Modeling the Impact of COVID-19 on Wildfire Management

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COVID-19 Fire Modeling Team

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Abstract

Motivation. The World Health Organization declared COVID-19 a global pandemic on March 11, 2020 just as the southwestern region begins to see increased fire activity. The project PIs had been collaborating on other wildfire projects but also had expertise in infectious disease modeling. We rapidly developed a model of COVID-19 in a single incident to gauge the potential for widespread transmission on moderate to large incidents. We quickly recognized the need for risk assessment tools as well as a model capable of evaluating systemic risks across the entire season. Our project has two primary objectives: 1) design a risk assessment tool applicable to the unique risks posed by the COVID-19 pandemic, and 2) develop an agent-based model of infectious disease transmission across all potential incidents over the course of the season.

Methods. The team developed very different outputs to accomplish the two objectives (i.e., risk assessment tool and seasonal model). The risk assessment tool was designed in an interactive dashboarding environment known as R Shiny. The intention was to create a simple and intuitive decision support tool that could be used by internet-connected devices or printed out and used offline. We took inspiration from existing risk assessment tools but pioneered a new visual presentation of the information. We analyzed usage trends as a measure of value to the wildland fire community. The project's second objective necessitated the development of a novel agent-based model of SARS-CoV-2 transmission across the season. Agent-based models simulate disease transmission between individuals and track the health status of those individuals over the course of the simulation. We based the simulation on observed resource assignment patterns in recent fire seasons. We simulated health interventions' potential health and workforce capacity effects, including vaccination uptake rates and module-as-one.

Key Findings. The risk assessment tool was reviewed by experts and used in the field during the 2020 and 2021 seasons. The PIs received positive feedback over the course of the two seasons, which was corroborated by detailed usage metrics. Further assessment of the risk assessment tool is challenging because we lack systematic data on critical outcomes. The agent-based model yielded several findings. First, the model suggests that off-fire transmission (firefighters off duty) poses a larger risk to workforce capacity and firefighter health than on-fire transmission. Second, workforce capacity depends on individual behaviors both on and off of incidents - high compliance and vaccine uptake can reduce workforce capacity impacts.

Policy Implications. The COVID-19 pandemic posed operational and health risks to the wildland firefighting system. The model and risk assessment tool provided relevant and timely information when little information was available on the potential risks to firefighter health and workforce capacity.

Objectives

The COVID-19 Fire Modeling Team (CFMT) was assembled in the spring of 2020 to address the impacts of COVID-19 on the wildland fire management system. As the COVID-19 pandemic began to unfold, the team developed a compartmental epidemiological model to examine the potential impacts of COVID-19 spread in fire camps (Thompson, Bayham, and Belval 2020). The team proposed leveraging the effort to produce a decision support tool to assess COVID-19 risk on an incident. However, funding was needed to add capacity to the team to complete the proposed work. The CFMT proposed three objectives for the project: 1) continued model improvement and development, 2) immediate work with managers to examine mitigation strategies for the 2020 fire season, including the development of a dashboard for managers to use, and 3) information dissemination for late 2020 and future fire seasons. The work done throughout the project's duration was unlike most JFS projects. Because the COVID-19 situation was rapidly evolving, the team provided science-based recommendations and tools to managers as new needs arose. Throughout the project, CFMT members were in contact with JFS board members to ensure that the work funded by the grant matched the JFS intentions for the funding. Despite the rapidly evolving management needs, the CFMT completed all the stated goals of the initial proposal, as well as developing additional products.

One of the needs identified after JFS funding was received was a scale- and scope-appropriate tool to support incident-level assessment of COVID-19 risk, particularly on large, long-duration incidents where hundreds to thousands of fire personnel can be mobilized and where the likelihood of infectious disease transmission is generally higher. The CFMT pivoted quickly to address this. After prototyping the COVID-19 Incident Risk Assessment Tool with fire managers and risk practitioners, including early-season use on several incidents, the CFMT built an online dashboard that was used operationally throughout the 2020 fire season. The tool was designed to support the assessment of risks to firefighter health and workforce capacity at the incident level. Our ends-based objectives for the tool were that it could capture local and up-to-date knowledge of conditions, track changing conditions over time, promote situational awareness, help identify mitigations within the scope of control of the incident management organization, and, most importantly, facilitate communication, deliberation, and information sharing throughout the interagency response network. As a means-based objective, and as suggested in early feedback, we wanted the tool to be simple to use and interpret by on-the-ground fire personnel who are typically under considerable time pressures with high workloads.

The dashboard that contained the COVID-19 Incident Risk Assessment Tool also included an epidemiological simulation of a COVID-19 outbreak in a single fire camp, which was based upon the initial compartmental epidemiological model. This interactive dashboard allowed users to explore the impact of different policies (i.e., different epidemiological parameters) under different incident scenarios (e.g., fire duration, number of personnel).

In parallel with the development of the COVID-19 Incident Risk Assessment Tool and the single-incident COVID-19 simulation dashboard, the team continued to improve our epidemiological models of COVID-19 spread between firefighters assigned to fires. While the initial compartmental epidemiological model explored the implications of a COVID-19 outbreak on a single fire (Thompson, Bayham, and Belval 2020), potential system-wide impacts had not yet been explored (National Wildfire Coordinating Group 2021). The CFMT felt it was critical to explore potential health and workforce capacity impacts by modeling the movement of wildfire suppression resources across the country over an entire fire season and the corresponding potential for disease spread and cascading outbreaks across wildfire incidents. Work on this model continued into the spring of 2021, as degradation of workforce capacity and operational readiness were acutely felt at times during the 2020 fire year, and there was high uncertainty around the level of personnel that might be vaccinated, the level of continued adoption of spread mitigations, and the characteristics of the ever-evolving virus. This model provided insights into the systemic impacts of COVID-19 on the entire wildland fire management system (Belval et al. 2021).

The CFMT met the three stated objectives: 1) continued epidemiological model development, 2) decision support dashboard, and 3) information dissemination. The modeling and dashboarding efforts led to two publications, and another is currently under review (Belval et al. 2021; Thompson, Bayham, and Belval 2020; Thompson et al. 2021). Members of the CFMT presented the modeling work at both the joint 16th International Wildland Fire Safety Summit and 6th Human Dimensions of Wildland Fire Conference (Belval 2021)and American Society of Tropical Medicine and Hygiene (Bayham 2020). Insights from the project were presented by Thompson to senior key decision-makers in the USDA Forest Service across numerous briefings (including the Chief, the Undersecretary, the Deputy Secretary, and Secretary of Agriculture) and were shared with other groups, including the Wildland Fire Medical and Public Health Advisory Team. The CFMT also responded to several media requests (e.g., (Boone 2021; Pulkkinen 2020; "Colorado Edition: Managing Resources" 2020). The CFMT produced two interactive dashboards to provide decision support and translate epidemiological risk to the fire incident context. The dashboards were integrated into the Risk Management Assistance dashboard during the 2020 fire season and featured on the front page of the Fire Science Exchange Network. In addition to the dashboards, members of the CFMT produced two informational videos explaining how to use the dashboards.

Background

Fire personnel know all too well the occurrence and unpleasantness of "camp crud," a respiratory illness that is annually transmitted to many of these personnel while they spend time at fire camps (Wildland Fire Lessons Learned Center 2020). COVID-19 is a dramatically different disease than camp crud. Not only is SARS-Cov-2 highly transmissible, but symptoms can also be substantially more severe than those of camp crud, and smoke exposure may complicate the risk of infection and the severity of the disease if contracted (Navarro et al. 2021). Therefore in the spring of 2020 the CFMT identified the urgent need to understand how COVID-19 may impact wildfire incident management personnel and activities.

A wildland fire incident may pose unique challenges to avoiding the spread of SARS-Cov-2 among deployed firefighters. During an actively managed incident, hundreds to thousands of firefighters may be dispatched to the incident. Because many of these fires occur in remote areas, and the personnel are not local, there can be substantial logistical challenges with providing basic services for all the personnel. Historically, these logistics have been met by setting up fire camps. These fire camps are sites at which the personnel are provided with food, water, areas for sleeping, and sanitary services during the time they are assigned to work on the fire (NWCG 2018). While these traditional large fire camps do provide important services, the conditions include high-density living and working conditions, limited hygiene, and a transient workforce, which "create an ideal environment for the transmission of infectious diseases." (National Wildfire Coordinating Group 2020). The fire camp is not the only place that a virus might spread throughout personnel. For example, the incident command post, the location where the primary logistics functions of the fire are administered (NWCG 2018), may also provide opportunities for spread.

