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Evaluating fireline effectiveness across large wildfire events in north-central Washington State

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Abstract

Background Wildfires are increasing in incidence, size, and severity in the USA along with associated firefighting costs. Evaluation of firefighting containment and mop-up activities are crucial to reduce costs and to inform safe and effective wildfire response. As geospatial technologies advance, fireline effectiveness metrics have continued to be updated and improved. However, to develop standard analysis protocols and performance evaluations, there is a need to understand how widely metrics vary within and across fire events and are dependent on the different sources and accuracy of geospatial datasets, including firelines, fire perimeters, and severity layers. To ascertain the usefulness and limitations of four fireline effectiveness metrics, we evaluated several metrics including ratios of fireline engaged, held, and burned over. We performed a sensitivity analysis across 13 recent wildfires in north-central Washington State.

Results Our study found that fire perimeter source and fireline buffer width had the largest impact on quantified fireline effectiveness metrics. Misclassification of firelines produced dramatic erroneous results which artificially increased the effectiveness and decreased suppression effort. High-severity fires were shown to be less effective across all fireline types and required higher suppression than most low- and moderate-severity fires.

Conclusion Our results suggest that the fireline effectiveness methodology we tested was robust but could benefit from further refinement with the additional step of visual inspection for fireline misclassifications and database errors. Users should also consider evaluating a range of buffer widths prior to calculating fireline metrics to allow for some minor discrepancies between firelines and fire perimeters. Importantly, our results showed that for high-severity burns firelines were less efficient, and the placement of firelines should be carefully considered to more efficiently allocate firefighting resources and new dozer lines within high-severity landscapes, such as dense mixed conifer forests.

Keywords Accuracy, Bulldozer, Fireline, Fireline effectiveness, Fire suppression, Hand lines, MTBS, SBS, Burn severity, Washington State

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Resumen

Antecedentes Los incendios de vegetación se están incrementando en incidencia, tamaño, y severidad en los EEUU, y los costos asociados para su combate también están aumentando. La evaluación de las actividades de contención y liquidación de incendios son cruciales para reducir los costos y asegurar una respuesta segura y efectiva. A medida que las tecnologías geoespaciales avanzan, las métricas usadas para determinar la efectividad de línea de fuego continúan siendo actualizadas y mejoradas. Por supuesto, es necesario entender cuán ampliamente éstas varían entre diferentes paisajes y dentro de cada incendio, y cómo varían las fuentes y exactitud de los datos geoespaciales, para desarrollar protocolos de análisis estándar y la evaluación de su performance. Para verificar la utilidad y limitaciones en la efectividad de cuatro métricas diferentes, cuantificamos la efectividad de la línea de fuego usando diferentes métricas (relaciones de la línea de fuego comprometida, sostenida, y totalmente quemada) y análisis de sensibilidad a través de un rango de incendios recientes en el centro-norte del estado de Washington. Nuestro análisis evaluó 13 incendios y la influencia de la severidad del incendio, la fuente indicativa del perímetro de fuego, la exactitud espacial de línea de fuego, y el ancho buffer de la línea de fuego, en los resultados de las métricas de líneas de fuego.

Resultados Nuestros resultados encontraron que la fuente del perímetro de fuego y el ancho del buffer de la línea fuego tuvieron el impacto más grande en la métrica de cuantificación efectiva de la línea de fuego. La errónea clasificación de líneas de fuego como no líneas de fuego produjo resultados dramáticamente erróneos que incrementaron artificialmente la efectividad y decrecieron los esfuerzos de supresión. Los fuegos de alta severidad mostraron tener una menor línea de fuego efectiva en todos los tipos de líneas de fuego y requirieron de una supresión más alta que la mayoría de las líneas de severidades bajas y moderadas.

Conclusión Nuestros resultados sugieren que la efectividad en la metodología que probamos fue robusta, pero que puede ser beneficiada con un posterior refinamiento que implique el paso adicional de una inspección visual de las clasificaciones erróneas y de errores en las bases de datos. Los usuarios deberían también considerar evaluar un rango de líneas de fuego buffer antes de calcular las métricas de las líneas de fuego para permitir una menor discrepancia entre líneas de fuego y perímetros del fuego. De manera importante, nuestros resultados también mostraron que, para los incendios de alta severidad, las líneas de fuego fueron menos eficientes, y su ubicación debe ser cuidadosamente considerada para reducir la aplicación ineficiente de los recursos destinados al combate dentro de paisajes con alta severidad de fuegos, como los bosques mixtos de coníferas.

Background

The cost of fighting wildfires is increasing with lengthening and more severe wildfire seasons (Calkin et al. 2015, Katuwal et al. 2017, Gannon et al. 2020). Large, summer wildfires are responsible for the majority of firefighting costs, particularly within forested landscapes that burn under extreme weather conditions (Gebert et al. 2007, Calkin et al. 2015). Direct suppression is not only expensive but can be associated with long-term ecological impacts, including soil erosion and exposure to invasive species that necessitate post-fire rehabilitation (D'Antonio et al. 1999, Backer et al. 2004, Merriam et al. 2006, Mornoney and Rundel 2013). While fire events themselves can contribute to soil erosion and the spread of invasive species, construction of dozer lines in particular can create more localized topsoil disturbance. While dozer lines may assist in suppression efforts, they also may lead to unintended consequences such as increased erosion, longer vegetation recovery, and the spread of invasive species (Merriam et al. 2006, Finney et al. 2009, Katuwal et al. 2016).

Because firelines may be associated with adverse ecological impacts and are expensive to implement, we need metrics to evaluate the effectiveness of firelines, particularly within large incidents that are disproportionally contributing to rising wildfire costs (Butry et al. 2008, Finney et al. 2009, Holmes and Calkin 2012, Katuwal et al. 2016). With consistent metrics of effectiveness, post-fire assessments can inform where and how firelines can be constructed in wildland fire operations. Due to the high costs of large wildfire events and the potential for future events to occur, recent studies have evaluated the cost and benefits of different firefighting techniques (Katuwal et al. 2017, Belval et al. 2019, Plucinski 2019, Bayham and Yoder 2020). However, quantifying fireline effectiveness is not straightforward and standard protocols are nascent. Knowledge of fireline effectiveness and efficiency can help provide significant improvements for geospatial tools such as the Wildland Fire Decision Support System (WFDSS) as well as may aid fire manager's allocation of resources for wildfire events and mop-up activities (Gebert and Black 2012, Thomas et al. 2018b).

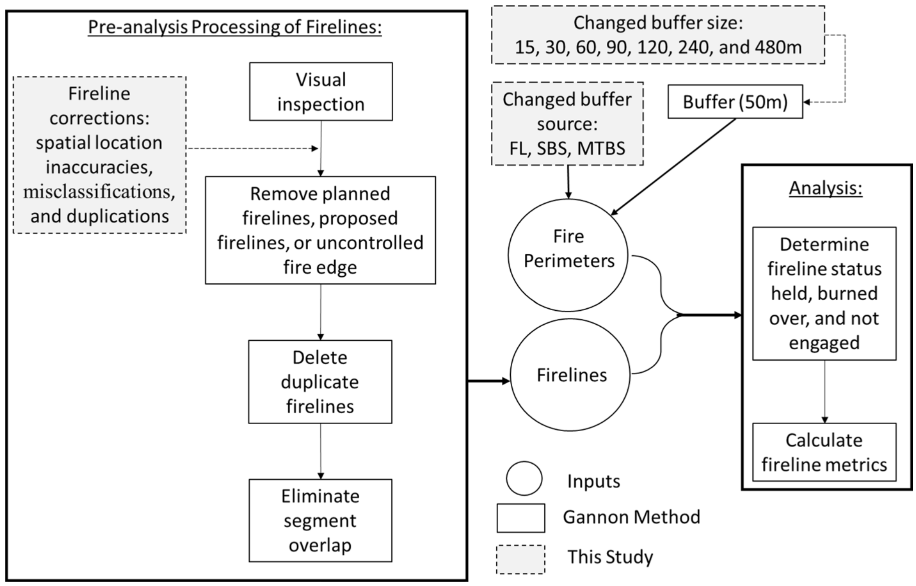

Fig. 1 Workflow of fireline effectiveness method updated by Gannon et al. (2020) and the additional analyses in this study including fire perimeter source, fireline corrections, and buffer size

The fireline effectiveness metrics were created by Thompson et al. (2016) and further refined by Thompson et al. (2018a) and were designed to evaluate the success and usefulness of firelines as barriers to fire spread after the occurrence of a fire event. In a recent case study evaluation of fireline records from 33 large fires across the western USA, Gannon et al. (2020) presented an update to the fireline effectiveness methodology. Although results from Gannon et al. (2020) were promising, the case study approach warranted further evaluation for broader scale application. The methodology used by Gannon et al. (2020) relies on two types of geospatial inputs: fireline locations and type and fire perimeters (Fig. 1). However, there are source, accuracy, and analysis challenges associated with using these inputs to develop fireline effectiveness metrics. For example, there are several geospatial databases available that define fire perimeters, which may have no spatial resolution or accuracy information associated with them. Geospatial data for fireline locations also frequently contain errors. In addition, Gannon et al. (2020) applied a 50-m buffer around delineated firelines to determine if a fireline has truly been engaged by the fire. As this is a newer methodology, the extent to which buffer size impacts fireline engagement outcomes is largely unknown.

