4 %	0.8 ± 1.5	24.4 %	1.1 ± 2.0	0.13	↑ 40.2 %
Nose	90	36.9 %	2.2 ± 2.9	45.4 %	3.1 ± 3.4	0.04*	↑ 23.0 %
Sinus	90	27.8 %	1.8 ± 3.0	39.0 %	2.9 ± 3.7	0.04*	↑ 40.3 %
Cough	88	28.4 %	0.4 ± 0.7	40.6 %	0.7 ± 1.1	0.02*	↑ 42.9 %
Wheezing	90	12.5 %	0.2 ± 0.6	25.0 %	0.4 ± 0.9	<0.01**	↑ 100.0 %
Sputum production	90	23.1 %	0.3 ± 0.7	32.3 %	0.6 ± 0.9	0.02*	↑ 39.8 %
Shortness of breath	90	7.2 %	0.2 ± 0.9	18.3 %	0.5 ± 1.1	0.02*	↑ 154.2 %

Acronyms: SD = standard deviation.
*: p-value <0.05; **: p-value <0.01.

Table 5
Spirometry and FeNO (Mean ± SD) of wildland firefighters before and after firefighting shifts. Lung function was tested on the first day (Day 1, pre- and post-shift), while FeNO was measured on the second and third days (Day 2 and 3, pre- and post-shift). Bold font indicates statistical significance.

Spirometry (Day 1)	Pre-shift[b]	Post-shift[b]	Cross-shift change (*p*-value)
N of paired samples	17	17	
PEF (L/s)	10.66 ± 1.32	10.50 ± 1.44	−0.16 ± 0.18 (0.37)
PEF%[a]	103.29 ± 12.30	103.18 ± 17.04	−0.12 ± 2.36 (0.96)
FEV_1 (L)	4.72 ± 0.57	4.68 ± 0.61	−0.04 ± 0.03 (0.30)
FEV_1%[a]	103.12 ± 9.35	102.29 ± 9.35	−0.82 ± 0.74 (0.28)
FVC (L)	6.06 ± 0.73	5.94 ± 0.73	**−0.12 ± 0.03 (< 0.01)**
FVC%[a]	108.71 ± 8.28	106.35 ± 8.11	**−2.35 ± 0.64 (< 0.01)**
FEV_1/FVC	0.78 ± 0.06	0.79 ± 0.06	**0.01 ± 0.00 (0.01)**
FeNO	**Pre-shift**	**Post-shift**	**Cross-shift change (*p*-value)**
N of paired samples	19	19	
FeNO (ppb, Day 2)	18.88 ± 9.73	15.38 ± 9.32	**−3.50 ± 0.95 (< 0.01)**
FeNO (ppb, Day 3)	19.84 ± 9.98	20.92 ± 12.76	1.08 ± 0.96 (0.28)
N of paired samples	38	38	
FeNO (ppb, Days 2 & 3)	19.36 ± 9.73	18.15 ± 11.37	−1.21 ± 0.95 (0.21)

Acronyms: SD = standard deviation; PEF = peak expiratory flow; PEF% = percent of predicted PEF; FEV_1 = forced expiratory volume in one second; FEV_1% = percent of predicted FEV_1; FVC = forced vital capacity; FVC% = percent of predicted FVC; FeNO = fractional exhaled nitric oxide; ppb = part per billion.

[a] NHANESIII reference prediction equations used for parameter estimates (Hankinson et al., 1999).

[b] There were 17 wildland firefighters who had valid spirometry tests (Quality Grades "C" or better) in both pre- and post-shifts. Two firefighters who are not included in the analysis had quality grading scores lower than D in post-shift.

FVC after the shift, respectively. FEV_1 and FVC reflect overall lung function (Csonka et al., 2024; Wang et al., 2020; Gao et al., 2023). In addition, PEF% did not decrease across shift, indicating WFFs were blowing into the spirometer as hard for the post-shift measurements as they were for the pre-shift (Pellegrino et al., 2005; Miranda et al., 2012; Santos et al., 2016). This might suggest that WFFs could have had mild air trapping due to exposure to smoke-filled environments, rather than fatigue (Alter et al., 2020; Adam et al., 2014). The contrast between the cross-shift (FEV_1 and FVC reduced) and cross-season (PEF reduced) results likely reflect the portion of the respiratory airways being impacted across the exposure periods. The decline in PEF across the season indicates adverse responses in the large airways that may be associated with cumulative exposure across the wildland fire season (Csonka et al., 2024). As already noted, their cross-shift declines without change in PEF could be a result of mild air trapping potentially due to intensive acute exposure that quickly resolves following the cessation of exposure (Moitra et al., 2021; Alter et al., 2020; Adam et al., 2014).

