CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/WF23093

International Journal of WILDLAND FIRE
International Association of Wildland Fire

Drivers of international fire management personnel deployed to the United States

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Received: 16 June 2023
Accepted: 22 February 2024
Published: 15 March 2024

Cite this: Bloem S *et al.* (2024) Drivers of international fire management personnel deployed to the United States. *International Journal of Wildland Fire* **33**, WF23093. doi:10.1071/WF23093

ABSTRACT

Background. The rising occurrence of simultaneous large wildfires has put strain on United States national fire management capacity leading to increasing reliance on assistance from partner nations abroad. However, limited analysis exists on international resource-sharing patterns and the factors influencing when resources are requested and deployed. **Aims.** This study examines the drivers of international fire management ground and overhead personnel deployed to the United States. **Methods.** Using descriptive statistics and case examples data from 2008 to 2020, this study investigates the conditions under which international personnel are deployed to the United States and their relationship to domestic resource strain. Factors such as fire weather, fire simultaneity, and the impact on people and structures are analysed as potential drivers of demand for international resources. Additionally, barriers to resource sharing, including overlapping fire seasons between countries are examined. **Key results.** The findings indicate that international personnel sharing is more likely when the United States reaches higher preparedness levels, experiences larger area burned, and when fires pose a greater impact on people and structures. However, overlapping fire seasons can limit the ability to share resources with partner nations. **Conclusions and implications.** Understanding the factors influencing resource sharing can help improve collaboration efforts and enhance preparedness for future wildfire seasons.

Keywords: fire management, International resource sharing, international cooperation, key drivers, personnel, resources, simultaneity, wildfire.

Introduction

In the United States (US), national capacity can become overwhelmed when large wildfires occur simultaneously, leading fire management agencies to send requests for support from partner nations abroad. The occurrence of multiple large, high-intensity wildfires at the same time has been increasing in the US in part due to climate change (Podschwit and Cullen 2020; Cullen *et al.* 2021; Iglesias *et al.* 2022). Furthermore, increased simultaneity between regions that share suppression resources internationally can limit the number of resources shared (Bloem *et al.* 2022). Still, there is limited analysis of the factors determining when international resources are requested and deployed. This paper seeks to fill this essential gap by investigating the drivers of international sharing of ground and overhead personnel for deployment in the US.

The western US has seen an increase in large, high-intensity wildfire, sometimes referred to as 'megafire' occurrences, a trend that will likely continue due to climate change (Dennison *et al.* 2014; Podschwit *et al.* 2018; Iglesias *et al.* 2022). Suppression cost is also expected to increase due to the location of fires in relation to people and structures (Stavros *et al.* 2014; Barbero *et al.* 2015; Podschwit *et al.* 2018; Bayham and Yoder 2020; OMB (Office of Management and Budget) 2022). In addition, the co-occurrence of large fires has been increasing, and thus fire management has become more complex (Podschwit and Cullen 2020; Abatzoglou *et al.* 2021; McGinnis *et al.* 2023). Climate change is already extending the fire weather season duration and increasing the occurrence of extreme fire weather (Jolly *et al.* 2015; Higuera and Abatzoglou 2021;

Jain *et al.* 2022). Long-term strategies to adapt western US forests to climate change are necessary, but suppression efforts remain important. Thus, the utility of international resources has increased substantially as global simultaneity of fires continues to rise (Prichard *et al.* 2021; Bloem *et al.* 2022).

International resource sharing for fire suppression is achieved through a variety of mechanisms globally and the development of these international agreements has been explored recently (Bloem *et al.* 2022). For example, the European Union (EU) has set up a multilateral sharing mechanism for suppression resources among EU countries. However, the US relies on bilateral resource agreements with its sharing partners where one country sends resources (in the case of wildland fire suppression, this is typically personnel) directly to the country experiencing wildland fire that outstrips their domestic fire management capacity. There has been research examining determinants of foreign aid allocation (including bilateral aid). While significant drivers can differ between studies, there is evidence that humanitarian foreign aid versus development foreign aid is driven less by donor self-interest in terms of political or economic concerns and more by level of humanitarian need, media coverage, and typically given to poorer nations (e.g. Alesina and Dollar 2000; Eisensee and Strömberg 2007; Hoeffler and Outram 2011; Becerra *et al.* 2014; Cheng and Minhas 2021; Mogge *et al.* 2023). There is some evidence that aid may strengthen ties between donor and recipient nations (Peterson 2017). However, fire resources deployed by Canada, Australia, and Mexico to the US cannot really be considered humanitarian bilateral aid as these resources, typically personnel, are paid for by the US. Therefore, the applicability of foreign aid literature, which typically examines financial resources shared by high-income countries with low-income countries, is limited. In addition, wildland fire is a somewhat unique natural disaster, in that the use of highly qualified personnel can impact the trajectory of the disaster. Most natural disasters occur completely outside the realm of human control (e.g. earthquakes, hurricanes), and the impacts of the natural disaster are mitigated by resources sent to the impacted area. The sharing of highly qualified personnel to combat wildland fires while they are ongoing can mitigate the damage done by the fire, not just impacts of the damage. Thus, assistance that flows directly from one government to another in the form of skilled personnel (here, wildland firefighters) may have different drivers than financial aid. This new type of sharing arrangement as a partnership between nations regardless of income may become more common in a world that is facing a greater threat from climate change, however the complex drivers of these relationships are beyond the scope of this paper.

The US has been sharing resources with specific partner nations for many years, while formal bilateral agreements began in the early 2000s with Canada, Australia, New Zealand, and Mexico (Goldammer 2013; Bloem *et al.* 2022; USDA Forest Service Fire & Aviation 2022). While the Canadian Interagency Forest Fire Centre (CIFFC) in Canada, and the Australasian Fire Emergency Service Authorities Council (AFAC) in Australia coordinate resource exchanges, their respective provinces and states control the deployment of personnel resources. US states also have regional compacts with Canadian provinces (Tymstra *et al.* 2020) but these are beyond the scope of this paper. At the federal level, US Forest Service's Fire and Aviation Management national headquarters, in cooperation with the Department of the Interior Office of Wildland Fire coordinate international resource sharing (USDA Forest Service Fire & Aviation 2022). This is accomplished through the National Multi-Agency Coordinating Group, which includes federal and state representation, and the Australasian Fire Emergency Service Authorities Council (NICC) (USDA Forest Service Fire & Aviation 2022). Resource requests to international partners are considered when the US reaches national preparedness level 4 or 5 (Bloem *et al.* 2022). A recent qualitative study of drivers and barriers found that according to fire managers from the US, Canada, and Australia, international sharing is considered valuable and is facilitated by the use of similar Incident Command Systems (ICS), strong personal relationships with a long history of collaboration, and the maturity of the network of wildland sharing partners (Bloem *et al.* 2022). Furthermore, sharing has become easier as the frequency of exchanges has increased and with improvements in the documentation of processes such as operating plans. Some fire managers noted that barriers to international resource sharing included the cost of requests, varying protocols, and role definitions despite use of the ICS, travel challenges, and processes for identifying personnel able to travel (Bloem *et al.* 2022).