To date, the impact of fire severity on fireline effectiveness has not been well studied. Previous studies have shown that fire containment probability is influenced by a variety of factors such as topography, weather, and amount, type, and structure of fuels (Plucinski 2012, Rodrigues et al. 2020). These same factors also affect fire severity (Keeley 2009, Perry et al. 2011). Fire severity is often linked to fuels which were linked to costs of fire containment, not effectiveness (Moghaddas and Craggs 2007, Stephens et al. 2009, Beverly 2017, Loomis et al. 2019).

In this study, we evaluated a methodology for fireline effectiveness across 13 recent wildfires in north-central Washington State. These wildfires were included in our study because they represent mostly large, regional wildfire events that have become increasingly common in the eastern Cascade Mountains. In particular, the 2014 and 2015 wildfire seasons were record-setting wildfire events with large investments in wildland firefighting operations (NWCC 2014, NWCC 2015, U.S. Forest Service 2015). Across the 13 wildfire events, we evaluated a total of 2200 km of fireline, including 1742 km of newly constructed bulldozer and hand lines with an estimated total firefighting cost of $300 million USD. The main objective of this study was to explore the factors that influence the quantification of fireline effectiveness using the refined methodology of Gannon et al. (2020) and to determine the outcomes associated with constructed firelines in large wildfire events. Specifically, we tested the sensitivity of fireline metrics to the geospatial source of fire perimeters, accuracy of digitized firelines, and fireline buffer size. Because fireline effectiveness is likely influenced by the fire environment, we also evaluated if burn severity had any relationship with fireline effectiveness.

Methods

In this study, we followed methods introduced by Thompson et al. (2016) and the refined analysis by Thompson et al. (2018a) and Gannon et al. (2020). We included our own additional methods for manual corrections and changes to buffer sizes. Hereafter, we referred to these methods as the fireline effectiveness method. We calculated four fireline metrics (Tr, Er, HEr, HTr) that quantify fireline effectiveness

- Tr: ratio of total fireline length versus the total wildfire perimeter. This metric provides a measure of fireline investment for a given wildfire event.
- Er: ratio of engaged fireline versus total fireline length. This metric evaluates the total length of the fireline that was engaged in the wildfire (either held or burned over) and can be used to assess if the fireline was needed or warranted.
- HEr: ratio of held fireline versus the total fireline that was engaged by the fire. This metric provides an assessment of the actual effectiveness of the constructed fireline in containing wildfires.
- HTr: ratio of held fireline to total fireline length. This metric provides an overall assessment of how well firelines performed, incorporating both where firelines contained fire spread and the investment in fireline construction.

Gannon et al. (2020) used wildland fire operations records of wildfire perimeters and fireline datasets available from the National Interagency Fire Center. They included pre-analysis processing on fireline data and spatial processing techniques to identify fireline type and visual inspection to identify suspect geometry. Within the Gannon et al. (2020) case study, a 50-m buffer was delineated around the fire perimeter to define held, engaged, or burned over fireline due to the imprecision associated with perimeter edges and fireline locations. In this study, we used the opportunity to evaluate three different source perimeters, re-digitized and corrected fire line geometry errors, and evaluated a range of buffer

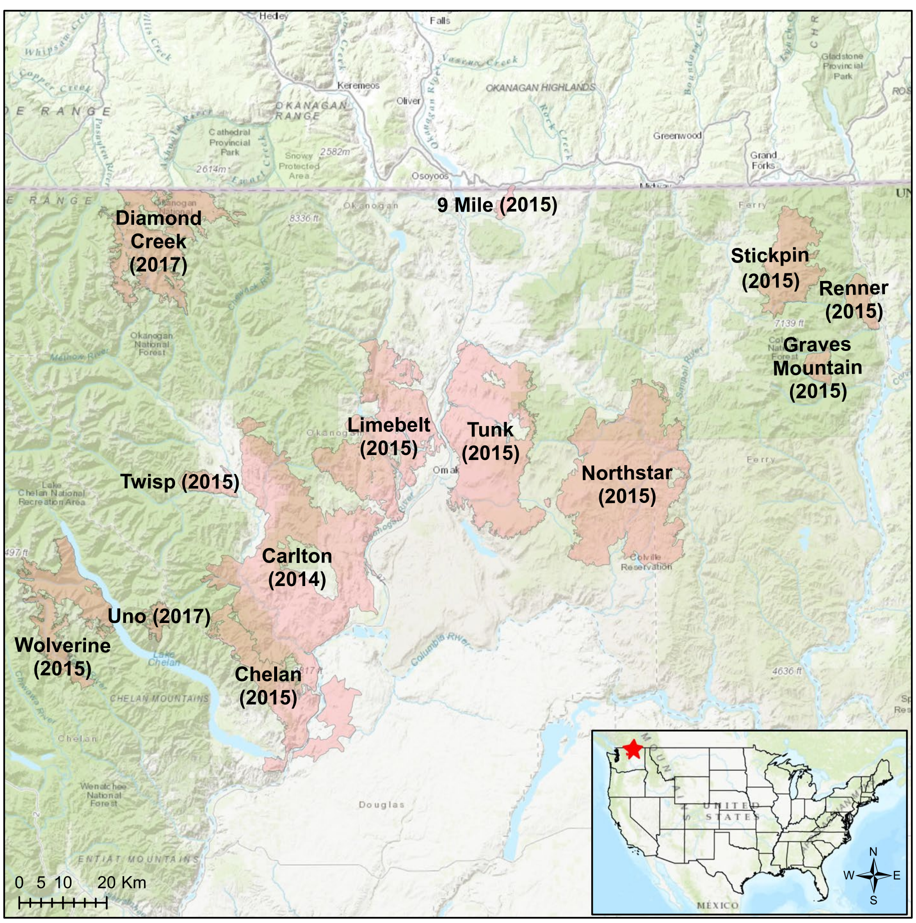

Fig. 2 Study area, including the thirteen wildfires in north-central Washington State

sizes to assess the influence of perimeter source data, digitizing and classification errors, and buffer width on metrics of fireline effectiveness (Fig. 1).

Fire perimeters

Thirteen fires were chosen in north-central Washington State from 2014 to 2017 that span a range of vegetation types, including forests, grasslands, shrublands, agriculture, and small urban areas (Fig. 2). These fires were selected based on the availability of fireline datasets and those that were present in the MTBS database for our study area. Fire sizes ranged from 19 to 1117 km^2. We selected perimeters from three different sources: fireline perimeter (FL) associated with the generation of the initial fireline dataset creation, Monitoring Trends in Burn Severity database perimeters (MTBS), and soil burn severity (SBS) perimeters obtained from the BAER (Burned Area Emergency Response) database. Fireline records and their associated FL perimeters were obtained from the National Wildland Fire Coordination Group (NWCG). Perimeters from MTBS and SBS are based on 30-m Landsat TM satellite imagery and their derived indices of NBR, dNBR, and rdNBR (Eidenshink et al. 2007). SBS incorporates additional field data to verify the accuracy of fire data and correct any errors found from the initial burn perimeter (Parson et al. 2010). Perimeters for the 2017 Diamond Creek fire were based on MTBS and SBS source layers that extended into Canada; these were clipped at the USA and Canada border using the ArcGIS 10.8 clip tool.

Firelines

Three types of fireline were included: hand line, completed bulldozer line, and road as completed line. These types were most common within our dataset and are frequently used in wildland firefighting and prescribed burn operations. Hand lines are linear fire barriers that are constructed using hand tools to remove fuels, scrape, and dig to mineral soil to control and prevent the spread of fire (Weir et al. 2017). Completed bulldozer lines, or dozer lines, are linear fire barriers that are constructed using the front blade on a bulldozer that are used to remove fuels, scrape, and dug to mineral soil; in our study, these were sometimes developed as a new line but more often constructed along old dirt roads or trails to clear vegetation and enlarge the width of the original pathway. Road as a completed line is an established roadway either paved or unpaved that can be used as a fire barrier. One of the main differences between the road as completed and completed bulldozer lines is that the road as completed lines often only require minor amounts of fuel removal or the application of additional flame retardant around the roadways to improve their overall effectiveness (Weir et al. 2017). Firelines attributed as completed lines were not included in this analysis. Gannon et al. (2020) note that this fireline category is generally assigned "to large portions of wildfire perimeters, often with highly irregular boundaries that do not correspond to logical locations to construct firelines." We chose not to include this category in our analysis because it was difficult to interpret the relevant scope of influence and use of completed lines within fire operations.