Managing the personnel assigned to a fire is a difficult and complex task. Wildfire response organizations scale up as the size and complexity of the incident increases, which necessitates networked coordination and communication across a variety of functions and with numerous local agencies, managers, and stakeholders (Nowell and Steelman 2019; 2015; Nowell et al. 2018). The initial compartment epidemiological model of SARS-CoV-2, developed by the CFMT, suggested that the risk of COVID-19 outbreak at a traditional large fire camp setting could be substantial and supported the broadscale implementation of mitigations, including screening and social distancing measures such as expanded use of telecommunications rather than in-person briefings and dispersed rather than concentrated camping (Thompson, Bayham, and Belval 2020). These mitigation measures and response to diagnosed cases of COVID-19 further complicated the work of the incident management organization, expanding the response network to interface with entities such as local public health agencies, hospitals, and emergency operations centers.

Accordingly, there is a clear role for decision support to inform and enhance coordination and communication efforts (Greiner, Schultz, and Kooistra 2021; Rapp et al. 2020). Despite early issuance of medical and public health guidance to support wildfire management functions under a COVID-19 modified operating posture (National Wildfire Coordinating Group 2021), an identified gap in tools for incident managers was a scale- and scope-appropriate tool to support incident-level assessment of COVID-19 risk. This spurred the CFMT to develop the online Incident Risk Assessment Tool, a dashboard that allowed managers to input characteristics of the fire known to exacerbate detrimental COVID-19 outcomes (case counts and infected individual outcome) that then rated the fire as low, medium, or high risk. This tool was used by several incident management teams over the summer of 2020.

Another gap identified by the CFMT in the late summer of 2020 was an assessment of the potential systemic impacts of COVID-19. Individual fires are not managed in a vacuum; wildland firefighters, particularly those working on large fires, are a highly transient workforce that travels between wildland fires in response to suppression needs. This travel can be across substantial distances. Regions with low or moderate fire activity allow some of their firefighters to be reassigned to other regions that need additional firefighting capacity (Belval et al. 2017). For example, firefighters from the Southwestern region are often used to support fires in the Northern Rockies because the peak fire seasons differ across the regions. Figure 1 depicts the incoming assignments to a particular fire in Montana originating from all over the country and the outbound reassignments. These cross-boundary assignments provide flexibility in wildfire response capacity as single incidents can require thousands of personnel; however, they also pose a potential threat in the context of infectious disease spread. Reassignments from one fire to another often happen within a few days; thus, an outbreak of disease at one fire has the potential to spread to other fires. These cascading effects can accelerate SARS-CoV-2 spread across the national wildland firefighting workforce as the fire season progresses. In addition to the health risks associated with SARS-CoV-2 outbreaks, multiple fires with outbreaks could lead to resource deficits, with a sizable portion of firefighters out sick or quarantined (e.g., "Managing a COVID-19 Worst-Case Scenario The Cameron Peak Fire Story" 2021). Because the firefighting workforce is finite and, at the height of the fire season, some requests for firefighters go unfilled (Belval, Stonesifer, and Calkin 2020), losing a portion of the workforce to sickness and quarantine is a significant concern. Therefore, there was a need for model-based assessment of COVID-19 risk at the national, seasonal scale.

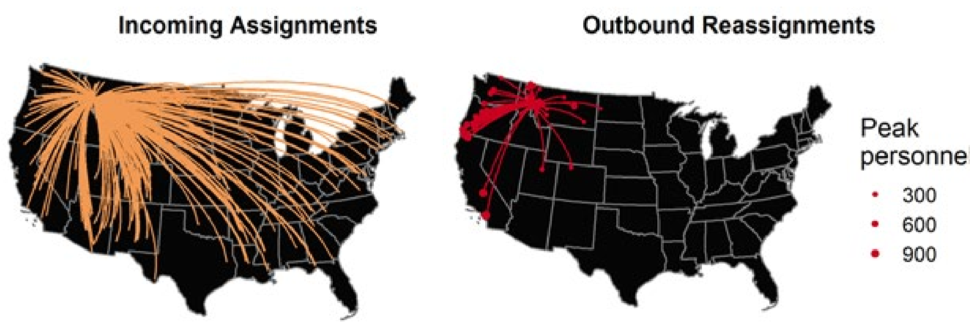

Figure 1: Historical assignment/reassignment data for a single fire in Montana. The map of incoming assignments shows the range of origins for personnel assigned to a fire that started on July 15, 2017. The outbound reassignments shown include all incidents to which personnel went, given nine or fewer days between demobilization at the first fire and mobilization at the second fire.

The CFMT focused on two primary projects: the development of an integrated epidemiology and resource assignment model and the development of a COVID-19 Incident Risk Assessment Tool. While these projects are closely related, the methods and results are fundamentally different.

Therefore, we structure the following sections around the projects, describing the methods and results within each project.

Integrated Epidemiology and Resource Assignment Model

Materials and Methods

Agent-based models (ABMs) have been adapted to model the spread of SARS-CoV-2 for a variety of settings. ABMs have been used to describe SARS-CoV-2 spread within cities (Wallentin, Kaziyeva, and Reibersdorfer-Adelsberger 2020; Firth et al. 2020) and at the national level (Li and Giabbanelli 2020; Rockett et al. 2020) primarily to describe disease dynamics and examine the potential impact of various intervention strategies (Jalayer, Orsenigo, and Vercellis 2020). They have also been used to identify locations at high risk of driving infection outbreaks and to simulate SARS-CoV-2 spread between locations (Holmdahl et al. 2021). An ABM is the ideal tool to examine infection spread within the wildland fire response community as it allows for explicit modeling of interactions between individuals and can track the movement of individuals between fire locations.

We develop an epidemiological ABM to simulate the transmission of SARS-CoV-2 across the wildfire response system based on actual historical assignment data to study the potential impacts of the pandemic on wildfire response capacity throughout the season. Some details are provided below and in Figure 2, and additional details are available in the manuscript associated with this work (Belval et al. 2021). The granularity of the model allows us to investigate the burden of COVID-19 as well as its impact on workforce capacity on multiple scales, from individual fires to the system as a whole.

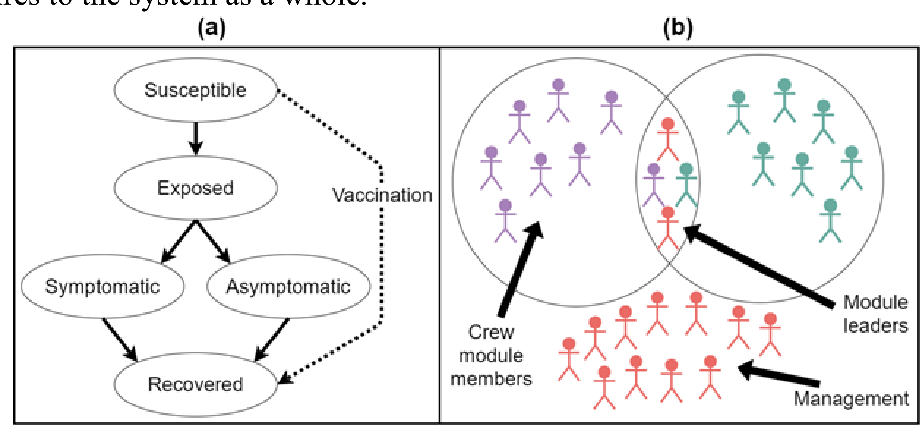

Figure 2. (a) The possible viral states which individuals may travel through in simulations. The arrows indicate possible paths that individuals may take through the viral states. An individual may move directly from susceptible to recovered only if vaccinated. (b) Interactions between personnel on a single fire. Crew module members (individuals of the same color) interact only with other members of the same module, with the exception of module leaders, who interact both with their module members and with other module leaders. Management personnel cannot effectively form modules and thus interact with all other management personnel as well as a proportion who interact with the crew module leaders.

