Summer 2024

Environmental Health and Impact of Workload on Errors for Wildland Fire Personnel

Michael Bryan Held
Missouri University of Science and Technology

ENVIRONMENTAL HEALTH AND IMPACT OF WORKLOAD ON ERRORS FOR WILDLAND FIRE PERSONNEL

by

MICHAEL BRYAN HELD

A THESIS

Presented to the Graduate Faculty of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN BIOLOGICAL SCIENCES

2024

Approved by:

Dr. Robin Verble, Advisor
Dr. Matthew Thimgan
Dr. Dev Niyogi

PUBLICATION THESIS OPTION

This thesis consists of two articles, formatted for publication in their respective journals:

Paper I, found on pages 3 - 37, has been published in the Journal of Fire Ecology in February of 2024. The citation of the publication is: *Held, M.B., Ragland, M.R., Wood, S. et al. Environmental health of wildland firefighters: a scoping review. fire ecol 20, 16 (2024).* *https://doi.org/10.1186/s42408-023-00235-x*

Paper II, found on pages 38 - 62, has been formatted and submitted for publishing in the Journal of Human Factors.

ABSTRACT

This thesis offers an analysis of how environmental health and workload affect wildland fire dispatchers and firefighters, combining results from two studies. The first study, "Environmental Health of Wildland Firefighters: A Scoping Review," performs a scoping review of scientific literature that examines the unique environmental health challenges wildland firefighters face. The review points out the increased risks to safety, health, and well-being from more exposure to natural hazards, identifying key research gaps and priorities. It stresses the need to broaden the geographic and demographic scope of studies, improve analytical methods, and increase research funding and focus for wildland firefighters.

The second paper, "Relationships Between Workload and Error in Wildland Fire Dispatchers," explores how workload metrics and error rates correlate in wildland fire dispatchers. By analyzing data from 2022 to 2023, this study reveals the subtle interactions between operational demands and errors, providing insights into improving safety and efficiency in managing wildland fire incidents.

Together, these studies make a significant contribution to emergency management and environmental health by highlighting the complex factors that affect the safety and health of those on the front lines of wildfire management through a multidisciplinary approach to tackle these challenges, underscoring the importance of targeted strategies, comprehensive training, and a stronger focus on safety culture in wildland fire response efforts.

ACKNOWLEDGMENTS

I want to express my love, appreciation, and gratitude to my mother and father during this adventure. Without their support, my journey to complete this thesis would have been almost impossible. My mother’s drive and my father’s guidance were essential to my success. Thank you.

I want to thank Dr. Robin Verble, a person whose love for things from the 80’s and 90’s made me feel more at ease and more comfortable overall in coming to this university from 2000 miles away. The journey was littered with so much learning and experience that will be valuable as I aspire to continue on in academia. What I have taken from this is the way to be a professional in academia and how to approach the amount of hard work that is thrown at you. Thank you.

To Dr. Matt Thimgan and Dr. Dev Niyogi, our interpersonal interactions and your guidance will not be forgotten. I hope you know how much I do appreciate you and your lessons.

I also want to thank and acknowledge Jennifer Harrell. Her composure and dedication to the work, education, and her family were inspiring. You will be an amazing success in your career if you are even ten percent of the quality of an individual you are. Thank you for being there for me.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

In the face of escalating wildfire incidents across the globe, exacerbated by climate change and expanding human settlements into fire-prone areas, the roles of wildland firefighters and dispatchers have never been more critical. These professionals, who stand on the frontline of one of nature's most formidable challenges, navigate a landscape marked by both physical danger and intricate logistical coordination. This thesis delves into the interconnected worlds of wildland firefighters and fire dispatchers, exploring the multifaceted challenges they encounter, from environmental health risks to the complexities of workload and error management in high-stress situations.

Wildland firefighters engage directly with wildfires, operating in conditions that pose significant risks to their physical and mental health. Their work demands exceptional physical endurance, tactical acumen, and psychological resilience, as they confront not only the immediate threats of flames but also the long-term health implications of exposure to hazardous environments. The transition from the frontline to the dispatch center is a path taken by many in this field, carrying with them invaluable experience but also, potentially, the cumulative health impacts of their firefighting careers.

Fire dispatchers, often veterans of wildland firefighting themselves, play a pivotal role in the strategic management and operational success of fire suppression efforts. Their transition from operational firefighting to dispatch roles introduces a unique perspective into the dispatch environment, blending firsthand knowledge of the fireline with the critical responsibilities of logistical support and decision-making. However, this shift also encapsulates a transition of challenges, where the physical demands of firefighting give way to the mental and emotional rigors of workload management and error mitigation in the dispatch center.

This thesis presents an integrated examination of these two crucial components of wildfire management. The first study focuses on the environmental health concerns of wildland firefighters, highlighting the specific risks associated with their vital work and the imperative for targeted health and safety interventions. The second study shifts the lens to wildland fire dispatchers, examining the dynamics of workload and error in the dispatch centers, with a particular emphasis on how the experiences of former wildland firefighters influence operational efficiency and safety outcomes.

By weaving together these two strands of research, the thesis seeks to underscore the continuity of experience and risk that links the front lines of firefighting with the strategic hub of dispatch operations, advocating for a holistic approach to health, safety, and efficiency that recognizes the shared journey of these professionals. Through this comprehensive exploration, the thesis contributes to a deeper understanding of the needs and challenges of wildland fire responders, offering insights that can inform more effective strategies for support and intervention.

PAPER

I. ENVIRONMENTAL HEALTH OF WILDLAND FIREFIGHTERS: A SCOPING REVIEW

M. Bryan Held[1], Miranda Rose Ragland[1], Sage Wood[1], Amelia Pearson[1], Seth Wayne Pearson[2], Olivia Chenevert[1], Rachel Marie Granberg[2], Robin Michelle Verble[1,3]

[1]400 West 11th Street, Rolla, Missouri, USA 65409; Environmental Science Program, Department of Biological Sciences, Missouri University of Science & Technology

[2]United States Department of Agriculture Forest Service

[3]Corresponding author, verbler@mst.edu; 1-573-341-7274

ABSTRACT

Background: Wildland firefighters are likely to experience heightened risks to safety, health, and overall well-being as changing climates increase the frequency and intensity of exposure to natural hazards. Working at the intersection of natural resource management and emergency response, wildland firefighters have multidimensional careers that often incorporate elements from disparate fields to accomplish the tasks of suppressing and preventing wildfires. Thus, they have distinctly different job duties than other firefighters (e.g., structural firefighters) and experience environmental health risks that are unique to their work. We conducted a scoping review of scientific literature that addresses wildland firefighter environmental health and analyzed geographic and demographic trends, sample sizes, patterns in analysis, and topical themes.

Results: The majority of studies have clustered in a few highly developed countries, and in the United States within California and Idaho. Many studies fail to consider the impact that demographic factors may have on their results. The number of studies published annually is increasing and themes are broadening to include social and psychological topics; however, most authors in the field have published an average of < 3 articles.

Conclusions: We identify three areas that we believe are imminent priorities for researchers and policymakers, including a lack of diversity in study geography and demography, a need for more complex and interactive analyses of exposure, and prioritization of wildland firefighters in research funding and focus.

Keywords: occupational health, mental health, performance, safety, well-being, medical, demography, geography,

List of Abbreviations: WFF = wildland firefighters; PPE = personal protective equipment

1. INTRODUCTION

Broadly, environmental health considers existing and potential hazards, access and equity in provisioning care and resources, and exposure incurred in an environment (Huber *et al.* 2011). As our global environment shifts with changing climates, environmental health impacts will be inequitably distributed among professions and geographic locations. Wildland firefighters, due to the nature of their work, are likely to see significantly increased environmental health risks as both hazards and their exposure increase due to the increased frequency and intensity of wildfires (Podur & Wotton 2010). Thus, wildland firefighter environmental health scientists are faced with an imminent challenge. They must necessarily create interdisciplinary solutions, relying on concepts from medical, occupational, environmental, and sociological fields to infer the conditions and state of the wildland firefighting workforce; in tandem, they must also identify the contributing factors that may promote or detract from the overall health and well-being of said population to rapidly address these looming issues (Huby & Adams 2009, Huber *et al.* 2011, Brown 2013).

Wildland firefighting is often considered a subfield of a broadly or diffusely defined field of 'firefighting' due to the smoke, flame, and heat exposure sustained by workers. Firefighting is included even more broadly as part of emergency management and disaster response, since workers in these fields are generally trained in incident command systems and can conduct interagency work that may include performing tasks that are not exclusive to fire suppression (e.g., traffic control and mitigation, evacuation, establishment of safety zones and shelters, etc., VanDevanter *et al.* 2010, Thompson *et al.* 2018). While wildland firefighters may work in emergency management periodically and some commonalities with structural firefighting do exist, many of the occupational and environmental exposures and hazards that WFF face are distinctly different from other classes of emergency responders and firefighters. Here, we defined a wildland firefighter as per Ragland *et al.* (in press) as a person "who is tasked with preventing, actively suppressing, or supporting the active suppression of fires occurring in natural or naturalized vegetation" and included such job categories as operational wildland firefighters (e.g., engine crews, hand crews, hotshot crews, smokejumpers, rappelers), fire prevention, fuels management specialists, fire ecologists, fire planners, wildland fire dispatchers, fire cache managers, fire equipment operators, and fire aviation.

Wildland firefighters' work is unique in the physiological, psychological, performance, and safety demands it imposes on its workers: 1) WFF work in natural environments and are exposed to natural elements for extended periods of time, sometimes multiple days; 2) They often are working in remote settings, which can mean crews are socially isolated for prolonged periods; 3) Wildland fires are often sustained events with unpredictable shifts in intensity occurring in rugged terrain, so the physicality of the work requires burst energy combined with extended periods of high endurance and high impact activity; 4) Many wildland firefighters wear significantly less PPE than structural firefighters (e.g., minimal or no respiratory or airway protection), though they endure sustained and prolonged smoke exposure. This combination of exposure and physiological demands significantly alters the risk equation for injury, illness, and stress-related impacts on mental health and social interactions (Alfano *et al.* 2021).

A study by the United States Bureau of Labor Statistics found that wildland firefighters account for 25% of all firefighter fatalities despite being only about 2% of the total firefighting workforce in the United States: This was attributed to an increased likelihood of multi-casualty events because of a crew-based workforce (Clarke & Zak 1999). However, from 2007 to 2016, the top three causes of wildland firefighter death included heart attacks (24%), vehicle accidents (20%), and aircraft accidents (18%); entrapments were the fourth most common cause of death (PMS 841 2017). Despite this, wildland firefighter environmental health remains understudied relative to structural firefighting and other high-risk job fields (e.g., timber cutting, mining). Here, we identify the scope of the literature at present and gaps in knowledge within the field of wildland firefighter environmental health (Munn et al. 2018). We focus on the geographic distribution of studies, sample size, topical biases, trends in demographics, and experimental design to highlight the need for more diversified work, a clearer understanding of the interactive effects of exposure and physiology, and sustained research.

1.1. PUBLICATION ANALYSIS

We assembled literature with an exhaustive Google Scholar search using the terms 'wildland firefighter', 'wildland firefighter environmental health', 'wildland firefighter health', 'wildland firefighter occupational health', and 'wildland firefighter mental health'. We supplemented this search with known literature previously acquired through other means. We acquired all literature in which the title or abstract explicitly mentioned or referenced: wildland firefighters, firefighter health, safety, well-being, recruitment, and/or retention. Papers were acquired directly from Google Scholar sources or using the Missouri University of Science and Technology Interlibrary Loan (ILLiad) Department when complete versions were unavailable elsewhere. Digital complete versions of all papers were compiled in a Google drive accessible to all authors.

All citations were entered in a .CSV file with basic information (authors, year, journal, volume, page numbers) and then binned topically. We also recorded study location; study year; study length; total sample size; whether the study analyzed direct or indirect effects of fire; whether the analysis considered age, gender, and ethnicity; and the findings of the study. We defined a direct effect as one that was directly attributable to a wildland fire or one that happened while on a wildland fire, whereas an indirect effect may have occurred secondary to or had a wildland fire as a contributing factor in its emergence but could not be causally linked to the fire itself. We excluded studies where wildland firefighters were less than 5% of the total study population, non-scientific studies (i.e., personal narratives), literature reviews, non-peer reviewed materials (except theses and dissertations), and materials that mentioned wildland firefighters as a motivator for the study but did not address a question directly related to WFF (i.e., Riley *et al.* 2022). Topical bins were informed by a word cloud created from the titles of papers that met the criteria for study inclusion (Fig. 1).

We identified four bins, psychological/sociological, medical, occupational/safety, and performance, to which all studies were assigned. We assigned each paper to a single bin that best fits its theme. Within a bin, we examined additional parameters as appropriate. Psychological and sociological studies were those that considered the impacts of wildland firefighting careers on mental health, mental well-being, community and peer-to-peer interactions, sleep, and behavioral stress responses. Medical studies were those that considered impacts of the career on physical health, physical well-being, physiology, anatomy, and/or longevity. We considered performance studies to be those that measured how physical, chemical, mental, or other environmental parameters changed wildland firefighter ability to complete tasks, tests, or other job metrics. Occupational and safety studies were defined as those that considered how worker safety, well-being, or health influenced work outcomes. Occupational and safety studies also included studies examining ways to increase worker safety and well-being, including improvements to PPE. Analyses were conducted from October 2022 - January 2023 and included literature published before January 2023.

1.2. STUDY SUMMARIES

A total of 140 papers were included in this study, within which we identified 371 total authors (Table 1). Individual authors published 1.55 papers on average (range 1 - 11). When we included only authors that had published more than one paper, the mean number of papers per author was 2.99. The median sample size across all studies was 35 individuals (quartile: 14.5 - 114.75). Studies were conducted primarily in highly developed countries and the western United States (Figs. 2 & 3) and focused on operational wildland firefighters (N = 142). Overall, the annual number of publications on WFF environmental health has steadily increased since the 1990s (Fig. 4). In addition to narrow geographic scopes, most studies have analyzed few demographic variables (Fig. 5). Medical and occupational studies comprised several of the articles we analyzed (41.4% and 39.3%, respectively).

1.3. MEDICAL STUDIES

We identified 58 studies that addressed medical topics in wildland firefighter environmental health. Of these, cardiovascular disease, and risk (N = 14, 24.1%), smoke and pulmonary and respiratory impacts (N = 11, 19.0%), and heat exposure (N = 10, 17.2%) were the most examined subjects. Median study size was 36.5 participants (quartile: 11.5 - 105.75), and most studies took place in North America (N = 42) and Europe (N = 12). The longest study followed participants for three fire seasons (approximately 3 years). Four (6.9%) studies included ethnicity in their analyses; 26 (44.8%) included age, and 19 (32.8%) included gender. Studies were most often conducted as direct assessments of wildland fire impacts on health (N = 41, 70.7%).

Overall, these studies attributed a suite of medical risks to WFF exposure to wood smoke, particulate matter, ash, soil, heat, and prolonged physiological stress. Short-term smoke inhalation effects were reported, but these effects appeared to dissipate rapidly (Dorman & Ritz 2014, Wu et al. 2021); however, other studies found that 65% of career WFF complain of respiratory symptoms (Swiston et al. 2008), suggesting that long-term effects may exist, even if they are not readily apparent. Smoke exposure was also linked to cardiopulmonary disease and chronic bronchitis (Main et al. 2020), cardiovascular disease, stroke (Jeklin et al. 2021), and acute cardiovascular events (Hunter et al. 2014). While few COVID data exist for WFF, acute and chronic smoke exposure and dense crew housing may increase risk and vulnerability to infection and may make symptom-based pulmonary diagnoses more difficult (Metz et al. 2022).

Physical injury rates on the job for WFF are 20% (Christison et al. 2021, Garcia-Heras et al. 2022), and heat-related stress and injury risk are exacerbated by the personal protective equipment and packs (20.5 kg +) that WFF are required to wear (Carballo-Leyenda et al. 2019). Common injury sites include the knees, low back, and shoulders, and 30% of all injuries are the result of a slip, trip, or fall (Moody et al. 2019). Fitness directly impacted physiological indicators of muscle damage and short-term overuse, and higher levels of physical fitness were an indicator of decreased risk for rhabdomyolysis (Christison 2020).