We conducted a more in-depth visual inspection and manual correction of spatial and attribute errors found within the fireline dataset. To minimize judgment errors or bias, one analyst was used for all fireline corrections to review and correct firelines for all 13 fires. The fireline datasets were considered to be complete, and as such, no additional lines were added during the correction. Firelines were examined for accuracy using pre- and post-fire National Agriculture Imagery Program imagery from 2013-2019 (National Agriculture Imagery Program 2019). Geospatial fireline datasets also were edited to correct any spatial inaccuracies, misclassifications, or duplications. Overlapping ends of adjacent segments and ends that were not correctly adjoined were edited and snapped correctly into place. Firelines that were not correctly aligned on the imagery were adjusted to better represent the correct spatial alignment of the firelines (Fig. 3). Any duplicate firelines were removed from the dataset.

Misclassifications were identified during the visual inspection phase using fire perimeters, fireline attribute data, and before and after fire NAIP imagery. Identified misclassifications were reclassed to correct classification, using notes within the dataset, SBS data, spatial imagery, and visual inspection against pre- and post-burn NAIP imagery to identify the correct fireline interpretations. Any unclear or uncertain firelines were assessed by an additional analyst. If classification was still uncertain, the fireline segment was left unaltered. After these corrections, the fireline effectiveness method outlined in Gannon et al. (2020) was followed for the identification and correction of duplicate firelines and overlapping segments not found during the initial visual inspection and correction phase.

Buffer width analysis

To account for minor digitizing or alignment errors, it is necessary to define a buffer width around firelines before calculating fireline metrics. To inform the selection of a relevant buffer width, we evaluated a range of buffers from 15, 30, 60, 90, 120, 240, and 480 m. Increments were based on 30-m increments because Landsat TM imagery with 30-m pixel resolution was used in the construction of the SBS and MTBS fire perimeters.

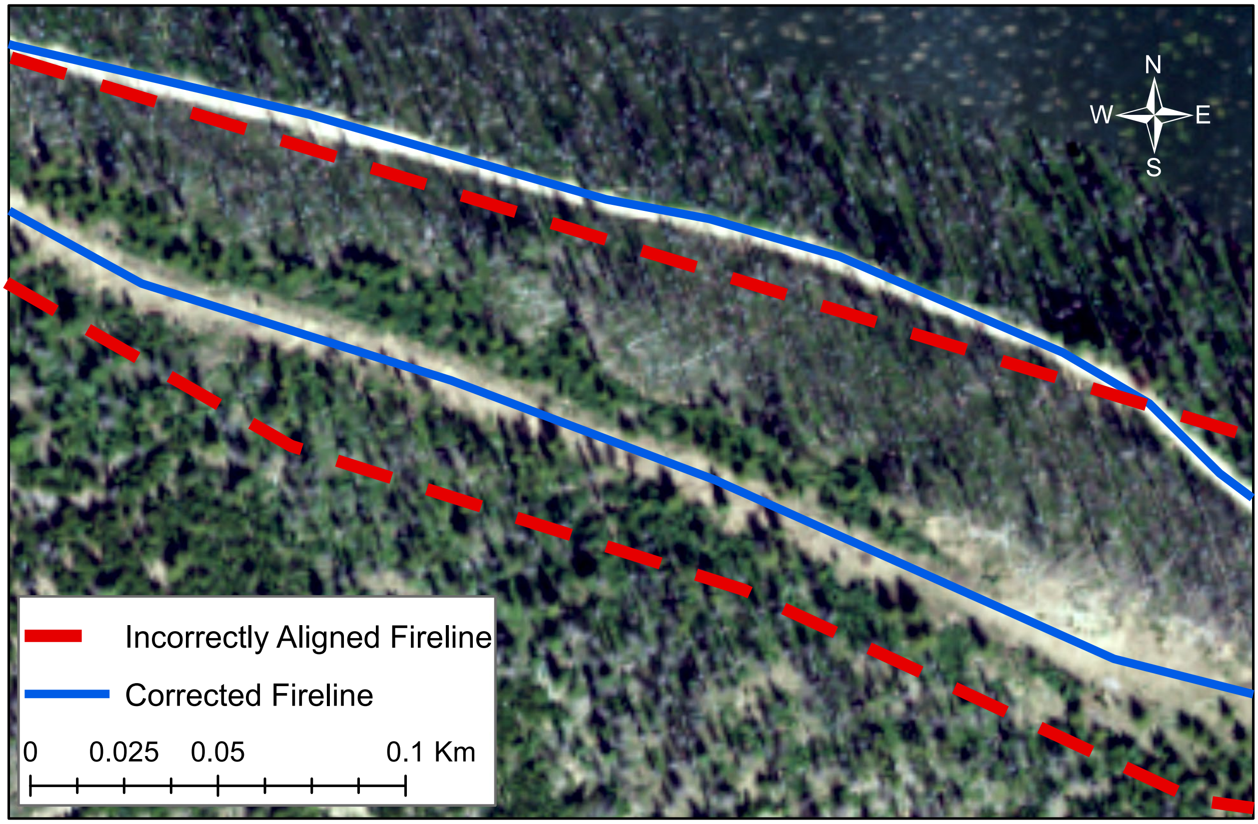

Fig. 3 Example of incorrectly aligned fireline and the corrections made in order to better align the fireline with after-fire imagery from a 2017 NAIP orthophoto

Soil burn severity

To determine fire severity, we used the SBS data layer that was classified into four categories: unburned/extremely low, low, moderate, and high. We chose to use SBS instead of MTBS burn severity because SBS include additional field verification that can increase its overall accuracy. Soil burn severity is created by the Burn Area Emergency Response teams (BAER) by using pre-fire and post-fire Landsat to create a delta normalized burn ratio (dNBR) layer that is used to classify burn severity, which is then verified by BAER field teams to further improve the accuracy of SBS. Due to the costs involved, not all fires within the USA have SBS layers. For this study, SBS was unavailable for Tunk, Northstar, and 9-Mile fires and was not included in the analysis and comparison to other fire perimeters. The inclusion of SBS, MTBS, and FLS datasets allowed for the comparison of the most readily available fire perimeters sources and data that can be used by managers and researchers without the need of additional processing.

Results

Overall, a total of 2205 km of fireline was evaluated in this analysis, including 1566 km (71%) of constructed bulldozer lines, 463 km (21%) of hand lines, and 176 km (8%) of road as completed lines. Not counting road as completed lines, a total of 1742 km of new firelines were constructed in these wildfires. Because the wildfires had such large perimeters, the amount of firelines did not exceed the total fire perimeter for most wildfires (Table 1). However, the total fireline length exceeded wildfire perimeters for the Kettle Complex fires (Renner, Stickpin, and Graves Mountain) and 9-Mile fire. A majority of fireline metrics fall below 1.0 and are considered within a “low” category of suppression effort. Our results are in agreement with Gannon et al. (2020), who reported a similar pattern with over half of all the fires having a Tr $\leq$ 1.0 and HTr $\leq$ 0.5.

