Development of a New Open-Source Tool to Map Burned Area and Burn Severity

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Abstract—Accurate and complete geospatial fire occurrence records are important in determining postfire effects, emissions, hazards, and fuel loading inventories. Currently, the Monitoring Trends in Burn Severity (MTBS) project maps the fire perimeter and burn severity of all large fires on public lands. Although the MTBS project maps a large proportion of the fire acreage, it maps a smaller proportion of the actual number of fires in the United States, thereby creating a data gap. To fill this data gap, fire scientists at the U.S. Geological Survey (USGS) Earth Resources Observation and Science Center (EROS; Sioux Falls, South Dakota) proposed creating an open-source Fire Mapping Tool (FMT; available at https://mtbs.gov/qgis-fire-mapping-tool) as part of a two-phase National Aeronautics and Space Administration (NASA) Applied Fire Science Program grant. Phase II developed the FMT to map burn perimeters and severity not included in the MTBS database. This paper will focus on Phase II and will explain the algorithms that enhance the FMT's functionality, demonstrate fire mapping procedures, and provide an example comparison between MTBS analyst fire products and those mapped using the FMT. The overall goal in the production of the FMT was to provide a freely available tool that can be used to map fires anywhere in the world.

Keywords: fire, Monitoring Trends in Burn Severity (MTBS), Normalized Burn Ratio (NBR), differenced NBR (dNBR), burn severity thresholding

INTRODUCTION

The Monitoring Trends in Burn Severity (MTBS) project was initially tasked to map the burned area and burn severity of fires ≥ 402 ha in the western and ≥ 202 ha of the eastern United States (Eidenshink et al. 2007). Although the MTBS project's acreage threshold accounts for the majority of burned areas in the United States, the project misses a large number of small burned areas (Howard et al. 2014). Multiple burned area products are available that include smaller fires (Leblon et al. 2016) that MTBS misses; however, they have varying levels of accuracy and may not provide an estimate of burn severity. New tools need to be developed that allow users to easily adjust potential fire perimeters from burned area products and map fire perimeters and estimate burn severity (Picotte et al. 2014).

Currently, the MTBS project uses Landsat 30-m data products to map fire perimeters and burn severity for the conterminous United States, Alaska, Hawai'i, and Puerto Rico. MTBS analysts carry out a labor-intensive burn mapping protocol: (1) the identification of a fire using the Fire Occurrence Database; (2) identification and retrieval of postfire (at the minimum) and potentially prefire Landsat imagery; (3) processing of Landsat imagery and production of Normalized Burn Ratio (NBR; Key and Benson 2006) derivatives; (4) creation of differenced Normalized

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Burn Ratio (dNBR; Key and Benson 2006) image if post- and prefire images are available; (5) creation of a fire perimeter shapefile by tracing the outline of the fire perimeter visible within Landsat imagery; (6) determination of a dNBR offset to characterize potential between-image changes other than fire (Key 2005); (7) production of Relativized dNBR (RdNBR; Miller and Thode 2007) maps; and (8) visual determination of low, moderate, and high burn severity thresholds (Eidenshink et al. 2007). Because MTBS maps the entirety of the outside of the fire perimeter and does not map unburned islands within the fire perimeter, MTBS fire perimeter data tend to have errors of commission (Kolden and Weisberg 2007; Kolden et al. 2012; Sparks et al. 2015). There are also potential concerns with using the MTBS burn severity products, because burn severity thresholds are not consistently applied between fires and do not necessarily relate to the total amount of vegetation damage (Kolden et al. 2015). However, potential spatial patterns of burn severity can be useful to managers, and thresholds could be modified by ground-collected data that assess ground-based fire effects (e.g., Composite Burn Index [CBI] data).

Filling the small fire data gap was part of Phase I of the NASA Applied Sciences Program "Utilization of Multi-Sensor Active Fire Detections to Map Fires in the United States" project (Howard et al. 2014). Although modeling procedures to map fires within the Grand Canyon and in northern Florida were developed (Howard et al. 2014), this development became redundant with the advent of the Burned Area Essential Climate Variable (BAECV; Hawbaker et al. 2017). BAECV is a burned area product that combines burn probability modeling with a region growing algorithm to map potential burned areas that are approximately 4 ha or larger in size (Hawbaker et al. 2017). Currently the 1984-2015 BAECV data are available for the conterminous United States. (https://www.sciencebase.gov/catalog/item/57867943e4b0e02680c14fec, accessed 3/13/2018). However, users should be aware of the BAECV product's varying level of regional accuracy that was best in the Arid West and Mountain West and worst in the Great Plains and Eastern United States. (Vanderhoof et al. 2017a; Vanderhoof et al. 2017b). Leveraging BAECV data will allow users to potentially obtain a fire perimeter for any fire event greater than 4 ha visible with Landsat imagery.

The second phase (i.e., Phase II) of the NASA Applied Sciences Program "Utilization of Multi-Sensor Active Fire Detections to Map Fires in the United States" project was to create a tool that would allow users to map fires in a similar fashion to MTBS (Howard et al. 2014). Tools were developed during the first phase of the project to follow the MTBS processing steps to create burn perimeters and severity imagery; however, additional work was needed to refine them and make them easily accessible to users. This paper will explain the refinements, including the incorporation of algorithms to calculate the dNBR offset and burn severity thresholds, and subsequent integration of this functionality into the open-source FMT (available at https://mtbs.gov/qgis-fire-mapping-tool) Quantum Geographic Information System (QGIS) package (QGIS Development Team 2013) to facilitate the burn severity mapping processes. Finally, an example of the FMT's use in the creation of fire perimeter and burn severity products compared with MTBS products will be presented.