4.3. *Cross-season and cross-shift changes in FeNO*

FeNO significantly decreased across the wildfire seasons and increased in the off-season (Table 3). During the mid-season 'active fire' event, FeNO also significantly decreased across the work shift on one of the days it was measured but not when averaged across the two measurement days (Table 5). This finding aligns with those of Miranda et al. (2012) who reported WFFs had a reduced level of FeNO after firefighting (from 22.88 to 18.21 ppb). The decreased FeNO in WFFs is contrary to the change that was hypothesized. However, multiple studies have reported that chronic tobacco smokers tend to have lower FeNO than non-smokers (cigarette smokers: 18–23 ppb vs. non-smoker: 14 ppb; Shisha smokers: 24 ppb vs. non-smokers: 31 ppb) (Malinovschi et al., 2006; Nadif et al., 2010; Meo et al., 2014). These results are also similar to those observed in this study in which smokers had a lower FeNO level compared to non-smokers in the pre-season measurement (2018: 33.03 vs. 37.68 ppb; 2019: 35.01 vs. 35.21 ppb).

The suppression of the activities of inducible and endothelial nitric oxide synthase and conversion of nitric oxide (NO) to peroxynitrite by reactive oxygen and nitrogen species in smoke are among the possible mechanisms that underlie the repressive effects of tobacco smoking on FeNO (Meo et al., 2014; Barua et al., 2003; Jacinto et al., 2017) and are likely involved in reduction in FeNO during the wildfire season among the WFFs. Whereas negative feedback on NO synthesis in the respiratory airways due to high concentration of NO in tobacco smoke has been proposed as a potential mechanism for the transient reduction in FeNO immediately following smoking (Hoyt et al., 2003). NO exposure was not measured in the current study and the observed acute decrease in FeNO across the firefighting work-shift is less explainable.

Post-season measurement was taken within 5 days of the most recent exposure, so some of the pre-to post-season reduction in FeNO might be due to acute and not the cumulative cross-season occupational exposure to wildland fire smoke. This result is likely not confounded by medication use since six WFFs report prescription medication use for allergy or asthma symptoms throughout the study and only two had paired data that could be used in the statistical analyses. In addition, no WFF reported experiencing severe respiratory symptoms in pre- and post-season questionnaires.

4.4. *Self-reported respiratory symptoms*

In agreement with previous studies (Gaughan et al., 2008; Rothman et al., 1991), we observed WFFs had higher symptom scores at the end of the fire seasons (Table 4). We also noted that cross-seasonal increases in symptom scores and prevalence were higher in 2018 than in 2019. Similar to lung function declines, these results could be due to extended work shifts during the 2018 fire season. The symptom scores in the 2018 and 2019 pre-seasons are similar. Furthermore, the scores significantly decreased for most symptoms during the off-season from 2018 post-season to 2019 pre-season, including nose, sinus, cough, wheezing, sputum, and shortness of breath (from −2.0 to −0.4, p-values ≤ 0.05). These results further indicate the importance of the off-season period for the symptoms to resolve and the respiratory health to recover among the WFFs.

4.5. *Limitations*

The WFFEHE study is based on open cohort design, in which WFFs entered and left the study during the follow-up period. We carried out a sensitivity analysis for the WFFs who completed the tests for all four cross-season measurements (spirometry: 44; FeNO: 40) (Table 3) and the results were similar compared to those of all firefighters in the opened cohort who had paired samples for any cross-seasonal comparisons. However, it is conceivable that WFFs with better lung function preferentially remained as the study progressed. This could have biased results towards the null due to the healthy worker effect.

While the selection bias towards healthier firefighters could have occurred as the study progressed, WFFs in this study are primarily from IHCs and are the most highly trained wildland firefighters in the United States. They are expected to maintain a high level of physical fitness and engage in regular physical training because of the demanding nature of their job and fireline responsibilities. Consequently, the healthiness of the WFFs who completed the study and those who did not is likely comparable. Furthermore, there were no differences in spirometry parameters, demographic, and health-modifying factors that were measured between the two groups (Table A.6 and A.7). Therefore, selection bias and its effect are likely minimal in this study.

The total number of responses to wildland and prescribed fire incidents was reported at the individual level and was included as a covariate in the statistical model. However, the cumulative number of days worked at wildland fires was only reported at the crew level and adjusting for firefighter crew did not impact the results (Table A.5). In addition, the number of firefighting responses for individual WFF was inversely associated with off-season lung function recovery but was not associated with changes from pre-to post-wildland fire season. Although every member of a crew completed post-season measurements on the same date within 5 days following the last wildland fire suppression work, information about the number of days since the last firefighting prior to pre-season measurements was unavailable. Therefore, the impact of acute (most recent) exposure on the cross-season changes in lung function and FeNO was not conducted.