To the best of our knowledge, this is the first paper that investigates the drivers of international fire management resource deployment of ground and overhead personnel to the US. Intra-national sharing has been studied to examine drivers of sharing of wildland engines within the US (Belval *et al.* 2017) and found that fire activity in both the sharing and receiving region is a driver of resource sharing. Previous research has evaluated the drivers of suppression costs and resource counts in the US (Gebert *et al.* 2007; Donovan *et al.* 2011; Yoder and Gebert 2012; Gude *et al.* 2013; Hand *et al.* 2014, 2016, 2017; Bayham and Yoder 2020; Bayham *et al.* 2020; Cullen *et al.* 2023). There is evidence that fire intensity, area burned, and population considerations such as total housing value and media coverage significantly influence wildfire cost (Gebert *et al.* 2007; Donovan *et al.* 2011; Gude *et al.* 2013). Additionally, resource scarcity, as measured by high national preparedness levels, has been found to be associated with fire danger indices, total area burned, and the number of concurrent Type 1 or Type 2 fires (Cullen *et al.* 2021). These studies show that large fire suppression costs and personnel use are associated with, but not solely predicted by, area burned. Fire management has been observed to be both reactive and proactive, since resource orders are based not only on observed weather and fire activity but anticipated fire growth in the near future (Bayham *et al.* 2020). This is a key characteristic of international resource sharing, as a lag of days to weeks before shared resources are received is not uncommon, while discussions about potential requests are often conducted even further in advance (Bloem *et al.* 2022).

This paper seeks to resolve the drivers of international ground and overhead personnel deployed to the US during 2008–2020. We examine the conditions under which international personnel are deployed and how this relates to domestic personnel strain in the US. We also examine the role of fire weather, simultaneity of complex fire incidents across the west and the impact of wildfire on people and structures as potential drivers of demand for international resources. Potential barriers that may limit international sharing are also examined, for example, for overlap of fire seasons between sharing partners. The paper first outlines the data sources used and then the methodology applied. The results section presents the number of resources received in the US from international sharing partners as well as the relevant time period, country of origin, how different potential drivers of international resource sharing relate to the number of resources received, and case studies of specific fire incidents. The paper concludes with a discussion of the implications of these findings, the limitations of this study and potential future research directions.

Data

This study uses daily fire management data, wildfire characteristics and fire weather indicators for the western US between 2008 and 2020. The focus is the western US since all international ground and overhead personnel deployed to the US during the study period were sent to western states. The temporal range was based on fire management data availability. A limitation of this study is the modest number of years with available data resulting in limited sample size.

This study relies on several fire management databases. Data on US national and geographic area coordination center (GACC) preparedness levels (PLs), international resources deployed (ground and overhead personnel), Type 1 or Type 2 Incident Management Teams (IMTs), burned area, number of uncontained large fires, and number of daily requests were drawn from US Incident Management Situation Reports (IMSR) (Nguyen *et al.* 2024). National PLs are a categorical measure of fire suppression resource availability with 1 representing ample fire management resources and 5 representing highly constrained national resources,often where several geographic areas are experiencing complex fire incidents simultaneously, exhausting national resources (NIFC 2020*a*). National Type 1 IMTs and Type 2 IMTs are assigned to manage large-scale fire incidents and their deployment can be considered a proxy for fire complexity (NIFC 2023). The number of domestic personnel deployed as well as 'unable to fill' requests (UTFs) on each day were gathered from the Resource Ordering and Status System (ROSS) prior to March 2020 and the Interagency Resource Ordering Capability (IROC) after March 2020. Information on the number of structures damaged, threatened, and destroyed, as well as the number of fatalities and injuries associated with each incident to date were gathered from the Incident Status Summary report database (ICS-209 PLUS) (St. Denis *et al.* 2023).

Additionally, daily Fire Weather Index (FWI) data from the Canadian Forest Fire Weather System, were sourced from ERA-5 at 0.25-degree horizontal resolution. Daily average values of FWI for the western US were calculated for forested and woodland areas as defined by Moderate Resolution Imaging Spectroradiometer (MODIS) between 103°W and the Pacific Ocean. We averaged FWI across the domain for forested and woodland areas as a significant amount of resources are dedicated to forest fires. Thus, FWI is correlated with burned area in forests (Gebert *et al.* 2007; Abatzoglou *et al.* 2018, 2021). Moreover, previous studies have shown that macroscale FWI is a proxy for synchronous fire danger and resource strain (Bowman *et al.* 2017; Abatzoglou *et al.* 2018, 2021). Similarly, daily mean FWI were calculated for sharing partners Canada and Australia to identify potential effects of fire weather overlap. The average daily FWI were calculated for forested and woodland areas of the suth-west of Canada (110°W to the Pacific and south of 55°N) and the south-east of Australia (28°N, 130°E) as these areas have high fire activity and population density (Stocks *et al.* 2002; Bowman *et al.* 2017; Abatzoglou *et al.* 2018; Australian Burea of Statistics 2022). We additionally isolate south-west Canada from central and east Canada as the primary fire season in south-west Canada overlaps with the peak fire season in the western US when resources have been requested.

The specific geographical boundaries of the western US differ slightly depending on the indicator, as the databases use different geographic criteria. Data from IMSR and ROSS/IROC were refined to focus on western US GACCs that received international resources from 2008 to 2020, specifically in northern California, southern California, the northwest, and the Northern Rockies. Indicators from Incident Status Summary report database (ICS-209 PLUS) were filtered based on longitude, encompassing 103–125 W (the Pacific Ocean), and excluding fires in Alaska and Hawaii.