METHODS

MTBS Historical Data

MTBS historical metadata (available at https://www.mtbs.gov; accessed on 03/18/2018) was compiled for 18,497 fires that occurred between 1984 and 2014 within the conterminous United States, Alaska, Hawai'i, and Puerto Rico. Fires may have been assessed using either a single scene (i.e., postfire only NBR) or dNBR assessment strategy depending on image availability. Each fire was subsequently classified by its assessment strategy. Overall, 11,998 and 6,599 fires were classified by dNBR and NBR assessment strategies, respectively. Additional information that was obtained from the metadata included the MTBS id, dNBR offset value if the dNBR assessment strategy was used, and low, moderate, and high burn severity thresholds when assessed. All postfire NBR, dNBR, and classified burn severity image products were also obtained for each fire. Metadata and imagery were then used in the development of the dNBR offset process, thresholding process, and assessment of each process.

dNBR Offset Process

Currently, MTBS analysts calculate the dNBR offset by manually selecting hundreds to thousands of unburned pixels within the dNBR image that are outside the fire perimeter but occur within a similar vegetation type. The mean of all selected pixels is then calculated. If the mean dNBR value (unitless) is between -50 and 50 and the standard deviation is < 50, the offset is considered acceptable. If the value of the offset violates either assumption, then this indicates that the pre- and postfire images may not be seasonally and temporally similar (Key 2005; Key and Benson 2006; Zhu et al. 2006), suggesting that the analyst should pick more similar pre- and postfire Landsat imagery if available.

The MTBS dNBR offset logic was adjusted and automated by examining all unburned pixels in the postfire dNBR image. The unburned range of dNBR pixels was set to between -100 and 100, as suggested by Key and Benson (2006). Instead of selecting pixels from a limited region outside the fire perimeter, all unburned pixels within the clipped dNBR image extent (fire extent + 3,000 m) were selected. The median offset was calculated in lieu of calculating the mean offset value according to MTBS protocols to remove the effect of outlying values. Additionally, the standard deviation of all unburned pixels was calculated. The dNBR offset and standard deviations were subsequently calculated for all dNBR-assessed MTBS fires. Unfortunately, the standard deviation of all unburned pixels was not calculated for the MTBS dNBR offset value, making a comparison between standard deviations between the two methodologies impossible.

Similarity between analyst and calculated dNBR offset values was assessed by calculating goodness of fit (i.e., R^2). To determine whether differences existed between MTBS analyst and calculated dNBR offsets, the percentage of both datasets that fell within the suggested ±50 range was assessed. The percentage of overlap between analyst and calculated dNBR offsets that ranked outside the ±50 range was also assessed. Only the calculated method was assessed for the percentage of fires with dNBR offset unburned pixel standard deviation values ≥ 50.

Burn Severity Threshold Process

MTBS analysts visually assess the unburned/low severity breakpoint (Eidenshink et al. 2007), which may not be consistently done for each fire and requires that analysts be trained in the thresholding process. To create a level of consistency and to create a starting point from which to map the low/unburned burn severity breakpoint, an algorithm was developed that examines all pixels within a range of values of NBR and dNBR and subsequently suggests an unburned/low severity breakpoint using the Otsu thresholding method (Otsu 1979). The Otsu method is a nonparametric thresholding technique that optimizes the threshold grayscale image classes (Otsu 1979). This methodology has been previously used to determine the burned/unburned threshold (Melgani et al. 2002).

The Otsu method was applied to a range of potential unburned pixel values starting at -100 and ranging to 269 for dNBR and > 300 for NBR images to the clipped NBR and dNBR images for all 1984-2014 MTBS mapped fires. Similar methodologies were applied for the low/moderate and moderate/high dNBR and NBR thresholds by varying the range of the data input. Low/moderate severity ranges for dNBR were specified as 270 to 439 and NBR were -65 to 300. High severity ranges were > 440 and < -65 for dNBR and NBR, respectively. These dNBR thresholds approximately encompass previous thresholds determined by comparing ground-collected CBI data with dNBR in multiple studies (Cocke et al. 2005; Epting et al. 2005; Hall et al. 2008; Key and Benson 2006; Picotte and Robertson 2011b). NBR breakpoints follow those from Picotte and Robertson (2011b).

To compare the low, moderate, and high severity thresholds, it was then determined how many times the calculated thresholds were within ±50 units of dNBR or NBR compared with the value of the analyst-derived thresholds for the MTBS data. This ±50 threshold is an adequate level of between-analyst accuracy by the MTBS program. Percent agreement was calculated for dNBR and NBR separately by each severity class, by summing the number of times burn severity thresholds were within ±50 of one another and dividing by the total number of samples per severity class.

FMT Development

At the end of Phase I of NASA Project, open-source tools had been developed to map fires and to view the fires and the imagery (Howard et al. 2014). This process included some of the MTBS processes such as ordering and processing Landsat imagery to Top of Atmosphere (TOA) reflectance, the creation of NBR imagery, modeling of fire perimeters, and the visualization of data within the MTBS QuickLook tool (Howard et al. 2014). To make it easier for users to examine imagery and map fires, all processes (excluding the modeling of fire perimeters) were redeveloped in the QGIS (QGIS Development Team 2013) environment as the FMT plugin (fig. 1).

