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Identifying opportunities for the use of broadcast prescribed fire on Colorado's Front Range

Robert N. Addington[a,*], Brian G. Tavernia[a,1], Michael D. Caggiano[b], Matthew P. Thompson[c], Jason D. Lawhon[a,2], John S. Sanderson[a,3]

[a] The Nature Conservancy, Colorado Field Office, 2424 Spruce Street, Boulder, CO 80302, United States
[b] Colorado Forest Restoration Institute, Colorado State University, Fort Collins, CO 80523, United States
[c] USDA Forest Service, Rocky Mountain Research Station, 240 West Prospect Road, Fort Collins, CO 80523, United States

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ABSTRACT

Increasing the pace and scale of fuel treatments to protect social and ecological values from severe wildfire is a major initiative of numerous land management agencies, organizations, and collaborative groups throughout the western United States, including the Colorado Front Range. Broadcast prescribed fire is a relatively low-cost, effective management tool for achieving fuels reduction at scale but is often challenging to implement due to complex socio-ecological factors. We present results of a multi-criteria suitability analysis intended to identify need, opportunities, and constraints for the use of broadcast prescribed fire on Colorado's Front Range based on spatial factors including wildfire hazard, vegetation and fuel types, historical fire regimes, presence of existing fuel treatments, wildland-urban interface development, and predicted prescribed fire behavior. Within our 1.7 million-hectare (ha) analysis area, over 228,000 ha (approximately 13%) were classified as highly suitable for broadcast prescribed fire. Areas of high suitability were split roughly 50:50 between public federal lands (5.3%) and private lands (6.1%), emphasizing the importance of implementing prescribed fire across ownerships to meet management objectives at scale. Patch size analysis revealed opportunities for large-scale (> 500 ha) prescribed fire projects spatially distributed throughout the Front Range. These areas may serve as anchors for developing projects focused on protecting values at risk, including wildland-urban interface communities and water resources. Results of this analysis can be used in collaborative settings to develop comprehensive fuels reduction and forest restoration strategies that incorporate the use of prescribed fire, including identifying where mechanical treatments could be applied on the landscape to facilitate the use of broadcast prescribed fire over large extents, as well as where prescribed fire may be a viable option for long-term maintenance of treatments. While our analysis focuses on the Colorado Front Range, it can be replicated in other fire-prone areas of the western United States based on the availability of local data.

1. Introduction

Like many fire-prone regions of the western United States, the Colorado Front Range has experienced numerous large, high-severity fires in recent decades (Lynch, 2004; Graham et al., 2012). In many cases, these fires have adversely impacted social and ecological values, including life and property, natural resources, and ecosystem services (Lynch, 2004). Heavy fuel loads, high forest densities, human ignitions, drought and extreme fire weather (e.g., high temperatures, winds, and low relative humidity) have all been cited as contributing factors to wildfire on the Front Range (FRFTPR, 2006; Hunter et al., 2007; Balch et al., 2017), while extensive exurban development within the wildland-urban interface has increased the exposure of human values to wildfire (Calkin et al., 2014; Liu et al., 2015).

Fuel treatments have increased in response to wildfire activity throughout the western United States. Fuel treatments change the amount and arrangement of vegetation by mechanically and/or manually removing vegetation, often combined with some form of treating residual slash through practices such as mastication, lop-and-scatter, or pile burning (Hunter et al., 2007; Reinhardt et al., 2008;

* Corresponding author.
E-mail address: raddington@tnc.org (R.N. Addington).
[1] Present address: National Audubon Society, 231 West 800 South, Ste. E, Salt Lake City, UT 84101, United States.
[2] Present address: USDA Forest Service, Rocky Mountain Region, 1617 Cole Boulevard, Lakewood, CO 80401, United States.
[3] Present address: Center for Collaborative Conservation, Colorado State University, Fort Collins, CO 80523, United States.

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Collins et al., 2010). Broadcast prescribed fire, defined as the deliberate burning of wildland fuels under specified environmental conditions (Helms, 1998), is another important management practice to achieve fuels reduction objectives. In general, fuel treatments are aimed at reducing canopy cover and surface and ladder fuel loads to reduce the potential for active crown fire, or the spread of fire through the forest canopy (Agee and Skinner, 2005; Hunter et al., 2007; Stephens et al., 2012). These practices often also seek to protect values at risk and create tactical opportunities for fire suppression. Restoration-based treatments may go further to incorporate additional natural resource benefits such as wildlife habitat enhancement, and they typically also consider stand spatial structure and enhancing features such as openings and groups of trees (Larson and Churchill, 2012; Addington et al., 2018).