Medical incidents are the leading direct cause of WFF death in the United States (Butler et al. 2017), but substantial gaps exist in our understanding of both long- and short-term medical impacts of the physiological strain, environmental exposure, and additional risk factors incurred during wildfires and other portions of WFF careers. No studies consider the impacts of wildland firefighting on endocrine function, microbiomes, digestive function and nutrition, skin infection, vision and ocular systems, fertility, long-term neurological risks, cancer risk (except lung cancer, Navarro et al. 2019), or reproductive health or gestation. Further, studies of WFF-specific injury recovery and surgical outcomes are non-existent. These areas represent potential avenues of future exploration.

1.4. PSYCHOLOGICAL & SOCIOLOGICAL STUDIES

We identified 11 studies of psychological and sociological factors in wildland firefighter environmental health. These studies were published between 2011 and 2022 and most addressed sleep (N = 5) and post-traumatic stress disorder (N = 2). Studies were conducted in North America (N = 6), Australia (N = 3), Europe (N = 1), and Israel (N = 1), and were generally single-survey, single-trial, or single-season events (N = 10, 90.1%). The longest study was 30 months in duration (Cherry et al. 2020). The median sample size was 37 participants (quartile: 11 - 102). Over half of the studies utilized surveys (N = 6, 54.5%); common techniques were interviews (N = 5, 45.5%) and experimental trials (N = 3, 27.3%). Nine (81.8%) studies considered indirect effects of wildland fire careers; whereas two (18.2%, both addressing sleep) directly examined fireline effects. A single study (9.1%) considered gender and age jointly (Theleritis et al. 2020), and a single study considered age and ethnicity jointly (Leykin et al. 2013). One study considered gender alone (Vincent et al. 2015).

Psychological studies primarily centered on maintaining cognitive performance and either mitigating, managing, or assessing environmental factors that may precipitate declines via stress (Palmer 2014), sleep deprivation (e.g., Cvim et al. 2015), lack of training and support (Cherry et al. 2021), or poor diet (Bode et al. 2022). Conspicuously absent from many studies were considerations of mental health history or neurodivergence, which have been demonstrated to impact WFFs' descriptions of their experiences in the field (Ragland et al. in press). Mental health and social support are emerging fields of interest in WFF environmental health research, but few studies have directly sought to understand the diverse experiences of this population through direct interviews, surveys, or focus groups. The ones that have shown grim results: For example, one survey found that 16% of WFF respondents have had suicidal thoughts that were worsened by the stress of their jobs (Verble et al. 2022). As the field continues to develop, research that values the lived experiences and authentic voices of WFF should be the top priority. Second, we should prioritize additional work that supports WFF mental health through intervention, training, screening, and field-based initiatives.

1.5. PERFORMANCE STUDIES

Performance studies combine medical and occupational elements to assess human biometrics that can be related to job-specific tasks. A total of 16 WFF environmental health performance studies were identified, conducted between 1999 - 2022. The most common topics addressed were performance on work tests (N = 4) and rate of travel (N = 2). Most studies were conducted in North America (N = 4) and two were conducted in Europe (N = 2, Spain). Common biometrics utilized were walking and running speed, skin and core temperature, and body mass. Sample sizes ranged from 8 - 320 participants with a median of 52.5 (quartile: 17 - 80.5). Fifteen studies lasted for one fire season (approximately 6 months) or less. One study ran for four years (Gaskill et al. 2020). Of all topical areas, performance studies were the most likely to consider demographic factors. Fifteen studies (93.8%) considered some combination of age and gender, together or independently (4 both, 11 gender, 5 age); however, none considered ethnicity. Six studies performed direct fireline measures of performance (37.5%).

1.6. OCCUPATIONAL & SAFETY STUDIES

We identified 55 studies that covered topics relating to occupational health and safety of WFF. Studies were published between 1993 - 2022 in North America (N = 46), Europe (N = 5), Australia and Asia (N = 3), and Latin America (N = 1). One study (Carballo-Leyenda *et al.* 2022) occurred in both Europe and Latin America and is included in the count for both regions. Themes included job-based environmental exposure, with smoke accounting for a plurality of studies (smoke: N = 13, 23.6%; heat: N = 3, 5.5%; other: N = 1, 1.8%), personal protective equipment (N = 7, 12.7%), leadership and decision making (N = 6, 10.9%), fatalities and injuries (N = 6, 10.9%), evacuation and safety zones (N = 5, 9.1%), communication (N = 4, 7.3%), training (N = 4, 7.3%), gender (N = 3, 5.5%), and impacts of the job on task performance (N = 2, 3.6%). A total of 37 (67.3%) studies included human participants; the mean number of participants per study was 31 (quartile: 15 - 245).

Study length varied widely by methodology. The longest study retrospectively analyzed 70 years of fatality data (Cardil *et al.* 2017) and the shortest observed wildland firefighters on an active wildfire for 4 six-hour shifts (Phillips *et al.* 2015). The majority of studies observed direct effects of fire (N = 37, 67.3%). Few studies accounted for age

(N = 10, 18.2%), gender (N = 12, 21.8%) or ethnicity (N = 1, 1.8%) in their analyses. While many studies included human subjects, less than half included survey responses of participant experiences (N = 21, 38.2%). All studies focused on operational wildland firefighters' working environments.

Occupational studies often cited a lack of sufficient training for and use of safety equipment (e.g., hearing protection, Broyles et al. 2019), high rates of job-related environmental exposure to pollutants (e.g., Adetona et al. 2017), gender disparity (Reimer 2017), and a need for improved psycho-social support systems (e.g., Leduc 2020) as key priorities for improvements to the field. While safety is often considered in the context of operations and protective gear (e.g., McQuerry & Easter 2022), less work has been done to assess cultural and social aspects of safety and well-being in occupational settings, and this is also an important line of future research.

1.7. CRITICAL GAPS IN KNOWLEDGE

Our review identifies three emergent themes – 1) a lack of geographic and demographic diversity, 2) limited knowledge of the interaction between physiological factors and the natural environment, and 3) a broad need for prioritization of WFF interests in research. Addressing these themes will represent improvements toward enhancing the comprehensivity, inclusivity, applicability, and relevance of future research and help advance the state of the field.

Multiscale geographic diversity is essential to fully encompass the heterogeneity of landscapes, ecosystems, and wildland firefighters that exist. To date, wildland firefighter environmental health has been completely unstudied in significant portions of the globe where fires are most widespread and deadly (Figs. 2 & 3). Fireline hazards, smoke composition, interpersonal interactions, and pre-existing medical risks will vary among localities and populations: Neglecting to consider these differences leaves a substantial portion of the world's WFF without access to quality environmental health data and unable to make informed decisions to protect themselves from unnecessary exposures. For example, Wu et al. found that wildland firefighters in the midwestern United States who worked on prescribed burns have a higher incidence of urinary mutagenicity and systemic oxidative changes associated with smoke exposure than WFF in other areas of the country (2020), highlighting the importance of geographic diversity of studies.

Further, wildland firefighting strategies and wildland firefighter demographics vary significantly across geographic regions. Our review suggests that studies that consider the impacts of gender, age, ethnicity, and other demographic variables on environmental health are far too uncommon. Environmental justice research has repeatedly demonstrated that the effects of environmental inequities are disproportionately born by minority groups (e.g., Bullard & Wright 1993, McGregor et al. 2020), and work by Verble et al. found similar results for wildland firefighters: Non-white wildland firefighters were more likely to experience injury or illness on the fireline than white WFF (2022). Further, variables such as sexual orientation, veteran status, and mental health status have also been shown to impact how WFF characterize their work experiences (Ragland et al. in press). By neglecting to consider these and other likely important demographic and socioeconomic data, important patterns and contributing factors to environmental health risk are likely being obscured.

The current state of WFF environmental health literature almost exclusively considers operational wildland firefighters (except Palmer 2014). While operational wildland firefighters are the most conspicuous members of the enterprise, wildland firefighting consists of an interconnected web of actors, each contributing to the success of suppression efforts through their roles. Wildland firefighters include people working in wildland fire dispatch, logistics, radio operations, incident command, aviation, supply cache management, and fuels management, among others. Some of these WFF may not experience heat or smoke exposure, but they experience many other high-stress and demanding elements of the wildland fire environment, including trauma, sleep deprivation, driving and transportation hazards, interpersonal interactions, and others. Further studies are needed to understand the impacts of the work environment on their health and well-being.

Additionally, the field has a deficient understanding of the relationship between physiological and physical parameters of WFF work and exposure. As wildland firefighters work harder in smokier conditions, their ventilation rate increases, which likely increases the amount of exposure to airborne particulate matter and smoke. Likewise, not all positions on a fireline experience the same amount of smoke, and this is largely governed by terrain and atmospheric conditions. Reinhardt and Ottar linked smoke exposure to fireline position, fire type (prescribed fires yielded more exposure), task, and weather (2004); however, they stopped short of incorporating WFF physiological measurements such as heart rate and ventilation rate into their study. We could identify no studies that included the combination of physiology, local geography, and exposure; however, synthesizing these variables will further resolve our understanding of fireline risk and inform future fire management and decision-making.

Since 2009, the United States National Institutes of Health has funded less than $2 million in research that directly and primarily examined wildland firefighter environmental health (NIH RePORT 2022). In 2022, the United States Congress and President Joe Biden passed and signed legislation aimed at improving wildfire response and wildland firefighter working conditions (H.R. 4274 2021-2022). While a portion of those funds ($103 million) was set aside for WFF health and wellbeing programs, no portion was specifically designated for research in those topics. Increasing focused and dedicated research efforts requires the commitment of both researchers and government agencies: Our study found that researchers often pursued topics long enough to publish 1 - 3 papers, suggesting that funding may be a significant limiter in their ability to sustain research in this arena. This means that researcher attrition may be driving a lack of deep exploration in the field, leaving critical gaps in knowledge and unaddressed needs for the WFF population. The scope of the current WFF environmental health literature reveals a dire need for more research into the psychological, physical, occupational, and overall health, well-being, and safety of a workforce tasked with defending communities, protecting natural resources, and preventing future wildfires.

DECLARATIONS

Ethics Approval & Consent to Participate

Not applicable. No human subjects were used in this study.

Availability of Data & Materials

All articles used in this publication are available online through their respective publishers and also at www.wildlandfiresurvey.com.

Competing Interests

None

Authors' Contributions

RMV compiled literature, wrote the manuscript, and conducted analyses. RMG conceived the project and compiled the original literature. MRR compiled and organized literature, edited the manuscript, conducted analyses, and binned data. OC, AP, and SWP binned data and conducted analyses. SW conducted analyses, prepared figures, and binned data. MBH wrote the manuscript and analyzed and binned data.

ACKNOWLEDGEMENTS

A particularly deep thank you to the Missouri S&T Interlibrary Loan staff who worked tirelessly to acquire and amass literature for this project. The Missouri S&T Biological Sciences Write Club encouraged the production of this manuscript.

Funding

Students were supported through a grant from the United States Department of Defense (Grant No. W911NF2220200).

Authors' Information

SWP and RMG are wildland firefighters and have a vested personal interest in high-quality working environments. MBH and MRR are graduate researchers. OC, SW, & AP are undergraduate researchers.

Table 1. Works included in the scoping analysis by topical bin.

Topical Bin	**Relevant Citations**
Medical	Abreu *et al.* 2017, Adetona *et al.* 2011, Adetona *et al.* 2013, Adetona 2016, Adetona al. 2017, Betchley *et al.* 1997, Britton *et al.* 2013, Broyles *et al.* 2017, Carballo-Leyanda *et al.* 2018, Cherry *et al.* 2022, Christison *et al.* 2021, Christison 2015, Christison *et al.* 2021a, Collins 2018, Cuddy *et al.* 2015, Cuddy & Ruby 2011, Domitrovich 2011, Dorman & Ritz 2014, Ferguson *et al.* 2016, Ferguson *et al.* 2017, Ferreira Saint Martin & Rosenkranz 2018, Garcia-Heras *et al.* 2022, Gaugh et al. 2014, Gaugh et al. 2014a, Gurney *et al.* 2021, Gurney et al. 2021a, Hunter *et al.* 2014, Jacquin *et al.* 2011, Jeklin *et al.* 2021, Main *et al.* 2020, Metz *et al.* 2022, Miranda *et al.* 2012, Moody *et al.* 2019, Navarro *et al.* 2019, Navarro *et al.* 2021, Nelson *et al.* 2020, Niyatiwatchanchai *et al.* 2022, Oliveira *et al.* 2016, Oliveira *et al.* 2020, Pelletier *et al.* 2022, Pryoer & Suyama 2015, Ramos & Minghelli 2011, Reinhardt & Ottmar 2004, Robertson *et al.* 2017, Rodriguez-Marroyo *et al.* 2022, Ruby *et al.* 2003, Ruby *et al.* 2003a, Semmens *et al.* 2016, Slaughter *et al.* 2004, Smith *et al.* 2013, Sol *et al.* 2018, Swiston *et al.* 2008, Vincent *et al.* 2017, Watkins *et al.* 2012, Wolfe *et al.* 2012, Wolkow *et al.* 2015, Wu *et al.* 2020, Wu *et al.* 2021
Occupational Health & Safety	Nelson *et al.* 2020, Robinson *et al.* 2008, Materna *et al.* 1993, Roberts 2002, Taylor *et al.* 2007, Fryer 2012, Fryer *et al.* 2013, Page & Butler 2018, Laws *et al.* 2020, Hummel *et al.* 2020, Sun *et al.* 2000, Yoo *et al.* 2000, Materna *et al.* 2010, Navarro *et al.* 2017, Campbell *et al.* 2017, Rosie *et al.* 2022, Lewis & Ebbeck 2014, Gabor 2015, Bellingar 1994, Butler & Cohen 1998, Domitrovich 2011, Pena Cueto 2018, Bridget *et al.* 2018, Wu *et al.* 2020, Wu *et al.* 2021, Adeton *et al.* 2012, Adetona *et al.* 2017, Burbank 2016, Rose 2019, Waldron & Ebbeck 2015, McDonald & Shadow 2003, Miranda 2010, Phillips *et al.* 2012, Amster *et al.* 2013, Britton *et al.* 2013, Gordon & Lariviere 2014, Phillips *et al.* 2015, Waldron *et al.* 2015, Cardil *et al.* 2017, Fox *et al.* 2017, Reimer 2017, Reimer & Eriksen 2018, Belval *et al.* 2018, Collins 2018, Broyles *et al.* 2019,

Table 1. Works included in the scoping analysis by topical bin (cont.).

	Page *et al.* 2019, Carballo-Leyenda *et al.* 2019, Reinhardt 2019, Bayham *et al.* 2020, Nagavalli *et al.* 2020, Leduc 2020, Semmens *et al.* 2021, Navarro *et al.* 2021, Carballo-Leyenda *et al.* 2021, Carballo-Leyenda *et al.* 2022, Mcquerry & Easter 2022
Performance	Carballo-Leyenda *et al.* 2021, Ruby *et al.* 2022, Domitrovich 2011, Sullivan 2020, Campbell *et al.* 2017, Sullivan *et al.* 2020, Sharkey 1999, Phillips *et al.* 2018, Ruby 1999, Lui *et al.* 2014, Strang 2018, Gumieniak *et al.* 2018, Gaskill *et al.* 2020, Leduc *et al.* 2022, DenHartog *et al.* 2016 Gumieniak *et al.* 2018, Gaskill *et al.* 2020, Leduc *et al.* 2022, DenHartog *et al.* 2016
Psychological & Sociological	Cvim et al. 2015, Williams-Bell et al. 2017, Vincent et al. 2015, McGillis et al. 2017, Cherry et al. 2021, Theleritis et al. 2020, Leykin et al. 2013, Palmer 2014, Palmer et al. 2011, Bode et al. 2022, Collins 2018

Figure 1. Word cloud of publication titles that were analyzed for this study. Word size relates to frequency of occurrence. Themes related to traditional wildland fire values of performance, exposure, suppression, occupational health, and safety emerged as the most frequently used words. Culture, monitoring, comparison, training, methods, communication, and practices were much less frequently used in titles. Other important factors in environmental health such as well-being, mental health, co-worker interactions, demographic factors, and social support systems are absent.