The FMT provides users with every MTBS processing step outlined in the introduction section. Additional functionality has been incorporated into the FMT to allow users to query the Landsat archive to determine scene availability; examine Normalized Difference Vegetation Index curves for similarity between Landsat scenes; process all Landsat products downloaded from the USGS EROS Science Processing Architecture (Jenkerson 2013) website (https://espa.cr.usgs.gov/, accessed 4/6/2018); produce NBR images; create burn perimeter and mask shapefiles; generate dNBR imagery if pre- and postfire imagery is available; automatically determine the dNBR offset; produce RdNBR imagery if pre- and postfire imagery are available; suggest dNBR or NBR low, moderate,

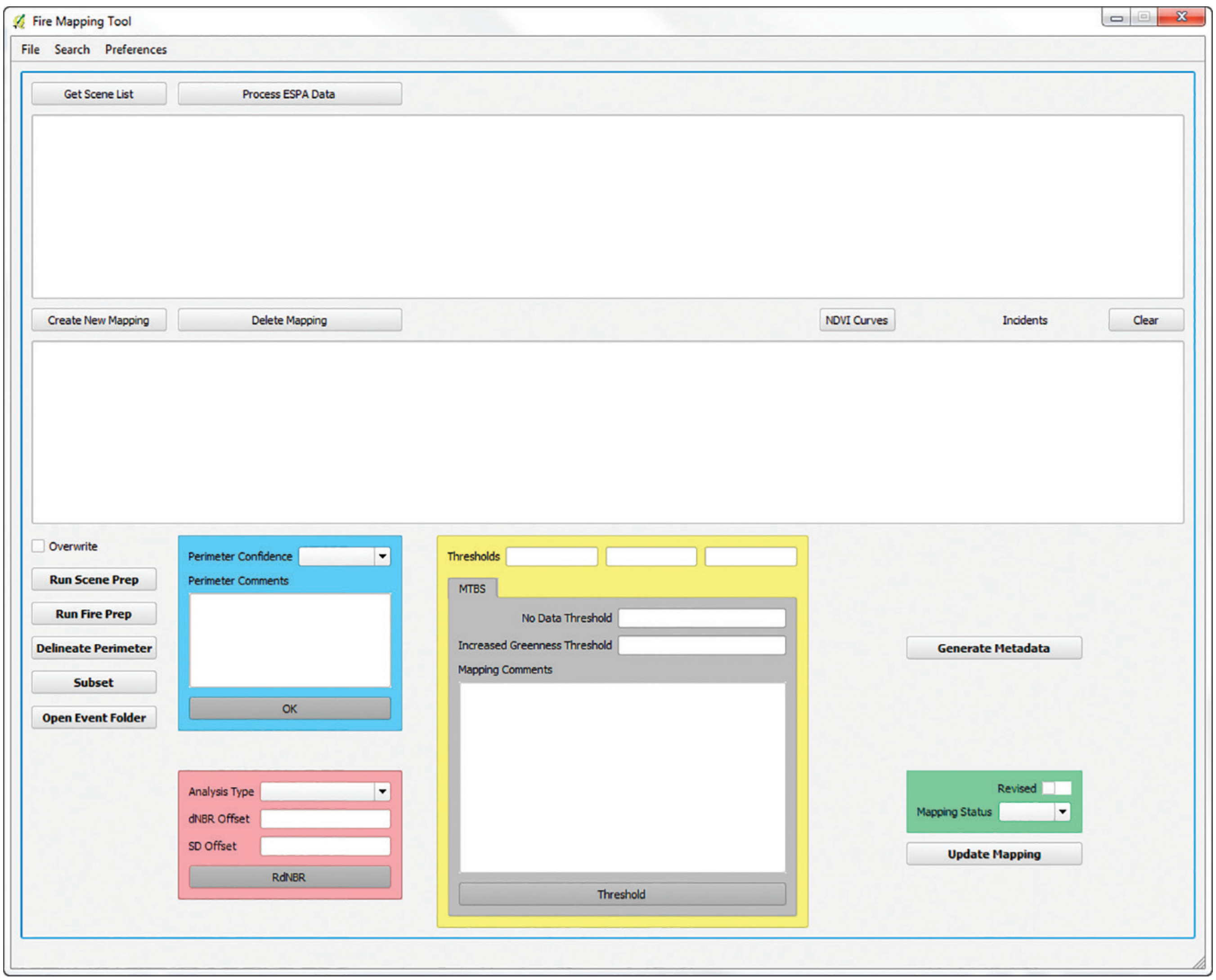

Figure 1—Fire Mapping Tool (FMT) interface.

and high burn thresholds; create the thresholded burn severity product; and produce metadata. The overall goal is to automate the MTBS image processing steps, while allowing users to visually examine the imagery within QGIS and manually edit shapefiles based on an examination of the imagery.

FMT Example

To demonstrate how the FMT can be used to map fires, the June 15, 2015, Paradise fire in the U.S. State of Washington was examined (fig. 2). The original MTBS-mapped products (https:\\www.mtbs.gov) for the Paradise fire were downloaded for comparison and to determine which pre- and postfire Landsat images were originally used by MTBS to map the fire. Prefire Landsat 8 Operational Land Imager (OLI) TOA reflectance corrected from July 29, 2014, and postfire August 8, 2016, Landsat 8 OLI TOA reflectance (fig. 2) imagery were ordered and downloaded from the ESPA Landsat data ordering and processing site. The FMT and the QGIS mapping interface were then utilized to map the burn perimeter and severity using the following steps (see https://mtbs.gov/qgis-fire-mapping-tool for additional documentation about the FMT tool):

1. Process all downloaded pre- and postfire Landsat TOA OLI imagery by extracting the reflectance image bands (2-7), stacking the Landsat image bands into one image, reprojecting the Landsat