Despite increased emphasis on fuel treatments, recent analyses suggest that the current scale of treatments is insufficient to restore landscape-scale forest structure, composition, and characteristic fire regimes (North et al., 2012; Vaillant and Reinhardt, 2017; Kolden, 2019). Several recent studies point to the need for increased use of broadcast prescribed fire as a means of scaling up fuel treatments beyond mechanical treatments alone (North et al., 2012; Stephens et al., 2016; Walker et al., 2018). Prescribed fire can often be applied over larger extents and in areas inaccessible to mechanical equipment due to terrain or lack of roads (Hunter et al., 2007). Prescribed fire is also typically less expensive compared to other fuels reduction practices, and thus represents a more economically viable treatment option, especially for the long-term maintenance of treatments (Hunter et al., 2007; Hartsough et al., 2008; North et al., 2012). Prescribed fire is particularly important in reducing surface fuels following mechanical treatments, with several recent studies showing that mechanical treatments not followed by prescribed fire are less effective – and in some cases ineffective – in changing wildfire behavior (Graham et al., 2012; Martinson and Omi, 2013). Prescribed fire also reestablishes a keystone ecological process important for nutrient cycling, regeneration of fire-adapted vegetation, and maintenance of habitat features for fire-dependent fauna that cannot be mimicked with mechanical treatments alone (Falk, 2006; Reinhardt et al., 2008; Stephens et al., 2012; Ryan et al., 2013; Hmielowski et al., 2016). Yet, despite these benefits, broadcast prescribed fire is often challenging to implement due to a host of factors, including high fuel loads, proximity to values at risk within the wildland-urban interface, weather conditions, smoke management and air quality regulations, agency resource capacity, and political and social license (Gass, 2008; Collins et al., 2010; Quinn-Davidson and Varner, 2012; Stephens et al., 2012; Ryan et al., 2013; Kolden, 2019; Schultz et al., 2019).

Spatially identifying opportunities and constraints for broadcast prescribed fire can help to address implementation challenges and can inform comprehensive landscape-scale fuels reduction and forest restoration strategies that incorporate prescribed fire (Hiers et al., 2003; Hmielowski et al., 2016). In this paper, we present a multi-criteria suitability analysis for the use of broadcast prescribed fire in managing fuels and forest structure on Colorado's Front Range. We spatially evaluated opportunities and constraints for the use of prescribed fire, including wildfire hazard, forest and fuel types, historical fire regimes, existing fuel treatments, wildland-urban interface values, and prescribed fire behavior. We asked three questions in our analysis: (1) how much area in total is suitable for broadcast prescribed fire on the Front Range and what is the spatial distribution; (2) how are suitable prescribed fire areas distributed according to land ownership; and (3) how much opportunity exists for planning large-scale (> 500 ha) prescribed fire projects? Cumulatively these questions are designed to identify opportunities for the development of prescribed fire projects among a wide range of agencies, organizations, and collaborative groups involved in fuel treatments on the Colorado Front Range.

2. Methods

2.1. Analysis area

The Front Range represents the eastern face of the southern Rocky Mountains where the Rocky Mountain physiographic province meets the Great Plains (Fenneman, 1931). The Front Range extends from southern Wyoming to southern Colorado and is characterized by a highly populated urban corridor containing the cities of Denver, Colorado Springs, Boulder, and Fort Collins. Dominant vegetation types include grasslands and shrublands at lower elevations (below approximately 1600 m) that transition to ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) woodlands and mixed-conifer forests at intermediate elevations (approximately 1800 m–2500 m), and to lodgepole pine (*Pinus contorta* Douglas ex Loudon) and spruce-fir (*Picea engelmannii* Parry ex. Engelm – *Abies lasiocarpa* (Hook.) Nutt.) vegetation types at higher elevations (approximately 2700 m–3500 m) (Marr, 1961; Peet, 1981; Veblen and Donnegan, 2005). Historically, the Front Range was characterized by a mixed-severity fire regime, with low-severity fire occurring at regular intervals (< 20-year fire return interval) at lower elevations and transitioning to less frequent, mixed- and high-severity fire at higher elevations (Veblen et al., 2000; Kaufmann et al., 2006; Hunter et al., 2007; Sherriff et al., 2014; Addington et al., 2018).

Within the larger Front Range landscape, we selected a sub-region of the Southern Rocky Mountain ecoregion encompassed by a nine-county area for our analysis (Fig. 1). This analysis area represents the focal area of the Front Range Roundtable, a collaborative fuels and forest management group on the Front Range (FRFTPR, 2006). The analysis area was approximately 1.7 million hectares in size and contained a diverse mix of land owners, including public federal lands (e.g., National Forest System and National Park Service lands), public non-federal lands (e.g., state, county, and municipal lands), land-trust lands, and private lands.

2.2. Structure of the suitability analysis

Across the study area, we calculated suitability for prescribed fire in a continuous grid of 270 m (7.29 ha). We defined suitability as the product of five factors that govern decisions about where prescribed fire can be implemented (Table 1). These factors represent the need for fuel treatment based on wildfire hazard, the appropriateness of vegetation types and management units for prescribed fire, and two major constraints on where prescribed fire can be used: proximity of infrastructure within the wildland-urban interface and predicted fire behavior. Specifically, prescribed fire suitability (S) was calculated as:

$$S = WH * VFH * T * WUI * PFB \tag{1}$$

where WH, VFH, T, WUI, and PFB are suitability factors, scaled 0–1, corresponding to wildfire hazard (WH), vegetation-fuels-historical fire (VFH), treatment history (T), wildland-urban interface (WUI), and prescribed fire behavior (PFB). Each of these factors is described in detail below. Unless otherwise indicated, all geoprocessing was done in the GIS software ArcMap 10.3 (Environmental Systems Research Institute [ESRI], Redlands, CA, USA).