Our simulations use personnel assignment data from three historical fire seasons (2016-2018) to represent a range of possible outcomes for the coming fire season. Each individual simulation covers a single year and provides a possible disease spread outcome for that fire season. On the first day of the season (the day of the first assignment in our data), the probability of each individual being in an initial viral state is driven by a set of predetermined parameters (see Belval et al. 2021 for specifics). The model then steps through each day in the fire season, checking daily on each individual's assignment, module, and the role and simulating and tracking individuals' daily viral, vaccination, and isolation/quarantine status. Individuals' contacts with others in their module and leaders' contact with each other is modeled on each incident; an average number of infection-spreading contacts is calculated for each module and the group of leaders. This average number of infectious contacts that lead to a new infection is used as the mean of a Poisson distribution that is used to randomly assign to each individual on that module the number of successful infectious contacts they had that day. Any individual assigned one or more infection-producing close contacts with an infectious individual becomes exposed. Individuals who are off fire may contact SARS-CoV-2 with a probability dependent upon local transmission. Exposed and infectious individuals' states are re-evaluated daily, and individuals move from exposed to symptomatic or asymptomatic and from symptomatic or asymptomatic to recovered based upon the daily probability of changing viral states (see Belval et al. 2021 for specifics). In addition to the daily re-evaluation of infectious states, individuals are also assessed for isolation. Symptomatic individuals are assigned to be in isolation based upon a random draw. Individuals within the same module as an isolated individual are then quarantined. Individuals move out of isolation, and vaccination occurs based upon the isolation and vaccination methods described above. A detailed description of the ABM algorithm, the distributions used for draws, and the associated parameters can be found in the publication associated with this work (Belval et al 2021). We simulate the model 100 times in each scenario (Baseline, High Compliance, Low Compliance) for each fire season to illustrate the uncertainty due to stochastic transmission. The simulation model and supporting functions were developed using R (R Core Team 2019) are available as an R package (Dilliott 2021c).

To build our fire assignment dataset, we identified the set of large wildland fires (i.e., fires assigned a Type 1, Type 2, Type 3, National, or Area Command incident management team or incident commander) that burned in the US in 2016, 2017, and 2018 using data archived in the Resource Ordering and Status System (see Thompson, Bayham, and Belval 2020; Belval et al. 2017; Belval, Stonesifer, and Calkin 2020; Lyon et al. 2017 for previous peer-reviewed studies using this data). Using these data, we can track individuals uniquely across the fire season, identifying their daily assignments to large fires, the role they play on those fires, and the geographic area within which they are working.

The calibration of the parameters representing the reproductive capacity of the virus are presented in detail in the manuscript associated with this work (Belval et al. 2021). We aimed to have a median reproductive number for SARS-CoV-2 of 1.8, 1.34, and 0.8 people infected by a single infectious person for the Low Compliance, Baseline, and High Compliance scenarios, respectively. These reproductive numbers assume an R_0 of 2.4 (Wu, Leung, and Leung 2020), with the low compliance, baseline, and high compliance scenarios representing, respectively, a 25%, 44%, and 67% reduction in transmission compared to uncontrolled transmission.

We develop scenarios to address two key uncertainties in the interplay between the fire season and the COVID-19 pandemic: vaccination and social distancing behaviors of wildland fire personnel and the spatiotemporal variation of fire occurrence. We address the uncertainty in vaccination rate and compliance to social distancing behaviors among wildland fire personnel by creating three distinct behavioral scenarios: a low behavior compliance scenario, a baseline scenario, and a high behavior compliance scenario. The "Low Compliance" scenario assumes less compliance with infection control measures (i.e., low effort to maintain social distancing and lower percentages of individuals correctly diagnosing their symptoms) and fewer vaccinated individuals. The "High Compliance" scenario assumes more compliance with social distancing, more frequent diagnosis of symptoms, and more vaccinated individuals. The "Baseline" scenario assumes a moderate level of social distancing compliance, symptom identification, and vaccination. The specific parameters used for each scenario can be found in (Belval et al. 2021). We address the variation in fire occurrence patterns by using fire assignments from three distinct fire seasons: 2016, 2017, and 2018. These years cover a range of spatial and temporal demand for wildland fire suppression resources.

We simulate the model 100 times in each scenario (Baseline, High Compliance, Low Compliance) for each fire season to illustrate the uncertainty due to stochastic transmission and yearly variation in firefighter assignments. We focus on four outcomes relevant to the wildfire management community: 1) the number of cumulative infections over the season, 2) outbreaks of COVID-19 on individual fires, 3) reassignments of infectious personnel between fires, and 4) workforce absenteeism due to quarantine. We report median values of the 100 simulations along with the interquartile range (IQR; indicates the central 50% of the distribution).

Results and Discussion

Figure 3 illustrates the number of cumulative infections contracted both on and off of active duty across the three scenarios over the duration of the season using 2017 fire assignment data. There were 43,360 personnel assigned to at least one large fire in 2017. Figure 3 shows that the number of infections acquired off-fire is substantially more than those acquired on-fire.

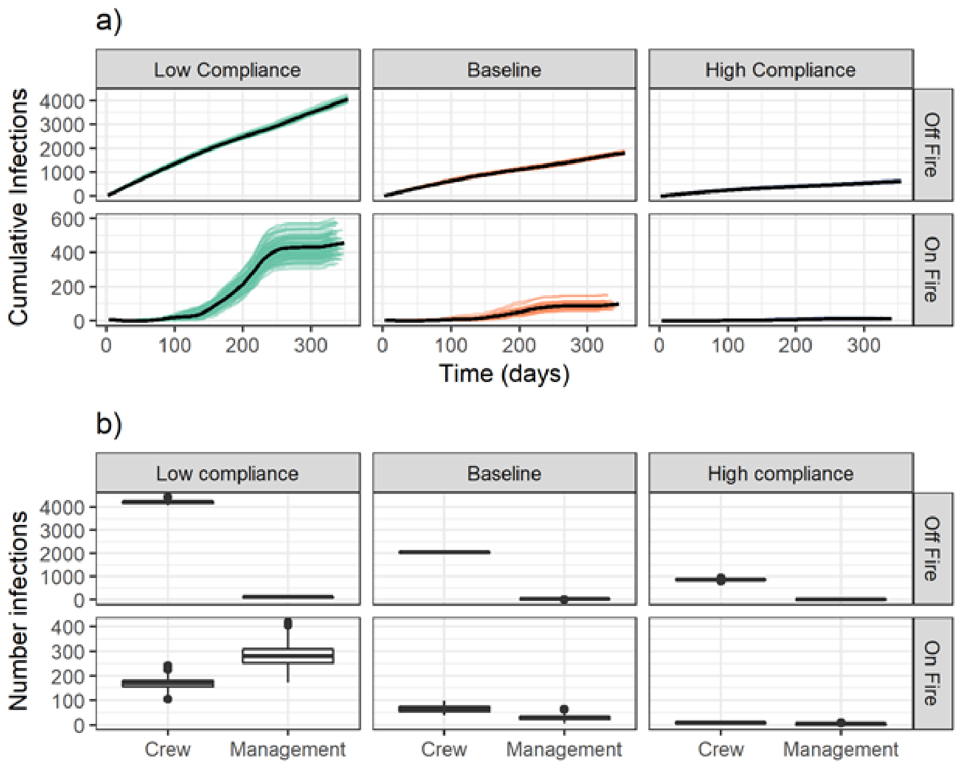

Figure 3. Daily cumulative infections by compliance scenario on and off fire (a) and annual cumulative infections by personnel type (b). In (a), each line is associated with a single scenario run while the bolded lines show the run with the median number of cumulative infections incurred. The total cumulative infections across the 2017 season by scenario and personnel role are shown in (b), with cases attributed to assignment status at time of exposure.