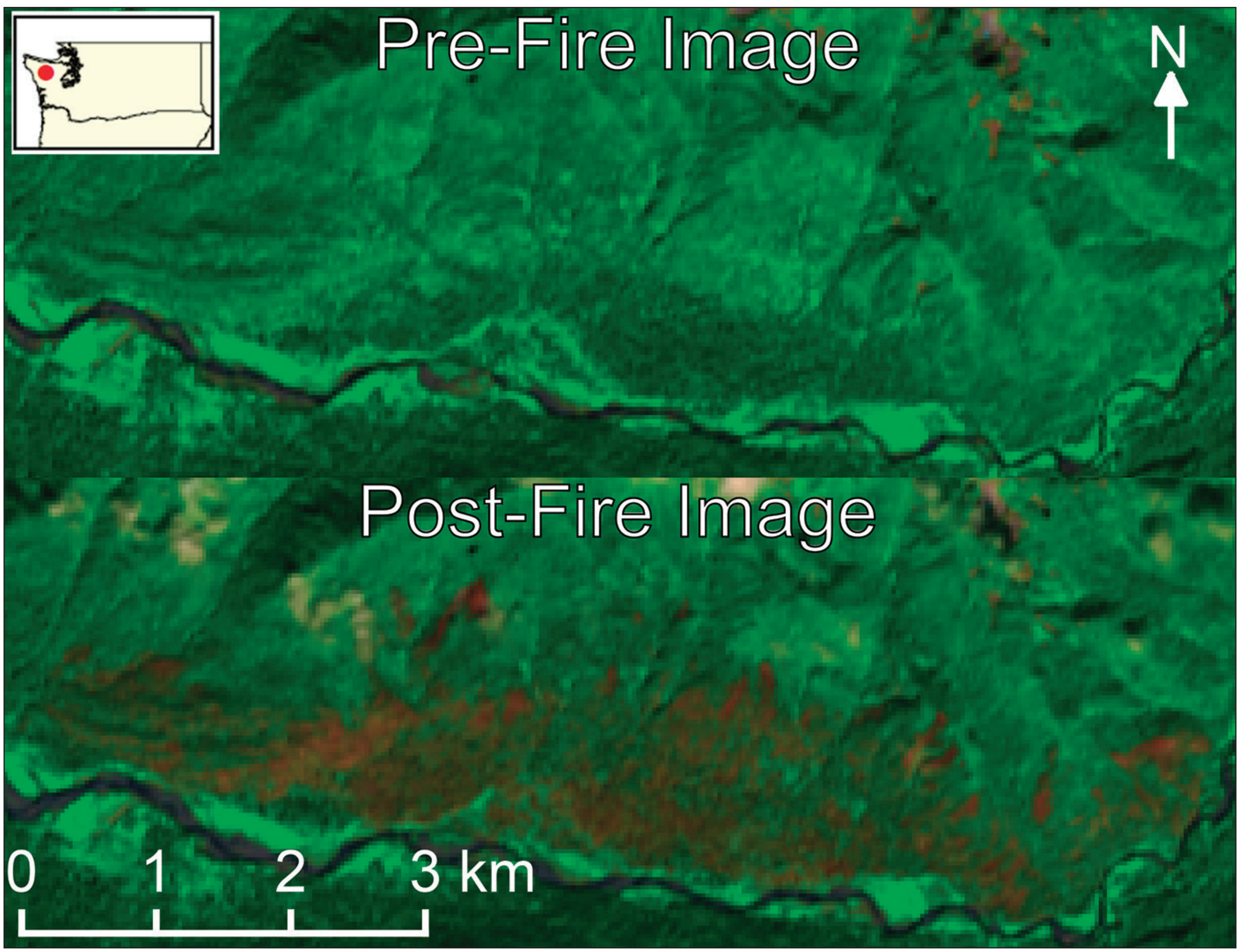

Figure 2—Prefire (July 29, 2014) and postfire (August 8, 2016) Landsat 8 Operational Land Imagery (OLI) images used in mapping the June 15, 2015, Paradise Fire in the U.S. State of Washington (highlighted in inset map). Landsat images are shown using the shortwave infrared band combination 7, 5, and 4.

image to the Albers Equal Area CONUS projected coordinate system, and producing an NBR image ([band 5 – band 7]/[band 5 + band 7]).

2. Subtract NBR values from prefire NBR values to produce the dNBR image (fig. 3).
3. Automate production of empty fire perimeter and mask (for masking any image anomalies such as clouds, cloud shadows, or water) shapefiles.
4. Manually copy fire perimeter and mask perimeters from the MTBS shapefiles into the previously empty shapefiles within the QGIS mapping interface to allow for consistent comparison between the MTBS and FMT created products (fig. 4).
5. Automatically subset all reflectance, NBR, and dNBR images to the fire perimeter bounding box buffered by 3,000 meters.
6. Automatically calculate the dNBR offset and burn severity thresholds from the subset imagery.
7. Apply the burn severity thresholds to the dNBR imagery to create the burn severity image product.

No effort was made to change the calculated dNBR offset and burn severity thresholds to demonstrate how the automated process compared to the MTBS analyst-mapped version of the Paradise fire, although this can be done manually within the FMT.