2.2.1. Wildfire hazard (WH)

We included wildfire hazard in the analysis because a primary goal of broadcast prescribed fire on the Front Range is to reduce hazardous fuels. We adopted Scott et al.'s (2013) definition of wildfire hazard, which integrates both burn probability and fire intensity. To develop a wildfire hazard layer for the Front Range, we used 270-m resolution burn probability (BP) and conditional fire intensity (FIL) layers from the National Fire Simulation System (FSim) data product (Finney et al., 2011; Short et al., 2016). FSim modeled wildfire occurrence and growth under tens of thousands of hypothetical wildfire seasons that incorporate a range of weather and fuel moisture conditions and fire

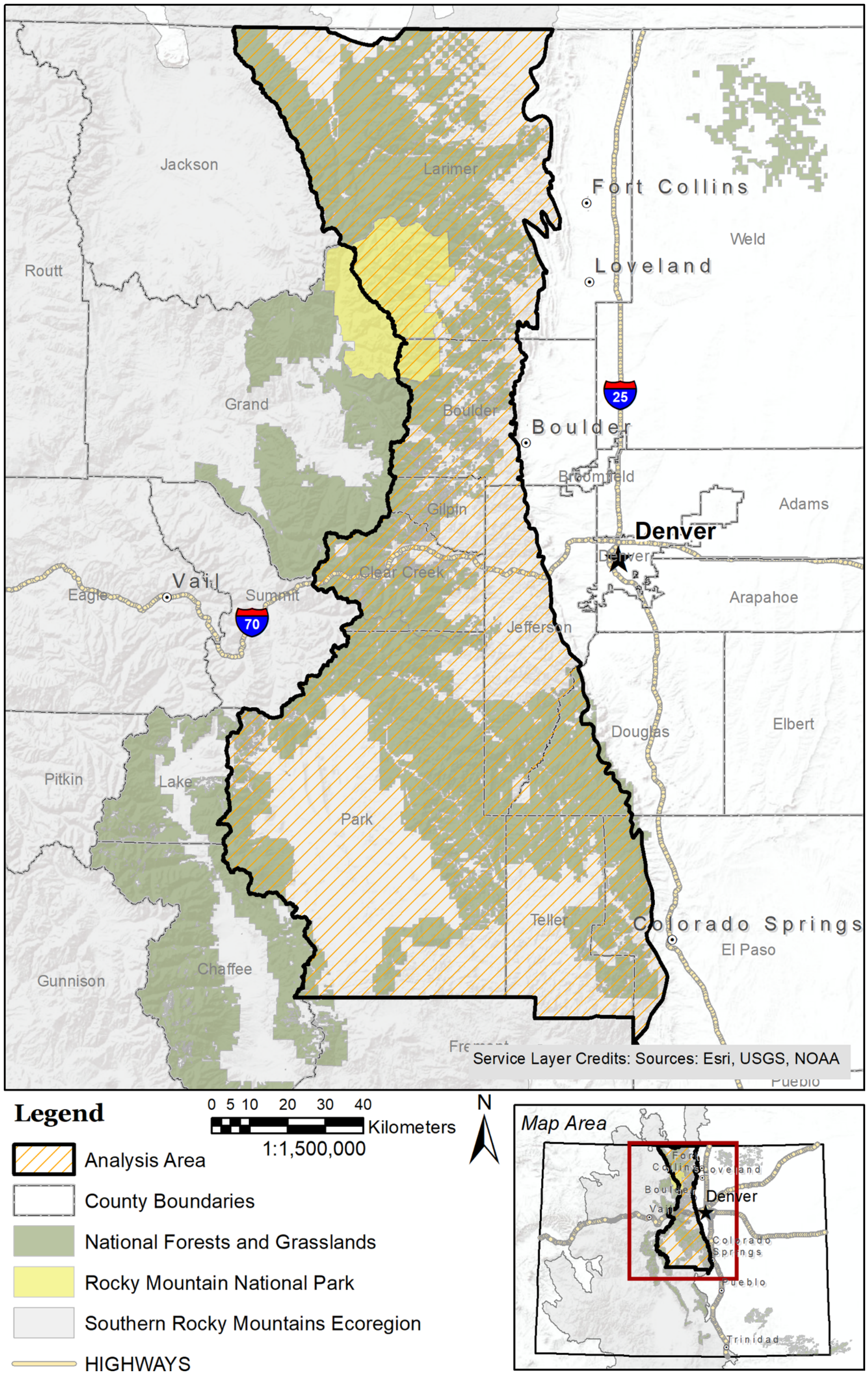

Fig. 1. Colorado Front Range analysis area encompassing a nine-county area within the Southern Rocky Mountain ecoregion.