Fireline engagement varied considerably. Fires with very low engagement were located mainly in roadless areas with firelines generally constructed as remote contingency lines. Of the 2205 km of fireline evaluated

Table 1 Wildfire statistics and metrics included length of fire perimeter (Per), burned over (BO), held (Held), not engaged (NE), total fireline (TL), total engaged (Eng) distances, and percent change of length from the original to corrected firelines (PC). Fireline metrics include total fireline length to fire perimeter ratio (Tr), engaged fireline to total fireline ratio (Er), held-to-engaged fireline ratio (HEr), and held-to-total fireline ratio (HTr), reported for three perimeter sources, including FL, SBS, and MTBS

		Fire area and perimeter		Fireline distances						Fireline metrics			
Fire	Type	Area ha	Per km	BO km	Held km	NE km	TL km	Eng km	PC %	Tr	Er	HEr	HTr
2014 wildfires													
Carlton Complex	FL	104,453	403.2	116.6	123.6	145.1	385.2	240.2	−0.1	0.96	0.62	0.51	0.32
	SBS	103,490	437.9	77.3	153.4	154.5	385.2	230.7	−0.1	0.88	0.6	0.66	0.4
	MTBS	111,730	387.6	179.9	74.7	130.7	385.2	254.5	−0.1	0.99	0.66	0.29	0.19
2015 wildfires													
9-Mile	FL	1907	26.8	1.1	21.8	4.6	27.4	22.9	2.2	1.02	0.83	0.95	0.79
	MTBS	2045	27.6	6.9	17.6	2.9	27.4	24.5	2.2	0.99	0.9	0.72	0.64
Chelan Complex	FL	35,800	336.4	10.3	60.2	62.4	133	70.5	0.7	0.4	0.53	0.85	0.45
	SBS	36,006	330.8	14.5	60.2	58.2	133	74.7	0.7	0.4	0.56	0.81	0.45
	MTBS	33,651	329.1	25.3	44.3	63.4	133	69.6	0.7	0.4	0.52	0.64	0.33
Graves Mountain (Kettle)	SBS	3462	40.1	22	32.6	88.3	143	54.7	130.5	3.57	0.38	0.6	0.23
	MTBS	3464	40.1	22	32.9	88	143	55	130.5	3.57	0.38	0.6	0.23
Lime Belt	FL	53,625	452.8	76.1	97.9	75.9	249.8	173.9	1.3	0.55	0.7	0.56	0.39
	SBS	54,000	420.6	78.4	98.2	73.3	249.8	176.5	1.3	0.59	0.71	0.56	0.39
	MTBS	55,482	324.9	86.3	95.2	68.3	249.8	181.5	1.3	0.77	0.73	0.52	0.38
North Star	FL	85,741	344.2	35.2	67.2	148	250.4	102.4	1.5	0.73	0.41	0.66	0.27
	MTBS	88,443	270.7	38.2	69.4	142.7	250.4	107.7	1.5	0.92	0.43	0.64	0.28
Renner (Kettle)	SBS	5574	42.6	20.6	28.8	55	104.4	49.4	153.0	2.45	0.47	0.58	0.28
	MTBS	5656	44.8	20.8	29.9	53.7	104.4	50.7	153.0	2.33	0.49	0.59	0.29
Stickpin (Kettle)	SBS	21,739	143.8	43.1	68.5	231.9	343.5	111.6	191.5	2.39	0.32	0.61	0.2
	MTBS	21,901	134.5	49.5	59.8	234.2	343.5	109.2	191.5	2.55	0.32	0.55	0.17
Tunk Block	FL	65,765	417.5	35.9	93.7	57.2	186.8	129.6	−24.3	0.45	0.69	0.72	0.5
	MTBS	72,888	244	102.9	39.4	44.5	186.8	142.3	−24.3	0.77	0.76	0.28	0.21
Twisp River	FL	4538	41.8	4.4	3.9	1.9	10.2	8.3	6.6	0.24	0.82	0.47	0.38
	SBS	4541	42	4.4	3.9	1.9	10.2	8.3	6.6	0.24	0.82	0.47	0.38
	MTBS	4558	39.6	4.5	3.8	1.9	10.2	8.3	6.6	0.26	0.82	0.46	0.38
Wolverine Complex	FL	29,628	491.2	4.1	34.5	151.1	189.7	38.6	1.7	0.39	0.2	0.89	0.18
	SBS	26,437	427.9	0.2	5.9	183.6	189.7	6.1	1.7	0.44	0.03	0.97	0.03
	MTBS	26,843	361.5	5.3	0.9	183.5	189.7	6.2	1.7	0.52	0.03	0.14	0
2017 wildfires													
Diamond Creek	FL	13,018.3	183.9	0	1.3	63.6	64.9	1.3	1.0	0.35	0.02	1	0.02
	SBS	37,755.7	634.4	0	1.3	63.6	64.9	1.3	1.0	0.1	0.02	1	0.02
	MTBS	36,809.5	423.8	0	0.6	64.3	64.9	0.6	1.0	0.15	0.01	1	0.01
Uno Peak	FL	3500.91	109.8	0.9	2.7	113.3	117	3.6	0.3	1.07	0.03	0.74	0.02
	SBS	3463.83	120.9	1	2.6	113.4	117	3.6	0.3	0.97	0.03	0.73	0.02
	MTBS	3592.9	77.5	0.8	2.6	113.6	117	3.4	0.3	1.51	0.03	0.76	0.02

in this study, a total of 972 km (44%) was engaged by the wildfires. Fires with the highest fireline engagement (over 70%) were 9-Mile, Lime Belt, Tunk Block, and Twisp River. Held-to-engaged fire ratios (HEr) were over 0.5 for most wildfires, reflecting a relatively high success rate. For wildfires with a low engagement ratio, the HTr are also low, including wildfires that burned mostly in roadless areas with more distant firelines (Wolverine and Diamond Creek) as well as the Kettle Complex fires. Among the wildfires with the highest fireline effectiveness are 9-Mile, Carlton Complex, and Chelan Complex.

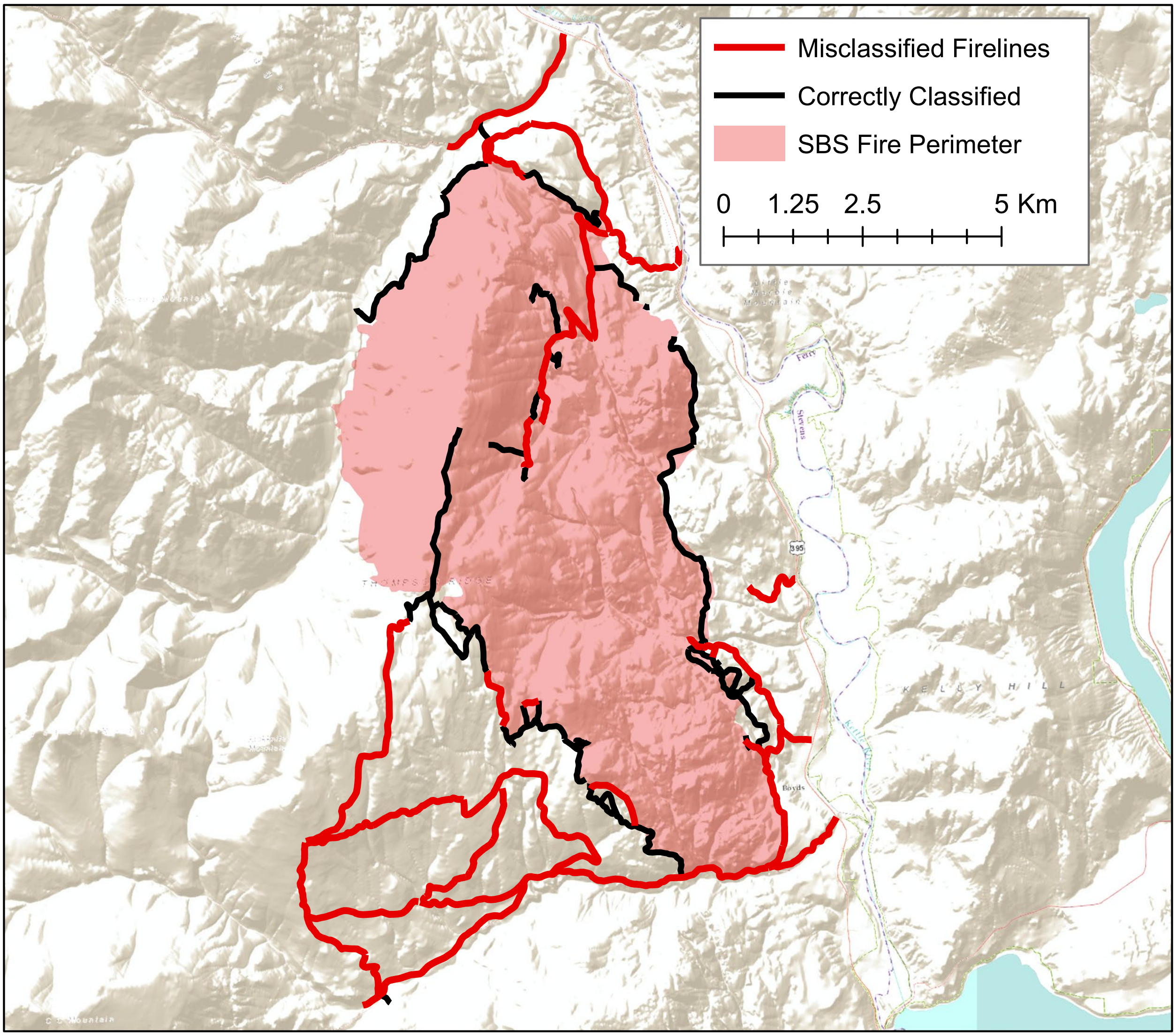

Fig. 4 Example of misclassified firelines in the Renner fire that were reclassified as road as complete or bulldozer lines