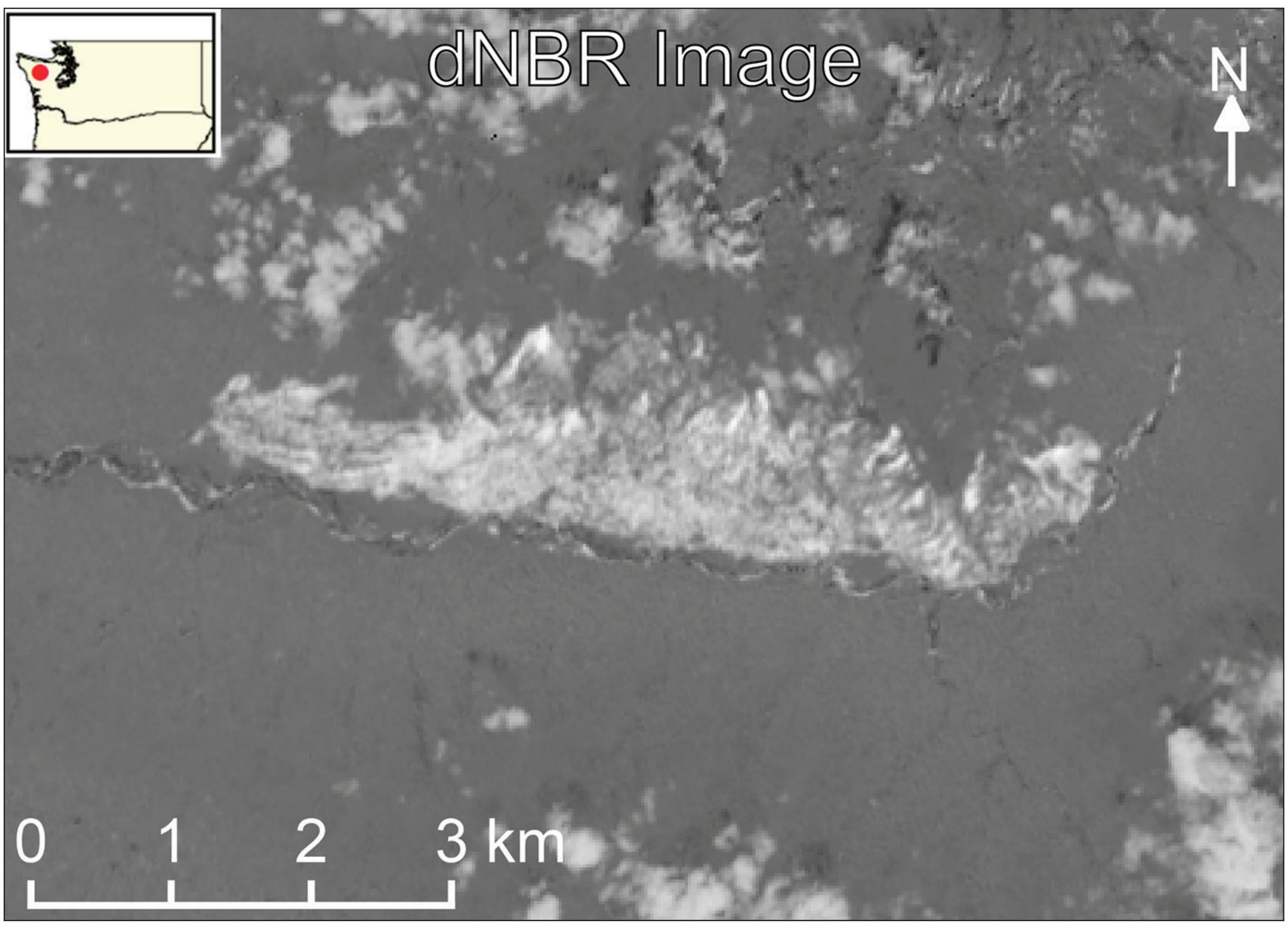

Figure 3—The differenced Normalized Burn Ratio (dNBR) image used for the June 15, 2015, Paradise Fire in the U.S. State of Washington (highlighted in inset map). Higher dNBR values (lighter colors) indicate potential changes between pre- and post-fire NBR images, including those resulting from fire.