suppression tactics. The FSim data product is based on LANDFIRE (Rollins, 2009; https://www.landfire.gov) data layers from 2012 (Short et al., 2016). The BP layer represents the number of times a grid cell burns divided by the total number of wildfire seasons simulated. Given that a grid cell burns, FIL represents the probability of fires with flame lengths of: < 0.61 m; 0.61 < 1.22 m; 1.22 < 1.83 m; 1.83 < 2.44 m; 2.44 < 3.66 m; or > 3.66 m. Fires with ≥1.22 m flame lengths cannot be suppressed by direct attack with hand tools and handline, based on fire behavior hauling charts (Andrews and Rothermel, 1982). We summed probabilities for FIL classes ≥1.22 m and multiplied this layer by the burn probability layer to develop a continuous surface of wildfire hazard where 0 represents low hazard (conversely, low priority for prescribed fire) and 1 represents high hazard (high priority) (Table 2; Fig. 2A).

2.2.2. *Vegetation-fuels-historical fire (VFH)*

Prescribed fire is most often applied on the Front Range in vegetation types that are adapted to relatively high-frequency, low-intensity fires. To identify opportunities for the use of prescribed fire, we combined layers representing existing vegetation, fuel loads, and historic low-severity fire regime. We mapped existing plant communities and fuel loads using 30-m resolution, 2012 existing vegetation type (EVT)

Table 1
Spatial factors for evaluating broadcast prescribed fire suitability on the Colorado Front Range.

Spatial Factors	Suitability
Wildfire hazard	Prioritize areas where integrated wildfire hazard (burn probability × conditional fire intensity level) is high to achieve hazardous fuels reduction and wildfire risk mitigation objectives
Vegetation type, fuels, and historical fire regimes	Prioritize fire-prone vegetation types (e.g., ponderosa pine woodlands and dry mixed-conifer forests), as well as grass, grass-shrub, timber-understory, and timber-litter fuel models. Prioritize areas of historical low-severity fire based on the model of Sherriff et al. (2014)
Existing fuels reduction and forest restoration treatments	Prioritize areas previously treated by mechanical treatments and prescribed fires
Wildland urban interface	Prioritize areas that are outside of the wildland urban interface, defined as areas greater than or equal to 1 home per 16 ha (USDA and USDI, 2001)
Prescribed fire behavior	Prioritize areas where predicted fire behavior under prescribed fire weather and fuel moisture conditions is mild to moderate (< 2.44 m flame lengths)

Table 2
Factors, criteria, and suitability scores for evaluating areas of high opportunity for broadcast prescribed fire. See Table 3 for more information about suitable vegetation types and fuel models.

Factors	Criteria			Score
Wildfire hazard	Continuous hazard surface			0–1
Vegetation type; fuels; historical fire regime	Vegetation type	Fuel model	Historical fire	
	High suitability	High suitability	Low-severity	1.00
	High suitability	High suitability	Mixed-severity	0.50
	Low suitability	Low suitability	Low-severity	0.50
	Low suitability	Low suitability	Mixed-severity	0.25
	No suitability	No suitability	Mixed-severity	0.00
Existing treatments	Mechanical or manual treatment (since 2002)			1.00
	Prescribed fire (since 2002)			0.95
	Mechanical or manual treatment (unknown year)			0.90
	Unknown treatment			0.80
	No treatment			0.50
Wildland urban interface	Non-WUI			1.00
	WUI ($\geq$6.17 buildings/km^2 to < 123.55 buildings/km^2)			0.50
	WUI ($\geq$123.55 buildings/km^2)			0.25
Prescribed fire behavior (flame length, m)	16.1 km/h*	32.2 km/h		
	< 1.22	< 1.22		1.00
	< 1.22	1.22–2.44		0.80
	< 1.22	> 2.44		0.20
	1.22–2.44	1.22–2.44		0.60
	1.22–2.44	> 2.44		0.10
	> 2.44	> 2.44		0.00

* 6.1 m wind speeds used in FlamMap to represent a midflame wind speed of 4.8–16.1 km/h based on adjustment factors for partially sheltered and unsheltered fuels provided in Andrews (2012).

and fire behavior fuel model (FBFM) layers from LANDFIRE. The EVT layer represents broad vegetation complexes based on Landsat imagery, field referenced vegetation training databases, and biophysical gradients (Rollins, 2009), while the FBFM layer represents fuel types and fire behavior predictions under various fuel moisture and weather conditions, based on Scott and Burgan (2005). We chose the 2012 layers and aggregated them to 270 m to match the vintage and resolution of BP and FIL layers.

Areas historically characterized by a low-severity fire regime were also mapped by applying the model of Sherriff et al. (2014), which identifies historical low-severity fire regimes for a subset of EVTs as occurring primarily below 2263 m in elevation or above 2263 m on gentle slopes ($\leq 4°$). We mapped areas meeting these elevational and topographic criteria using a 30-m resolution digital elevation model (DEM) layer available from LANDFIRE, and we aggregated the resulting layer to a resolution of 270 m. We filtered the layer to apply only to the subset of EVTs identified in Table S1 of Sherriff et al. (2014). Note that we assumed the model could be extended south into three counties (El Paso, Park, and Teller) not included in Sherriff et al.'s (2014) study.