The number of contacts and the intensity of those contacts is not homogeneous across personnel. This is reflected in our model structure and parameters. We, therefore, examined the number of on-fire infections that occurred specifically within management personnel and crew personnel modules (Figure 3b). We find that in the Low Compliance scenario, there is a relatively high ratio of management to crew infections for cases incurred on a fire as compared to those incurred off fire. As compliance with mitigation measures increases, the ratio of management to crew on-fire cases goes down. This likely reflects the contact structure for management personnel (they are exposed to more people each day) and the isolation procedures (only the symptomatic person isolates if they are management as opposed to the entire module for crew personnel). The implications of the higher caseloads incurred on fire by management personnel has significant implications. First, management personnel tend to be older than crew personnel, which means they are also at higher risk of severe symptoms. Second, key management positions require high levels of qualifications, so higher caseloads in management personnel may burden the wildland firefighting system more than caseloads in crew personnel.

The spatio-temporal variation in fire activity between seasons did not substantially affect simulated cases of SARS-CoV-2 incurred on fire across the Baseline scenario. We do observe a slightly higher level of cumulative simulated infections overall using 2017 and 2018 assignments than those from 2016; this is because the total number of personnel assigned to a large fire was higher in the 2017 and 2018 scenarios, leading to a larger pool of personnel that can be infected off fire. Because there was little variation in disease spread patterns by assignment-year in on-fire infections, we focus the rest of our results on scenarios based upon the 2017 fire assignments.

While the number of individual cases is an important systemic outcome, outbreaks of COVID-19 on a wildfire incident can add a substantial burden on the management team. Therefore, for each simulation, we counted the number of cases of SARS-CoV-2 on each fire. If a fire incurred at least two cases from different crew modules, two management personnel with cases, or a combination of crew and management personnel with cases, we counted that fire as having an outbreak for that run. Figure 4a shows the percentage of runs for which each incident had an outbreak by the maximum number of personnel assigned to the fire on a single day. We find that the incidents most likely to see outbreaks are the incidents with the highest number of maximum personnel assigned. Compliance with interventions has a greater impact the larger the number of personnel on the fire. While the maximum number of personnel on the fire has a strong relationship with the percentage of runs in which each fire experiences outbreaks, duration of the fire also plays an important role. We single out two fires in Figure 4a: the points associated with one fire are circled in blue (the "many-outbreaks fire") and the points associated with the second fire have pink squares around them (the "fewer-outbreaks fire"). When we examine the number of personnel on the fire over time (Figure 4b), we see that the many-outbreaks fire lasted much longer than the fewer-outbreaks fire.

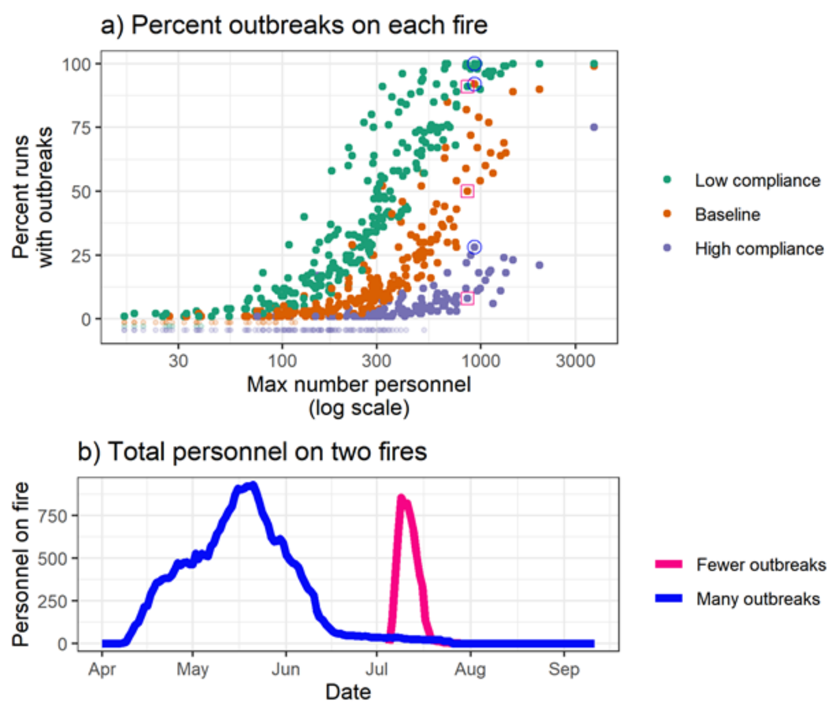

Figure 4. a) Percentage of runs for which each fire had an outbreak by scenario and maximum number of personnel assigned to the fire on a single day. Two fires are singled out: the points associated with a "many outbreaks" fire are circled in blue and the points associated with a

"fewer outbreaks" fire have a pink square around them. b) The number of personnel over time for the "many outbreaks fire" and the "fewer outbreaks fire" that are indicated in (a).

To explore the risk of personnel transmitting disease from one fire to another, we examined the number of infectious assignments and reassignments. These metrics provide a way to quantify the difference in risk from personnel contracting the virus off fire and bringing it to their assignment versus the risk from personnel bringing the virus from one fire to another. We find that the number of infectious assignments from personnel who contracted SARS-CoV-2 off fire is higher than the number of infectious reassignments from personnel who went from one fire to another while in an exposed or infectious state (Figure 5a). Management personnel have a relatively high risk of being reassigned while infectious relative to the number of infectious assignments they have, particularly in the Low Compliance scenario.

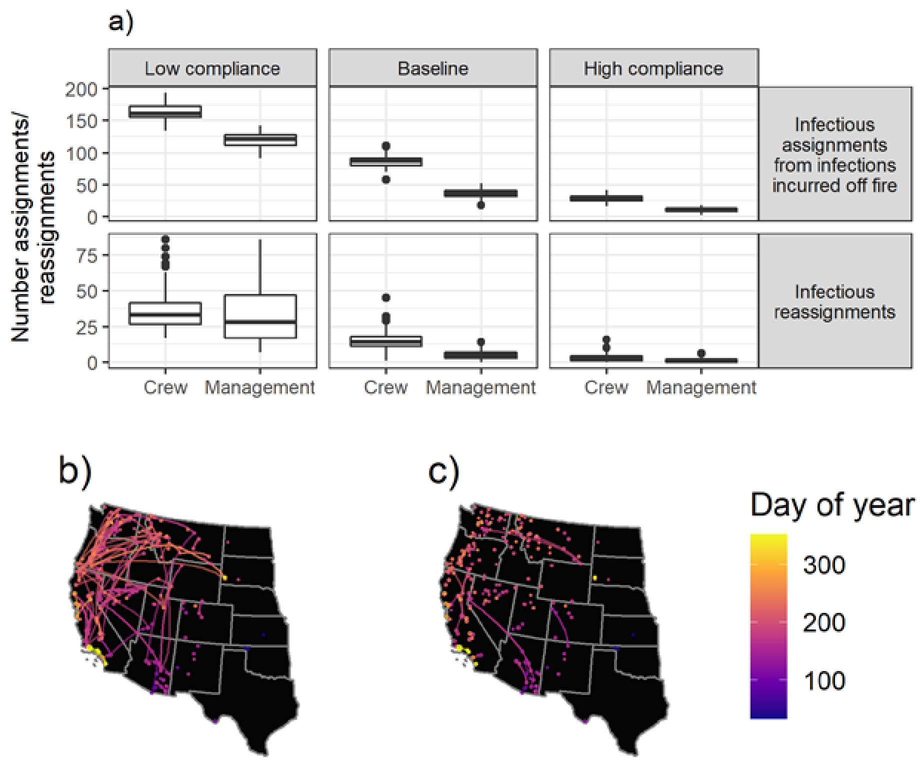

Figure 5. a) The number of infectious assignments and reassignments by scenario and personnel type for the 2017 fire assignment data. b) A map of the infectious reassignments that occurred during the Low Compliance run using 2017 data that had the highest number of infectious reassignments (i.e., the worst case scenario observed). c) A map of the infectious reassignments that occurred during the High Compliance run using 2017 data that had the highest number of infectious reassignments. All large fires included in the analysis are mapped as points, with the point size corresponding to the maximum number of personnel assigned to the fire on a single day. Lines connecting fires indicate infectious reassignments.