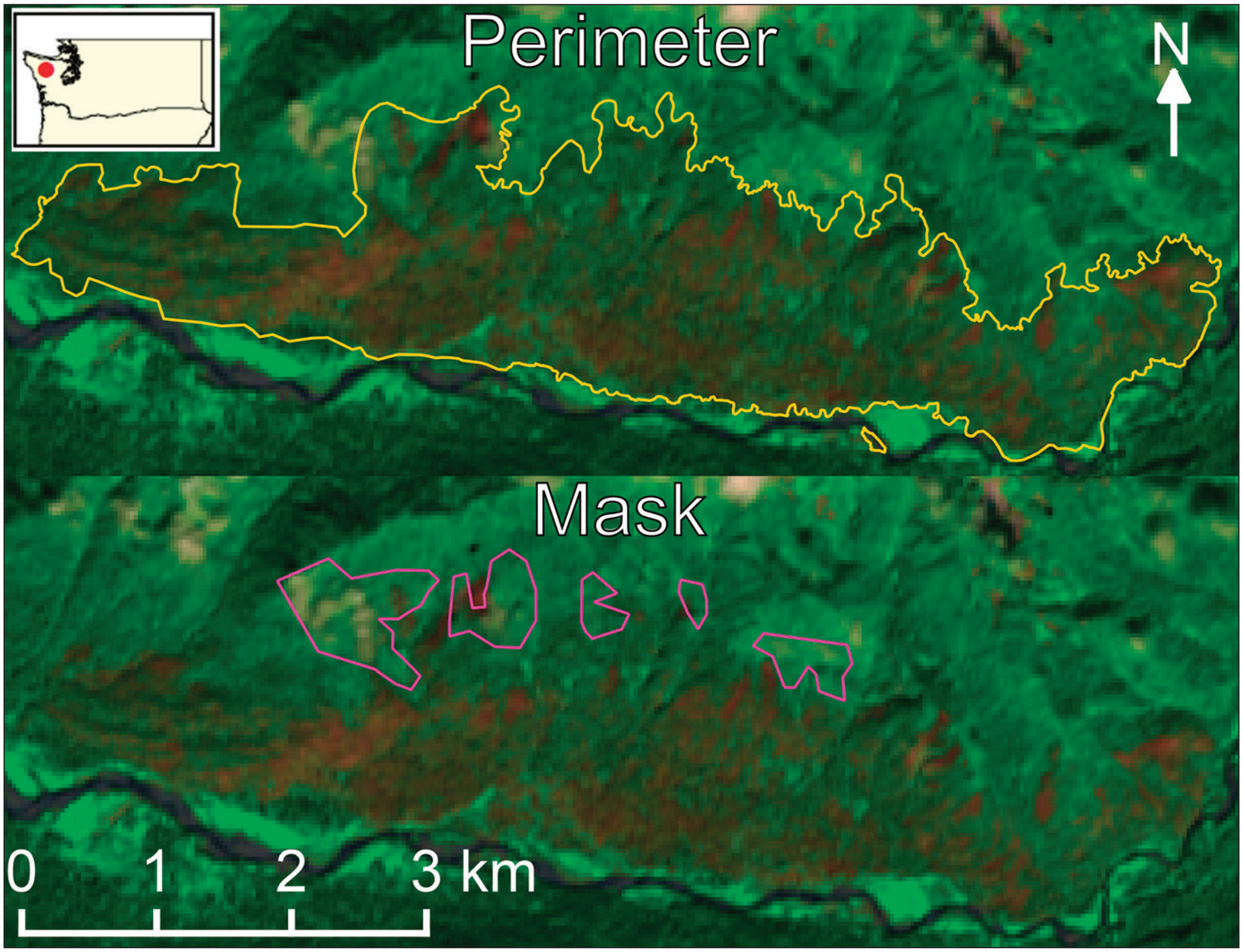

Figure 4—Fire perimeter (yellow) and masked clouds (pink) shapefiles obtained from the Monitoring Trends in Burn Severity (MTBS) project are overlain on Landsat imagery for the June 15, 2015, Paradise Fire in the U.S. State of Washington (highlighted in inset map).

RESULTS

dNBR Offset Comparison

Overall, the calculated dNBR offsets were in agreement with those estimated by MTBS analysts (fig. 5). As values of the offset increased to 100 or decreased to -100, the strength of the relationship between analyst and calculated dNBR offsets was reduced. Calculated offsets had a narrower range (-84 to 83) than the analyst-derived offsets (-243 to 373). The median value of dNBR offsets were similar for the analyst (median = 5.0) and calculated (median = 4.0) estimates.

When dNBR offset values are evaluated by whether they are outside the ±50 range, 22 percent of analyst and 10 percent of calculated offsets violated this threshold. Thirty-five percent of analyst dNBR offset values that were outside the ±50 range were also estimated as outside the range by the calculated methodology. Seventy-nine percent of the calculated dNBR offset values that were outside the ±50 range were also estimated as outside the range by the MTBS analysts.

The median standard deviation of unburned pixels used in the calculation of the dNBR offset values was 42. Of these calculated standard deviation values, 13 percent were ≥50 and had a median value of 52. One percent of all calculated dNBR offset values had both ≥50 standard deviation and dNBR offset values outside the ±50 range.

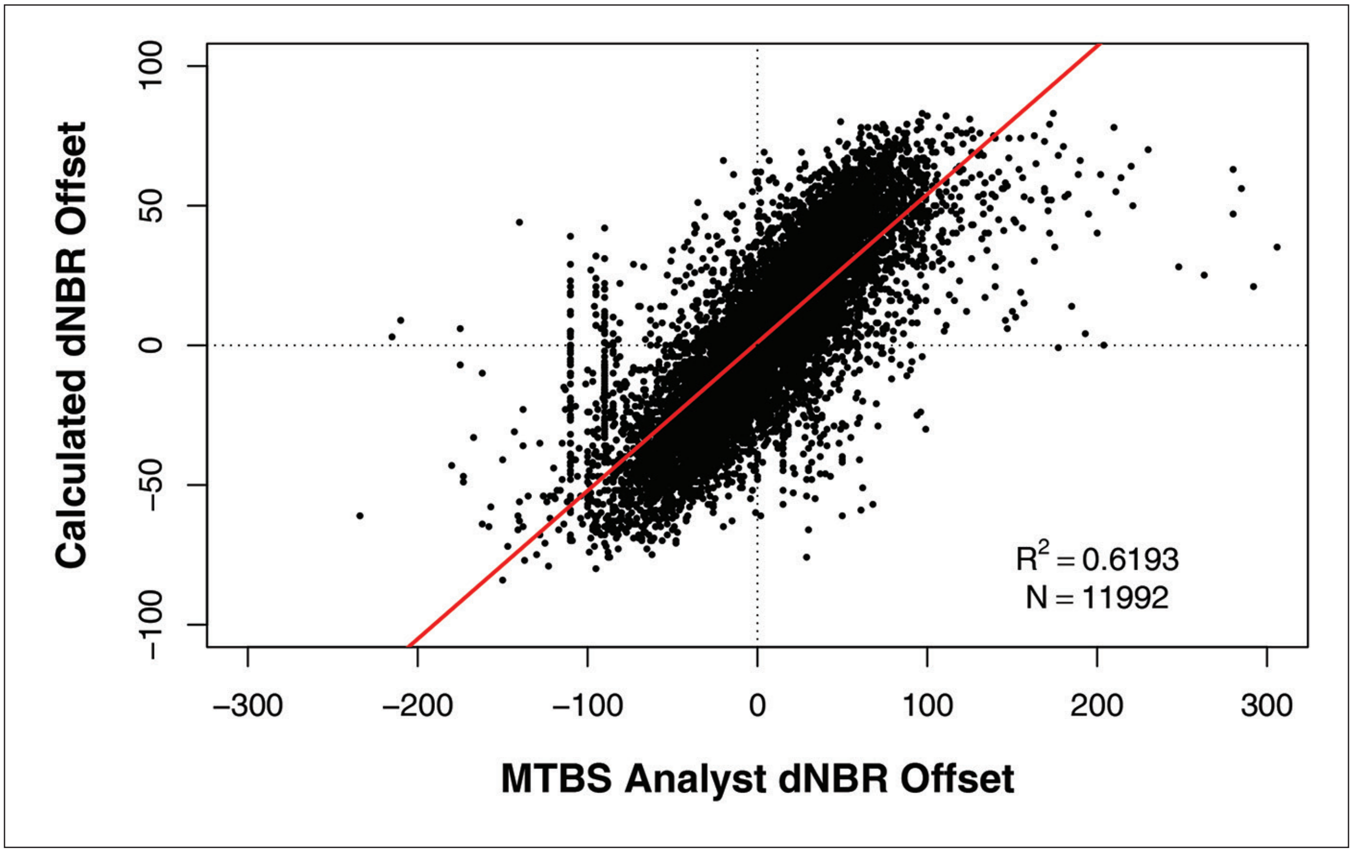

Figure 5—Linear regression between Monitoring Trends in Burn Severity (MTBS) analyst differenced Normalized Burn Ratio (dNBR) and calculated dNBR offset for 1984-2014 MTBS mapped fires.