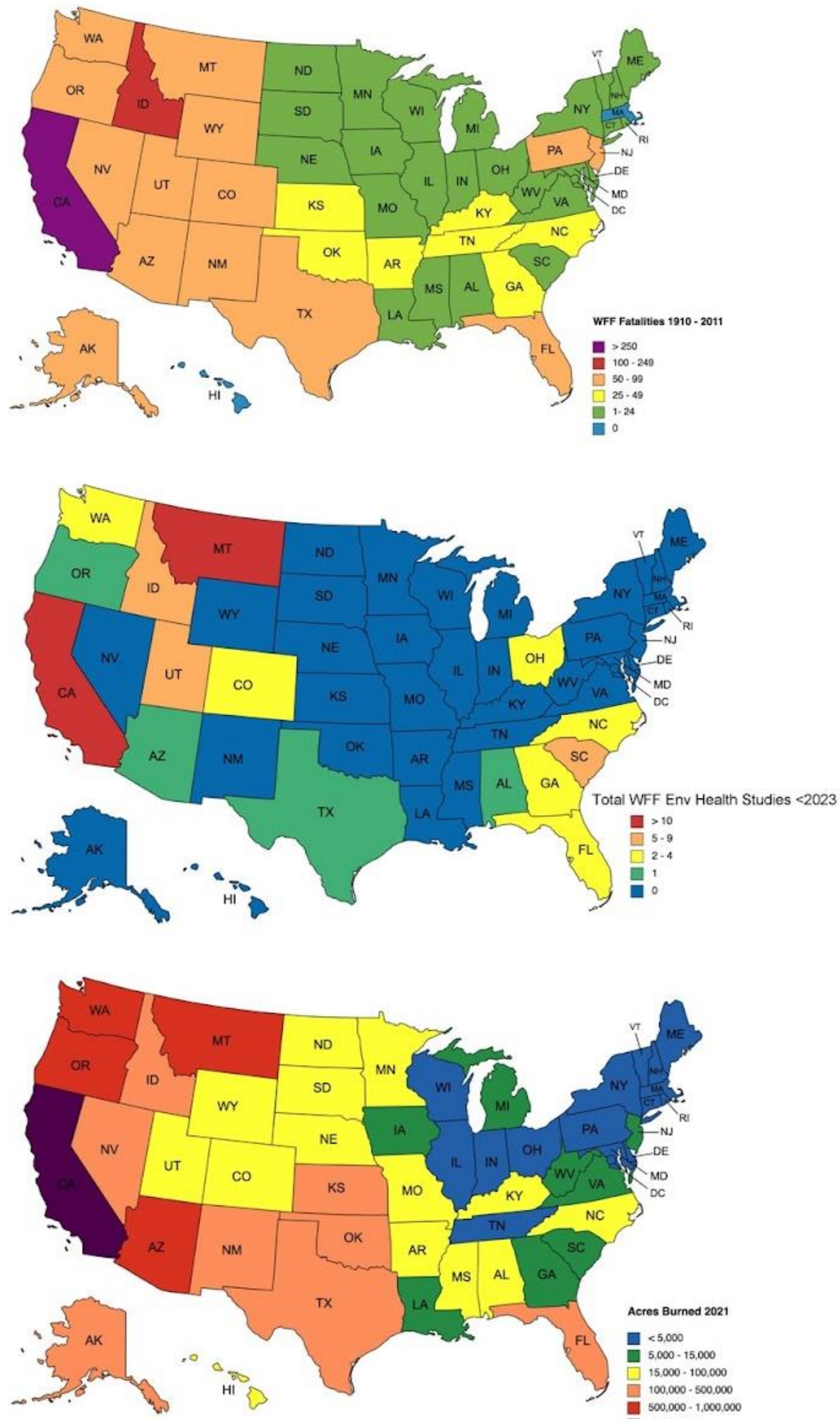


Figure 2. The United States's distribution of wildland fire environmental health studies does not match the distribution of wildland fires or wildland fire fatalities, suggesting there is a need for a broader geographic distribution of study areas.

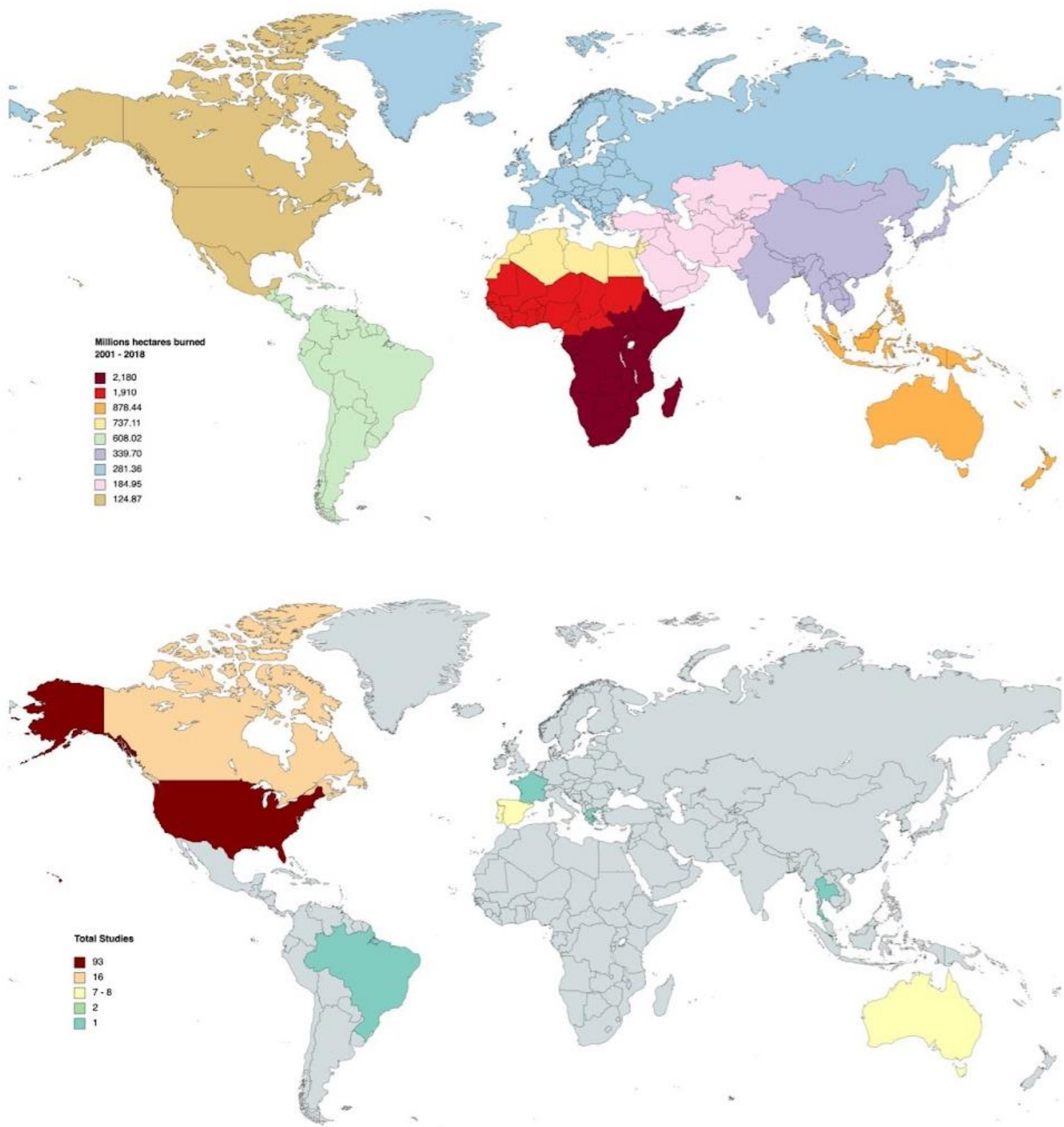


Figure 3. Studies of wildland firefighter environmental health are geographically scattered and are not occurring in areas that receive the highest amount of wildfire. Countries in gray have zero studies conducted in their borders.

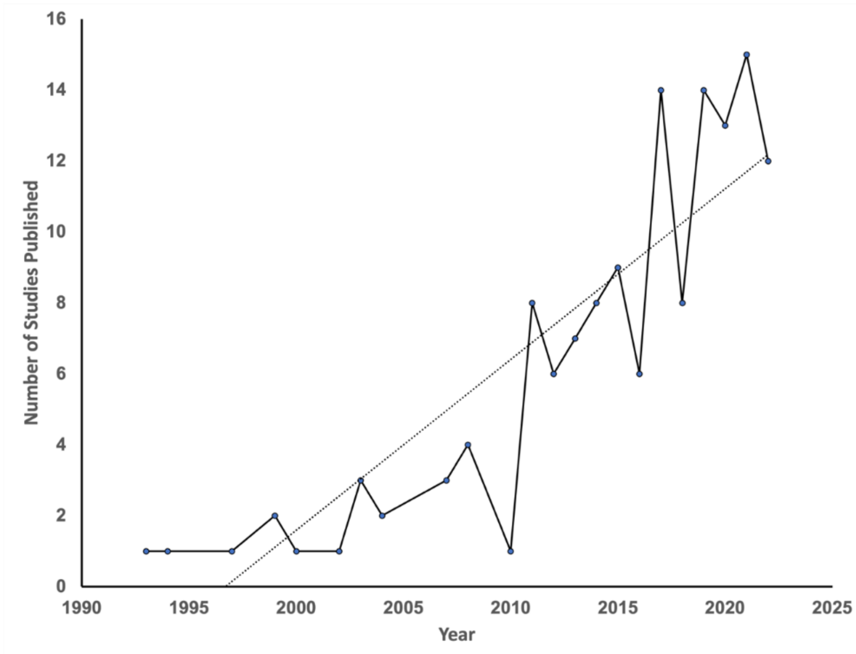


Figure 4. The total number of studies published annual increased since the first studies on WFF were published. X = year. Y = number of studies published annually.

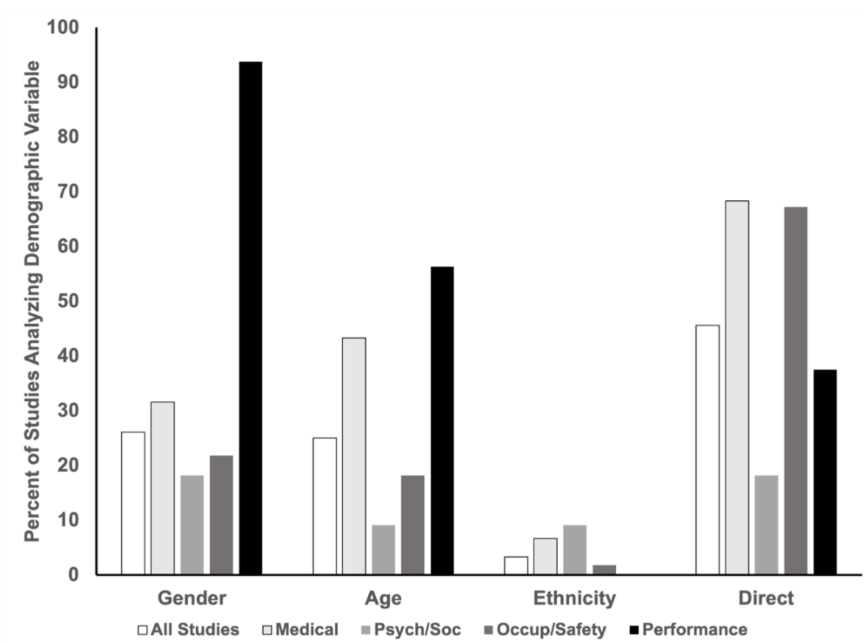


Figure 5. Percentage of studies considering gender, ethnicity, or age directly in analyses by topical bin. “All studies” is a category where the data are summated for all topical bins to allow visualization of trends in the entire set. Y axis = percentage of studies including a demographic variable of interest in their analysis. X axis = categorical variables (topical bins).

REFERENCES

Abreu, A., Costa, C., Pinho e Silva, S., Morais, S., do Carmo Pereira, M., Fernandes, A., Moraes de Andrade, V., Teixeira, J.P., & Costa, S. 2017. Wood smoke exposure of Portuguese wildland firefighters: DNA and oxidative damage evaluation. Journal of Toxicology and Environmental Health 80: 596-604.

Adetona, A.M., Adetona, O., Gogal, Jr. R.M., Diaz-Sanchez, D., Rathbun, S.L., & Naeher, L.P. 2017. Impact of work task-related acute occupational smoke exposures on select proinflammatory immune parameters in wildland firefighters. Journal of Occupational and Environmental Medicine 59: 679-690.

Adetona, O., Hall, D.B. & Naeher, L.P. 2011. Lung function changes in wildland firefighters working at prescribed burns. Inhalation Toxicology 23: 835-841.

Adetona, O., Simpson, C.D., Onstad, G., & Naeher, L.P. 2012. Exposure of wildland firefighters to carbon monoxide, fine particles, and levoglucosan. Annals of Occupational Hygiene 57: 979-991.

Adetona, O., Simpson, C.D., Sjodin, A., Calafat, A.M., & Naeher, L.P. 2017. Hydroxylated polycyclic aromatic hydrocarbons as biomarkers of exposure to wood smoke in wildland firefighters.

Adetona, O., Zhang, J., Hall, D.B., Wang, J-S., Vena, J.E., & Naeher, L.P. 2013. Occupational exposure to woodsmoke and oxidative stress in wildland firefighters. Science of the Total Environment 449: 269-275.

Alfano, C.A., Bower, J.L., Connaboy, C., Agha, N.H., Baker, F.L., Smith, K.A., So, C.J., & Simpson, R.J. 2021. Mental health, physical symptoms, and biomarkers of stress during prolonged exposure to Antarctica's extreme environment. Acta Astronautica 181: 405-413.

Bellingar, T.A. 1994. The development of prototype wildland firefighter protective clothing. Thesis. Auburn University.

Belval, E.J., Calkin, D.E., Wei, Y., Stonesifer, C.S., Thompson, M.P., & Masarie, A. 2018. Examining dispatching practices for Interagency Hotshot Crews to reduce seasonal travel distance and manage fatigue. International Journal of Wildland Fire 27: 569-580.

Betchley, C., Koenig, J., van Belle, G., Checkoway, H., & Reinhardt, T. 1997. Pulmonary function and respiratory symptoms in forest firefighters. American Journal of Industrial Medicine 31: 503-509.

Bode, K., Smith, L., Wells, T., Wollengerg, G., & Joyce, J. 2022. The relationship between diet and suicide risk and resilience in wildland firefighters. Current Developments in Nutrition 6: 348.

Britton, C., Lynch, C.F., Ramirez, M., Torner, J., Buresh, C., & Peek-Asa, C. 2013. Epidemiology of injuries to wildland firefighters. The American Journal of Emergency Medicine 31: 339-345.

Britton, C., Ramirez, M., Lynch, C.F., Torner, J., & Peek-Asa, C. 2013. Risk of injury by job assignment among federal wildland firefighters, United States, 2003-2007. International Journal of Occupational and Environmental Health 19: 77-84.

Brown, P. 2013. Integrating medical and environmental sociology with environmental health: crossing boundaries and building connections through advocacy. Journal of Health and Social Behavior 54: 145-164.

Broyles, G., Butler, C.R., & Kardous, C.A. 2017. Noise exposure among federal wildland fire fighters. The Journal of the Acoustical Society of America 141: 177-183.

Broyles, G., Kardous, C.A., Shaw, P.B., & Krieg, E.F. 2019. Noise exposures and perceptions of hearing conservation programs among wildland firefighters. Journal of Occupational and Environmental Hygiene 16: 775-784.

Bullard, R.D., & Wright, B.H. 1993. Environmental justice for all: community perspectives on health and research. Toxicology and Industrial Health 9: 821-841.

Burbank, M.D. 2016. Crisis decision making: an examination of executive leadership in a state forestry service. Thesis. Texas A&M University.

Butler, B.W. & Cohen, J.D. 1998. Firefighter safety zones: a theoretical model based on radiative heating. International Journal of Wildland Fire 8: 73-77.

Campbell, M. J., Dennison, P. E., & Butler, B. W. 2017. A LiDAR-based analysis of the effects of slope, vegetation density, and ground surface roughness on travel rates for wildland firefighter escape route mapping. International Journal of Wildland Fire 26: 884-895.