A comparison of two specific runs illustrates the effectiveness of mitigation measures in reducing infectious reassignments. A map of the worst-case scenario for reassignments (i.e., the highest number of infectious reassignments observed) in the Low Compliance scenario is shown in Figure 5b, while a map of the worst-case scenario for infectious reassignments in the High Compliance scenario is shown in Figure 5c. In the Low Compliance worst-case scenario, we can observe disease being transferred between fires across space and time, while in the High Compliance worst-case scenario, we see many fewer infectious reassignments.
In addition to the health of firefighting personnel, agency administrators are concerned with workforce capacity and the ability to accomplish firefighting objectives. When a firefighter self-identifies as infected, that individual's module is quarantined to reduce transmission. However, vaccinated individuals are not required to quarantine after exposure under current guidance (National Wildfire Coordinating Group 2021). Figure 6 compares the number of firefighter days missed by scenario, showing the number of days that individuals that would be required to quarantine given no vaccination (that is, all individuals quarantine regardless of vaccination state) and the number of days that individuals that are actually required to quarantine (i.e., vaccinated individuals are excluded). In the Baseline scenario, SARS-CoV-2 exposure and quarantine lead to 1007 [IQR 842-1198] firefighter days missed, which represents less than 1% of the total assigned days. As a point of comparison, the Cameron Peak Fire alone could have accounted for more than 2,000 worker days missed. The median number of worker days missed for the Baseline scenario is slightly lower than the median of the Low Compliance scenario. The High Compliance scenario yields the fewest worker days missed, but the distribution shows that higher impacts on workforce capacity are possible, highlighting the uncertainty faced by fire managers throughout the pandemic. We summarize worker days missed in each of the mitigation scenarios across years 2016 - 2018 and find no qualitative difference in the result between years (see the supplementary materials of Belval et al. 2021).

Figure 6. The distribution of worker days missed by scenario. The red denotes all workdays missed by vaccinated and unvaccinated firefighters while the blue denotes workdays missed by only unvaccinated firefighters. The Only Unvaccinated indication captures current guidance. Brackets indicate the interquartile range and plus signs indicate the median value for each distribution.

Our results suggest that vaccination and disease spread mitigations reduce the total number of SARS-CoV-2 infections in the wildland fire community, as well as reducing the number of infectious assignments and infectious reassignments to wildland fires. In addition, vaccination

and disease spread mitigations lower the probability of outbreaks on individual fires and reduce workforce absenteeism. In our results, we observe many more infections incurred off-fire than while firefighters are on assignment and, similarly, more infectious assignments than reassignments. We do observe differential risk levels for crew personnel and management personnel. Below we discuss the implications of these results on the wildland firefighting system, as well as discussing some of the mechanisms that may be driving these results.
The national wildland firefighting system relies on the scalable mobilization of individuals and groups of individuals from around the nation, and these individuals may serve in different roles and capacities depending on their qualifications and the needs of the incident. The population structure at a fire incident and its evolution over time as resources are mobilized/demobilized creates complex networks of interaction such that every incident carries different degrees of transmission risk. Fire personnel can be mobilized from all around the country, including reassignments from other incidents, such that there are systemic interdependencies in risk of transmission and potential for cascading outbreaks. In summary, the structure and function of the wildland firefighting system pose a unique set of risks from COVID-19, requiring a tailored approach to characterizing those risks.

Our primary focus here was analyzing potential COVID-19 impacts on workforce health and capacity, a topic of growing importance as increasing fire activity is expected to further strain the response capabilities of the system (Abatzoglou et al. 2021). There are three primary workforce-related factors to consider. First, not captured in our analysis but worth mentioning, management of COVID-19 creates additional workload burden including screening/testing, isolating/quarantining, and interfacing with entities such as local public health agencies and hospitals – and this burden increases with the number of infections and outbreaks. Second, worker absenteeism due to isolation/quarantine requires greater coordination and prioritization of scarce resources both within and across incidents, and in some cases, results in unfilled resource requests and understaffed incidents (Belval, Stonesifer, and Calkin 2020). Depending on the degree of scarcity and substitutability of the affected resources (Stonesifer, Calkin, and Hand 2017), this could result in the inability to implement preferred strategies and tactics (e.g., lack of crews) or incident management organizations operating outside of their typical span of control (e.g., lack of key management personnel). Third, and perhaps most important to the workforce, missed days can translate into a loss of assignments and loss of pay. For some of the firefighting workforce, the bulk of their annual salary comes from their time on assignment when their pay rate is increased due to overtime hours and hazard pay. In some cases, due to minimum personnel requirements for certain assignments, entire crews could be deemed unqualified if only some members of their team are in isolation or quarantine. Vaccination, in such cases, would insure against crew members having to quarantine due to exposure and would make more crews generally more available for assignments.

This point naturally leads to the primary finding of this analysis that high vaccination rates in combination with the policy that vaccinated individuals do not need to quarantine after exposure results in significantly fewer worker days missed compared to other scenarios. The best case (High Compliance scenario with current quarantine policy) results in more than five times fewer missed worker days than the worst case (Low Compliance scenario without quarantine policy). Hence the importance of capturing uncertainty around vaccination uptake in the risk assessment and, more broadly, the importance of vaccination in maintaining system capacity.

Further, model results suggest that vaccination and disease spread mitigations reduce both infections and workforce absenteeism in the wildland fire community. There are two primary mechanisms at play: 1) vaccination and spread mitigation efforts keep infections low, leading to fewer isolations and 2) vaccinations allow exposed personnel to avoid quarantine. The contact structure of our ABM accounted for organizational structure and social distancing mitigations, and the ABM also captured heterogeneity in quarantine requirements according to individual agent and module status. The contact structure also led to the finding that infection risks may be higher for personnel that cannot "module as one."

ABM results also show that most infections incurred by wildland firefighting personnel are likely to be from off-fire sources rather than being incurred while on assignment. This implies that vaccination and mitigation techniques may prevent large outbreaks that cascade across the fire system, even in most Low Compliance scenarios. In other words, although the normal functioning of the system creates a systemic risk through reliance on a highly transient workforce with complex and dynamic exposure patterns, vaccination and social distancing on-fire can disrupt cascading outbreaks and effectively mitigate those systemic risks.

COVID-19 Incident Risk Assessment Tool

Materials and Methods

This section describes the development and application of a COVID-19 Incident Risk Assessment Tool. The tool is designed to support the assessment of risks to firefighter health and workforce capacity at the level of the population of fire personnel assigned to the incident. More specifically, the tool is intended for use on large, long-duration incidents where hundreds to thousands of fire personnel can be mobilized and where the likelihood of infectious disease transmission is generally higher. Our ends-based objectives for the tool were that it could capture local and up-to-date knowledge of conditions, track changing conditions over time, promote situational awareness, help identify mitigations within the scope of control of the incident management organization, and, most importantly, facilitate communication, deliberation, and information sharing throughout the interagency response network. We wanted the tool to be simple to use and interpret by on-the-ground fire personnel who are typically under considerable time pressures with high workloads.

After prototyping with fire managers and risk practitioners, including early-season use on several incidents, we built an online dashboard that was used operationally throughout the 2020 fire season. We structured the assessment as a hierarchical multi-criteria analysis. The scheme includes three risk factors (scored 3-9), each of which is rated based upon three subfactors (scored 1-3), which are combined as a weighted sum. The risk factor ratings are then combined as a weighted sum to yield a numerical incident-level risk score and a corresponding qualitative risk rating. We selected this framework based in part on recommendations from the field to foster consistency and familiarity with existing assessment products in WFDSS (Noonan-Wright et al. 2011).

Figure 7a displays the conceptual rose chart for how risk scores and ratings were visualized. The dashboard automatically creates figures for each factor and sub-factor and for the overall incident-level score. Each "petal" corresponds to an individual risk sub-factor, the size, and color of which vary depending on the assigned score. Figure 7b displays how each factor and sub-factor are rated on the dashboard itself. The greater the size of a petal, the greater its contribution to overall risk. Table 1 displays the risk assessment worksheet that forms the basis for how the chart is created. This worksheet was available for users as information and as a tool to download and fill out by hand.