We overlaid our EVT, FBFM, and historical fire regime layers and assigned suitability scores to unique combinations of these three layers (Table 2). For EVT and FBFM layers, we considered supporting information, such as biophysical setting descriptions provided by LANDFIRE and the judgements of local fire managers in determining suitability. For example, dry coniferous vegetation types such as ponderosa pine woodlands and grass and grass-shrub fuels models were deemed highly suitable. We combined the EVT and FBFM layers to identify overlap of suitable vegetation types with suitable fuel models, as well as to identify areas where vegetation types may be suitable but where fuel models suggested heavy surface fuel loads. In the latter case, we downgraded suitability scores based on fuel model designations. We incorporated the historical fire regime layer to further refine suitability determinations based on areas characterized by low-severity fire, but also retained areas mapped as mixed-severity fire historically (Table 2; Fig. 2B).

2.2.3. *Treatment areas (T)*

We expected previously treated areas to be highly suitable for

Table 3
Suitability determinations for primary (> 1% of analysis area) existing vegetation types and fire behavior fuel models contained within the LANDFIRE database for the Front Range analysis area.

Existing Vegetation Type (EVT)	Suitability
Southern Rocky Mountain Ponderosa Pine Woodland	High
Southern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest and Woodland	High
Inter-Mountain Basins Aspen-Mixed Conifer Forest and Woodland	High
Colorado Plateau Pinyon-Juniper Woodland	High
Southern Rocky Mountain Pinyon-Juniper Woodland	High
Rocky Mountain Lower Montane-Foothill Shrubland	High
Western Great Plains Shortgrass Prairie	High
Southern Rocky Mountain Mesic Montane Mixed Conifer Forest and Woodland	Low
Rocky Mountain Lodgepole Pine Forest	Low
Rocky Mountain Aspen Forest and Woodland	Low
Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland	None
Fire Behavior Fuel Model (FBFM)	**Suitability**
Grass (GR1, GR2, GR3, GR4)	High
Grass-Shrub (GS1, GS2)	High
Shrub (SH1, SH2, SH5, SH7)	High
Timber-Understory (TU1)	High
Timber-Litter (TL1, TL2, TL3, TL6, TL8, TL9)	High
Timber-Understory (TU5)	Low
Timber-Litter (TL4, TL5)	Low

broadcast prescribed fire as fuels have already been reduced in these areas and prescribed fire can help to maintain treatment effectiveness and desired forest structure and composition. We incorporated this dimension into our analysis considering the type, location, and timing of existing fuels reduction and forest restoration treatments based on a comprehensive interagency database of treatments on the Front Range (Caggiano, 2017). We included mechanical, manual, and prescribed fire treatments that had occurred since 2002, with the assumption that treatments prior to 2002 may no longer be considered effective and suitable for prescribed fire based on a general treatment lifespan of about 15 years (Hunter et al., 2007; van Mantgem et al., 2016). We created a 270-m raster layer in which we assigned highest suitability to grid cells mechanically and manually treated but not yet treated by prescribed fire (Table 2; Fig. 2C). We also included areas previously treated by prescribed fire but gave these areas slightly lower suitability scores relative to mechanically and manually treated areas, recognizing that these areas have already been treated with fire, but that repeated burning is important to maintain treatment effectiveness and increase treatment longevity.

2.2.4. Wildland-urban interface (WUI)

The presence of homes and other infrastructure can greatly constrain the use of prescribed fire. We factored this constraint into our analysis by mapping the wildland-urban interface (WUI), based on the definition of the WUI as any area within the wildland fuel matrix containing at least 6.17 housing units/km^2 (equivalent to at least 1 housing unit per 16.2 ha) (USDA and USDI, 2001; Radeloff et al., 2005). To map the WUI, we incorporated a database created by Caggiano et al. (2016) that utilized an object-based image analysis and supervised classification to extract building locations from 2013 National Agriculture Imagery Program (NAIP) imagery. The method results in building extraction accuracy greater than 95% at a precision of 100 m. We converted the point feature database into a 270-m resolution grid layer to represent building density by counting the number of buildings within a 16.2 ha circle centered on each 270 m grid cell. We gave WUI areas a lower suitability score compared to non-WUI areas and increased constraints on prescribed fire where building densities exceeded 123.55 buildings/km^2 (equivalent to 1 building per 0.81 ha) (Table 2; Fig. 2D). This approach provides a gradient of suitability within the WUI, recognizing that prescribed fire can occur within WUI settings but will likely become increasingly difficult to implement as building density increases due to factors such as smoke management and obtaining burn permits.