Campbell, M. J., Dennison, P. E., & Butler, B. W. 2017. Safe separation distance score: a new metric for evaluating wildland firefighter safety zones using lidar. International Journal of Geographical Information Science 31:1448-1466.

Carballo-Leyenda, B., Villa, J.G., López-Satué, J., Sanchez-Collado, P., & Rodríguez-Marroyo, J.A. 2018. Fractional contribution of wildland firefighters' personal protective equipment on physiological strain. Frontiers in Physiology 9: 10.

Carballo-Leyenda, B., Villa, J.G., López-Satué, J., Sanchez-Collado, P., & Rodríguez-Marroyo, J.A. 2019. Characterizing wildland firefighters' thermal environment during live-fire suppression. Frontiers in Physiology 10: 8.

Carballo-Leyenda, B., Villa, J.G., López-Satué, J., & Rodríguez-Marroyo, J.A. 2017. Impact of different personal protective clothing on wildland firefighters' physiological strain. Frontiers in Physiology 8: 44934.

Carballo-Leyenda, B., Villa, J.G., López-Satué, J., & Rodríguez-Marroyo, J.A. 2021. Wildland firefighters' thermal exposure in relation to suppression tasks. International Journal of Wildland Fire 30: 475-483.

Carballo-Leyenda, B., Gutierrez-Arroyo, J., Garcia-Heras, F., Sanchez-Collado, P., Villa-Vicente, J.G., & Rodriguez-Marroyo, J.A. 2021. Influence of personal protective equipment on wildland firefighters' physiological response and performance during the pack test. International Journal of Environmental Research and Public Health 18: 44935.

Carballo-Leyenda, B., Villa-Vicente, J.G., Rodríguez-Marroyo, J.A., Delogue, G.M., & Molina-Terrén, D.M. 2022. Perceptions of heat stress, heat strain and mitigation practices in wildfire suppression across southern Europe and Latin America. International Journal of Environmental Research and Public Health 19: 44938.

Cardil, A., Delogu, G.M., & Molina-Terrén, D.M. 2017. Fatalities in wildland fires from 1945 to 2015 in Sardinia (Italy). CERNE 23: 175-184.

Cherry, N., Bronznitsky, N., Fedun, M., & Zadunayski, T. 2022. Respiratory tract and eye symptoms in wildland firefighters in two Canadian provinces: impact of discretionary use of an N95 mask during successive rotations. International Journal of Environmental Research and Public Health 19: 136-158.

Cherry, N., Galarneau, J-M., Haynes, W., & Sluggett, B. 2021. The role of organizational supports in mitigating mental ill health in firefighters: a cohort study in Alberta, Canada. American Journal of Industrial Medicine 64: 593-601.

Christison, K.S. 2015. Muscle soreness and damage during wildland firefighter critical training. Thesis. University of Montana.

Christison, K.S., Gurney, S., & Dumke, C.L. 2021. Effect of vented helmets on heat stress during wildland firefighter simulation. International Journal of Wildland Fire 30: 645-651.

Clarke, C. & Zak, M.J. 1999. Fatalities to law enforcement officers and firefighters, 1997-97. In: Compensation and Working Conditions Summer 1999. Bureau of Labor Statistics. pp 3-7.

Christison, K.S., Gurney, S., Sol, J.A., Williamson-Reisdorph, C.M., Quindry, T.S., Quindry, J.C., & Dumke, C.L. 2018. Muscle damage and overreaching during wildland firefighter critical training. Journal of Occupational and Environmental Medicine 63: 350-356.

Collins, C.N. 2018. Understanding factors contributing to wildland firefighter health, safety, and performance: a pilot study on smokejumpers. Thesis. University of Idaho.

Cuddy, J.S. & Ruby, B.C. 2011. High work output combined with high ambient temperatures caused heat exhaustion in a wildland firefighter despite high fluid intake. Wilderness and Environmental Medicine 22: 122-125.

Cuddy, J.S., Sol, J.A., Hailes, W.S., & Ruby, B.C. 2015. Work patterns dictate energy demands and thermal strain during wildland firefighting. Wilderness and Environmental Medicine 26: 221-226.

Cvirn, M.A., Dorrian, J., Smith, B.P., Jay, S.M., Vincent, G.E., & Fergeson, S.A. 2015. The sleep architecture of Australian volunteer firefighters during a multi-day simulated wildfire suppression: impact of sleep restriction and temperature. Accident Analysis and Prevention 99: 389-394.

DenHartog, E.A., Walker, M.A., & Barker, R.L. 2016. Total heat loss as a predictor of physiological response in wildland firefighter gear. Textile Research Journal 86: 710-726.

Domitrovich, J.W. 2011. Aerobic fitness characteristics of United States wildland fire smokejumpers. Thesis. University of Montana.

Domitrovich, J.W. 2011. Wildland fire uniform configurations on physiological measures of exercise-heat stress. Thesis. University of Montana.

Dorman, S.C. & Ritz, S.A. 2014. Smoke exposure has transient pulmonary and systemic effects in wildland firefighters. Journal Respiratory Medicine 2014: 44935.

Ferguson, M.D., Semmens, E.O., Dumke, C., Quindry, J.C., & Ward, T.J. 2016. Measured pulmonary and systemic markers of inflammation and oxidative stress following wildland firefighter simulations. Journal of Occupational and Environmental Medicine 58: 407-413.

Ferguson, M.D., Semmens, E.O., Weiler, E., Domitrovich, J., French, M., Migliaccio, C., Palmer, C., Dumke, C., & Ward, T. 2017. Lung function measures following simulated wildland firefighter exposures. Journal of Occupational and Environmental Hygiene 14: 738-747.

Fox, R., Gabor, E., Thomas, D., Ziegler, J., & Black, A. 2017. Cultivating a reluctance to simplify: exploring the radio communication context in wildland firefighting. International Journal of Wildland Fire 26: 719-731.

Fryer, G.K. 2012. Wildland firefighter entrapment avoidance: developing evacuation trigger points utilizing the Wildland Urban Interface Evacuation (WUIVAC) fire spread model. Thesis. University of Utah.

Fryer, G.K., Dennison, P.E., & Cova, T.J. 2013. Wildland firefighter entrapment avoidance: modelling evacuation triggers. International Journal of Wildland Fire 22: 883-893.

Gabor, E. 2015. Words matter: radio misunderstandings in wildland firefighting. International Journal of Wildland Fire 24: 580-588.

Garcia-Heras, F., Gutierrez-Arroyo, J., Garcia-Heras, F., Rodriguez-Marroyo, J.A., Guereno, L., Carballo-Leyenda, B. 2022. Chronic pain in Spanish wildland firefighters. Journal of Clinical Medicine 11: 44936.

Gaskil, S.E., Dumke, C.L., Palmer, C.G., Ruby, B.C., Domitrovich, J.W., & Sol, J.A. 2020. Seasonal changes in wildland firefighter fitness and body composition. International Journal of Wildland Fire. 29: 294-303.

Gaughan, D.M., Siegel, P.D., Hughes, M.D., Chang, C., Law, B.F., Campbell, C.R., Richards, J.C., Kales, S.F., Chertok, M., Kobzik, L., Nguyen, P., O'Donnell, C.R., Kiefer, M., Wagner, G.R., & Christiani, D.C. 2014. Arterial stiffness, oxidative stress, and smoke exposure in wildland firefighters. American Journal of Industrial Medicine 57: 748-756.

Gaughan, D.M., Piacitelli, C.A., Chen, B.T., Law, B.F., Virji, M.A., Edwards, N.T., Enright, P.L., Schwegler-Berry, D.E., Leonard, S.S., Wagner, G.R., Kobzik, L., Kales, S.N., Hughes, M.D., Christiani, D.C., Seigel, P.D., Cox-Ganser, J.M., & Hoover, M.D. 2014. Exposures and cross-shift lung function declines in wildland firefighters. Journal of Occupational & Environmental Hygiene 11: 591-603.

Gordon, H., & Lariviere, M. 2014. Physical and psychological determinants of injury in Ontario forest firefighters. Occupational Medicine 64: 583-588.

Gumieniak, R.J., Gledhill, N., & Jamnik, V.K. 2018. Physical employment standard for Canadian wildland firefighters: examining test-retest reliability and the impact of familiarisation and physical fitness training. Ergonomics 61: 1324-1333.

Gurney, S.C., Christison, K.S., Stenersen, T., & Dumke, C.L. 2021. Effect of uncompensable heat from the wildland firefighter helmet. International Journal of Wildland Fire 30: 990-997.

Gurney, S.C., Christison, K.S., Sol, J.A., Quindry, T.S., Quindry, J.C., & Dumke, C.L. 2021. Alterations in metabolic and cardiovascular risk factors during critical training in wildland firefighters. Journal of Occupational and Environmental Medicine 63: 594-599.

Huber, M., Knottnerus, J.A., Green, L., van der Horst, H., Jadad, A.R., Kromhout, D., Leonard, B., Lorig, K., Loureiro, M.I., van der Meer, J.W.M., Schnabel, P., Smith, R., van Weel, C., & Smid, H. 2011. How should we define health? British Medical Journal 343: d4163.

Huby, M. & Adams, R. 2009. Interdisciplinarity and participatory approaches to environmental health. Environmental Geochemistry and Health 31: 219-226.

Hummel, A., Watson, K., & Barker, R. 2020. Comparison of two test methods for evaluating the radiant protective performance of wildland firefighter protective clothing materials. ASTM International STP 1593: 178-194.

Hunter, A.L., Unosson, J., Bosson, J.A., Langrish, J.P., Pourasar, J., Raftis, J.B., Miller, M.R., Lucking, A.J., Boman, C., Nystrom, R., Donaldson, K., Flapan, A.D., Shah, A.S.V., Pung, L., Sadiktsis, I., Masala, S., Westerholm, R., Sandstrom, T., Blomberg, A., Newby, D.E., and Mills, N. 2014. Effect of wood smoke exposure on vascular function and thrombus formation in healthy fire fighters. Particle and Fibre Toxicology 11: 44939.

Jacquin, L., Michelet, P., Brocq, F., Houel, J., Truchet, X., Auffray, J., Carpentier, J., & Jammes, Y. 2011. Short-term spirometric changes in wildland firefighters. American Journal of Industrial Medicine 54: 819-825.

Jeklin, A.T., Perrotta, A.S., Davies, H. W., Bredin, S.S.D., Paul, D.A., & Warburton, D.E.R. 2021. The association between heart rate variability, reaction time, and indicators of workplace fatigue in wildland firefighters. International Archives of Occupational and Environmental Health 94: 823-831.

Laws, R.L., Jain, S., Cooksey, G.S., Mohle-Boetani, J., McNary, J., Wilken, J., Harrison, R., Leistikow, B., Vugia, D.J., Windham, G.C., & Materna, B.L. 2020. Coccidioidomycosis outbreak among inmate wildland firefighters: California, 2017. American Journal of Industrial Medicine 64: 266-273.

Leduc, C., Giga, S.I., Fletcher, I.J., Young, M., & Dorman, S.C. 2022. Effectiveness of fitness training and psychosocial education intervention programs in wildland firefighting: a cluster randomised control trial. International Journal of Wildland Fire 31: 799-815.

Leduc, C. 2020. Development, implementation and evaluation of fitness training and psychosocial education interventions in wildland firefighting. Thesis. Lancaster University.

Lewis, A., & Ebbeck, V. 2014. Mindful and self-compassionate leadership development: preliminary discussions with wildland fire managers. Journal of Forestry 112: 230-236.

Leykin, D., Lahad, M., & Bonneh, N. 2013. Posttraumatic symptoms and posttraumatic growth of Israeli firefighters, at one month following the Carmel fire disaster. Psychiatry Journal 2013: 44931.

Lui, B., Cuddy, J.S., Hailes, W.S., & Ruby, B.C. 2014. Seasonal heat acclimatization in wildland firefighters. Journal of Thermal Biology 45: 134-140.

Main, L.C., Wolkow, A.P., Tait, J.L., Gatta, P.D., Raines, J., Snow, R., & Aisbett, B. 2020. Firefighter's acute inflammatory response to wildfire suppression. Journal of Occupational and Environmental Medicine 62: 145-148.

Materna, B.L., Koshland, C.P., & Harrison, R.J. 1993. Carbon monoxide exposure in wildland firefighting: a comparison of monitoring methods. Applied Occupational and Environmental Hygiene 8: 479-487.

Materna, B.L. Jones, J.R., Sutton, P.M., Rothman, N. & Harrison, R.J. 2010. Occupational exposures in California wildland fire fighting. American Industrial Hygiene Association Journal 53: 69-76.

McDonald, L. S.& Shadow, L. 2003. Precursor for Error: An analysis of wildland fire crew leaders' attitudes about organizational culture and safety. Third International Wildland Fire Conference 2003: 44938.

McGillis, Z., Dorman, S.C., Robertson, A., Larivie're, M., Leduc, C., Eger, T., Oddson, B.E., Larivie're, C. 2017. Sleep quantity and quality of Ontario wildland firefighters across a low-hazard fire season. Journal of Emergency Management 59: 1188-1196

McQuerry, M. & Easter, E. 2022. Wildland firefighting personal protective clothing cleaning practices in the United States. Fire Technology 58: 1667-1688.

Metz, A.R., Bauer, M., Epperly, C., Stringer, G., Marshall, K.E., Webb, L.M., Hetherington-Rauth, M., Matzinger, S.R., Totten, S.E., Travanty, E.A., Good, K.M., & Burakoff, A. 2022. Investigation of COVID-19 outbreak among wildland firefighters during wildfire response, Colorado, USA 2020. Emerging Infections Diseases 28: 1551-1558

Miranda, A.I., Martins, V., Cascão, P., Amorim, J.H., Valente, J., Borrego, C., Ferreira, A.J., Cordeiro, C.R., Viegas, D.X., & Ottmar, R. 2012. Wildland smoke exposure values and exhaled breath indicators in firefighters. Journal of Toxicology and Environmental Health 75: 831-843.

Miranda, A.I. 2010. Monitoring of firefighters exposure to smoke during fire experiments in Portugal. Environment International 36: 736-745.

Moody, V.J., Purchio, T.J., & Palmer, C.G. 2019. Descriptive analysis of injuries and illnesses self-reported by wildland firefighters. International Journal of Wildland Fire 28: 412-419.

McGregor, D., Whitaker, S., & Srithran, M. 2020. Indigenous environmental justice and sustainability. Current Opinion in Environmental Sustainability 43: 35-40.

Munn, Z., Peters, M.D.J., Stern, C., Tufanaru, C., McArthur, A. & Aromataris, E. 2018. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC Medical Research Methodology 18: 143.

Nagavalli, A., Hyummel, A., Akyildiz, H.I., Morton-Aslanis, J., & Baker, R. 2020. Advanced layering system and design for the increased thermal protection of wildland fire shelters. ASTM International STP 1593: 102-116.

Navarro, K.M., Cisneros, R., Noth, E.M., Balmes, J.R., & Hammon, S.K. 2017. Occupational exposure to polycyclic aromatic hydrocarbon of wildland firefighters at prescribed and wildland fires. Environmental Science & Technology 51: 6461-6469.

Navarro, K.M., Butler, C.R., Fent, K., Toennis, C.K. Sammons, D., Ramierez-Cardenas, A., Clark, K.A., Smith, D.L., Alexander-Scott, M.C., Pinkerton, L.E., Eisenberg, J., & Domitrovich, J.W. 2021. The wildland firefighter exposure and health effect (WFFEHE) study: rationale, design, and methods of a repeated-measures study. Annals of Work Exposures and Health 66: 714-727.

Navarro, K.M., Kleinman, M.T., Reinhardt, T.E., Balmes, J.R., Broyles, G.A., Ottmar, R.D., Naher, L.P., & Domitrovich, J.W. 2019. Wildland firefighter smoke exposure and risk of lung cancer and cardiovascular disease mortality. Environmental Research 173: 462-468.

Navarro, K.M., West, M.R., O’Dell, K., Sen, P., Chen, I-C, Fischer, E.V., Hornbrook, R.S., Apel, E.C., Hills, A.J., Jarnot, A., DeMott, P., & Domitrovich, J.W. 2021. Exposure to particulate matter and estimation of volatile organic compounds across wildland firefighter job tasks. Environmental Science & Technology 55: 11795-11804.