The sample was filtered for national PL of 3 or higher when international resources are more likely to be requested leaving 840days from 2008 to 2020. Not all days are included in the sample because IMSR reports are conducted daily only during the peak fire season and less frequently at other times of the year. Additionally, a small number of days were removed due to missing data. In our sample, international ground and overhead personnel were received by the US during 18% of days.

Incident-level fire information was gathered from ICS-209 PLUS reports and IROC/ROSS data for specific fires and complexes of interest. Furthermore, descriptive statistics on Canadian national PLs were collected from the online archive of National Wildland Fire Situation Reports and Canadian Interagency Forest Fire Centre National Annual Reports (CIFFC 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2023), and statistics on military resource sharing within the US are from the National Interagency Coordination Center Wildland Fire Annual Reports (NIFC 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020*b*).

Materials and methods

Descriptive statistics about when international ground and overhead personnel were sent, fire incident level case studies, the role of overlapping fire seasons between sharing partners, the role of the military, and a correlation plot of the number of international resources deployed with various indicators are presented to highlight information on how and when international personnel are requested in the US. We examined conditions under which international personnel are received, by which nation and how this sharing relates to national indicators of resource strain such as UTFs and PL. The analysis also includes the 2020 fire season, comparing incidents where international personnel were received and where they were not. The 2020 fire season was examined as it was a challenging season and the year the US received the largest amount of ground and overhead personnel from abroad (NIFC 2020*b*; Belval *et al.* 2022; Bloem *et al.* 2022). The total area burned, crews and overhead requested and filled were well above the 10-year average. In addition, these requests came in the late season when resources are more limited. Only in the 2020 fire season were we able to gather incident-level information for international personnel destinations.

We examine correlations between the daily number of international personnel deployed to a host of fire season characteristics (including number of acres burned to date in currently active fires, number of uncontained large fires to date, average daily FWI of the west), values at risk (i.e. number of injuries and fatalities, and number of structures damaged, destroyed or threatened to date in the west) and international partner fire and resource strain (measured as average daily FWI of south-west Canada and south-east Australia) and domestic personnel resource strain (measured as the number of Type 1 or Type 2 Incident Management Teams (IMTs) deployed, number of personnel deployed, number of UTFs in the west). Correlations were calculated using the Spearman correlation method.

Additionally, we developed a logistic regression model to assess the association between a set of precursor variables and whether international resources (overhead and ground personnel) were deployed that day. This model is presented in the supplemental materials since the very small number of days on which international resources are deployed necessarily restricts our ability to assess associations across a broad range of conditions or to generalise (Appendix 1).

Results

Ground and overhead personnel from international partners were deployed during four fire seasons between 2008 and 2020. International sharing occurred in 2008, 2015, 2018 and 2020 (Fig. 1). In 2008 at the peak of sharing, Australia and New Zealand sent 69 personnel from 15 July to 15 August (Table 1). When resources first arrived, the national PL was 5 and the priority of the northern California GACC was 1 with a PL of 5 while the southern California GACC had a priority ranking of 3 with a GACC PL of 4. During this period, international personnel were only sent to the US when the national PL had reached 5 (Table 1). The fraction of days between 2008 and 2020 when the national PL was 3, 4, and 5 that had international sharing was 21/442 (5%), 50/229 (22%) and 76/169 (45%), respectively. Resources were typically sent during mid-July to September, the summer/early fall, coinciding with the peak western US fire season. The 2020 fire season represents the first time in history that resources were requested from Mexico during a time in which resources were also sent by Canada. Australia had difficulty sending resources during this time as they had just come off a severe fire season themselves and were struggling with COVID travel restrictions and protocols (Bloem *et al.* 2022).

In terms of timing, international personnel tend to arrive around the peak domestic personnel day in the West and the peak UTF day (Fig. 2). For example, in 2018, the peak personnel day (August 6) coincided with the peak UTF day and the day international resources first arrived. International resources tend to be deployed for a short period during the time of greatest resource strain and deployment. As highlighted in our analysis below, UTFs are only somewhat correlated with international personnel sharing compared with domestic personnel. This may be because fire managers tend to stop making requests for resources when they know that those requests will not be fulfilled, and that UTF numbers for 2020 were artificially low due to the transition from IROC to ROSS.

International resources are deployed to fires with a wide range of characteristics, not necessarily the largest incidents. Table 2 identifies fires to which international resources were sent in 2020 and how they rank on key dimensions in comparison with other top ranked fires in