Comparison of original and corrected firelines

In our evaluation of the fireline metrics methodology, we first determined if fireline datasets could be used directly from firebox records or if quality assurance and quality control (QA/QC) measures were needed to correct for digitizing and misclassification errors. We found several inconsistencies that suggest that some broad QA/QC should be conducted prior to evaluating fireline effectiveness. The largest errors were associated with the Kettle Complex fires (Graves, Renner, and Stickpin) in which many misclassification errors resulted from road as completed line and bulldozer lines that were erroneously classified as uncontrolled fire edge in the initial dataset (Fig. 4). Most fireline edits did not lead to a significant increase or decrease in total fireline length and thus did not substantially change fireline metrics. The corrections of the Tunk firelines had the largest decrease in total length of −24.3%. This large decrease was caused by the removal of duplicate firelines. For example, the Twisp River fire had a 6.6% change, but the total amount of fireline change was only 0.62 km of the 10.2-km fireline length (Table 1). These minor corrections produced little to no change to effectiveness (HTr) and suppression metrics (Tr) (Fig. 5). Corrections to the total length of firelines in the Carlton Complex fires were similarly minor. However, large misclassification errors substantially influenced metrics for Renner, Stickpin, and Graves

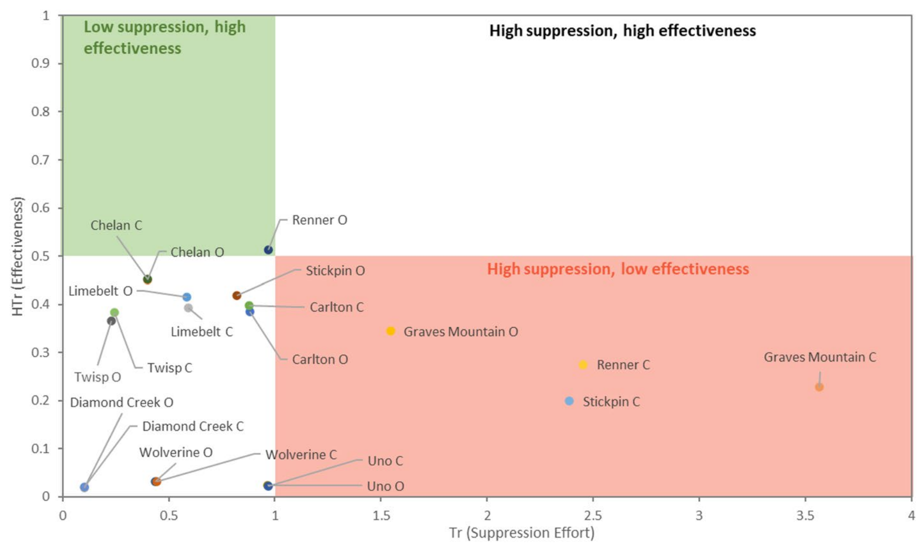

Fig. 5 Plot of fireline effectiveness for SBS original and modified fires. Fires ending with O are original unmodified firelines while those ending with C have been corrected

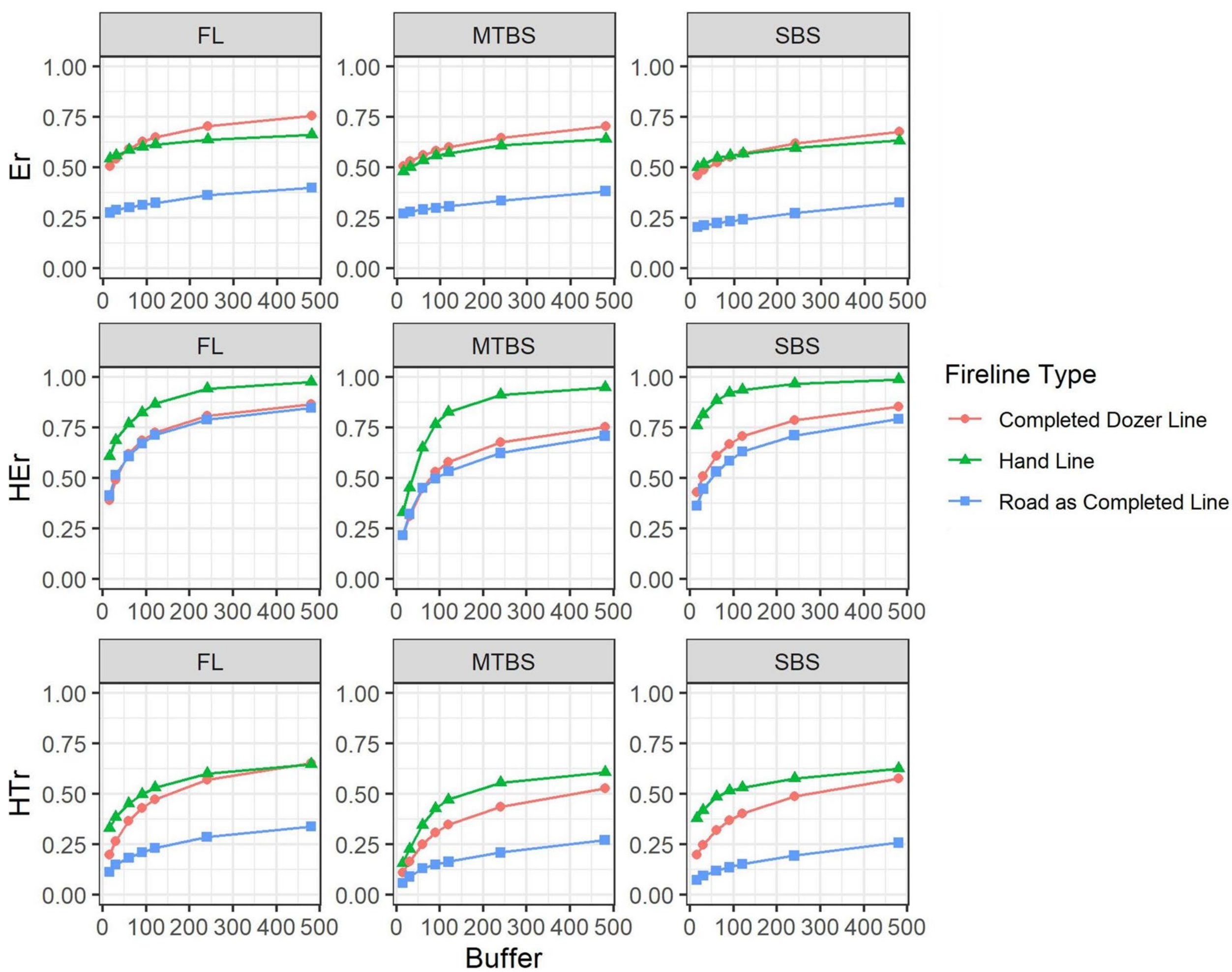

Fig. 6 Effect of buffer width around fire perimeters on the Er, HEr, and HTr

Mountain (Fig. 5, Table 1). Misclassification errors led to a substantial increase in total fireline length with an increase of 130.5% for Graves Mountain, 153.0% for Renner, and 191.5% for Stickpin. Had these misclassification errors not been corrected, they would have led to interpretations of higher overall effectiveness and lower suppression effort.

Buffers and firelines

Selected buffer width has a marked influence on fireline effectiveness for the three types of fireline we evaluated (Fig. 6). With increased buffer width, the estimated length of engaged firelines and line held increased but estimates of firelines that were not engaged and burned over decreased. For example, the amount of engaged bulldozer line for the fireline perimeter was 506.4 km at 15 m, 591.7 km at 60 m, 650.0 km at 120 m, 704.8 km at 240 m, and 756.1 km at 480 m. As such, buffer width directly impacted the inputs used in the calculation for Er, HEr, and HTr and the evaluation of fire effectiveness (Fig. 6).

After examining our results, a 60-m buffer was determined to be a reasonable selection for calculating effectiveness metrics for our burn severity analysis. The 60-m buffer allowed for a more accurate representation of how fires were interacting along the firelines. Lower buffer sizes underestimated fire engagement and burn over, while overestimating non-engagement. Larger buffer widths created the opposite problem with overestimation of fire engagement and burn over, and underestimation of non-engagement. Gannon et al. (2020) used a similar-sized buffer of 50 m. In addition, 60 m is the width of two 30-m Landsat pixels and aligns better with the fire perimeters of MTBS and SBS within our study. This is because a 30-m Landsat imagery is used in the creation of MTBS and SBS data during their fire perimeter delineation process.