Nelson, J., Chalbot, M-C.G., Pavicevic, Z., & Kavouras, I.G. 2020. Characterization of exhaled breath condensate (EBC) non-exchangeable hydrogen functional types and lung function of wildland firefighters. Journal of Breath Research 14: 44937.

Nelson, J. Chalbot, M-C.G., Tsiodra, I., Mihalopoulos, N. & Kavouras, I.G. 2020. Physiochemical characterization of personal exposures to smoke aerosol and PAHs of wildland firefighters in prescribed fires. Exposure and Health 13: 105-118.

Niyatiwatchanchai, N., Pothirat, C., Chaiwong, W., Liwsrisakun, C., Phetsuk, N., Duangjit, P. & Choomuang, W. 2022. Short-term effects of air pollutant exposure on small airway dysfunction, spirometry, health-related quality of life, and inflammatory biomarkers in wildland firefighters: a pilot study. International Journal of Environmental Health Research 44941

Oliveira, M., Slezakova, K., Jose Alves, M., Fernandes, A., Teixeira, J.P., Delerue-Matos, C., Carmo Pereira, M., & Morais, S. 2016. Firefighters' exposure biomonitoring: impact of firefighting activities on levels of urinary monohydroxyl metabolites. International Journal of Hygeine and Environmental Health 219: 857-866.

Oliveira, M., Costa, S., Vaz, J., Fernandes, A., Slezakova, K., Delerue-Matos, C., Teixeira, J., Carmo Pereira, M., & Morais, S. 2020. Firefighters exposure to fire emissions: Impact on levels of biomarkers of exposure to polycyclic aromatic hydrocarbons and genotoxic/oxidative-effects: Journal of Hazardous Materials 383: 44936.

Page, W.G., & Butler, B.W. 2018. Fuel and topographic influences on wildland firefighter burnover fatalities in Southern California. International Journal of Wildland Fire 27: 141-154.

Page, W.G., Freeborn, P.H., Butler, B.W., & Jolly, W.M. 2019. A classification of U.S. wildland firefighter entrapments based on coincident fuels, weather and topography. Fire 2: 44949.

Palmer, C.G., Gaskill, S., Domitrovich, J., McNamara, ., Knutson, B., & Spear, A. 2011. Wildland firefighters and attention deficit hyperactivity disorder (ADHD). Proceedings of the Second Conference on the Human Dimensions of Wildland Fire. GTR-NRS-P-84. 45182.

Palmer, C.G. 2014. Stress and coping in wildland firefighting dispatchers. Journal of Emergency Management 12: 303-314.

Pelletier, C. Ross, C., Bailey, K., Fyfe, T.M., Cornish, K. & Koopmans, E. 2022. Health research priorities for wildland firefighters: a modified Delphi study with stakeholder interviews. British Medical Journal 12: 44936.

Peña Cueto, J.M. 2018. Evaluation of a web-based performance program for wildland firefighters. Thesis. University of Montana.

Peters, B., Ballmann, C., Quindry, T., Zehner, E.G., McCroskey, J., Ferguson, M., Ward, T., Dumke, C., & Quindry, J. 2018. Experimental woodsmoke exposure during exercise and blood oxidative stress. Journal of Occupational and Environmental Medicine 60: 1073-1081.

Phillips, D.B., Ehnes, C.M., Welch, B.G., Lee, L.N., Simin, I., & Petersen, S.R. 2018. Influence of work clothing on physiological responses and performance during treadmill exercise and the wildland firefighter pack test. Applied Ergonomics 68: 313-318.

Phillips, M., Netto, K., Payne, W., Nichols, D., Lord, C., Brooksbank, N., & Aisbett, B. 2015. Frequency, intensity, time and type of tasks performed during wildfire suppression. Occupational Medicine and Health Affairs 3: 44935.

Phillips, M., Payne, W., Lord, C., Netto, K., Nichols, D., & Aisbett, B. 2012. Identification of physically demanding tasks performed during bushfire suppression by Australian rural firefighters. Applied Ergonomics 43: 435-441.

PMS 841. 2017. NWCG report on wildland firefighter fatalities in the United States: 2017-2016. National Wildfire Coordinating Group.

Podur, J. & Wotton, M. 2010. Will climate change overwhelm fire management capacity? Ecological Modeling 221: 1301-1309.

Pryor, R.R. & Suyama, J.F. 2015. The effects of ice slurry ingestion before exertion in wildland firefighting gear. Prehospital Emergency Care 19: 241-246.

Ragland M, Harrell J, Ripper M, Pearson S, Granberg R and Verble R (2023) Gender, sexual orientation, ethnicity and socioeconomic factors influence how wildland firefighters communicate their work experiences. Frontiers in Communication. 8:1021914. doi: 10.3389/fcomm.2023.1021914

Ramos, C., & Minghelli, B. 2011. Prevalence and factors associated with poor respiratory function among firefighters exposed to wildfire smoke. International Journal of Environmental Research and Public Health 19: 8492-8502.

Reimer, R.D. 2017. The wildfire within: firefighter perspectives on gender and leadership in wildland fire. Thesis. Royal Roads University.

Reimer, R.D., & Eriksen, C. 2018. The wildfire within: gender, leadership and wildland fire culture. International Journal of Wildland Fire 27: 715-726.

Reinhardt, T.E., & Ottmar, R.D. 2004. Baseline measurements of smoke exposure among wildland firefighters. Journal of Occupational and Environmental Hygiene 1: 593-606.

Reinhardt, T. 2019. Factors affecting smoke and crystalline silica exposure among wildland firefighters. CERNE 16: 175-184.

Riley, K.L., O'Connor, C.D., Dunn, C.J., Haas, J.R., Stratton, R.D., & Gannon, B. 2022. A national map of snag hazard to reduce risk to wildland fire responders. Forests 13: 1160-1175.

Roberts, M.S. 2002. A case study of three women firefighters in their assimilation into a medium-sized fire department in southern California. Thesis. California State Polytechnic University.

Robertson, A.H., Lariviere, C., Leduc, C.R., McGillis, Z., Godwin, A., Lariviere, M., & Dorman, S.C. 2017. Novel tools in determining the physiological demands and nutritional practices of Ontario fire rangers during fire deployments. PLOS ONE 12: 44944.

Robinson, M.S., Anthony, T.R., Littau, S.R., Herckes, P., Nelson, X., Poplin, G.S., & Burgess, J.L. 2008. Occupational PAH Exposures during prescribed pile burns. Annals of Occupational Hygiene 52: 497-508.

Rodríguez-Marroyo, J.A., Carballo-Leyenda, B., Sánchez-Collado, P., Suárez-Iglesias, D., & Villa, J.G. 2022. Effect of exercise intensity and thermal strain on wildland firefighters' central nervous system fatigue. Cognitive Computing and Internet of Things 43: 58-63.

Rose, R. 2019. Evaluation of wildland firefighter leadership. Thesis. Central Washington University.

Rosie, J., Williams, J., Barker, R., Morton-Aslanis, J. 2022. Field and full-scale laboratory testing of prototype wildland fire shelters. International Journal of Wildland Fire 31: 518-528.

Ruby, B.C., Leadbetter III, G.W., Armstrong, D.W., Gaskill, S.E. 2003. Wildland firefighter load carriage: effects on transit time and physiological responses during simulated escape to safety zone. International Journal of Wildland Fire 12: 111-116.

Ruby, B.C., Shriver, T.C., Zderic, W., Sharkey, B. Burks, C., Tysk, S. 2022. Total energy expenditure during arduous wildfire suppression. Medicine & Science in Sports and Exercise 34: 1048-1054.

Ruby, B.C. 1999. Energy expenditure and energy intake during wildfire suppression in male and female firefighters. Wildland Firefighter Health and Safety: Recommendations of the April 1999 Conference 9E92P47: 26-31.

Ruby, B.C., Schoeller, D., Sharkey, B., Burks, C., Tysk, S. 2003. Water turnover and changes in body composition during arduous wildfire suppression. Medicine & Science in Sports & Exercise 35: 1760-1765.

Saint Martin, D.R.F., Rosenkranz, M. 2018. Accelerometer-based physical activity and sedentary time assessment in Brazilian wildland firefighters - Brasilia Firefighters Study: 2052. Medicine and Science in Sports and Exercise 50: 499.

Semmens, E.O., Domitrovich, J., Conway, K., Noonan, C. 2016. A cross-sectional survey of occupational history as a wildland firefighter and health. American Journal of Industrial Medicine 59: 330-335.

Semmens, E.O., Leary, C., West, M., Noonan, C., Navarro, K., Domitrovich, J. 2021. Carbon monoxide exposures in wildland firefighters in the United States and targets for exposure reduction. Journal of Exposure Science & Environmental Epidemiology 31: 923-929.

Sharkey, B. 1999. Demands of the job. Wildland Firefighter Health and Safety: Recommendations of the April 1999 Conference 9E92P47: 20-25.

Slaughter, J.C., Koenig, J., Reinhardt, T. 2004. Association between lung function and exposure to smoke among firefighters at prescribed burns. Journal of Occupational and Environmental Hygiene 1: 45-49.

Smith, W.R., Monopoly, G., Byerly, A. 2013. Mercury toxicity in wildland firefighters. Wilderness & Environmental Medicine 24: 141-145.

Sol, J.A., Ruby, B., Gaskill, S., Dumke, C., Domotrovich, J. 2018. Metabolic demand of hiking in wildland firefighting. Wilderness and Environmental Medicine 20: 304-314.

Strang, J.T. 2018. Metabolic energy requirements during load carriage: implications for the wildland firefighter arduous pack test. Thesis. University of Montana.

Sullivan, P.R. 2020. Modeling wildland firefighter travel rates across varying slopes. Thesis. University of Utah.

Sullivan, P.R., Campbell, M., Dennison, P., Brewer, S., Butler, B. 2020. Modeling wildland firefighter travel rates by terrain slope: results from GPS-tracking of type 1 crew movement. Fire 3: 44940

Sun, G., Yoo, H.S., Zhang, X.S., Pan, N. 2000. Radiant protective and transport properties of fabrics used by wildland firefighters. Textile Research Journal 70: 567-573.

Swiston, J.R., Davidson, W., Attridge, S., Li, G., Brauer, M., van Eeden, S. 2008. Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. European Respiratory Journal 31: 129-138

Taylor, J.G., Gillette, S., Hodgson, R., Downing, J., Burns, M., Chavez, D., Hogan, J. 2007. Informing the network: improving communication with interface communities during wildland fire. Human Ecology Review 14: 198-211.

Therelitis, C., Psarros, C., Mantonakis, L., Roukas, D., Papaioannou, A., Paparrigopoulos, T., Bergiannaki, J. 2020. Coping and its relation to PTSD in Greek firefighters. The Journal of Nervous and Mental Disease 208: 252-259.

Thompson, M.P., MacGregor, D.G., Dunn, C.J., Calkin, D.E. & Phipps, J. 2018. Rethinking the wildland fire management system. Journal of Forestry 116; 382-390.

Toups, Z.O. & Kerne, A. 2007. Implicit coordination in firefighting practice: design implications for teaching fire emergency responders. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. April 2007. pp 706-716.

United States House of Representatives. 2021-2022. H.R. 4274: Wildland Firefighter Fair Pay Act. 117th Congress. 30 June 2021.

VanDevanter, N.L., Abramson, P., Howard, D., Moon, J., Honore, P.A. 2010. Emergency response and public health in Hurricane Katrina. Journal of Public Health Management and Practice 16: e16-e25.

Verble, R., Pearson, S., & Granberg, R. 2022. Wildland Fire Survey. www.wildlandfiresurvey.com

Vincent, G., Ferguson, S., Tran, J., Larsen, B., Wolkow, A., Aisbett, B. 2015. Sleep restriction during simulated wildfire suppression: effect on physical task performance. PLOS ONE 10: 44942.

Vincent, G., Aisbett, B., Larsen, B., Ridgers, N., Snow, R., Ferguson, S. 2017. The impact of heat exposure and sleep restriction on firefighters' performance and physiology during simulated wildfire suppression. International Journal of Environmental Research and Public Health 14: 180-195.

Waldron, A.L., Ebbeck, V. 2015. Developing wildland firefighters' performance capacity through awareness-based processes: a qualitative investigation. Journal of Human Performance in Extreme Environments 12: 44938.

Waldron, A.L., Schary, D., Cardinal, B. 2015. Measuring wildland fire leadership: the crewmember perceived leadership scale. International Journal of Wildfire 24: 1168-1175.

Williams-Bell, F.M., Aisbett, B., Murphy, B., Larsen, B. 2017. The effects of simulated wildland firefighting tasks on core temperature and cognitive function under very hot conditions. Frontiers in Physiology 8: 44936.

Wolfe, C.M., Green, W., Cognetta Jr., A., Hatfield, H. 2012. Heat-induced squamous cell carcinoma of the lower extremities in a wildland firefighter. Journal of American Dermatology 67: E272-E273

Wolklow, A., Ferguson, S., Vincent, G., Larsen, B., Aisbett, B., Main, L. 2015. The impact of sleep restriction and simulated physical firefighting work on acute inflammatory stress responses. PLOS ONE 10: 44943.

Wu, C-M., Adetona, O., Song, C. 2021. Acute cardiovascular responses of wildland firefighters to working at prescribed burn. International Journal of Hygiene and Environmental Health 23: 113827-113833.

Wu, C-M., Adetona, A., Sing, C. 2020. Measuring acute pulmonary responses to occupational wildland fire smoke exposure using exhaled breath condensate. Archives of Environmental and Occupational Health 75: 65-69.

Wu, C-M., Warren, S., DeMarini, D., Song, C., Adetona, O. 2020. Urinary mutagenicity and oxidative status of wildland firefighters working at prescribed burns in a midwestern US forest. Occupational and Environmental Medicine 78: 315-322.

Wu, C-M., Song, C., Cartier, R., Kremer, J., Naeher, L., Adetona, O. 2021. Characterization of occupational smoke exposure among wildland firefighters in the midwestern United States. Environmental Research 193: 110541-110549.

Yoo, H.S., Sun, G., & Pan, N. 2000. Thermal protective performance and comfort of wildland firefighter clothing: The transport properties of multilayer fabric systems. ASTM International Selected Technical Papers STP 1386: 504-518.

II. RELATIONSHIPS BETWEEN WORKLOAD AND ERRORS IN WILDLAND FIRE DISPATCHERS

ABSTRACT

Workload and errors in the workplace are critical factors affecting productivity, safety, and outcomes across various industries. This study focuses on wildland fire dispatchers, examining workload metrics and error rates at the Missouri Iowa Interagency Dispatch Center (USMOMOC) in Rolla, Missouri, USA. Utilizing data from WildCAD reports spanning 2022 and 2023, we analyzed dispatch activities, error types, and workload parameters. Workload metrics encompassed resources managed, acreage affected, law enforcement involvement, private assists, and other operational demands. Errors were categorized based on added, omitted, transposed, unclear, and indecipherable information, among others. Through rigorous analysis, the study aimed to define workload measures, quantify error frequency and types, and explore the relationship between workload and error occurrences. We found that levels of workloads and errors both follow seasonal patterns, and more workload relates to more errors. This study provides valuable insights into the challenges faced by wildland fire dispatchers and offer opportunities for enhancing safety and efficiency in wildland fire incident management.

1. INTRODUCTION

The relationship between workload and error is a fundamental aspect of human performance across professional environments. Workload refers to the amount of work or tasks that an individual, group, or system is expected to perform within a specific period and relates to the amount of mental and physical effort required to accomplish a task (Andrejko-Gworek, 2020). Its measurement encompasses the total amount of work, including responsibilities, assignments, or projects, that must be completed. Increased growth of research firmly evidences the key position that a balanced workload plays in avoiding cognitive overload and sustaining minimum performance. Kruger (2008) suggests that equitable assessments and distribution of tasks in high-paced environments can help reduce the occurrence of work error in such settings because sharing the demands ensures that an individual will not be overworked should be done. Workload can vary significantly in terms of its nature and complexity, and it is often used to assess and manage the capacity and performance of individuals or resources within an organization (Singh et al., 2022). Workload can be measured in various ways, such as the number of tasks, the volume of work, the level of effort required, or the time it takes to complete specific tasks. The research by Schulman (2020) reveals the link between stressful working conditions and errors and undermines the common notions that interruptions and high productivity are the main causes of mistakes in high-stakes environments. Workload management is crucial in various fields, including business, education, healthcare, and information technology, as it helps ensure that tasks are allocated efficiently, deadlines are met, and individuals or systems are not overburdened, which can lead to stress and decreased productivity.