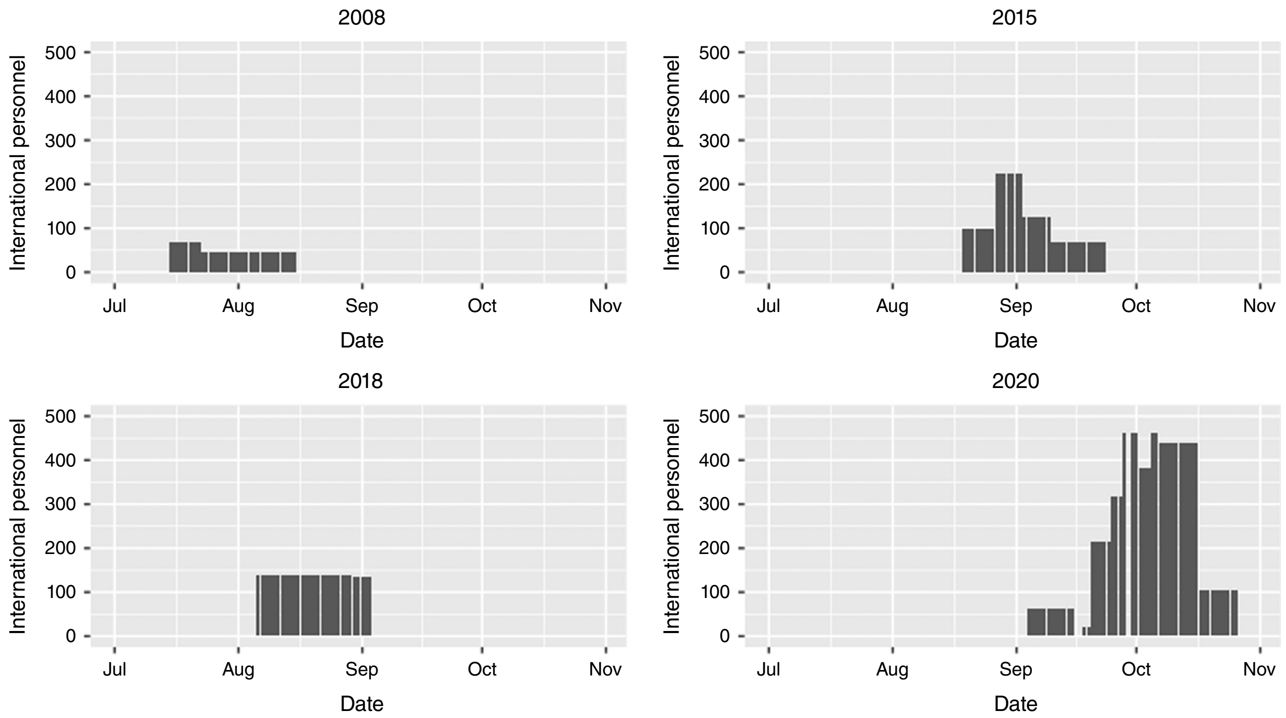

Fig. 1. The number of overhead and ground personnel sent by international partners to the United States between 2008 and 2020. Data are drawn from the US Incident Management Situation Reports (Nguyen *et al.* 2024). The upper left bar chart shows the number of overhead and ground personnel from international partners in the US during each day in 2008; the upper right is for 2015, the lower left is for 2018 and the lower right is for 2020.

Table 1. Incidents of international sharing of personnel (overhead and ground) to the US by year, specifying providing country, US geographic area (GACC), the peak number of personnel deployed to the US during the length of the international deployment, the national preparedness level (PL) on the fire day of international US Incident Management Situation Reports (IMSR) (Nguyen *et al.* 2024) resource arrival, the PL and the national priority rank of the geographic area to which the resources were sent, and the dates during which international resources were deployed.

Year	Countries providing	GACC	Peak personnel	National PL when resources first arrived	GACC Priority and PL when resources first arrived	Dates
2008	Australia & NZ	California	69	5	ONCC: 1,5 OSCC: 3, 4	15 July–15 August
2015	Canada	Northern Rockies	158	5	NRCC: 2, 5	19 August–24 September
	Australia & NZ	North-west	68	5	NWCC: 1,5	
2018	Australia & NZ	California & North-west	138	5	NWCC: 1, 5 ONCC: 3, 4 OSCC: 4, 4	6 August–3 September
2020	Canada	Northern California	225	5	ONCC: 1, 5	4 September–26 October
	Canada	North-west	195	5	NWCC: 2, 5	
	Mexico	Southern California	104	5	OSCC: 2, 5	

Data is drawn from the US Incident Management Situation Reports (Nguyen *et al.* 2024).

the US. For example, in 2020 Canada sent ground and overhead personnel to the North Complex in northern California and the Oregon fires of Beachie Creek and Lionshead (Barreda 2020; Gabbert 2020; USFS 2020). Additionally, Mexico sent resources to the SQF Complex in southern California (ABC 2020). Mexican resources were sent to the

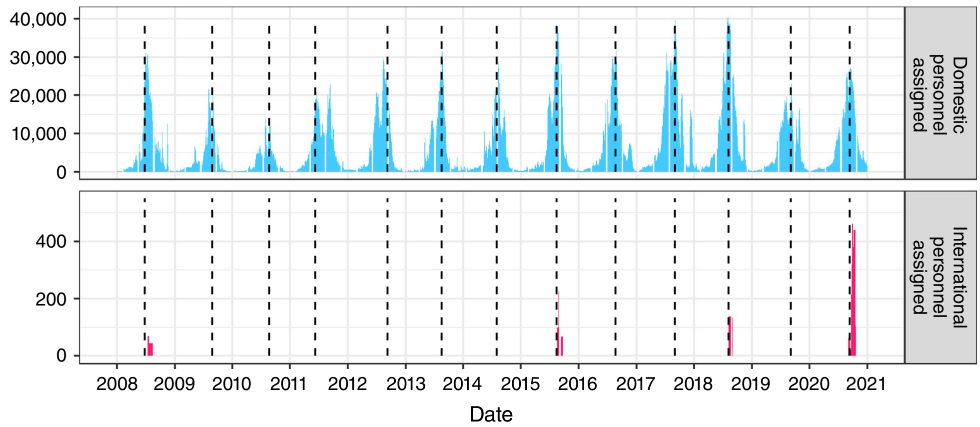

Fig. 2. Total (domestic and international; blue) and international (red) ground and overhead personnel assigned to wildland fires daily in the United States (US), 2008–2020. Dashed lines indicate the day of peak fire suppression resource scarcity in the US as measured by personnel associated with requests for resources that were returned 'unable to fill'.

closest fires to Mexico. The table highlights the large variability in terms of the types of fires that receive shared international resources. Some rank more highly in terms of people affected as gauged by injuries such as the SQF Complex Fire, while others such as the North Complex and Beachie Creek rank more highly in terms of structures damaged. All the fires receiving international resources were complex and managed by Type 1 or 2 incident teams but varied in their relative size, numbers of personnel assigned, and values threatened. The North Complex required a lot of resources and was at one point ranked 5th in terms of peak personnel, while the SQF Complex did not rank highly for peak personnel but ranked fourth for total personnel. It should be noted that the personnel data for Table 2 comes from ICS-209 PLUS and may differ slightly from ROSS/IROC personnel counts. ICS-209 PLUS data was used as final tallies for complexes were available as opposed to just individual fires.

The ratio of international personnel to daily peak personnel (domestic and international combined) was 0.213 for North Complex, 0.199 for SQF complex and 0.161 for the Oregon fires (Lionshead and Beachie Creek) according to ICS-209 PLUS data. These figures show that 15–20% or more of personnel on individual fires or complexes can come from international resources. However, in 2020, the share of resources provided by international resources during their peak personnel day (October 5) of the total deployed in the west was 2.48% using IROC data for daily personnel counts. These figures indicate that international personnel still contribute a relatively small share of total resources deployed per day. However, the personnel sent by international partners also tend to include more highly trained individuals of which there are fewer per country, which is one of the main reasons international resources are shared (Bloem et al. 2022).