Burn Severity Thresholding Comparison

Analyst and calculated low severity thresholds were similar for dNBR and exhibited a relatively high percent agreement (table 1). Moderate and high severity dNBR median thresholds exceeded the ±50 agreement threshold, although percent agreement for the moderate threshold was 41 percent. The percent agreement between analyst and calculated thresholds was always higher for dNBR (table 1) than for NBR (table 2) for all threshold groups.

The relationship between analyst and calculated NBR thresholds was poor, i.e., low percent agreement, for all severity threshold types (table 2). Calculated NBR burn severity thresholds were always much higher than the analyst-derived thresholds for all NBR threshold types. The difference between the analyst and calculated median NBR thresholds was only lower than the ±50 agreement threshold for high severity class.

Burn Mapping Example

The Paradise fire was mapped using the FMT in place of MTBS standard procedures. The main difference between these procedures for this example is that the dNBR offset and burn severity estimates were calculated using automated algorithms. Both the FMT calculated and MTBS analyst dNBR offset and offset standard deviation values were similar and < 50 (table 3). All dNBR burn severity thresholds were also similar (i.e., differed < 50) between the MTBS analyst and the FMT calculated values (table 3), which resulted in comparable burn severity classified images (fig. 6).

Table 1—Comparison between analyst and calculated dNBR burn severity threshold median values and standard deviations (StDev) for low, moderate, and high thresholds.

dNBR threshold	Analyst median	Analyst StDev	Calculated median	Calculated StDev	Sample size (N)	Agreement
Low	80	54.8	61	29.3	11,230	69%
Moderate	291	85.2	346	9.41	9,728	41%
High	510	123	590	78.6	7,395	28%

Table 2—Comparison between analyst and calculated NBR burn severity threshold median and standard deviations (StDev) values for low, moderate, and high thresholds.

NBR threshold	Analyst median	Analyst StDev	Calculated median	Calculated StDev	Sample size (N)	Agreement
Low	350	224.6	507	75.7	6089	22%
Moderate	-85	173	142	42.8	2245	10%
High	-200	152.3	-151	128.7	693	21%

Table 3—Comparison between MTBS analsyt and FMT calculated dNBR offset value, standard deviation (StDev), and burn severity breakpoints for low, moderate, and high thresholds for the June 15, 2015, Paradise fire.

	Low	Moderate	High	dNBR Offset Value	dNBR Offset StDev
MTBS analyst	100	321	588	15	27
FMT calculated	92	354	554	18	32

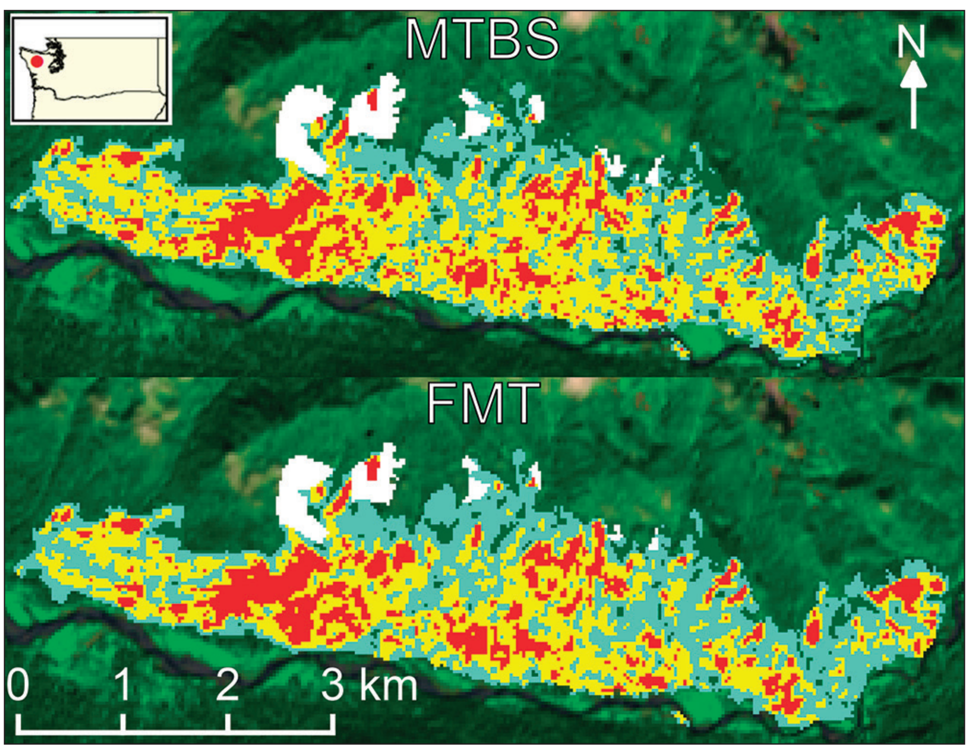

Figure 6—MTBS analyst and Fire Mapping Tool (FMT) burn severity images with unburned (dark green), low (mint green), moderate (yellow), and high (red) thresholds indicated for the June 15, 2015, Paradise Fire in the U.S. State of Washington (highlighted in inset map).

DISCUSSION

The FMT was developed to automate the MTBS fire perimeter and burn severity mapping procedures. The tool is fully functional and has the added features of automatically calculating dNBR offsets and burn severity thresholds. Comparisons between the MTBS analyst and FMT-derived dNBR offsets and burn severity thresholds by utilizing the 1984-2014 MTBS archive suggest that the FMT's dNBR offsets are comparable. However, suggested burn severity values may be very different from those obtained by MTBS analysts.