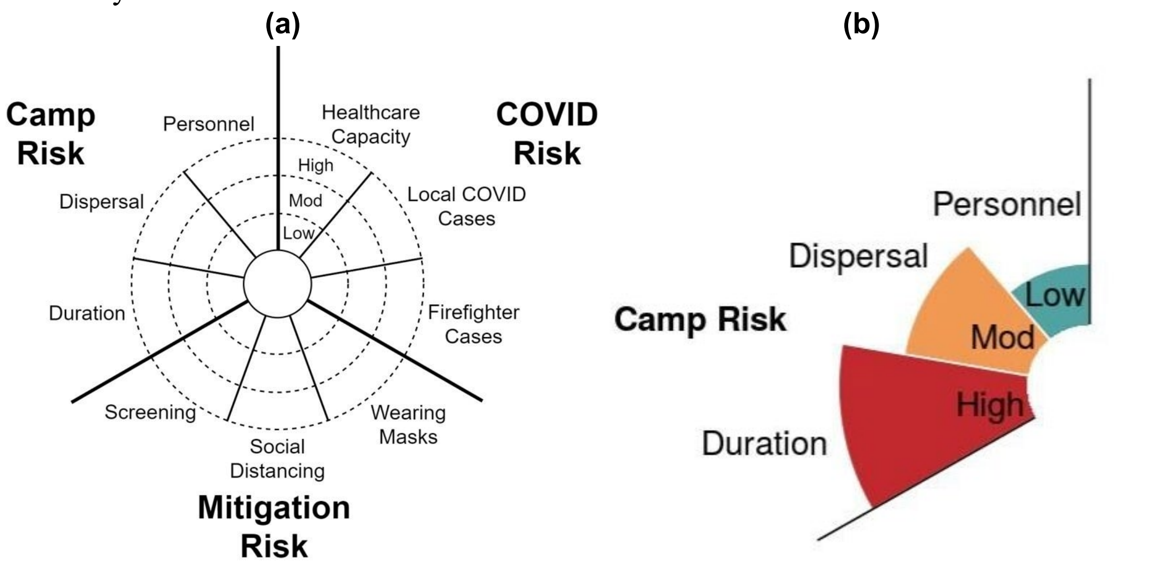

Figure 7: (a) Conceptual rose chart illustrating the hierarchical multi-criteria approach to estimating incident-level risk through assessment of risk factors and sub-factors. (b) Illustration of filling out rose chart on the online dashboard.

Table 1. Risk Assessment Worksheet that lays out the risk scoring and rating system all factors and sub-factors.

Risk Factors	Low Risk	Moderate Risk	High Risk	Score	Rating
	1	2	3		
ICP/Fire Camp Risk Status					
Personnel	Low (50-200)	Mod (200-500)	High (>500)		
Camp Dispersal	High dispersal	Moderate dispersal	Low dispersal		
Camp Duration	Short (< 5 days)	Medium (5-20 days)	Long (> 20 days)		
ICP/Fire Camp Risk Factor Total					
Mitigation Implementation Risk Status					
Screening Frequency	Always	Sometimes	Never		
Social Distancing Discipline	High compliance	Moderate compliance	Low compliance		
Cloth Masks	Always	Sometimes	Never		
Mitigation Implementation Risk Factor Total					
COVID Risk Status					
Firefighter Cases	Low (<= 2)	Mod (> 2, isolated)	High (> 2, many)		
Local Cases	Low amount	Mod amount	High amount		
Healthcare Capacity	High capacity	Mod capacity	Low capacity		
Surrounding Area & Community COVID Risk Factor Total					

Additional Risk Factors (Optional)					
Smoke, etc.					
Final Relative Risk Assessment					
Incident Risk Total					

In late June and early July 2020, an initial version of the risk assessment tool was used on multiple wildfire incidents in the southwestern USA. At the time, we had only developed the framework and shared an image mirroring the depiction of the tool with the relative risk-assessment from WFDSS. Assessment results were hand-drawn and shared with accompanying text narrative. Based on positive feedback from regional risk management specialists familiar with the tool's operational use, we proceeded with updating the graphical model and developing the software to streamline and expand the use of the online risk assessment tool.

In addition to working with subject matter experts and relying on their respective networks, we used multiple channels to share information about the COVID-19 Incident Risk Assessment Tool. Early on, we briefed senior leadership of the USDA Forest Service, who offered their support for continued development and use. We coordinated closely with agency personnel from Fire and Aviation Management, Office of Communications, and the Rocky Mountain Research Station. With their assistance, we developed an informational webpage about the project as well as an online tutorial hosted on the dashboard. We also worked with the agency's Risk Management Assistance program to host our dashboard on their decision support website during the 2020 fire season.

A primary channel we leveraged was virtual meetings hosted by Incident Management Remote Response (IMRR), a collaborative interagency effort to support rapid sharing of information and lessons learned across the fire response community. Through IMRR, we presented to groups of Incident Commanders, Agency Administrators, and Safety Officers, with hundreds of attendees in some cases. In these sessions, we provided contact information and were able to follow up directly with interested personnel, in some cases supporting the use of the tool in real-time. Lastly, we collaborated with the Joint Fire Science Program who distributed information about our tool through the Fire Science Exchange Network.

We built the COVID-19 Incident Risk Assessment tool using the R Statistical Computing Language (R Core Team 2019). The dashboard is built using Shiny and is hosted on shinyapps.io; the code for the Incident Risk Assessment tool is publicly available (Dilliott 2021a). Additional details about the software implementation can be found in the manuscript associated with this work (Thompson et al. 2021).

After prototyping and outreach efforts were complete, the COVID-19 Incident Risk Assessment Tool was released for operational use by appropriate individuals in the fire management community at their discretion. Field users on fire assignments generated the input data, interpreted the results, and communicated them within their incident response organizations and with partners. From this point forward, we made no further adjustments to the model but did aid with use and interpretation as requests arose.

The tool was developed under compressed time frames to support the immediate needs of the fire management community. Because the tool was released during an extreme fire season coincident with a pandemic, respondents from whom we solicited feedback were also operating under considerable time pressures and stresses. The prospect of limited documentation on use was foreseeable (including the possibility of offline use with the PDF version in areas with limited connectivity), as was the prospect of not knowing the total number of wildfire incidents at which the tool was used. These were acceptable tradeoffs, and we prioritized supporting COVID-19 assessment, mitigation, and communication efforts over comprehensively tracking and evaluating use. Nevertheless, we developed a three-tiered approach to the evaluation of the tool: (1) tracking online usage statistics; (2) examining actual use cases; and (3) examining user feedback.

Results and Discussion

The objective of this project was the development of the tool, so there is not a formal set of results. However, we did track the usage of the tool and report on the usage here.
We initially tracked dashboard usage using the built-in functionality provided by the shiny.io server. The usage statistics are tracked by the minute and include the number of active connections, Central Processing Unit (CPU) kernel usage in nanoseconds, and CPU user usage in nanoseconds. These usage statistics are shown over time in Figure 8, starting on 28 July 2020. The number of daily connections can be used as an estimate of the number of site visits the dashboard received. Because a single user may connect to the dashboard more than once per day, that metric can be higher than the number of daily unique site users.

The amount of CPU time used in kernel mode is associated with computing tasks such as application initiation, while the amount of CPU time used in user mode is associated with tasks such as application usage. Thus, for our dashboard, higher ratios of user mode to kernel mode CPU usage are likely to indicate users that are actually interacting with the dashboard as opposed to users who simply visit the site and do not interact with the application. These statistics from the shiny.io server show spikes in connections during key publication events such as the initial distribution the week of 28 July 2020, an email highlighting the application that was sent out on 4 September 2020, and a presentation that mentioned our team's work on 20 October 2020. However, we also observe ongoing routine usage of the app between publication events.