Overlapping fire seasons

An analysis was also conducted of overlapping high PL days in Canada and the US, which may constrain sharing potential. The data are insufficiently disaggregated to present a timeline of exact days of overlap for 2008–2020; however, some illustrative trends were noted. We note that no international resources were deployed to the US in 2017 despite national PL being at 4 or 5 for 75 days, compared with 2015 in which 43 days of PL of 4 or 5 were logged. However, we note that in 2015 there were no days of overlapping PL of 4 or 5 between Canada and the US, while in 2017 there were 66 days of overlap. In 2017, Canada instead received resources from Australia, New Zealand and Mexico while the US relied on domestic sharing and military personnel. In 2018, there were also a substantial number of days of overlapping high PL and severe fire seasons overall. Resources were sent from the US to Canada in 2018. However, this sharing consisted of only 12 personnel as opposed to the more usual counts ranging between 200 and 400. The US and Canada received resources from Australia, New Zealand and Canada also received resources from Mexico. In 2019, there were no overlapping high PL days between the US and Canada since the US had 0 days of PL 4 or 5, while Canada had 36, which resulted in the US sending 424 personnel to Canada. Finally, in 2020, the US had 71 days of PL 4 or 5 while Canada had 0 days of PL 4 or 5. The US received resources not just from international partners (Canada and Mexico) but also two battalions from the US military. This was one of the worst US fire seasons in history. California, in particular, faced an abnormal fire season during fall/early winter when domestic fire suppression capacity is lower (Belval et al. 2022). These examples imply that overlapping PL 4 or 5 between Canada and the US likely impacts sharing ability and willingness between the partners. Furthermore,

Table 2. Top 20 fire incidents in 2020 ranked by peak number of personnel on the fire on a single day (Peak Personnel), the total use of personnel across the duration of the fire (Total Personnel), the area burned (Acres), the number of structures damaged by the fire (Structures Damaged) and the number of injuries recorded on the fire (Injuries). Data on peak personnel and total personnel comes from archived assignment data (the Resource Ordering and Status System and the Interagency Resource Ordering Capability); data for fire size, structures damaged, and injuries comes from the ICS-209 PLUS. Fires are coloured to indicate if the fire received international resources and, if so, to indicate in which geographic area the fire was located (see footnotes).

Rank	Peak personnel	Total personnel	Area burned	Structures damaged	Injuries
1	Hog	Creek	August Complex	North Complex[A]	Cameron Peak
2	Silverado	August Complex	SCU Lightning Complex	LNU Lightning Complex	Creek
3	Glass	North Complex[A]	SHF Elkhorn	CZU Aug Lightning	August Complex
4	August Complex	SQF Complex[B]	Creek	Beachie Creek[A]	Red Salmon Complex
5	North Complex[A]	CZU Aug Lightning	LNU Lightning Complex	Glass	Grizzly Creek
6	LNU Lightning Complex	Cameron Peak	North Complex[A]	SHF Elkhorn	SQF Complex[B]
7	Creek	Lnu Lightning Complex	Pearl Hill	Creek	Dolan
8	Gold	Red Salmon Complex	Cameron Peak	Holiday Farm	North Complex[A]
9	July Complex	Lionshead[A]	Lionshead[A]	Almeda Drive	Mangum
10	Butte/Tehama/Glenn Complex	Glass	East Troublesome	East Troublesome	Slater
11	Bond	Bobcat	Beachie Creek[A]	Cameron Peak	El Dorado
12	Lionshead[A]	Gold	Bush	August Complex	Wood Springs 2
13	White River	SCU Lightning Complex	Cold Springs	Slater	Lionshead[A]
14	Apple	El Dorado	Mullen	Echo Mtn. Complex	Beachie Creek[A]
15	Walker	Apple	SQF Complex[B]	Lionshead	Archie Creek
16	Red Salmon Complex	Lake	Holiday Farm	SQF Complex[B]	Bighorn
17	S. Obenchain	Butte/Tehama/Glenn Complex	Slater	SCU Lighting Complex	Slink
18	Zogg	Dolan	Red Salmon Complex	Babb	Butte/Tehama/Glenn Complex
19	Lake	Hog	Pine Gulch	Zogg	Neffs
20	Cameron Peak	Slater	Riverside	Bobcat	Pumpkin

Colour legend: yellow cells, north California; red cells, north-west; purple cells, south California.
[A]Resources from Canada.
[B]Resources from Mexico.

since Canada's fire season is shorter than that of the US, and there is not much fire activity after the end of August (Magnussen and Taylor 2012), Canada also tends to release seasonally hired resources. This may also limit their ability to share outside of their typical fire season.

When does the military come in?

Military aircraft have been used to respond to wildfire in the US. Military aircraft can be outfitted with Modular Airborne Fire Fighting Systems (MAFFS), which provide the planes with the capability of dropping loads of water and flame retardants on the fire. In contrast to installing MAFFS on planes, a relatively straightforward procedure, deploying military personnel requires additional training for military personnel. Thus, military personnel deployments are relatively uncommon in the period 2008–2020. Military personnel provided support in 2015, 2017, 2018, and 2020. In these years, typically one battalion was deployed except in 2020 when two military battalions consisting of 233 soldiers and 245 marines were deployed. Military personnel are often deployed in conjunction with international resources, except in 2017. Military ground personnel are considered a complementary resource to international ground and overhead personnel to draw upon when national non-military resources are under strain. When both international and military ground personnel are received during a fire season, military personnel tend to come a few days before or after international resources arrive and stay for a similar duration. In 2020, the two military battalions were sent to different fire incidents than international personnel. One battalion was sent to the August Complex and another battalion was sent to the Creek Fire and then to the August Complex after the other battalion had left. The August Complex and Creek Fire are also included in the top 20 fire incidents of 2020 (Table 2).

Impact of timing and simultaneity

The Thomas Fire of 2017 was the largest fire in modern California history (Andone 2018). Furthermore, it was the costliest fire in US history at that time; with an estimated USD177 million in suppression cost and USD10 billion in associated damages (Andone 2018). The fire destroyed 1060 structures, damaged 274 others, and caused two injuries (CAL FIRE 2022). Nevertheless, no international resources were sent to the Thomas Fire as it occurred in December (12 April 17–1 December 18) rather than in the middle of the fire season (CAL FIRE 2022). International resources from Canada may have been freed up from national duties at this time of year, despite high PL overlap during the summer and potentially were available to share although many firefighters are hired seasonally and not available in winter (Magnussen and Taylor 2012). Australia and New Zealand may not have had available personnel as their fire season would have just started. Although it was an exceptional fall fire season in 2017 in California (NIFC 2017), the national PL in December changed only from PL1 to PL2 since most other parts of the country did not have significant active fires on the landscape competing for resources (NIFC 2017). Therefore, due to low national simultaneity, California was able to rely on domestic sharing rather than turning to military or international partners. This example demonstrates that timing with respect to the fire season, and simultaneity nationally, can affect the timing of international resource requests and assignments.