2.2.5. Prescribed fire behavior (PFB)

While the use of prescribed fire as a management tool is intended to reduce hazardous fuels, it cannot be implemented where predicted prescribed fire behavior may exceed holding capacities and escape containment. We used FlamMap, a landscape fire behavior model (Finney, 2006), to model fire behavior under prescribed fire weather and fuel moisture conditions. Base inputs to FlamMap including canopy cover, canopy height, canopy base height, canopy bulk density, fuel models, and terrain were gathered from LANDFIRE. We compiled fuel moisture values from various burn plans on the Front Range selected to represent a range of prescribed fire projects in both the southern Front Range (El Paso County) and the northern Front Range (Larimer County) (e.g., The Nature Conservancy, 2017). Fuel moisture inputs were as follows: 1 h fuel moisture of 7%; 10 h fuel moisture of 8%; 100 h fuel moisture of 9%; live herbaceous and woody fuel moisture of 50% and 150%, respectively. We used 6.1 m wind speeds of 16.1 km/h and 32.2 km/h to equate to midflame wind speeds of 4.8 km/h–16.1 km/h, which are desirable for prescribed fire operations (Kilgore and Curtis, 1987; Sackett et al., 1996). Wind adjustment factors for partially sheltered and unsheltered fuels were used to convert 6.1 m wind speeds to midflame wind speeds (Andrews, 2012). We assigned areas where predicted flame lengths were less than 1.22 m the highest suitability, followed by areas with flame lengths between 1.22 and 2.44 m, and areas greater than 2.44 m (Table 2; Fig. 2E). This approach allows for higher flame lengths under prescribed fire fuel moisture and weather conditions, as mixed-severity fire effects are a desirable outcome for prescribed fire on the Front Range.

We elected not to use features such as land ownership, administrative designations (e.g., Wilderness Area designations), and operational and containment features (e.g., roads) as initial constraints in the analysis. While such constraints exist on the Front Range, we felt that they could be incorporated post hoc at the burn planning stage when delineating prescribed fire project areas or individual burn units, as discussed in more detail below.

2.3. Overall suitability and validation

Overall prescribed fire suitability was calculated for each grid cell using Eq. (1) above. The overall suitability layer contained values ranging from 0 to 0.587. We used quantile classification to identify six suitability bins (with suitability ranges parenthetically noted): none (0), low (0–0.00204), low-moderate (0.00204–0.00637), moderate (0.00637–0.0159), moderate-high (0.0159–0.0427), and high suitability (0.0427–0.587). Quantile classification places an equal number of observations in each class and was chosen over other classification methods based on the distribution of the data and to reduce subjectivity associated with classification techniques such as manual breaks. We subsequently assigned each class a score from 1 to 6, with lowest or no suitability receiving a 1 and highest suitability a 6. We did this to make the final model outputs more interpretable and applicable to managers, and for model validation purposes, as described in more detail below.

To evaluate model performance, we compared our results to a sample of recently completed and planned prescribed fire projects on the Front Range. These projects were not part of the comprehensive fuels treatment database that served as one of the inputs to the analysis, and thus they serve as an independent check of model results. Using the suitability classes on a scale of 1–6, we calculated mean suitability for individual prescribed fire projects using the Zonal Statistics tool in ArcMap. We considered scores between 4 and 6 as being most suitable for prescribed fire.