Personal exposure concentration and firefighting task data were collected for one IHCs during a mid-season fire incident deployment (August 2019), but those data were not available for other wildfire events or firefighter crews. We also did not collect other surrogate exposure information such as intensity of smoke exposure and proximity to fire lines. In addition, WFFs did not report using any type of respiratory protection equipment. Therefore, we are unable to adjust for these variables in the linear mixed model. Although, two WFFs reported acute or chronic bronchitis during the wildland fire season in the 2019 post-season questionnaire, no WFFs reported severe respiratory conditions in the three weeks prior to spirometry test. Six WFFs indicated using over-the-counter allergy medicine throughout the study and only two had paired data that could be used in the statistical analysis. Therefore, these potential confounders were not adjusted for in the statistical models because of the small number of participants reporting these conditions.

During the three-day wildfire incident in 2019, the inhalation exposures of WFFs were monitored through personal air sampling and the air pollutants (e.g., toluene, ethylbenzene, and xylene isomers) were generally highest on the first day and lowest on the third day (Navarro et al., 2023). However, FeNO test was not performed on the first day due to logistical constraints. As our findings indicate that FeNO decrease after fire suppression shifts, it is possible that a larger FeNO reduction occurred on the first day and was not captured. In addition, WFFs were asked to refrain from smoking and consuming foods rich in nitrates (e.g., bacon, leafy green vegetables, lunch meats) an hour prior to the FeNO testing and before each test session we asked each WFF to self-report nitrate rich food consumption and recent smoking. If either were reported within one to two hours previous, FeNO testing was not performed. However, no objective measurement of compliance was conducted.

4.6. Implications

Participants in the study are career firefighters, physically fit, and are predominantly young, White, and male and more so than is indicated in available data for the demographic composition of WFFs (USGAO, 2022). While this might affect the generalizability of the results, the bias that this sample composition might have introduced is expected to be towards the null. Therefore, impairment of lung function by cumulative occupational exposure to wildland fire may be more severe among a more representative sample of WFFs.

These results imply that health surveillance of WFFs should include regular lung function testing. However, optimal definition of parameters including timing and frequency to guide implementation of such testing requires further research to clarify longer-term trajectory of lung function within the context of intermittency in exposure, exposure-response relationship, and vulnerability factors. The results also highlight the need for controls to reduce exposure. Current occupational exposure limit (OEL) for respirable particulates not otherwise regulated is 5 mg/m^3. However, particulate matter in wildland fire smoke often contains many biologically reactive compounds (Gould et al., 2024). Reinhardt and George (2019) have suggested using 1.0 mg/m^3 as a fireline-average OEL and 0.7 mg/m^3 for 8-hr shift-average respirable particulates exposure (Reinhardt and George, 2019). When the exposure concentration exceeds an OEL, appropriate respiratory protection should be used. New guidance allows voluntary use of NIOSH-approved N95 respirators by federally employed WFFs when not working at the fireline during wildfire deployments to help reduce wildland fire smoke exposure (NWCG, 2024; USDOI, 2025). This new policy can mitigate the risk of lung function impairment due to wildland firefighting.

5. Conclusions

Among the WFFs included in this study, most of lung function metrics decreased after 2018 fire season, with a significant decline in PEF and PEF%. No significant lung function changes were found in the 2019 fire season. These results could be due to higher cumulative days working at wildfire and prescribed fire incidents in 2018 than those in 2019. We also observed WFFs' lung function tended to recover through the off-season. FeNO significantly decreased on the second day of firefighting shift. Symptom prevalence and scores increased at the end of the season and decreased during the off-season. Although we observed evidence of recovery in lung function and respiratory symptoms, the effect of repeated injury-repair cycles due to firefighting is not clear and could be further researched in long-term studies in WFFs, especially in association with occupational exposure metrics.

CRediT authorship contribution statement

Chieh-Ming Wu: Writing – original draft, Formal analysis. **Kathleen Clark:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Olorunfemi Adetona:** Writing – review & editing, Supervision. **Kathleen Navarro DuBose:** Writing – review & editing, Validation, Project administration, Investigation, Data curation. **Corey Butler:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Alejandra Ramirez-Cardenas:** Writing – review & editing, Software, Project administration, Investigation. **James Odei:** Formal analysis. **Molly West:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization. **Christa Hale:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Disclaimer

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Reference to trade names or commercial products does not constitute endorsement and recommendation of use.

Ethics

This study was reviewed and approved by the Institutional Review Board at the NIOSH (18-WSD-01) and The Ohio State University (2022X0122). All participants signed informed consent at the time of enrollment.

Declaration of competing interest

The authors declare no competing interests.

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Appendix A. Supplementary data

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