In contrast, The North Complex burned during the peak of the 2020 fire season that became known as the worst fire season to date for California (Anguiano 2020; Belval *et al.* 2022). The 2020 North Complex was slightly larger than the 2017 Thomas Fire at 129 kha, but was only the sixth largest fire that season. The estimated suppression cost was slightly less than the Thomas Fire, totalling USD112 million. The North Complex burned from 17 August to 2 December, and was a devastating fire incident causing 16 fatalities (Anguiano 2020; NIFC 2020*b*). Due to the enormous resource strain in the western US when PL was 5, international crews were sent by Canada to support fire suppression for the North Complex.

Fig. 3 shows a map of ground personnel assignments in terms of crew, dozer, structure engine, and wildland engine sent to the North Complex of 2020 and the Thomas Fire of 2017. It is noted that about 15% of the resources involved in response to these events could not be attributed to a home base and thus were not included in the map. While the North Complex in northern California was similar to the Thomas Fire in terms of area burned, peak personnel, and total final suppression cost, it differed in terms of where mutual aid from other GACCs originated. The Thomas Fire relied more on adjacent GACCs while the North Complex received more resources from further distant GACCs and Canada. The Thomas Fire, despite being located in southern California, received more ground personnel and personnel hours from northern California than the North Complex.

Correlation plot

Fig. 4 shows how the daily number of international personnel correlates to potential explanatory variables. The plot shows a large amount of correlation between the explanatory variables. For example, the number of uncontained large fires is highly correlated with the area burned to date, the number of personnel assigned, and the number of Type 1 or 2 IMTs that are being utilised. International personnel are most highly correlated with the area burned to date and are also positively

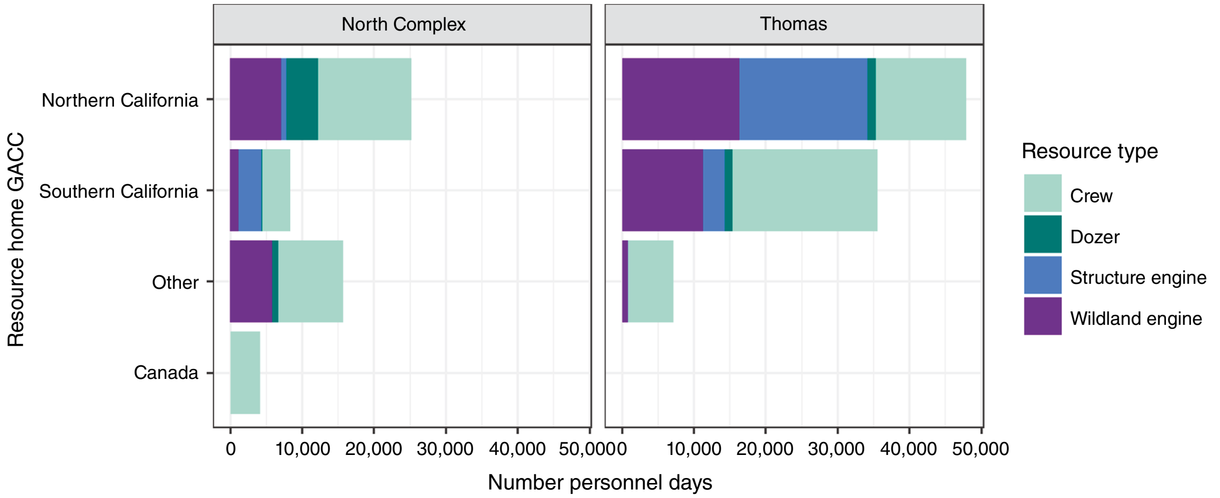

Fig. 3. A bar chart showing the number of personnel sent to the North Complex (2020) and Thomas (2017) fires.