To evaluate how prescribed fire suitability is distributed among land

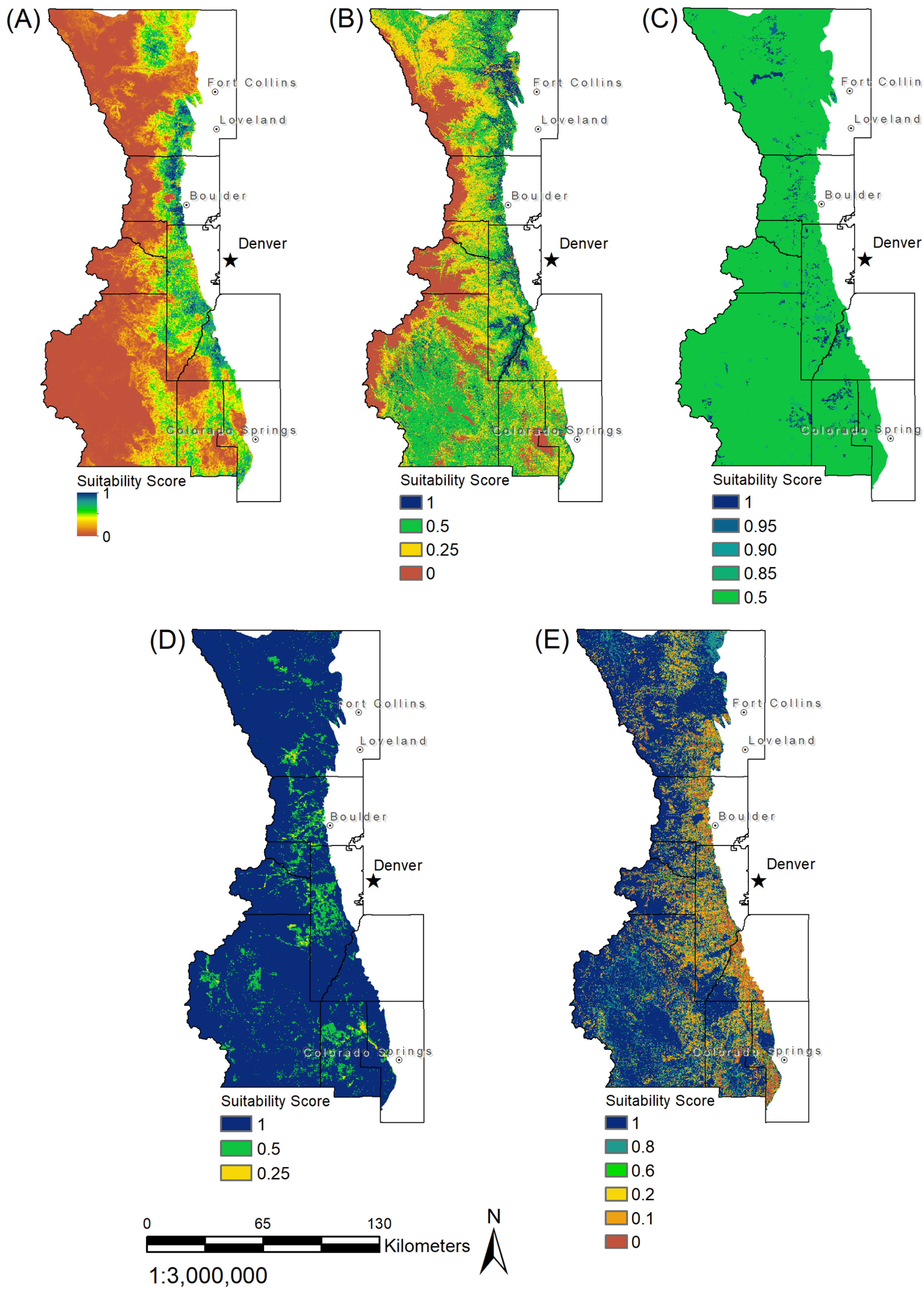

Fig. 2. Individual suitability layers used to determine overall suitability for broadcast prescribed fire on the Front Range, including (A) wildfire hazard (WH), (B) vegetation types, fuels, and areas of historical low-severity fire (VFH), (C) existing treatment areas (T), (D) wildland-urban interface (WUI), and (E) prescribed fire behavior (PFB).

Table 4
Suitability scores for recently implemented and planned burn units to serve as an independent validation of the suitability analysis. Mean suitability represents the spatial average of pixel suitability scores within each burn unit calculated using the Zonal Statistics tool in ArcMap. Suitability is on a scale of 1–6, with 1 being lowest suitability and 6 being highest suitability. Scores between 4 and 6 are considered moderately to highly suitable for prescribed fire.

Burn Unit	Size (ha)	Suitability
1	6.1	6.0
2	24.7	5.0
3	32.0	4.2
4	40.0	5.8
5	51.0	4.4
6	80.2	4.9
7	87.5	4.6
8	102.1	5.0
9	109.4	4.2
10	174.9	5.1
11	189.5	5.0
12	211.4	5.3
13	277.0	4.9
14	306.2	4.8
15	393.7	5.0
16	400.9	5.0
17	546.8	5.1
18	845.6	5.0

ownership categories, we used the Colorado Ownership, Management and Protection (COMaP) version 10 (CNHPGC, 2017) and tabulated acres within each suitability class by ownership categories. Land ownership categories included federal, state/county/municipal, land trust/non-governmental organization, and private lands.

2.4. Patch size analysis

We used Fragstats v. 4.2.1.603 (McGarigal et al., 2012) to quantify patch sizes for the high suitability class. Patches were defined using the 4-neighbor rule, i.e., a cell had to be adjacent to another cell of the same suitability class in one of the cardinal directions. We acknowledge that high suitability patches may be adjacent to moderate or low suitability pixels that could be incorporated into a larger prescribed fire project. However, limiting the output to the high suitability class can help to identify anchors around which large prescribed fire projects can be developed.

3. Results

Model validation suggested that the model performed well in identifying suitable areas for broadcast prescribed fire, based on an evaluation of 18 planned or recently completed prescribed fire projects (Table 4). These projects were spatially distributed throughout the Front Range and represented a range of project scales, from approximately 6 ha to greater than 500 ha. Mean suitability for individual prescribed fire projects ranged from 4.2 to 6.0, with an average of 5.0 across projects.