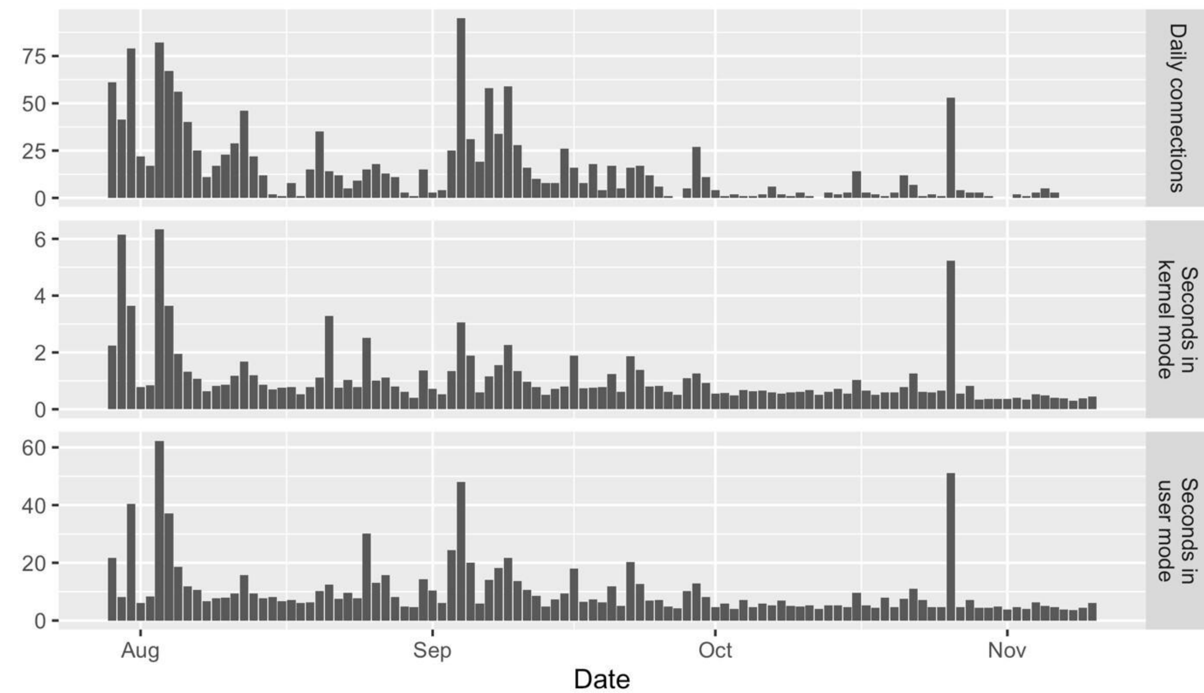

Figure 8. The daily connections, daily CPU usage in kernel mode, and daily CPU usage in user mode as tracked by the shiny.io server for 28 July 2020 through 10 November 2020.

To improve tracking of dashboard usage, on 10 September 2020, we enabled tracking by Google Analytics. We used the standard Google Analytics settings. The use of Google Analytics allowed us to track additional data on users, including location and if the visitor was new or returning. Figure 9 shows the geographic distribution of new and returning users from 10 September 2020 through 10 November 2020. The dashboard saw usage across all regions of the United States, both for new visitors and returning visitors. According to the tracking done by Google Analytics, most users of the dashboard visited only once (150 users between 10 September and 10 November 2020). However, there were 20 users who visited the dashboard twice and 15 users who visited the dashboard between three and eight times. Google Analytics may underestimate returning visitors, as users who use more than one device can be considered a new user for each device. These dashboard user statistics may slightly underestimate the usage of this decision support tool, as we did provide decision-makers with a fillable PDF that could be used offline.

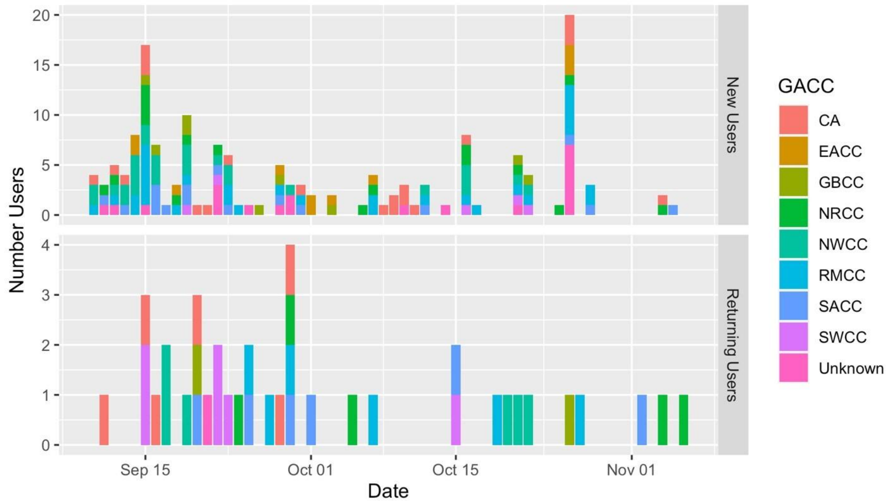

Figure 9. The number of dashboard users in the United States classified by geographic area coordinating center (GACC) and user status (new or returning) as tracked by Google Analytics for 10 September 2020 through 10 November 2020.

For illustrative purposes, here we present risk assessment results and user-specified rationales for a real incident. We anonymize any data that could identify personnel or the incident, consistent with our statement to users that the tool was for informational purposes only and would not be used for any official record keeping or documentation. Figure 10a displays the finalized rose chart with the overall risk score (19) and risk rating (high) from the real incident example. Users provided us with the rationales for all sub-factors. In this specific instance, Camp Risk Status and Mitigation Risk Status both rated as moderate, whereas COVID Risk Status rated as high due to multiple cases among fire personnel and concerns over limited local healthcare capacity. As a point of comparison, Figure 10b displays the finalized rose chart for an incident rated as moderate risk and with a very different breakdown of risk factors. In that case, the highest risk factor was ICP Risk Status, with an expectation of many personnel and a long-duration incident, but with the ability to widely disperse fire personnel at a large fire camp.

(a) **(b)**

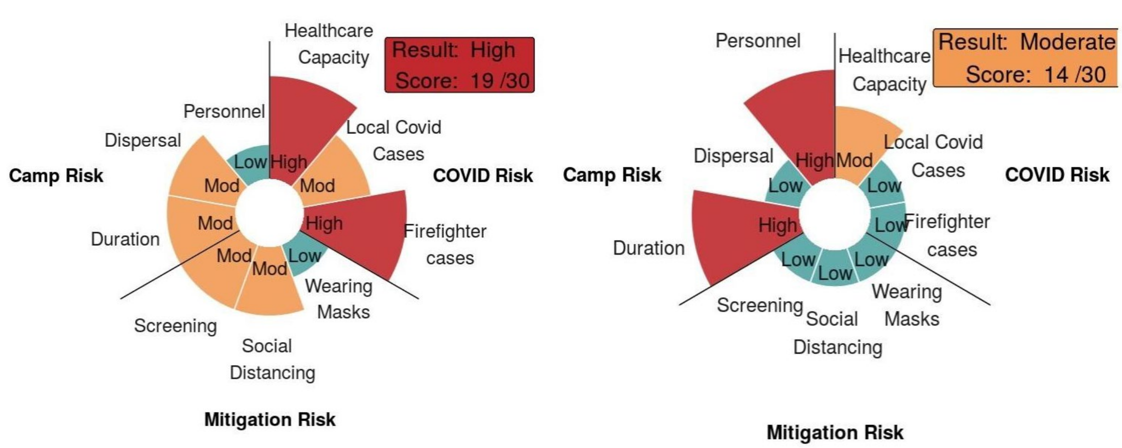

Figure 10. (a) Rose chart results from actual use case rating out as high risk (risk score of 19). (b) Rose chart results from a different actual use case rating out as moderate risk (risk score of 14).

It is worth reiterating that the primary intention of the tool was facilitating communication and coordination rather than predicting where COVID-19 spread might occur. With that said, a comparison of assessment results against observed case counts could help validate the internal logic of the assessment framework. Unfortunately, data on firefighter case counts is of poor quality, and federal wildfire management agencies in the United States did not publish official counts for COVID-19 cases occurring on wildfire incidents. To provide one example of validation, with an admittedly limited scope of inference, we are aware of one incident where the final score was 21/30 with a rating of high risk where widespread testing, contact tracing, and quarantining/isolating were initiated, and ultimately where multiple cases were confirmed (again, the incident details are anonymized).

A variety of personnel used the tool, including Agency Administrators, Safety Officers, Medical Unit Leaders, and COVID Advisors. Safety Officers appear to have been the primary user role, unsurprising given their responsibility to monitor all matters relating to the health and safety of response personnel. Feedback was generally positive and notably emphasized how the tool enhanced communication and coordination, especially across organizations like county commissioners and local public health agencies. However, at least one user noted the subjectivity of some of the risk factors and questioned whether they “got it right.” This points to a continued need to emphasize that the tool is not intended to be precise or predictive but rather to stimulate deliberation and communication. We will return to these points in the next section.