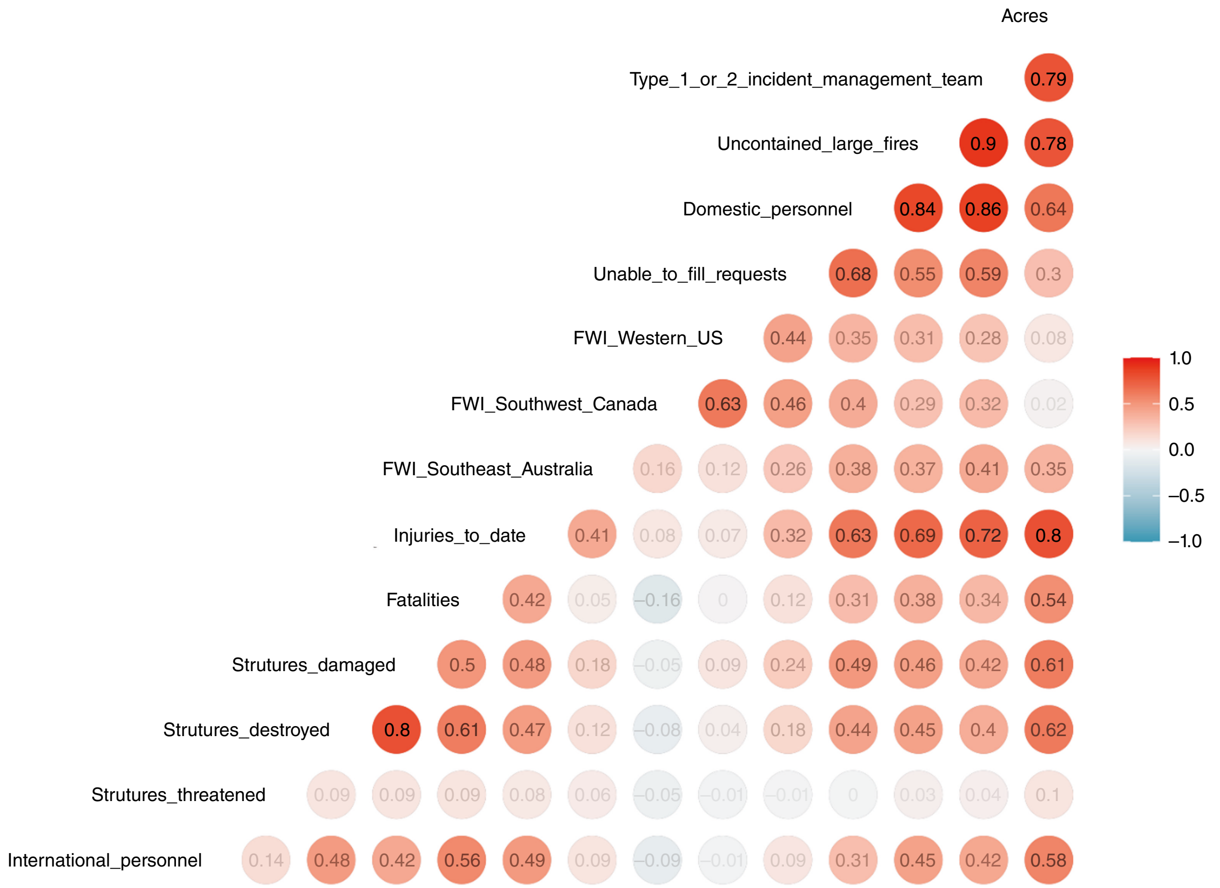

Fig. 4. Spearman correlation plot.

correlated with the number of uncontained large fires, the number of Type 1 or Type 2 IMTs, the number of personnel and the number of injuries, fatalities, structures damaged, and structures destroyed to date. Daily international personnel are not positively correlated with average FWI in the west. Mean daily FWI in western US is highly correlated with mean daily FWI in south-west Canada (r = 0.63) and somewhat correlated with mean daily FWI in south-east Australia (r = 0.12).

A multivariate logistic regression model was also developed (Appendix 1) but has severe limitations and should be interpreted with caution due to its small sample size, multicollinearity amongst regressors and overfitting. Despite these limitations, we find significant odds ratios greater than one for structures damaged to date, injuries to date, area burned to date in west and FWI for western US, and Type 1 or Type 2 IMT implying that when these variables increase, the likelihood that international resources will be shared that day increases as well.

Discussion and conclusion

The results presented show that international personnel sharing is more likely to occur with an increase to PL5, with increases in area burned or simultaneity of fire events, particularly when this activity has a greater impact on people and structures. Timing with respect to the fire season peak affects the distance resources may travel to help manage a particular fire incident. Potential barriers for international resource sharing can include simultaneous occurrence of intense fire seasons between resource partners or the occurrence of intense fire seasons during low availability of hired resources internationally, and other administrative hurdles such as travel issues. International resource sharing is just one option for fire managers during high demand moments. Other possible pressure release valves include requesting resource sharing from the military and reliance on private contract/concierge fire fighters (which is beyond the scope of this paper). Military ground personnel support often coincides with international sharing and has been activated during periods such as 2017 when international resources were unavailable. Still, in 2017 the military shared less resources than in 2015 so it is unclear what other suppression support systems were activated, if any.

Overlapping days of national PL 4 or 5 between Canada and the US seem to impact sharing. The positive correlation between the daily mean FWI in the US and Canada implies that increased FWI during the core fire season,as projected by climate models (Jolly *et al.* 2015; Abatzoglou 2019), increases the risk of overlapping fire seasons limiting the ability of partners to share (Flannigan *et al.* 2013). Likewise, an extension of the fire weather season in the US and Australia (Jolly *et al.* 2015; Abatzoglou 2019) may create more windows where resource sharing is limited. International deployment was not positively correlated with daily mean FWI in the western US possibly because sample size was limited to days where PL was 3 or higher in the US, and although FWI is associated with resource strain such as PL this relationship was more uncertain for days when PL was above 3 as FWI could fluctuate tremendously (Abatzoglou *et al.* 2021). The Spearman correlation coefficient between average FWI and international personnel was positive when all days were included. Another limitation in papers focusing on the western US and Canada may have resulted from the fact that the daily average FWI for south-west Canada did not include some other provinces such as Ontario, which control a large number of resources (although peak fire activity in central and eastern Canada often does not seasonally align with peak resource demand in the western US). Future projections of increasing co-occurrence of fire weather extremes in the West (Abatzoglou *et al.* 2021), and more broadly lengthening fire seasons globally (Flannigan *et al.* 2013; Jolly *et al.* 2015) not only suggest increased demand for international sharing but also diminished ability of current partners to continue to share resources during high demand periods.

Furthermore, requests are not necessarily systematic as there are many instances where resources were not deployed and the number of acres burned, number of fires, average FWI, number of structures damaged, and other key drivers were high. In some cases, this may be an indication of overlapping fire seasons between countries. For example, in 2017 both Canada and the US had intense fire seasons, and resources were not shared. This result may also be due to the newness of international collaboration efforts. Previous research indicates that these relationships are continuously developing, with improved processes to facilitate the exchange of resources (Bloem *et al.* 2022). Additional research on when and how resources are requested and supplied can help improve sharing processes.

Our findings are consistent with previous research on drivers of suppression expenditure and resource use in the US, as well as with the previous work on bilateral aid. Analysis of precursors of suppression expenditure, a proxy for demand for suppression resources, for individual large wildland fires such as area burned, values at risk, resource availability, detection time and region identified the largest factors to be fire intensity level, area burned and nearby housing value (Gebert *et al.* 2007); studies that improved upon this methodology found similar results (Yoder and Gebert 2012; Hand *et al.* 2016). A study focusing on the Sierra Nevada area of California with the outcome variable being daily fire expenditure, as opposed to final expenditure, found that nearby housing density significantly contributes to daily cost (Gude *et al.* 2013). Bilateral aid has historically also been driven by the level of humanitarian need as well as media coverage of disasters (e.g. Eisensee and Strömberg 2007; Hoeffler and Outram 2011; Dellmuth *et al.* 2021; Mogge *et al.* 2023). While we did not analyse fire intensity or housing value, area burned and similar proxy indicators for values at risk, humanitarian need, and media coverage such as injuries, fatalities and structures damaged and destroyed were identified as potential drivers of international resource sharing. Previous research found that the number of daily structures threatened is associated with an increased likelihood of deploying Type 1 crews but that deployment of Type 1 crews is associated with a decrease in the number of structures damaged (Bayham and Yoder 2020). The strong positive correlation between international personnel and structures damaged may be an indication that resources are deployed to the US for extremely complex fires when national resources are overwhelmed and making little impact on mitigating damage on structures threatened. It should be noted that even for suppression expenditure a significant portion of variation is not explained by previous research (Hand *et al.* 2016). This could be due to differences in fire management as a study of the influence of different IMTs on the deployment of wildfire suppression resources suggests (Hand *et al.* 2017).