The MTBS analyst and calculated dNBR offsets were remarkably similar, given that they were calculated using different methodologies. This suggests FMT's methodologies may be adequate for calculating the dNBR offset. FMT users should make sure that the dNBR offset value is within the ±50 range and find different pre- and postfire NBR image pairs if it exceeds this range. A significant percentage of the calculated offsets and standard deviations were outside the ±50 range, suggesting that there was some problem with the underlying imagery. Large differences between pre- and postfire NBR values, reflected in higher dNBR and subsequently offset values, may indicate variation in hydrology (Picotte and Robertson 2011a), phenology (Key 2006; Verbyla et al. 2008; Zhu et al. 2006), solar illumination (Veraverbeke et al. 2010; Zhu et al. 2006), topographical illumination (Veraverbeke et al. 2010), snow (Zhu et al. 2006), and vegetation change (Picotte and Robertson 2010; Zhu et al. 2006). Many of these problematic offsets were also validated by the comparison with MTBS analyst offsets, which also suggests that the tool is providing an adequate approximation of the offset.

Unlike an MTBS analyst, the FMT calculation does not assess whether the vegetation is similar between the areas within the burned and unburned areas. More dNBR imagery was identified by MTBS analysts as having a dNBR offset outside the ±50 range than those using the algorithm within the FMT, potentially because of the much larger sample size of pixels in different vegetation types that may not be representative of those within the burned area. Alternatively, by selecting a limited number of pixels within the unburned areas, MTBS analysts may overemphasize the values of some pixels that are not representative of the vegetation type.

The restricted range in unburned dNBR pixel values examined by the tool compared to MTBS analysts could also lead to an underestimation of the dNBR offset value. The FMT's median range of dNBR offset and standard deviation values was lower than that of MTBS, which potentially indicates that the tool's range of unburned pixels is too narrow. However, increasing the undisturbed pixel range below -100 would potentially introduce pixel values of postdisturbance regrowth, and increasing the value above 100 would potentially increase the number of postdisturbance pixels considered in the calculation of the dNBR offset value (Key and Benson 2006). This narrower range was therefore necessary to control for other potential disturbances or image anomalies (e.g., cloud shadows) that were not masked.

Although the current version of the FMT attempted to threshold low, moderate, and high burn severity breakpoints by utilizing the ranges developed by previous research with CBI, relationships between the assessed MTBS analyst breakpoints suggest that the calculated approach can yield much different values. This is potentially because 31 percent of the dNBR scene pairs exhibited issues in the image pairs, which was suggested by the ±50 dNBR offset or standard deviation values. Nonfire variation between pre- and postfire images can result in changes to the unburned/low threshold estimates (Key 2005; Picotte and Robertson 2011b). MTBS analysts examine the imagery to determine at what point the low severity threshold begins to include only pixels within the fire perimeter. If dNBR values are high or NBR values are low because of some nonfire change (e.g., phenology) within the postfire imagery, then the MTBS analyst may adjust the threshold value to account for this change. This analyst threshold adjustment may therefore be mostly due to the vegetation change in the imagery not resulting from fire.

Although the FMT was developed to automatically calculate burn severity thresholds based on past CBI thresholding efforts, there were limitations inherent in this approach. Burn severity estimated from dNBR/NBR and CBI has not been assessed in all burnable vegetation types, which may introduce error since severity thresholds can be directly related to vegetation type (Picotte and Robertson 2011b). The threshold ranges were developed from a limited number of studies and simplified to attempt to account for multiple vegetation communities. Another potential problem with the FMT's thresholding methodology is that time-since-fire is not considered when thresholding for burn severity. Time between fire and postfire image capture can directly influence the range of the burn severity breakpoints (Picotte and Robertson 2011b).

Comparisons between the calculated and MTBS methodology of determining low, moderate, and high severity breakpoints potentially suffers from the flaw that MTBS does not consistently map low, moderate, and high severity thresholds, although some effort was made for between-analyst cross calibration of burn severity thresholds (Eidenshink et al. 2007). Kolden et al. (2015) found that threshold breakpoints overlapped between severity classes, which indicates that MTBS thresholds can be subjective. This suggests that the non-overlap between the calculated and MTBS thresholds, especially for NBR thresholds, may not be problematic. The FMT's thresholding procedures have been developed to provide a more standardized and efficient framework for estimating burn severity.

CONCLUSIONS

Utilizing the FMT within the QGIS environment should allow users to quickly map postfire burn perimeters and severity using Landsat imagery. Most of the MTBS fire mapping capabilities have been automated within the FMT to assist users in producing MTBS-like products. The FMT has additional capabilities, including the dNBR offsetting and burn severity thresholding processes, which should provide a starting point for assessing the burn severity of fires.

More work needs to be done with the burn severity thresholding algorithms to tie remotely sensed estimates of burn severity with ground estimates, such as CBI. This would allow for a more direct comparison between mapped burn severity and actual on the ground metrics of burn severity, as suggested by Kolden et al. (2015) in their critique of MTBS data products. In the future, if more universal relationships between NBR or dNBR and CBI are developed via regression equations for specific vegetation types, it would be possible to integrate these equations into the FMT tool.

Although there has been extensive testing with the FMT, there are still potentially problems (i.e., bugs) that users will encounter. There are currently plans to keep the tool updated for the foreseeable future to deal with these potential problems. Additional capabilities to aid the user in mapping fires may also be added in the future, although no plans have been formulated for these tool improvements.

Because the FMT is open-source, freely available, and should work anywhere in the world, it is envisioned that this tool could help other countries develop an MTBS-like program. As previously mentioned, users should be careful especially when using the burn severity capabilities of the tool. The automated burn severity suggestions within the FMT may not work for vegetation communities outside the United States. If possible, users should use ground-collected data (e.g., CBI) to validate their burn severity thresholds.

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