The COVID-19 Incident Risk Assessment Tool was a rapidly developed product built for an urgent need under considerable time pressure and uncertainty. The tool joins a body of online tools to support risk-informed COVID-19 decision-making (e.g.,Chande et al. 2020) and that emphasize human health and safety risks to firefighters (e.g., Sol et al. 2018; Dunn et al. 2019; West et al. 2020; Viegas et al. 2009; Lahaye et al. 2018; Campbell et al. 2019; Jolly et al. 2019). Early use and feedback from the field improved the product and facilitated iterative prototyping, including multiple combinations of risk factors and different approaches to visualization.

The tool was not intended to be predictive, but rather its primary contributions were in supporting the identification of risk factors and available mitigations and in serving as a communication tool. Because of time pressures, the environment in which managers were operating, the rapid deployment of the tool during an ongoing fire season, and the choice to limit the collection of information, measures regarding the use of the tool are limited. We acknowledge limited feedback gathered from the field. However, use on even a modest number of incidents by the target user community can have an outsized impact as managers of the larger, longer duration, more complex incidents can be managing hundreds to thousands of individuals. Further, from the measures we do have as well as feedback from the field, it seems apparent that the tool helped to fill a critical information gap and supported risk-informed decision-making regarding incident logistics, operations, and COVID-19 mitigations. Usage statistics indicate operational use across multiple incidents over time and spanning multiple geographic areas (Figures 8, 9). Although not the only measure of success, the reception has been positive from agency leadership down to the operational users. We acknowledge a degree of subjectivity but would emphasize the intent to support risk-informed assessment and communication based on local conditions and expertise.

In addition to the risk assessment functionality, our dashboard also allowed users to examine various incident scenarios using epidemiological modeling (Thompson, Bayham, and Belval 2020; Dilliott 2021b). We also intend to keep the risk assessment dashboard online, and pending analysis of empirical case and vaccine rates in the firefighting community may update the risk assessment framework. Ideally, the relationships between incident management teams and public health officials, and others, established during the 2020 wildfire season can be reinforced to support information exchange (Steelman et al. 2014), and the COVID-19 Risk Assessment Tool can facilitate those efforts.

Conclusions and Implications for Management/Policy and Future Research

Our project resulted in several key findings. We review the key findings of each subproject and conclude with implications for management and policy. The development of a model integrating epidemiology and resource assignments provided several insights into the management of communicable disease risk on wildland fire incidents. First, the benefits of interventions depend on the nature of the incident. Screening incoming personnel is important to mitigate the risk of an outbreak during shorter incidents that escalate quickly. In contrast, during extended incidents, on-fire interventions like module as one are relatively more important. Second, the risk of system-wide workforce degradation depends on the behavior of personnel while assigned to the fire as well as the time those personnel are off duty. We assume that personnel face an infection risk similar to the general population while off duty. Our results suggest that many infections are likely acquired while off duty and that those personnel pose a risk of transmission to others during their subsequent assignment. Third, the extent of workforce degradation depends on the behavior of personnel and adherence to public health guidelines and policy. Low vaccine uptake and low compliance with public health guidance can lead to outbreaks that diminish workforce capacity.

In addition to the ABM being useful for examining the spread of SARS-CoV-2 within and across fire incidents, it can also be used to simulate the spread of other respiratory diseases. It is documented that the spread of “camp crud” (a generic term for any respiratory disease that spreads between personnel on wildland fire assignments) occurs on an annual basis. The results from this research have implications for the spread of a variety of infectious diseases, and the impact of the COVID-19 mitigation measures used herein may decrease disease and absenteeism from a variety of respiratory pathogens, including influenza and RSV (Olsen et al. 2020; Varela et al. 2021; Soo et al. 2020). There could also be similarities with other dynamic populations, such as emergency response or disaster relief, where the ABM could prove useful. In addition, this ABM might also be repurposed for a variety of other applications in fire, ranging from optimal coordination and routing of aircraft to individual crew member movement and engagement in containment activities.

Segueing now to the dashboard and, in particular, the Incident Risk Assessment Tool, there are several insights we gained that could help with future efforts intending to develop and deliver actionable decision support. First is the basic risk principle of aligning assessment tools with the scope and scale of the risk, as well as the information needs of those attempting to prevent and mitigate risk. Preexisting incident risk assessment tools generally focused on the scale of risk to the individual and not risks to the entire population of fire personnel, highlighting a clear and compelling need for tool development. Second, and building from the point about aligning to information needs, we benefited greatly from rapid and iterative prototyping with practitioners, and there is no doubt that the final product was much improved due to these interactions. Third, there is a need to balance simplicity and ease of use with the level of detail and robustness of the assessment. It is essential to account for the operating environment, time pressures, and available information of those using the tool. Similarly, it is important to recognize that the tool itself was conceived, built, and operationalized under conditions with substantial uncertainty and time pressure. It is our belief that the tool did help enhance situational awareness and facilitate communication of risks in some cases, and furthermore establishes a precedent and baseline for deploying and implementing assessment and decision support tools in response to emerging risks.

This project was deemed influential scientific information. It was featured by JFS in a Flash Friday highlight. The team's work and early insights influenced situational awareness at high levels, as Thompson was a core member on the Wildland Fire Medical and Public Health Advisory Team (MPHAT), which was established by the Fire Management Board in April 2020 to address medical and health-related issues specific to the interagency administration of mission-critical wildland fire management functions under a COVID-19 modified operating posture.

The current pandemic serves as a stark reminder that infectious disease will remain an ongoing threat to wildfire operations. The SARS-CoV-2 virus may eventually become endemic like other respiratory diseases, or new pathogens may emerge that lead to similar or more virulent diseases. The insights from this project are generally applicable to communicable diseases with similar transmission characteristics (e.g., airborne). Decisions support tools like the one we develop can be quickly adapted to similar threats. Social distancing protocols and module-as-one are effective mitigation measures. If future threats have high rates of asymptomatic infection, testing and screening protocols also have important roles to play.

This project is part of a growing body of work on firefighter health and well-being. The funding from JFS allowed the CFMT to continue developing insights and tools to fill critical knowledge gaps in a rapidly changing environment. We're grateful that JFSP invested in this project and hope that they continue to prioritize similar mission-critical and policy-relevant work in the future.

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Appendix B: List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

- COVID-19 Incident Risk Assessment Tool and Epidemiological Simulation Dashboard (a web-based dashboard for managers). Available at https://covid-camp-sim.shinyapps.io/covid_fire_dashboard/
- Video produced to explain the use of the COVID-19 Incident Risk Assessment Tool. Available at https://vimeo.com/446881251/9a60394b0c
- Video produced to explain the use of the epidemiological simulation dashboard. Available on the dashboard.
- Peer Reviewed Article (accepted): Thompson MP, Belval EJ, Dilliott J and Bayham J (2021) Supporting Wildfire Response During a Pandemic in the United States: the COVID-19 Incident Risk Assessment Tool. Front. For. Glob. Change 4:655493. doi: 10.3389/ffgc.2021.655493
- Peer Reviewed Article (under review): Belval EJ, Bayham J, Thompson MP, Dilliott j, Buchwald A (2021) Modeling the systemic risks of COVID-19 on the wildland firefighting workforce. Under review at Scientific Reports as of Sept 14, 2021. Preprint available at https://doi.org/10.1101/2021.09.15.21263647. This publication was designated as containing Influential Scientific Information and has already been through an internal USDA review (https://www.fs.fed.us/qoi/documents/2021/2021-Belval-Thompson-COVID-Seasonal-Analysis-After-Review.pdf).
- Conference presentation: Belval EJ, Thompson MP, Bayham J, Dilliott J, Buchwald A. (2021) Modeling COVID-19 impacts on wildland firefighting workforce capacity. Presented virtually at the joint 16th International Wildland Fire Safety Summit and 6th Human Dimensions of Wildland Fire Conference on May 28, 2021.
- Conference presentation: Bayham J, Belval EJ, Thompson MP, Dilliott J. Modeling COVID in Wildfire Camps. American Society of Tropical Hygiene and Medicine Annual Meeting (Virtual) on October 6, 2020.