Errors in the workplace are unintended mistakes or inaccuracies that occur in various tasks, processes, or decision-making within an organizational setting that result in deviations from intended or desired outcomes. They can manifest in different forms, such as computational errors, miscommunication, procedural mistakes, or faulty judgment. These errors can lead to setbacks, financial losses, compromised quality, or hindered productivity. In the context of a competitive and fast-paced work environment, errors can have detrimental effects on the organization's reputation and success. They can also impact employee morale and trust within the workplace, potentially causing stress and a decline in overall efficiency. According to Hancock and Matthews (2019), errors damage not only immediate operational outcomes but have long-term effects on organizational learning and adaptation, therefore they affect the future resilience of the organization. An essential aspect of comprehending errors in the workplace is to understand their categorization. Errors can be classified into various types, such as human errors, technical errors, systemic errors, and random errors. Human errors result from actions made by individuals, including mistakes in judgment, perception, or memory. Technical errors stem from faults in equipment, software, or tools. Systemic errors reflect issues within the organizational structure or processes that lead to mistakes. Random errors are more unpredictable and can occur sporadically due to unforeseen circumstances. By classifying errors, organizations can identify patterns, root causes, and implement effective preventive measures to reduce their occurrence and impact in the future. Figuring out error types helps organizations to come up with the right strategies on the spot. This is an important thing as by doing this, organizations see their success rate increase (Patel & Kaufman 2021). Every kind of error needs a different type of management action, which may vary from short practice improvement to a structural change, to eliminate the errors' incidence and influence.

The relationship between workload and error is dynamic and multifaceted, influenced by various factors including task complexity, time pressure, environmental conditions, individual characteristics, and organizational factors. High-stress situations, time constraints, and multitasking demands can amplify workload levels, heightening the likelihood of errors and impairing performance accuracy. Moreover, individual differences in cognitive abilities, experience levels, and stress tolerance can modulate the impact of workload on error susceptibility, highlighting the importance of personalized approaches to workload management and error prevention. In addition to individual factors, organizational and systemic aspects play a pivotal role in shaping the workload-error relationship. A study by Grailey et al. (2021) demonstrates how team dynamics and psychological safety aspects are some of the critical ones when it comes to the translation of workload pressures into increased error rates. The researcher posits that supportive team environments might mitigate the negative effects of high workloads. Organizational culture, resource allocation, training protocols, and work environment design can either mitigate or exacerbate workload demands and error rates. Effective workload management strategies, such as workload distribution, task prioritization, automation support, and adequate rest periods, are essential for optimizing performance while minimizing error risks across diverse operational contexts.

Increased occupational workload can significantly affect workers both physically and mentally, ultimately raising the likelihood of errors, as noted by Hancock & Warm (1989). The impact of heavier workloads varies based on individual physiological capacities and the nature and duration of tasks. According to Ellison and Caudill (2020), demand-control model highlights that matching job demands with loss of control at work can worsen the effect of workload, thus increasing the level of stress and the risk of errors. Research has indicated that higher workloads influence language use (Sexton & Helmreich, 2000), error rates (Raab & Grzybicki, 2006; Hart & Bortolussi, 1984), and stress perception (Morrison & Rudolph, 2006). Additionally, studies such as those by Chillarege & Iyer (1985) demonstrate that error rates may increase non-linearly with workload increases, indicating a critical threshold. Beyond this point, communication breakdowns and fatigue could significantly contribute to more frequent errors (Morrison & Rudolph, 2011).

Longer working hours are associated with an increased risk of errors. One study found that employees working more than 55 hours per week were at a significantly higher risk of making errors compared to those working 35-40 hours per week (Virtanen et al., 2015). This increase in errors is often attributed to the cumulative impact of long working hours on mental and physical fatigue. In addition, prolonged exposure to high work demands and long hours can result in chronic stress, which can impair cognitive functions and decision-making abilities. Chronic stress can lead to cognitive decline and increase the risk of error (Sindi et al. 2017). Furthermore, sleep deprivation due to extended work hours can lead to decreased alertness, impaired decision-making, and reduced overall performance, all of which increase the likelihood of errors (National Sleep Foundation, n.d.).

Errors in the workplace involve actions or decisions that deviate from established standards, expectations, or desired outcomes. According to James Reason's "Swiss Cheese Model," errors are often viewed as the result of multiple failures or holes aligning within a system, allowing an error to occur. These failures might include organizational, procedural, or human-related aspects, illustrating how errors can be a product of systemic issues rather than individual faults. Moreover, errors are not necessarily synonymous with negligence; they can result from genuine oversight, misjudgment, or lack of adequate resources or training. The interpretation of errors often relies on the deviation from predefined norms, best practices, or predefined guidelines, which are set to ensure optimal performance and prevent avoidable mistakes. Proportional logic cannot be applied to these systems and the likelihood of error, as the dynamic interplay in such a tightly coupled system means that environment, physiological state, and workload interact in non-intuitive ways (Morrison & Rudolph 2011). In Rudolph & Repenning's (2011) model of accidents and errors, they assume that 1- an organization faces a stream of varying non-novel unanticipated events, external to the individual workers, that may temporarily prevent completion of predicted actions; 2- that the organization has an appropriate response in its existing collective knowledge for the unanticipated events; and 3- the unanticipated event must be solved for perpetuation of the organizational mission. While this model does not include worker state (i.e., fatigue, cognitive performance, overall stress and mood), it does provide a basis for isolating workload variables that may increase the likelihood of errors.

Errors can have large consequences for the safety and outcomes of emergency and critical incidents. Across all careers, human factors account for 70-80% of all accidents (Ryerson & Whitlock 2005). Major disasters often have disproportionately smaller initial causes but can trigger cascading effects and breakdowns that increase the magnitude of disastrous effect (Morrison & Rudolph 2011). For example, incidents in aviation safety (Reason 1990), emergency and trauma medicine (Pham 2012), and incident response

(Weick 2007) have been attributed to initially small errors that cascade into much larger effects. However, in wildland fire, information about the human decisions that may have caused the accident is usually limited. Ryerson and Whitlock (2005) suggest that this may be due to the unavailability of direct observations or measurements, fear of blaming victims, investigators lacking tools, and operational focus in wildland fire culture (2005). McDonald & Shadow (2003) also discovered that, although generally supportive of safety standards, wildland firefighters often show reluctance toward their implementation. During the Dutch Creek Fire, communication was identified as a key point of failure in averting a tragedy incident (Gabor 2015).

2. MATERIALS AND METHODS

2.1. STUDY POPULATION

Our study examines workload and error rates in United States Department of Agriculture Forest Service (USFS) wildland fire dispatchers. Wildland fire dispatchers play a keystone role in effective communication during wildland fire operations, relaying information among physically disparate crews, to and from leadership, and with the public. Dispatchers help ensure a swift and organized reaction to protect lives, property, and natural resources during a wildland fire incident. Wildland firefighters perform duties such as emergency response coordination, resource allocation, incident information curation and management, communication networking, public information transfer, weather monitoring, logistics support, resource ordering and tracking, and personnel safety (i.e., crew check-in, check-out; United States Forest Service 2023). Recent analyses have found that wildland fire dispatcher centers may be overworked (Duval & Thompson 2023). Multiple surveys and press articles also suggest they are egregiously understaffed. Data from a 2023 survey (Watson et al. unpublished) found that wildland fire dispatchers feel overworked, underappreciated, and have high stress levels.

2.2. GOALS AND OBJECTIVES

Despite their important role in wildland fire management, the work of wildland fire dispatchers has not been reported in scientific literature. Further, factors that may contribute to error are unknown. Understanding these factors may help improve the overall safety and outcomes of wildland fire incidents. Our specific goals are to define and quantify measures of workload in wildland fire dispatchers, describe and quantify error type and frequency, and to analyze relationships between workload and error.

2.3. DATA COLLECTION

The study examined wildland fire dispatchers at the Missouri Iowa Interagency Dispatch Center (USMOMOC) located in Rolla, Missouri, USA. USMOMOC is responsible for dispatching resources across a geographical area encompassing parts of Missouri and Iowa (Fig. 1). We collected dispatcher demographic data and employment data, including gender, worker status (permanent center employee, temporary center employee), and daily number of hours worked, but chose to exclude many variables from analysis to protect participant anonymity. This project was approved by the University of Missouri Institutional Research Board Permit No. 2095791.

Data for the study were gathered from WildCAD reports from January-December 2022 and February -April and October-December 2023. WildCAD is a computer-aided dispatch system utilized by wildland fire agencies nationwide, wherein dispatchers document the movements, work details, and actions of operational team members within their designated zones (DOI 2023). WildCAD reports are initiated for any operational activity necessitating documentation by dispatchers. Initial error coding was performed by senior researchers in consultation with wildland fire dispatchers. Review of initial error coding was made by a minimum of two researchers. Once coding procedures were established, additional reports were coded by a minimum of two trained technicians employing the following operational definitions: When an error was identified, it was recorded in a database. Errors were recorded per dispatcher per day and then summated for the entire dispatcher center per day.

2.4. DATA ANALYSIS

We compared individual and summated workload variables and error variables to determine the relationship among them. We used multivariate correlations to examine relationships between workload and error terms and a principal component analysis to reduce data dimensionality for both workload and error variables and visualize relationships.

We compared differences among individual dispatchers using one-way analyses of variance and Tukey multiple comparison tests (ANOVAs, alpha = 0.05). We compared differences in daily mean individual errors and daily mean center errors by month and dispatcher employment status (temporary and full-time resident) using two-way

ANOVAs where month and employment status were the independent variables and mean error was the dependent variable (alpha = 0.05).

3. RESULTS

We examined a total of 449 incident reports recorded from 2022 – 2023 by 25 individual dispatchers at the USMOMOC. We identified 330 errors throughout the study period.

3.1. WORKLOAD

Total number of resources managed by dispatchers varied among months and was highest in March (Fig. 4, $p < 0.0001$).

3.2. ERRORS

Individual and daily center errors peak in March and followed similar seasonal trends to one another throughout the year (Fig. 2). There were no differences in individual errors among dispatchers ($p = 0.4675$). There were no differences in individual errors between temporary (mean = 0.82, SE = 0.181) and full time (mean = 0.65, SE = 0.010) dispatchers (Fig. 3, $p = 0.8129$). There were a mean 1.6 daily errors per day on days when the center was staffed exclusively with full-time resident employees; when temporary employees worked at the center, daily errors increased to 3.5 (Fig. 3, $p < 0.0001$).

3.3. RELATIONSHIPS BETWEEN WORKLOAD AND ERRORS

A non-linear (exponential) curve best modeled the relationship between hours worked (x) and individual errors (y, $R2 = 0.26$; Fig. 5). Total incidents managed was the workload variable that best correlated with individual errors ($R2 = 0.31$, $P < 0.001$).

4. DISCUSSION

This study is the first to characterize and describe workload and error rates in wildland fire dispatchers. The workload variable that best correlated with error was ‘total incidents managed’ with errors increasing with the total number of incidents being managed. This suggests that multitasking tradeoffs and attention breadth may play important roles in generating errors. The nature of this study lies in its focus on wildland fire dispatchers, a group whose workload and error rates have previously been underexplored within the realm of emergency response research. Until now, much of the literature has concentrated on urban emergency dispatch settings, overlooking the unique challenges posed by wildland firefighting scenarios. The finding that 'total incidents managed' is the workload variable most closely associated with error underscores a significant departure from the often-generic metrics used in other contexts, emphasizing the complexity and unpredictability inherent in wildland fire management. The research by Black et al. (2020) points out the distinctive problems in wildland fire management. The authors stress herein that wildland fire contradicts vastly with urban fire in terms of the complexity of the burning process in the natural environment as well as the uncertainty and idiosyncrasies of the fire which elevate logistics and decision-making process.

Further supporting the critical role of multitasking and attention breadth in error generation, Liu et al. (n.d.) highlight the cognitive limitations humans face when required to manage multiple tasks simultaneously. Their work suggests that as the number of incidents a dispatcher must manage increases, the ability to maintain focus and make accurate decisions decreases, a concept known as "cognitive load theory." This theory posits that there is a finite number of cognitive resources available for tasks such as memory, problem-solving, and attention (Kadir et al. 2021). When these resources are overtaxed by attempting to manage too many incidents at once, the likelihood of errors escalates, which is particularly perilous in high-stakes environments like wildland firefighting.

The implications of this study's findings are far-reaching, offering a vital insight into how emergency dispatch systems could be optimized to minimize errors. For instance, technological interventions, such as artificial intelligence (AI) and machine learning algorithms, could be developed to assist dispatchers in prioritizing incidents based on urgency and complexity, thereby reducing the cognitive load and potential for error (Bulikhov 2022; Kadir et al. 2021). This approach not only supports the dispatcher's decision-making process but also enhances the overall efficiency and effectiveness of wildland firefighting efforts.

The findings of this study elucidate the nuanced relationship between workload and error rates among wildland fire dispatchers, underscoring a critical concern for emergency management infrastructure. The exponential increase in errors relative to workload intensity highlights a systemic vulnerability in the wildland fire response framework, where the margin for error narrows as operational demands escalate. This relationship between workload and errors is reflective of broader trends observed across high-stakes industries such as aviation, healthcare, and nuclear power, where the consequences of errors can be catastrophic. Similar to the "Swiss Cheese" model proposed by Reason (1990), our findings suggest that errors in wildland fire dispatching are not isolated incidents but rather the culmination of systemic vulnerabilities, including understaffing, inadequate training, and cognitive overload among dispatchers. Moreover, the non-linear relationship between workload and errors aligns with theories of human performance and cognitive load (Sigwalt et al. 2020), indicating that there is a threshold beyond which additional workload does not just linearly increase error rates but does so exponentially. This is particularly concerning given the seasonal nature of wildland fires and the potential for sudden spikes in demand on dispatch centers (Binci & Scafarto 2019). Our research also sheds light on the differential impact of temporary versus full-time staffing on error rates. This finding suggests that the integration of temporary staff, while necessary during peak periods, requires targeted strategies to mitigate associated risks, such as comprehensive training and enhanced support systems.

The implications of our study extend beyond the immediate context of wildland fire dispatching to inform broader discussions on emergency management, human factors engineering, and organizational behavior. Future research should explore the effectiveness of various workload management strategies, such as the implementation of advanced technology, decision-support systems, and adaptive staffing models in mitigating error rates. Additionally, longitudinal studies could provide deeper insights into the long-term impacts of workload fluctuations on dispatcher well-being and operational efficiency (Langer et al. 2021). Investigating the role of organizational culture and leadership in fostering a safety-oriented environment could also yield valuable insights. An organizational culture that prioritizes safety, encourages open communication about errors, and supports continuous learning and improvement could be key in mitigating the impacts of high workloads.

ACKNOWLEDGEMENTS

The authors thank M. Ragland, L. Baiter, E. Kettler, J. Martin, A. Pearson, and J. Harrell for assistance with data collection. The Missouri Iowa Coordination Center and Mark Twain National Forest wildland fire staff provided data. We thank J. Cornelius, R. Watson, C. Rogers, and E. Wiersma for technical assistance, support, and guidance.

COMPETING INTERESTS

The authors declare no competing interests.

FUNDING SOURCES

This project was supported with funds from the Missouri S&T Center for Science, Technology and Society and the Department of Defense Leonard Wood Institute.

ETHICS STATEMENT

This project was approved by the University of Missouri System Institutional Research Board Permit No. 2095791.

Table 1. Operating definitions for error terms used in this study.

Term	**Definition**
Entry Disparity	Discrepancies in dates, times, or acreage suggesting later additions.
Added extra information	Duplication of information within the report
Omitted required information	Missing information, such as unrecorded resource releases
Transposed information	Input error resulting in recognizable but inaccurate data
Unclear	Vague statements not readily decipherable
Indecipherable	Information not understandable, including misused acronyms or text-to-speak
Missing information	Omitted essential details
Not closed	Incident left unresolved
Contradicting information	Conflicting data within the report
Operational field error	Incorrectly input or changed GPS coordinates
Strike error	Information struck from the report by dispatchers

Table 1. Operating definitions for error terms used in this study (cont).