Perimeter source

Most of the wildfires that we evaluated had three potential sources of final fire perimeters, including the original firefighting records from NWFCG (FL), MTBS, and SBS (Table 1). There were major differences in overall fire area and fire perimeters associated with these data sources. Most notably, the Diamond Creek Fire had the largest differences in overall fire area and estimated perimeter among perimeter sources (Fig. 7). For the FL perimeter, the burned area within the USA was only recorded while the MTBS and SBS perimeters included additional wilderness northward across the US/Canada border.

SBS was generally the most reliable source for final fire perimeters and is also associated with somewhat higher overall fireline effectiveness (Fig. 9). Unfortunately, SBS was not available for all wildfires within our study. However, a comparison of SBS and MTBS allowed us to fully understand the impacts fire perimeters could have on this fireline effectiveness methodology. MTBS was less accurate as a perimeter source and also does not typically

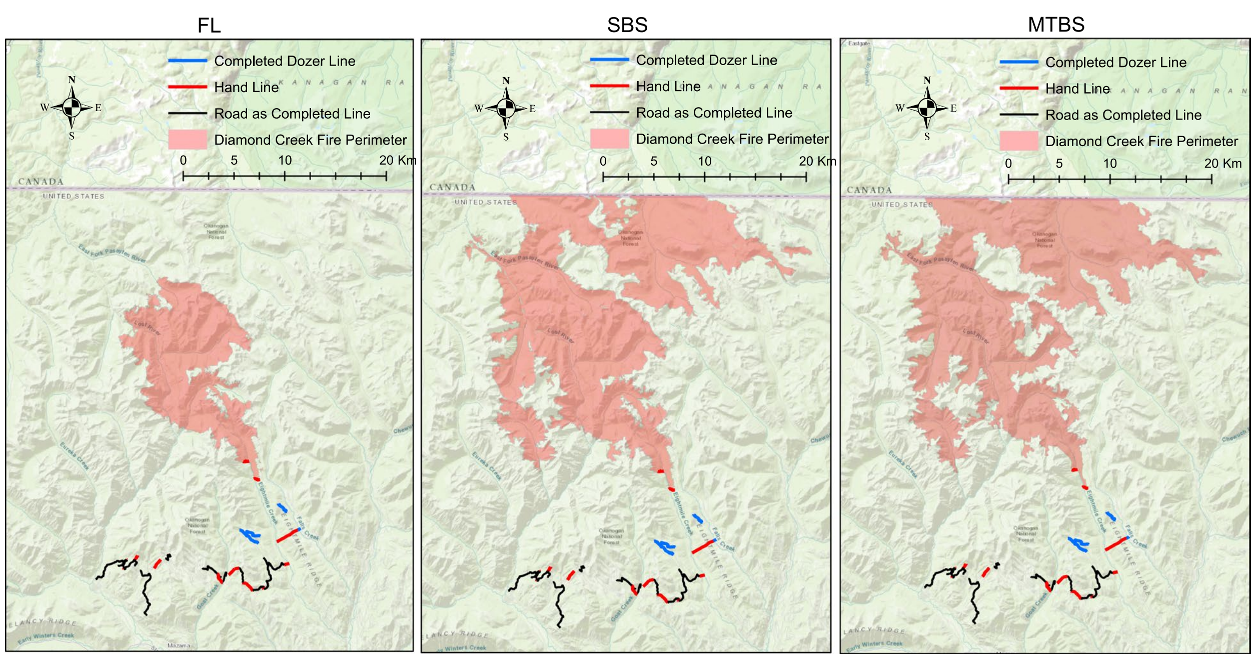

Fig. 7 Comparison of the FL, SBS, and MTBS fire perimeters in relation to the completed bulldozer line, hand line, and road as completed for the Diamond Creek fire. The SBS and MTBS fire perimeters were cut off at the US and Canada border

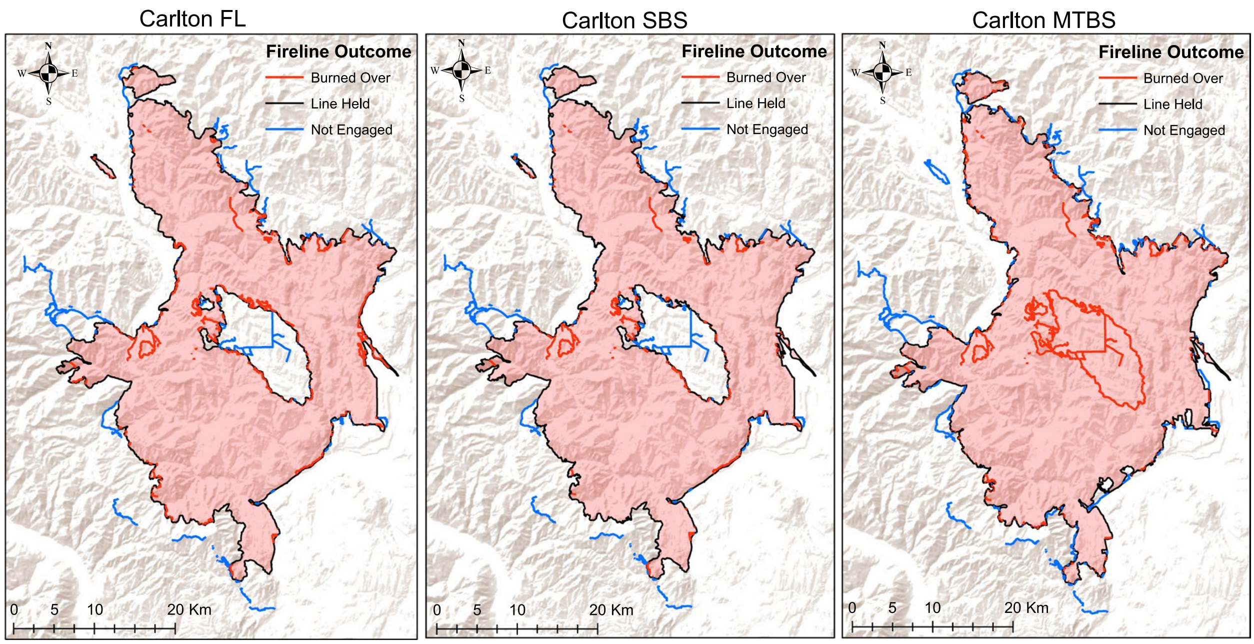

Fig. 8 Comparison of fireline outcomes on the Carlton Complex Fire using FL, SBS, and MTBS fire perimeters

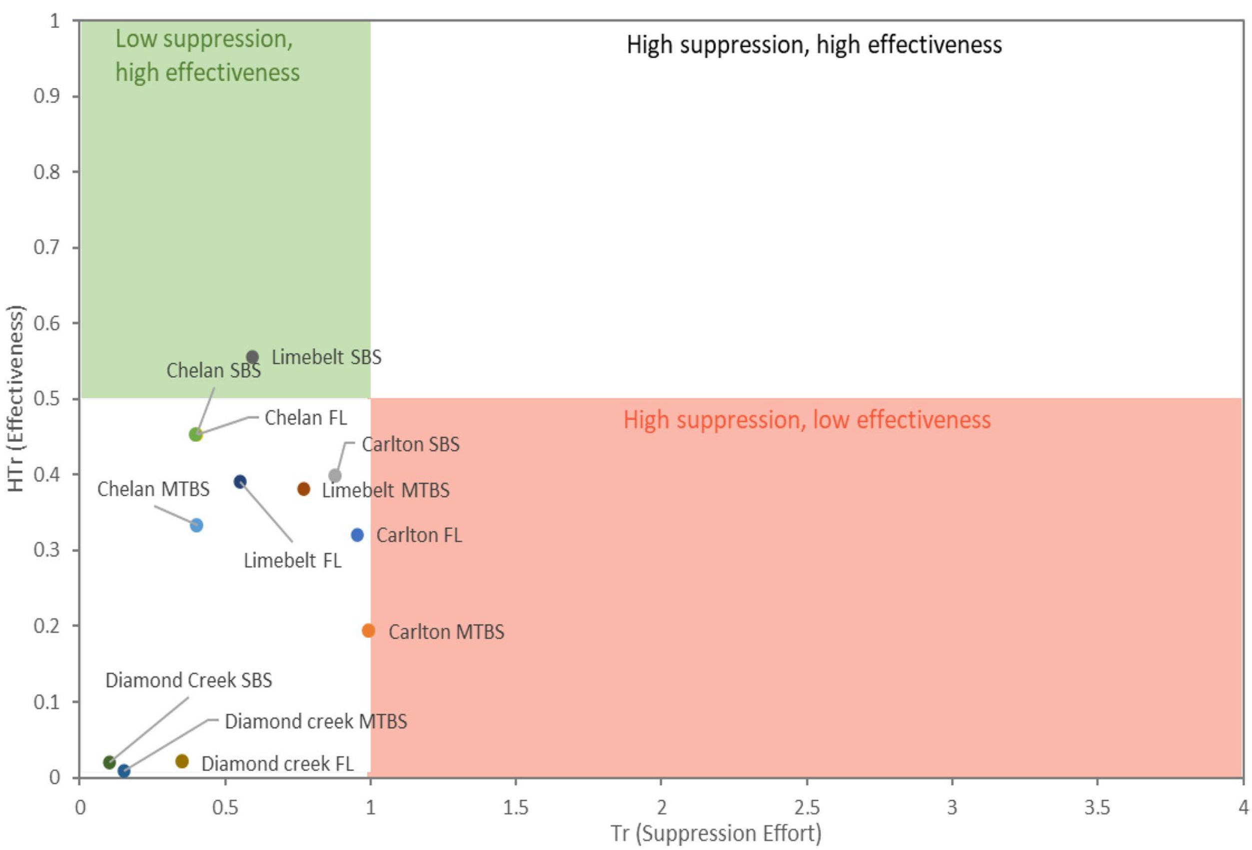

Fig. 9 Comparison of two fireline effectiveness metrics including an overall fireline effectiveness metric (held fireline length to total fireline length, HTr) vs. suppression effort (total fireline length, Tr). Only large fires that include all three source perimeters are displayed