Potentially important factors not included in our analysis that are sometimes included in models for expenditure and resource use include aspect, slope, elevation, fuel type, fire intensity and energy release component and values at risk such as reservation areas, media coverage, political pressure (in terms of congress years in office), and population density (Gebert *et al.* 2007; Donovan *et al.* 2011; Gude *et al.* 2013; Hand *et al.* 2016, 2017; Bayham and Yoder 2020). These variables and others like air quality could be explored as additional years of data become available. Another limitation of our study was data unavailability related to reporting of international resource sharing. Thus, we are unable to conduct regression analysis at the fire incident level. Additionally we do not address sharing occurrences with regard to aircraft resources and sharing for training purposes.

Our analysis identifies significant precursors of international resource sharing although causality cannot be assessed. Nevertheless, these results highlight areas for future research. The results also reinforce that more research on how resources are requested and supplied, and when this may not be possible, will help practitioners identify areas to improve international resource-sharing efforts. Moreover, our results could contribute to an examination of how future climate change could increase requests for international sharing, while requests become less likely to be filled. Future research directions could also include replicating this study in other nations and regions (e.g. EU). Furthermore, an economic benefit evaluation would be an interesting potential driver to test regarding when and how international resources are shared.

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Data availability. Data supporting reported results can be found in: US Incident Management Situation Reports (IMSR) (Nguyen *et al.* 2024); Resource Ordering and Status System (ROSS) prior to March 2020 and the Interagency Resource Ordering Capability (IROC) after March 2020; the Incident Status Summary report database (ICS-209 PLUS) (St. Denis *et al.* 2023); ERA-5; United States NIFC Annual Reports between 2008 and 2020 (https://www.nifc.gov/fire-information/statistics); Canada CIFFC Annual Reports from 2013 to 2020 (https://www.ciffc.ca/publications/canada-reports).

Disclaimer. The findings and conclusions in this report are those of the author(s) and should not be construed to represent any official USDA or U.S. Government determination or policy.

Conflicts of interest. The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript, or in the decision to publish the results.

Declaration of funding. Supported by the National Science Foundation Growing Convergence Research Program Award #2019762, Research Project: Managing Future Risk of Increasing Simultaneous Wildfires

Acknowledgements. Data Use Agreement-University of Washington, Evans School and the USDA, Forest Service Rocky Mountain Research Station (No. 22-JV-11221636-141).

Author contributions. Conceptualisation, S. B., A. C. C., E.B., and J. T. A.; methodology, analysis, and literature review, S. B.; data curation, E. B., S. B., and J. T. A.; writing original draft preparation, S. B.; writing- review and editing, S. B., A. C. C., E. B., J. T. A., and L. O. M.; visualisation, S. B. and E. B.; supervision, A. C. C.; project administration, S. B.; funding acquisition, A. C. C., J. T. A., and L. O. M.

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Appendix 1. Logistic Regression to predict whether international resources (overhead and ground personnel) were deployed that day.

We developed a multivariate logistic regression model to assess the association between a set of precursor variables and whether international resources (overhead and ground personnel) were deployed that day (Table A1 below). To proxy the impact of fire season we used the structures damaged and injuries to date for each year; these metrics were chosen as they are often covered in the media (Sachdeva and McCaffrey 2022) and media coverage is known to influence resource allocation (Donovan *et al.* 2011). To characterise the western US fire situation, we used area burned to date, uncontained large fires, FWI, and Type 1 or Type 2 Incident Management Team (IMT) that tend to be deployed to complex fires. To characterise resource strain, we included domestic personnel and UTFs as proxies. Year and month were also controlled as dummy variables. The analysis was performed using the R statistical software (version 2022.12.0 + 353) specifically leveraging the 'glm' package for multivariate logistic regression (Ihaka and Gentleman 1996). This model appears in this Appendix as a supplemental analysis since the very small number of days on which international resources are shared necessarily restricts our ability to assess associations across a broad range of conditions. The sample size includes all days categorised as PL3 or higher between 2008 and 2020 and totals 820 days. The sample size was restricted to days of PL3 or higher as these are the

Table A1. Logistic regression results for whether international resources (overhead and ground personnel) were deployed that day.

	Odds ratio	95% CI		Sig
Structures damaged to date	1.001	1.001	1.002	***
Injuries to date	1.015	1.006	1.026	**
Area burned to date	1.000	1.000	1.000	*
Uncontained large fires	0.936	0.875	0.995	*
Fire weather index	1.017	1.007	1.027	***
Unable to fill requests	0.985	0.951	1.017	
Personnel	0.999	0.997	1.000	
Type 1 or Type 2 incident management team	1.195	1.016	1.428	*

Year and Month of Year were also controlled for as Dummy Variables (2018 and 2020 were significant with respect to 2008).
P-value: *0.05, **0.01, ***0.001.

days that requesting international resources may actually be considered by fire managers and to improve statistical analysis as international resource sharing is a rare event. Robustness checks included running the multivariate logistic regression for all days included in IMSR and ICS-209plus and produced similar results (except the regressor on Type 1 or Type 2 IMT was insignificant and the regressor was greater than one for domestic personnel but still insignificant). International resources were shared on 147 of those days (about 18%).

Despite this limitation we find significant odds ratios greater than one for structures damaged to date, injuries to date, area burned to date in West and FWI for western US, and Type 1 or Type 2 IMT implying that when these variables increase, the likelihood that international resources will be shared that day increases as well. All of these things increase the likelihood that the fires will be covered by the media – which has been found to increase international cooperation in the past. The odds ratios are quite small (close to one) indicating a weak association. The number of uncontained large fires in the western US is a significant precursor for the presence of international resource sharing, and an increase in the number of uncontained large fires is associated with a decrease in the odds that international resources are deployed. This may be due to high correlation between many of the explanatory variables. The other precursors tested were not significantly correlated with the occurrence of international resource sharing.

International resource sharing can be considered a rare event and we only have data for a small set of years and thus the sample size is not big enough to split into training and validation sets to produce model fit statistics such as ROC curve. The model likely suffers from overfitting and multicollinearity among regressors. Exploratory analysis was conducted of additional multivariate linear regression analysis but was deemed inappropriate as Q–Q plots showed that residuals did not follow a normal distribution and there is high multicollinearity among predictor variables. Fire level analysis to investigate which fires are more likely to get international resources was also not possible as there was only data for 2020.