Term	**Definition**
Resources Managed	Total number of resources relayed, assigned, or dispatched during an incident, including crews, engines, and single resources
Total Acreage	Total amount of acreage burned during an incident.
Prescribed Fire	Fires planned by USFS or in conjunction with USFS.
Wildfire	Fires originating on lands protected by, owned by or managed by the USFS but unplanned by USFS
Structures Involved	Any manmade object involved in the fire
LEOs Involved or notified	Involvement or notification of law enforcement officers; not counted in resources managed
Local/Rural Firefighters	Involvement of local or rural firefighters
Private Property/Assist	Fire occurrence on private property or non-USFS land
Resource Order	Requisitioning of resources
False Alarm	Reports encompassing situations not requiring USFS intervention
Smoke Check	Deployment of resources to verify potential fire incidents based on detected smoke
Flight Follow	Tracking of aircraft paths by dispatchers
Incidents Managed	A numeric measurement of WildCad incidents initiated by a dispatcher during a time span

Table 2. Comparison of mean daily errors among months by individual dispatcher and dispatch center using Tukey HSD multiple comparison tests. Months connected by letters are not significantly different. Values listed are mean daily errors.

Month	**Individual Dispatcher**	**Dispatch Center**
January	0.45 ABC	0.73 A
February	0.44 ABC	1.17 B
March	1.25 A	4.13 B
April	1.00 AB	2.06 BC
May	0.19 ABC	0.31 BCD
June	0.17 ABC	0.17 BCD
July	0.13 BC	0.23 CD
August	0.01 BC	0.01 CD
September	0.02 BC	0.03 CD
October	0.01 C	0.01 D
November	0.41 BC	1.83 D
December	0.56 ABC	1.59 CD

Table 3. Correlation matrix of workload and error variables. Highlighted values have $p < 0.05$. Green highlights represent significant correlations between workload variables. Blue highlights represent significant correlation between error variables. Peach highlights represent significant correlations between error and workload variables.

	Hours Worked	Resources Managed	Total Acreage	Wildfire Acreage	No of RX Burns	Incidents w/ Structures Involved	Incidents w/ Law Enforcement	Incidents w/ Rural Firefighters	Incidents w/ Interagency or Private A:	Total Resource Orders	Total False Alarms	Total Smoke Checks	Total Flight Follows	Added extra information	Omitted required information	Transposed information	Unclear	Indecipherable	Missing information	Not Closed	Contradicting Information	Operational Field Error	Entry Disparity	Strike error
Hours Worked	1	0.1272	0.1024	0.0049	0.1179	0.0255	0.0414	0.0435	0.0076	0.0482	0.0413	-0.0146	-0.0304	0.0029	0.1753	0.0011	0.0446	0.075	0.0825	0.0724	0.0038	0.0015	0.0025	0.0025
Resources Managed	0.1272	1	0.2259	0.1941	0.331	0.2593	0.2653	0.2383	0.3013	0.2368	0.3897	0.1881	0.0906	0.1651	0.325	-0.0288	0.2195	0.0582	0.431	0.4681	-0.0125	0.0664	0.0386	0.0542
Total Acreage	0.1024	0.2259	1	0.5168	0.2779	0.4476	0.0171	0.053	0.077	0.0108	-0.1113	0.1067	-0.0558	-0.0061	0.1694	-0.0063	0.1215	0.0097	0.1011	0.1285	-0.0342	-0.0169	0.0232	-0.0176
Wildfire Acreage	0.0049	0.1941	0.5168	1	0.1371	0.6673	0.039	0.0999	0.2472	0.1016	-0.0803	0.0448	-0.0451	-0.0115	-0.0642	-0.01	0.1437	-0.0283	0.0197	-0.0464	-0.0255	-0.0141	0.1157	-0.0193
No of RX Burns	0.1179	0.331	0.2779	0.1371	1	0.0387	0.3652	0.3826	0.3283	0.4756	.-0.168	0.0424	-0.0862	0.1524	0.2722	0.0327	0.1936	0.0115	0.1228	0.2672	0.0309	0.0057	0.1589	0.0382
Incidents w/ Structures	0.0255	0.2593	0.4476	0.6673	0.0387	1	0.0498	0.1169	0.3193	0.0906	.-0.1058	0.0621	-0.0329	-0.0085	-0.0151	-0.0159	0.2682	-0.0136	0.0481	-0.0027	0.0221	0.0403	0.1174	-0.0372
Incidents w/ Law Enforc	0.0414	0.2653	0.0171	0.039	0.3652	0.0498	1	0.5074	0.4171	0.4977	.-0.1301	0.1108	-0.0633	0.1747	0.0794	-0.0177	0.1987	0.1157	0.0182	-0.0078	0.0059	0.0575	0.0942	0.0756
Incidents w/ Rural Firefi	0.0435	0.2383	0.053	0.0999	0.3826	0.1169	0.5074	1	0.2673	0.3159	.-0.1556	0.07	-0.0802	0.1066	0.0858	-0.0235	0.0812	0.2182	0.0645	0.048	0.0736	0.0926	0.2292	0.0939
Incidents w/ Interagenc	0.0076	0.3013	0.077	0.2472	0.3283	0.3193	0.4171	0.2673	1	0.4542	.-0.1021	0.1095	-0.0238	0.2052	-0.0099	-0.0157	0.2307	-0.0063	-0.0036	-0.0213	-0.0552	0.0543	0.0263	0.0356
Total Resource Orders	0.0482	0.2368	0.0108	0.1016	0.4756	0.0906	0.4977	0.3159	0.4542	1	.-0.1119	0.1865	-0.048	0.2224	0.0645	-0.0143	0.2972	-0.0001	-0.0264	-0.0362	-0.0168	-0.0202	0.0992	0.0047
Total False Alarms	0.0413	0.3897	-0.1113	-0.0803	-0.168	-0.1058	-0.1301	-0.1556	-0.1021	-0.1119	1	-0.1366	0.0208	-0.0124	0.0678	-0.0205	-0.0481	-0.0387	0.574	0.5626	-0.0557	-0.0291	-0.0476	0.0078
Total Smoke Checks	-0.0146	0.1881	0.1067	0.0448	0.0424	0.0621	0.1108	0.07	0.1095	0.1865	.-0.1366	1	-0.0556	0.2111	-0.0949	-0.0208	0.1589	-0.0592	-0.0156	-0.0925	0.0039	-0.0294	-0.0228	0.1272
Total Flight Follows	-0.0304	0.0906	-0.0558	-0.0451	-0.0862	-0.0329	-0.0633	-0.0802	-0.0238	-0.048	0.0208	-0.0556	1	0.0286	0.1271	-0.0101	-0.0349	0.0232	-0.027	0.047	0.0072	-0.0144	-0.0235	-0.0238
Added extra information	0.0029	0.1651	-0.0061	-0.0115	0.1524	-0.0085	0.1747	0.1066	0.2052	0.2224	-0.0124	0.2111	0.0286	1	-0.0121	-0.006	0.2882	-0.017	0.0276	-0.028	0.0905	-0.0085	0.2074	0.1138
Omitted required inform	0.1753	0.325	0.1694	-0.0642	0.2722	-0.0151	0.0794	0.0858	-0.0099	0.0645	0.0678	-0.0949	-0.0101	-0.0121	1	-0.0152	0.0232	0.0895	0.0097	0.3061	-0.0096	-0.0215	0.008	-0.0106
Transposed information	0.0011	-0.0288	-0.0063	-0.01	0.0327	-0.0159	-0.0177	-0.0235	-0.0157	-0.0143	-0.0205	-0.0208	-0.0101	-0.006	-0.0152	1	-0.0077	-0.0064	-0.0107	-0.0105	-0.0079	-0.0032	-0.0052	-0.0053
Unclear	0.0446	0.2195	0.1215	0.1437	0.1936	0.2682	0.1987	0.0812	0.2307	0.2972	-0.0481	0.1589	-0.0349	0.2882	0.0232	-0.0077	1	-0.022	0.1126	0.0294	0.0322	-0.0109	0.0998	0.0499
Indecipherable	0.075	0.0582	0.0097	-0.0283	0.0115	-0.0136	0.1157	0.2182	-0.0063	-0.0001	-0.0387	-0.0592	0.0232	-0.017	0.0895	-0.0064	-0.022	1	0.0484	0.1047	-0.0224	-0.009	-0.0148	-0.015
Missing information	0.0825	0.431	0.1011	0.0197	0.1228	0.0481	0.0182	0.0645	-0.0036	-0.0264	0.574	-0.0156	-0.027	0.0276	0.0097	-0.0107	0.1126	0.0484	1	0.7296	0.0487	-0.0152	0.1037	0.0738
Not Closed	0.0724	0.4681	0.1285	-0.0464	0.2672	-0.0027	-0.0078	0.048	-0.0213	-0.0362	0.5626	-0.0925	0.047	-0.028	0.3061	-0.0105	0.0294	0.1047	0.7296	1	0.0578	-0.0149	0.0382	-0.0246
Contradicting Informatic	0.0038	-0.0125	-0.0342	-0.0255	0.0309	0.0221	0.0059	0.0736	-0.0552	-0.0168	-0.0557	0.0039	0.0072	0.0905	-0.0096	-0.0079	0.0322	-0.0224	0.0487	0.0578	1	-0.0111	0.1517	0.0797
Operational Field Error	0.0015	0.0664	-0.0169	-0.0141	0.0057	0.0403	0.0575	0.0926	0.0543	-0.0202	-0.0291	-0.0294	-0.0144	-0.0085	-0.0215	-0.0032	-0.0109	-0.009	-0.0152	-0.0149	-0.0111	1	-0.0074	-0.0074
Entry Disparity	0.0025	0.0386	0.0232	0.1157	0.1589	0.1174	0.0942	0.2292	0.0263	0.0992	-0.0476	-0.0228	-0.0235	0.2074	0.008	-0.0052	0.0998	-0.0148	0.1037	0.0382	0.1517	-0.0074	1	0.1826
Strike error	0.0025	0.0542	-0.0176	-0.0193	0.0382	-0.0372	0.0756	0.0939	0.0356	0.0047	0.0078	0.1272	-0.0238	0.1138	-0.0106	-0.0053	0.0499	-0.015	0.0738	-0.0246	0.0797	-0.0074	0.1826	1

Table 4. Error terms used in results section of this paper.

Term	**Definition**
Center errors	Mean of all errors for all dispatchers working at a dispatch center on a given date
Dispatcher errors	Total errors made by an individual dispatcher on a given date or mean among pooled dispatcher groups

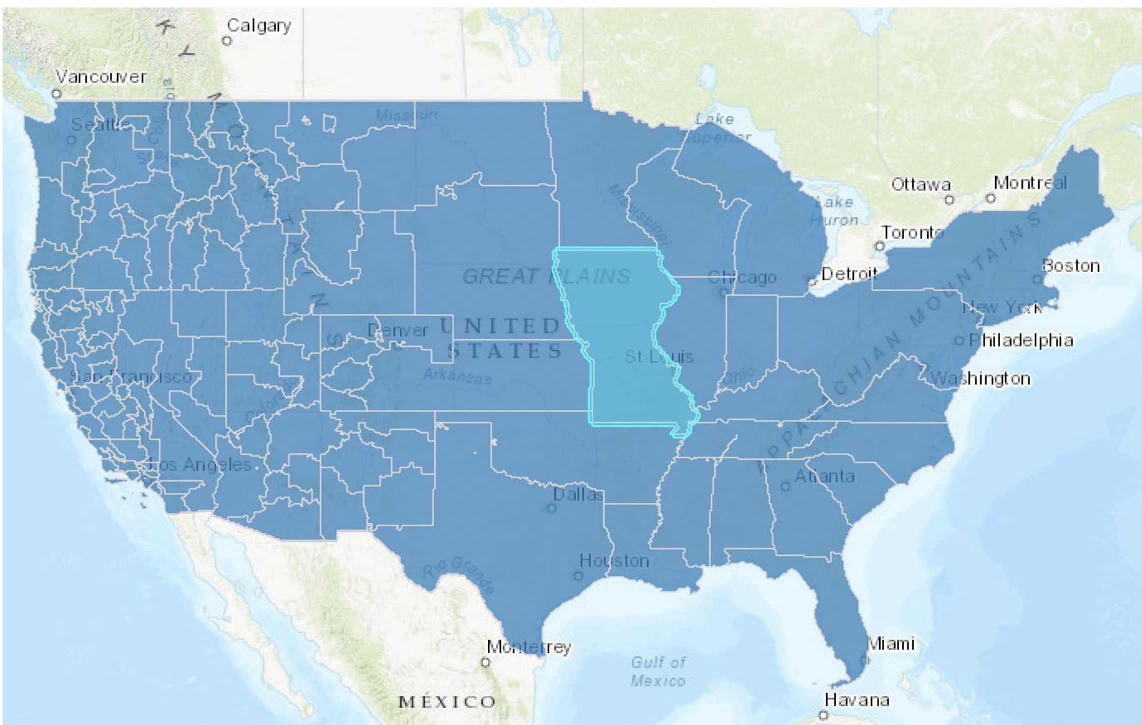


Figure 1. Boundaries of MOMOC in lighter shade of blue relative to rest of United States as defined by the National Interagency Fire Center national dispatch boundaries map, available at: https://data-nifc.opendata.arcgis.com/maps/edit?content=nifc%3A%3Anational-dispatch-boundaries.

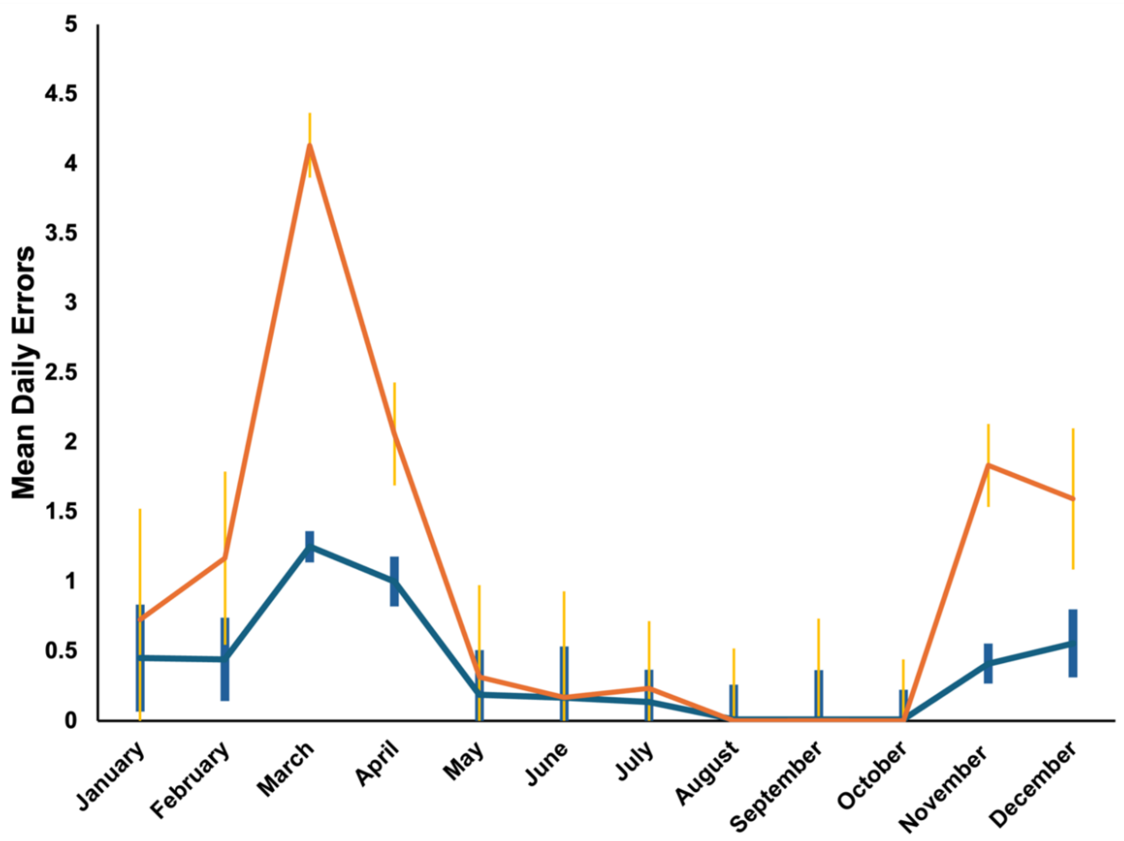
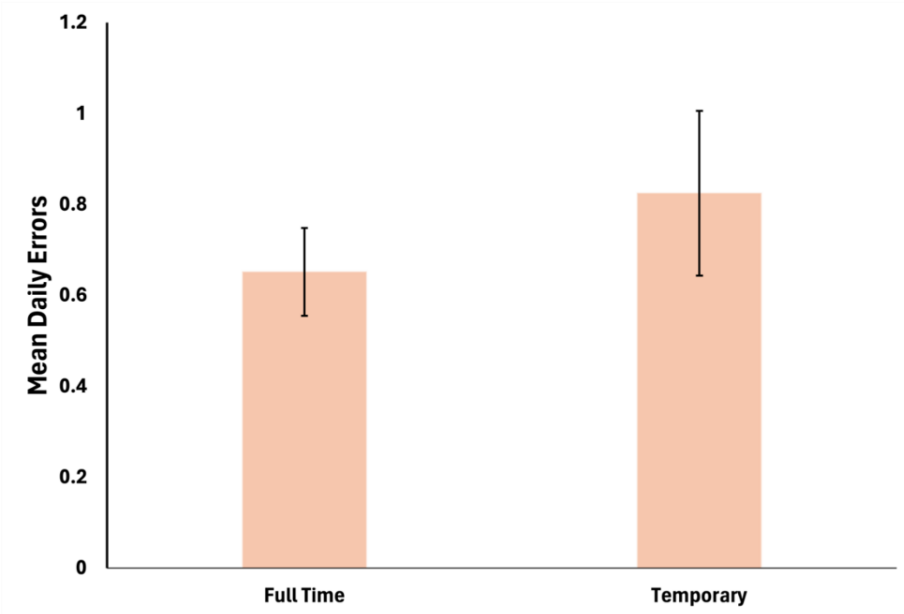


Figure 2. Blue = Mean daily individual dispatcher errors (y) by month (x) F = 5.4214 P < 0.001. DF = 11. Red = Mean daily center errors by month. F = 14.7236 P = 0.0001. DF = 11. Bars represent standard error.