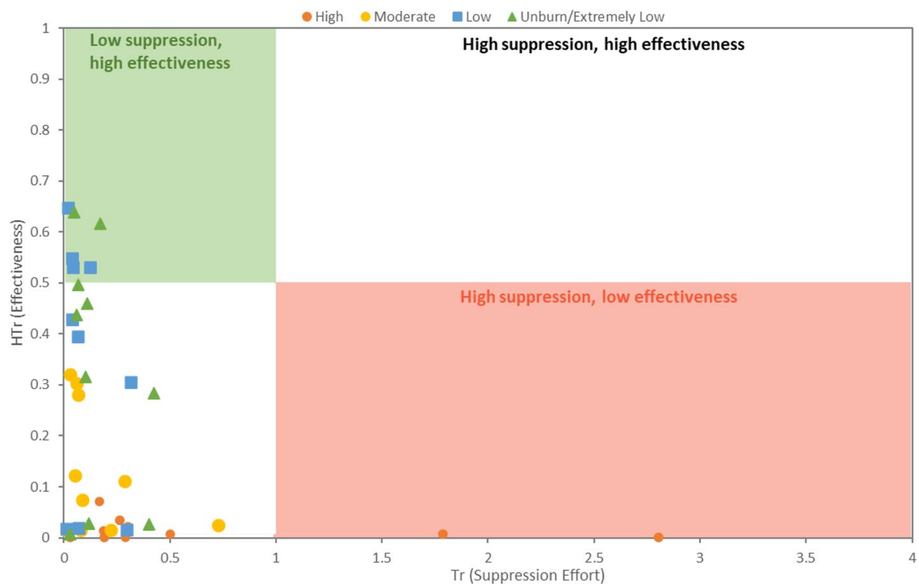

Fig. 10 Influence of fire severity on fireline effectiveness metrics where HTr is a measure of overall fireline effectiveness metric and Tr is a measure of suppression effort

delineate unburned patches within supported fire perimeters, leading to erroneous results that indicated higher burned over and engaged firelines and lower HEr and HTr results (Table 1). For example, the Carlton Complex contains a large, unburned island that is included in the MTBS fire perimeter, leading to firelines being erroneously determined as burned over and engaged and causing the fireline metrics of HEr and HTr to be 57% and 59% lower respectively than FL (Figs. 8 and 9).

Burn severity

Across all wildfires that we evaluated, areas that burned with low and unburned/extremely low burn severity are associated with low suppression effort, and firelines within these areas were highly effective (Fig. 10). Unburned/extremely low burn severity areas had much higher HEr than those burned at moderate and high severity. Moderate-severity areas generally had fewer firelines, but firelines were less effective. In contrast, high-severity fires required more suppression effort (Tr) and had lower effectiveness (HTr) than other fire severities (Fig. 10).

The majority of firelines, when engaged, were effective for unburned, low, and moderate burn severity classes (Fig. 10). When firelines were constructed and engaged (HEr), they were shown to be effective across all types of firelines. Because these were often very large fire events, the amount of firelines that was not engaged was also quite high with 1552 km of unengaged bulldozer line (35.5%), 939 km of unengaged road as completed (45.7%), and 775 km of unengaged hand line (44.7%). Bulldozer lines were the dominant fireline type and had a much greater engagement, held, and burned over length (Fig. 11). As such, the total fireline engaged, held, and burned over was the largest for bulldozer lines. While completed bulldozer lines had much greater application across the study area fires, there was shown to be little to no differences across severity for effectiveness (Fig. 11). Moderate-severity fires had the least engagement across all fireline types. High-severity fires had a greater amount of engagement across all fireline types than all other fire severity (Fig. 11). Overall, the results showed that the high-severity fires consistently had low amounts of effectiveness, even when suppression effort varied across different fires (Fig. 10).

Discussion

In this study, we applied methods from Gannon et al. (2020) to evaluate the sensitivity of fireline metrics to the geospatial source of fire perimeters, accuracy of digitized firelines, and fireline buffer size. We also evaluated if burn severity had any relationship with fireline effectiveness.

Based on our evaluation of fireline perimeter sources, we recommend careful examination of fireline perimeters and corrections prior to calculating fireline effectiveness metrics. Specifically, we found that MTBS fire perimeters for several fires were unreliable because they included large, unburned islands, thereby markedly reducing the fire effectiveness values. In the case of MTBS source perimeters, using field data, ancillary data, and an additional pre-processing review can be used to identify unburned islands and other errors within final

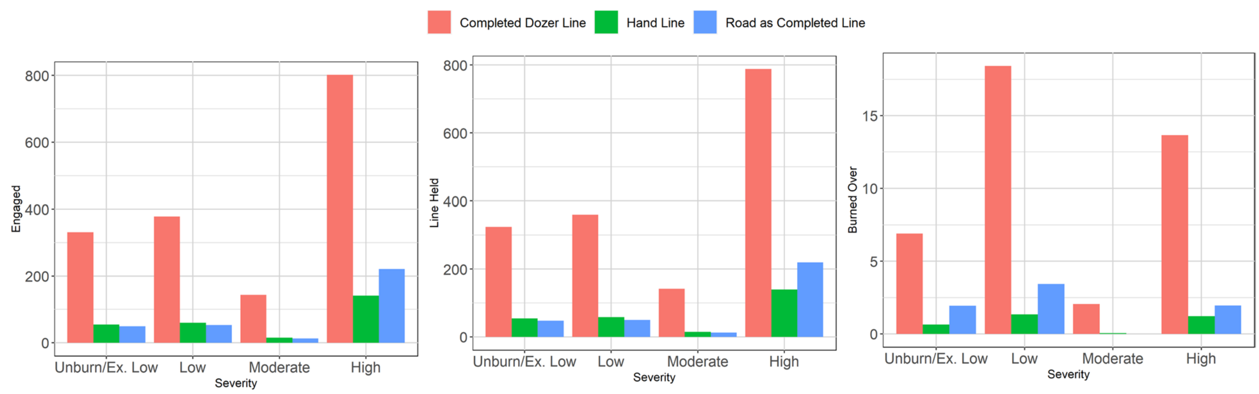

Fig. 11 Comparison of the length (km) of fireline engagement, line held, and burned over by type across four severity classes, including unburned/extremely low, low, moderate, and high severity. Due to the effectiveness of the line held, burned over length of fireline was extremely low and had to be displayed on a smaller scale to accurately depict differences

fire perimeters (Kolden et al. 2015, Sparks et al 2015, Meddens et al. 2016). Our comparison of fire perimeters underscores the importance of careful review of fireline perimeters to ensure consistency in datasets prior to calculating fireline effectiveness metrics across multiple fires.

During this study, we found that the amount of suppression effort (Tr) was influenced by a variety of factors. For the management of large fires, fireline construction often occurs simultaneously across multiple sectors to be able to contain or suppress on multiple fronts and fires (Finney et al. 2009). In the case of the Kettle Complex fires (Graves Mountain, Renner, Stockpin), the amount of total fireline was elevated because wildland fire planners treated the fires as a single complex and created long interconnected firelines across the three geographically distinct fires. The 9-Mile fire, the smallest fire in our study, had firelines that completely encircled its perimeter, leading to a higher Tr than some of the larger fires that did not completely encircle the fire. This suggests that while the suppression effort metric may be beneficial in the evaluation of fireline effectiveness, it must be placed in the context that these results are outcomes of fire management decisions and do not reflect the reasons behind those decisions (Belval et al. 2019, Bayham and Yonder 2020, Gannon et al. 2020).