A



B

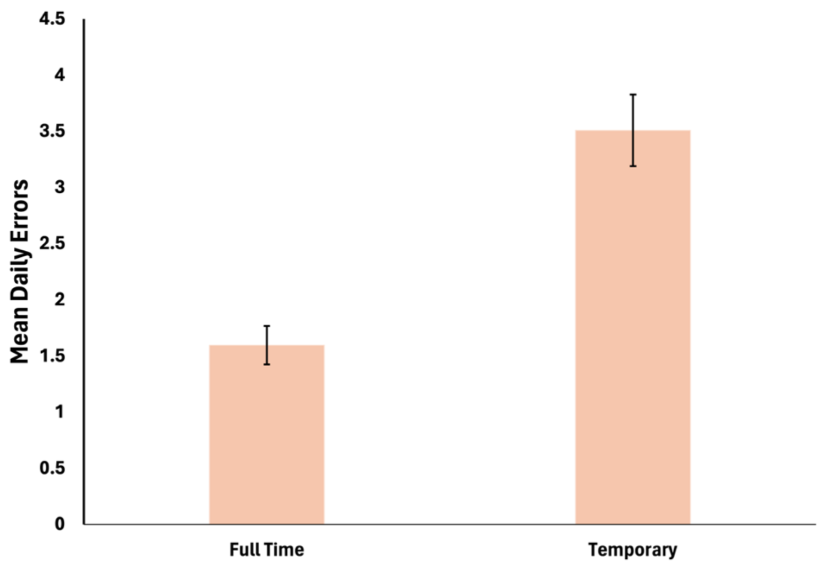


Figure 3. (a) Mean total daily individual errors (y) do not differ by employment status (x). F = 0.0561, p = 0.8129. DF = 1; however, the center as a whole makes more errors when temporary employees are present, versus exclusively full-time employees (3b). F = 14.7236. P < 0.0001. DF = 1. Bars represent standard error.

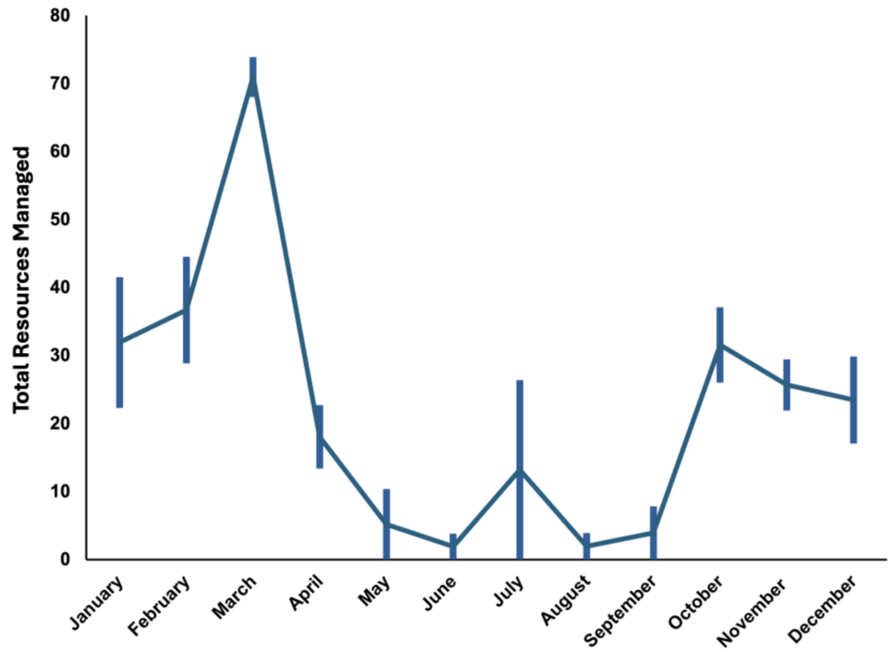


Figure 4. Mean number of resources managed per individual dispatcher for the center differs among months and is highest in March. F = 22.61. P < 0.0001 DF = 11. Bars represent standard error.

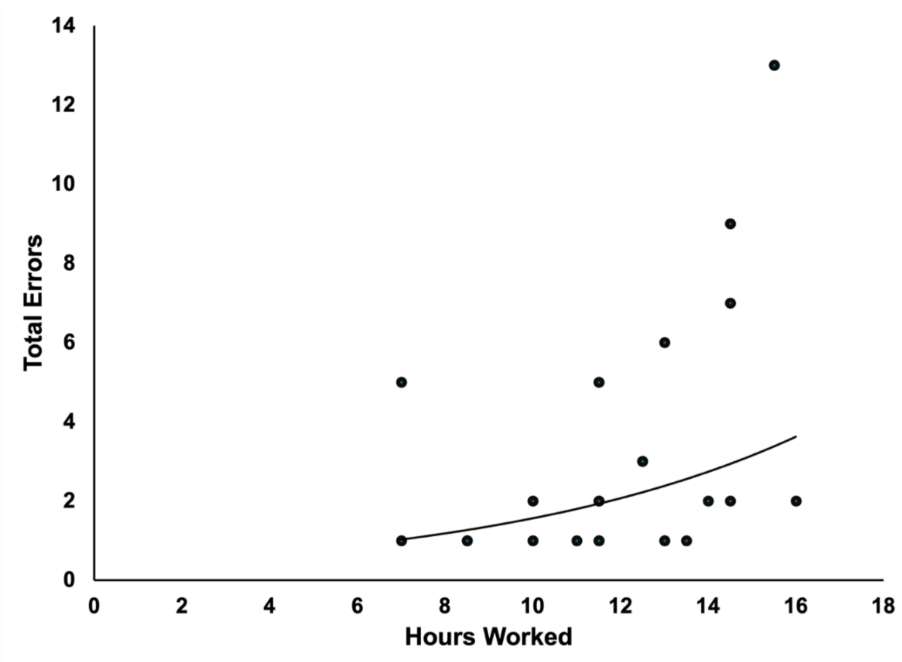


Figure 5. Total daily errors per dispatcher (y) by hours worked (x). Wald = 0.58. P = 0.4460.

REFERENCES

Andrejko-Gworek, B. 2020. Locus of Control and Mindfulness as Moderators of the Job Demand-Control Model: Effects on Burnout (Doctoral dissertation, Walden University).

Belval, E.J. & Thompson, M.P. 2024. A decision framework for evaluating the Rocky Mountain Area Wildfire Dispatching System in Colorado. Decision Analysis Advance Issue: 1-19.

Binci, D., & Scafarto, F. 2019. Leadership in safety-oriented organizations: an empirical study. International Journal of Decision Sciences, Risk and Management 8: 268-291.

Black, A. E., Hayes, P., & Strickland, R. 2020. Organizational learning from prescribed fire escapes a review of developments over the last 10 years in the USA and Australia. Current Forestry Reports 6: 41-59.

Black, A., Sutcliffe, K., Barton, M. & Dether, D. 2008. Assessing high reliability practices in the wildland fire community. Fire Management Today 68: 45-48.

Brook, K., Lin, D. M., & Agarwala, A. V. 2024. Practical approaches to implementing a safety culture. International Anesthesiology Clinics: 10-1097.

Bulikhov, D. 2022. Applied Effort Influence on Mental Workload Measures (Doctoral dissertation, Purdue University).

Chillarege, R. & Iyer, R.K. 1985. The effect of system workload on error latency: an experimental study. Sigmetrics 1985. Proceedings of the 1985 ACM Sigmetrics Conference on Measurement of Computer Systems. pp 69-77.

Ellison, J. M., & Caudill, J. W. 2020. Working on local time: Testing the job-demand-control-support model of stress with jail officers. Journal of Criminal Justice 70: 101717.

Grailey, K., Leon-Villapalos, C., Murray, E., & Brett, S. 2021. Exploring the factors that promote or diminish a psychologically safe environment: a qualitative interview study with critical care staff. BMJ Open 11: e046699.

Hancock, P. A., & Matthews, G. 2019. Workload and performance: Associations, insensitivities, and dissociations. Human Factors 61: 374-392.

Hancock, P.A. & Warm J.S. 1989. A dynamic model of stress and sustained attention. Human Factors 31: 519-537.

Kadir, S. U., Majumder, S., Chokra, A. D., Dubey, A., Neema, H., Laszka, A., & Srivastava, A. K. 2021. Reinforcement learning-based proactive control for transmission grid resilience to wildfire. arXiv preprint arXiv:2107.05756.

Kruger, A. 2008. A systems approach to the assessment of mental workload in a safety-critical environment (Doctoral dissertation, University of Pretoria).

Langer, M., König, C. J., & Busch, V. 2021. Changing the means of managerial work: effects of automated decision support systems on personnel selection tasks. Journal of Business and Psychology 36: 751-769.

Liu, G. N. Y., Triantis, K., Ghaffarzadegan, N., & Roets, B. Workload Dynamics in Safety-Critical Monitoring Roles: Evidence from the Belgian Railway Network. Available at SSRN 4760728.

McDonald, L.S. & Shadow, L. 2003. Precursor for error: an analysis of wildland fire crew leaders' attitudes about organizational culture and safety. Third International Wildland Fire Conference/AFAC Conference. Sydney, New South Wales, Australia. 3 October 2003.

Morrison, J.B. & Rudolph, J.W. 2011. Learning from accident and error: avoiding the hazards of workload, stress, and routine interruptions in the emergency department. Academic Emergency Medicine 18: 1246-1254.

Morrison, J.B., & Rudolph, J.W. 2006. Learning from accidents and error: Avoiding the hazards of workload, stress, and routine interruptions in the emergency department. Academic Emergency Medicine 18: 1246-1254.

National Sleep Foundation. 2023. How Much Sleep Do We Really Need? Available online at: https://www.sleepfoundation.org/how-sleep-works/how-much-sleep-do-we-really-need. Last accessed 2 February 2024.

Patel, V. L., & Kaufman, D. R. 2021. Cognitive informatics. In Biomedical Informatics: Computer Applications in Health Care and Biomedicine (pp. 121-152). Cham: Springer International Publishing.

Reason, J. 2000. Human error: models and management. BMJ, 320: 768–770.

Ryerson, M., & Whitlock., C. 2005. Use of human factors analysis for wildland fire accident investigations. In: Butler, B.W. and Alexander, M.E., eds. Eighth International Wildland Fire Safety Summit: Human Factors- 10 Years Later. Missoula, Montana, USA. 26-28 April. The International Association of Wildland Fire, Hot Springs South Dakota, USA.

Schulman, P. R. 2020. Organizational structure and safety culture: Conceptual and practical challenges. Safety Science 126: 104669.

Sexton, J.B., & Helmreich, R.L. 2000. Analyzing cockpit communication: the links between language, performance error, and workload. Human Performance in Extreme Environments 5: 63-68.

Sigwalt, F., Petit, G., Evain, J. N., Claverie, D., Bui, M., Guinet-Lebreton, A., ... & Lilot, M. 2020. Stress management training improves overall performance during critical simulated situations: a prospective randomized controlled trial. Anesthesiology 133: 198-211.

Sindi S, Kåreholt I, Solomon A, Hooshmand B, Soininen H, & Kivipelto M. 2017. Midlife work-related stress is associated with late-life cognition. Journal of Neurology 264:1996-2002

Singh, P., Bhardwaj, P., Sharma, S. K., & Agrawal, A. K. 2022. Psychological stress and job satisfaction in middle management executives: a test of job demand control support model. International Journal of Human Factors and Ergonomics 9: 372-388.

United States Department of Interior. 2023. Information technology. Accessed online at: https://www.doi.gov/wildlandfire/wfit#:~:text=WildCAD%20%3A%20computer%2Daided%20dispatch%20system,and%20equipment%20to%20new%20fires. Last accessed: 2 February 2024.

Virtanen, M., Jokela, M, Nyberg, S., Madsen, I.E.H., Lallukka, T., Ahola, K., Alfredsson, L., Batty, G.D., Bjorner, J., Borritz, M., Burr, H., Casini, A., Clays, E., Bacquer, D., Dragano, N., Erbel, R., Ferrie, J., Fransson, E., Hamer, M., & Kivimaki, M. 2015. Long working hours and alcohol use: systematic review and meta-analysis of published studies and unpublished individual participant data. BMJ 350: 18-27.

SECTION

2. CONCLUSIONS

In conclusion, this thesis has articulated the complex interplay between environmental health and workload pressures experienced by wildland fire personnel, underpinning the urgency for a cohesive response from government bodies, healthcare systems, and workplace safety regulators. The evidence presented within these pages highlights a stark reality: wildland fire personnel are subjected to extreme stresses that demand comprehensive support strategies.

Firstly, the necessity for increased government funding for research cannot be overstated. Our understanding of the multifaceted challenges faced by these workers remains incomplete. Enhanced funding would enable a broader scope of studies, encompassing diverse geographic and demographic areas and employing sophisticated analytical methods. This approach is vital not only for filling the existing knowledge gaps but also for pioneering innovations in fire management and safety protocols.

Moreover, the health care needs of wildland fire personnel warrant immediate and focused attention. The prolonged exposure to hazardous environments documented in this dissertation calls for a healthcare framework specifically tailored to address both the acute and long-term health ramifications. This includes not only physical but also psychological support, recognizing the intense mental strain associated with this line of work.

Furthermore, the improvement of working conditions is essential for safeguarding the well-being of these professionals. Our findings advocate for enhanced training programs, better personal protective equipment, and the implementation of stringent safety standards. Such measures would not only reduce the incidence of workplace injuries and fatalities but also foster a safer and more efficient operational environment. In essence, the support for wildland fire personnel must be comprehensive and multifaceted, reflecting the complexity of the challenges they face. It is imperative that these changes be driven by a concerted effort from all stakeholders involved, ensuring that the brave individuals on the front lines are equipped, protected, and supported as they undertake their critical roles in protecting our communities and natural landscapes.

VITA

Michael Bryan Held received his Bachelor of Science in Environmental Science and Policy in June 2022. He received his Master of Science in Biological Sciences in May 2024 from the Missouri University of Science and Technology.