We found that the fireline effectiveness method is robust to minor errors from spatial alignment and duplications without producing a direct impact upon the results of fireline effectiveness. Our results suggest that fine-scale correction to the spatial alignment of firelines is likely not needed because edits did not substantially influence fireline length and the results of fireline metrics. Because of the spatial resolution of Landsat and to account for minor spatial inaccuracies that existed without affecting the overall fireline effectiveness results, a 60-m buffer was determined to be a reasonable selection for buffer width.

It should be noted that misclassification errors of firelines can result in incorrect interpretations of fireline effectiveness. Misclassification errors occurred in the original fireline database of three fires: Renner, Stickpin, and Graves Mountain. While these errors can occur during fireline database creation, the current methods of Thompson et al. (2016), Thompson et al. (2018a), and Gannon et al. (2020) do not specifically account for these types of errors in their initial design. Because of this, we suggest that an additional step during the visual inspection phase be incorporated into the fireline effectiveness methodology. This step should specifically examine the fireline dataset for misclassification or database errors.

Our results demonstrate that buffer width selection has a potentially large impact on fireline effectiveness metrics. Buffer width therefore should be chosen carefully as it directly affected the determination of line held, burned over, not engaged, and fire effectiveness metrics. Because the shape of the buffer is inherently linked to the original fire perimeter input, the buffer width should be based upon the spatial resolution used in the creation of the fire perimeter. An arbitrarily chosen buffer width will have considerable impacts upon the overall accuracy of fireline metrics.

Fireline effectiveness metrics should be interpreted with the understanding that these analyses are retrospective. Often, there are specific circumstances that need to be understood before creating a final determination metrics and an interpretation specific to each fire. For example, fire suppression activities may choose to take advantage of the existing road network, or the topology may restrict the construction of new bulldozer or hand lines. Additionally, vegetation's composition, structure, and density may have a large impact on decisions regarding the construction of firelines.

The majority of firelines within our study were constructed bulldozer lines. Along with road as completed line, bulldozer line is one of the most common types of fireline, especially in areas that required the removal of heavy fuels (Phillips and Barny 1984; Holmes and Calkin 2012, Katuwal et al. 2016). However, our results indicated that the completed bulldozer lines were no more effective than other types of firelines across a variety of fire severities and that high-severity fires are difficult to contain regardless of fireline type. In fact, hand lines for low-severity fires had the least amount of burn over/engaged length when compared to completed bulldozer lines and road as completed. This is likely due to the strategic placement of hand lines as they are used less often due to the risks and costs associated with sending crew into the field and their use in mop-up operations. Overall, the effectiveness of hand lines may indicate that more careful placement of firelines will increase the fireline effectiveness. Further study is needed to examine the connection between fireline type, placement, and efficacy.

Although fireline effectiveness metrics are retrospective, our findings may still be informative for prioritization and placement of firelines in future wildland fire events. Specifically, we found that fireline effectiveness was low, regardless of fireline type, in high-severity burns. Where fires are likely to burn at higher severity due to weather, topology, or fuels (e.g., dense, mixed conifer forests), firelines are likely to be less effective. This may not be the most practical use of resources and could result in compounding wildfire impacts by contributing to higher mineral soil exposure, erosion potential, and corridors for invasive species (D'Antonio et al. 1999, Backer et al. 2004, Merriam et al. 2006, Mornoney and Rundel 2013, Calkin et al. 2015). These results are not novel and are well supported by standard nomograms of predicted fire behavior in wildland fuels and firefighting options (Rothermel 1983). Our study's fires contained a relatively small amount of moderate-severity fire pixels in comparison to low and high-severity fire pixels. Because of this, the moderate fire severity class was disproportionately less represented than all other fire severities that encountered the firelines. This tended to bias the results by suggesting that moderate-severity fires had the lowest amount of effectiveness. Additional research is needed to understand if similar methods can be applied to small and moderate size fire events especially those with underrepresented severity classes.

Conclusion

The results of this study suggested that this methodology is not only reliable for evaluating fireline effectiveness but also may assist in the strategic planning and placement of firelines for future operations. When evaluating the potential placement of firelines, fire managers often must act quickly to protect lives, infrastructure, and natural resources and can only work with the available data that they have been provided to them. With that in mind, this methodology, in conjunction with fire behavior and effect modeling, could be adapted for strategic planning and evaluation of the future placement of firelines to reduce the cost and site impacts.

One of the remaining challenges for fireline effectiveness evaluation is the quality of record keeping by wildland fire managers. Quality standards would greatly improve the accuracy of final firelines and wildfire perimeters. To ensure the accuracy of fireline effectiveness, more detailed record keeping of fireline construction and placement is needed. Based on existing fireline records, we could not distinguish between firelines that were constructed in advance of a progressing fire and those constructed during mop-up operations. In addition, completed lines should be properly attributed with a fireline type (e.g., newly constructed bulldozer line, reopened road, or existing road as completed line), intended purpose (e.g., barrier in advance of a fire front or fireline constructed in mop-up operations), and creation date. In the future, well-attributed fireline records that record the construction date would greatly refine the classification of fireline types and estimates of overall fireline effectiveness. Training and encouraging the use of implementation of GPS units on fireline crews in the field would also lead to more efficient and accurate fireline geospatial databases.

Firelines not only pose a significant economic investment but are also known to have a range of short- and long-term ecological impacts. Recovery of vegetation on firelines has been shown to be different in both vegetation recovery rate and vegetation type than adjacent burned areas (Cowling 1987, Young et al. 1997, D'Antonio et al. 1999). In particular, the construction of bulldozer firelines may cause long-term unintended consequences by altering the nutrient cycle, hydrologic function of the soil, erosion, and vegetation recovery (Young et al. 1997, D'Antonio et al. 1999, Brooks et al. 2004, Tulganyam 2015). Our study suggests that when fires were engaged by firelines, they were more likely to be held regardless of type. However, the large amount of unengaged firelines also indicates that firelines may be implemented more than needed. Applications of firelines should be carefully considered due to the economic and ecological costs associated with firelines, which can vary wildly due to fire severity, habitat, invasive species, fire regimes, and other abiotic/biotic considerations. More informed placement and use of firelines can not only increase their potential effectiveness but also mitigate the potential impacts of firelines in situations where they are likely to fail. For example, in forests that are susceptible to high-severity fire (e.g., mixed conifer forests with high accumulations of surface and canopy fuels), bulldozer lines are unlikely to hold and may not be worth the economic investment or the long-range ecological impact. Future studies are needed to understand how different ecosystems react to disturbance and implementation of firelines.

In addition, proactive fuel reduction treatments may reduce overall wildfire suppression costs and increase the effectiveness of future fire suppression efforts (Moghaddas and Craggs 2007, Stephens et al. 2009, Beverly, J. 2017, Loomis et al. 2019). While weather and topology cannot be altered easily to reduce the likelihood of a high-severity fire, fuels can be identified and managed before a fire incident occurs (Kalies and Kent 2016, Prichard et al. 2021). Mitigating the extent of high-severity fires, not only may reduce fire management costs, but also may prevent or reduce the adverse impacts these fires have on ecosystem resilience and natural resources (Thompson et al. 2017, Stevens-Rumann et al. 2018, McWethy et al. 2019). High-severity wildfires can pose secondary threats to water quality by increasing runoff and releasing sediment that contains nutrients and heavy metals into nearby watersheds (Biswas et al. 2007, Bladon et al. 2014, Bladon 2018). Accessing and identifying potential high-severity burn areas can be used to identify the risks to communities and to firefighters and improve the placement and efficiency of firelines (Haas et al. 2013, Dunn et al 2019, Schweizer et al 2019). Future research is needed on the strategic placement of firelines, coordinated with fuel reduction treatments, which would greatly assist wildland fire managers with rapid assessments to improve firefighting outcomes.

Supplementary Information

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Additional file 1: Table 1A. The area percentage across the four burn severity classes defined by SBS for 10 study area fires. **Table 2A.** The total cost of firefighting suppression and mop-up activities our study area fires. The calculation for millions of dollars for the parts of the fire complex of Kettle and Okanogan were based on the percentage of fire area to total area of complex fire. The total cost of Okanogan Complex and Kettle Complex was 46.3 and 37.6 million of dollars respectively.

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Code availability

Not applicable.

Authors' contributions

RL: conceptualization, methodology, investigation, formal analysis, writing, review, and editing. SP: conceptualization, methodology, investigation, writing, review, and editing. BK: conceptualization, methodology, writing, review, and editing. The authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed here are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors whose names appear on the submission approve the version to be published.

Competing interests

The authors declare that they have no competing interests.

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