The composite map of prescribed fire suitability across our 1.7 million ha analysis area showed over 228,000 ha in the high suitability class (Fig. 3; Table 5). Spatially, areas of high suitability were distributed throughout the Front Range, with some concentrations in the northern and southern Front Range (Fig. 3). Strong elevational and topographical gradients emerged as well, with areas of high suitability occurring primarily in lower-elevation settings and in gentle terrain at higher elevations. These spatial patterns are driven largely by the wildfire hazard (WH) and vegetation-fuels-historical fire (VFH) layers. Highest wildfire hazard exists in lower-elevation settings of the Front

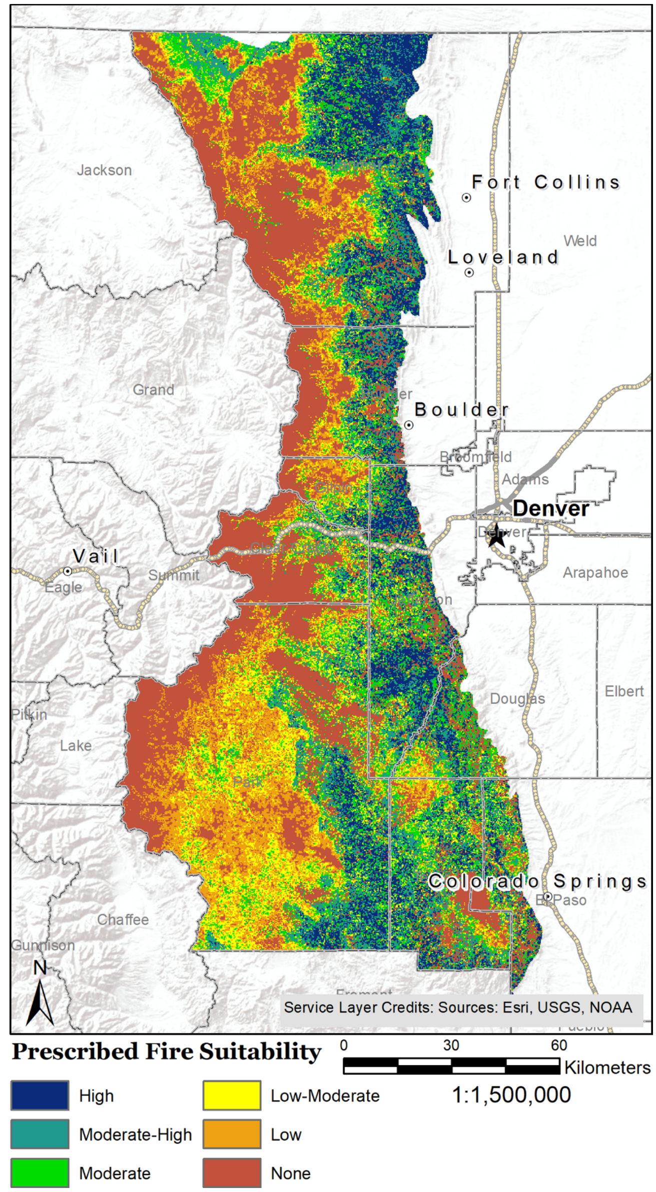

Fig. 3. Overall suitability for broadcast prescribed fire on the Front Range based on wildfire hazard, vegetation types, fuels, and areas of historical low-severity fire, existing treatment areas, wildland urban interface, and prescribed fire behavior.

Range, as do dry forest types historically adapted to low- and mixed-severity fire (Fig. 2A and B). Areas of low to no suitability occurred mostly in higher-elevation settings where wildfire probability is low and where subalpine and alpine vegetation types occur. Densely populated areas of the wildland-urban interface were also low in suitability due to constraints incorporated into the analysis as building densities increased (Fig. 2D).

Land ownership within our analysis area consists primarily of federal National Forest System lands and private lands. Federal lands make up approximately 970,000 ha (57% of the analysis area) while private lands occupy over 600,000 ha (35% of the analysis area) (Table 5). Areas of high suitability for prescribed fire were split roughly 50:50 between public federal lands (5.3%) and private lands (6.1%), with an additional 1.8% on state, county, and municipal lands. Of the 970,000 ha of public federal lands, 89,834 ha were in the high suitability class, representing 9.3% of the public federal lands area.

Table 5
Area (ha) and percentage of the Front Range analysis area by suitability class and land ownership category. St/Co/Mun stands for State/County/Municipal lands and LT/NGO represents lands owned by land trusts or non-governmental organizations.

Ownership	Suitability Class						
	High	Moderate-High	Moderate	Low-Moderate	Low	None	Total
Federal	89,834 (5.3%)	102,475 (5.9%)	117,769 (6.9%)	111,704 (6.5%)	117,850 (6.9%)	428,600 (25.1%)	968,235
St/Co/Mun	30,195 (1.8%)	18,735 (1.1%)	16,140 (0.9%)	17,058 (1.0%)	14,667 (0.9%)	23,867 (1.4%)	120,664
LT/NGO	3,032 (0.2%)	2,019 (0.1%)	2,026 (0.1%)	2,361 (0.1%)	43,300 (0.3%)	6,174 (0.4%)	19,945
Private	105,019 (6.1%)	104,195 (6.1%)	92,925 (5.4%)	96,920 (5.7%)	91,321 (5.3%)	109,678 (6.4%)	600,061
Total	228,082	227,426	228,862	228,045	228,169	568,321	1,708,907

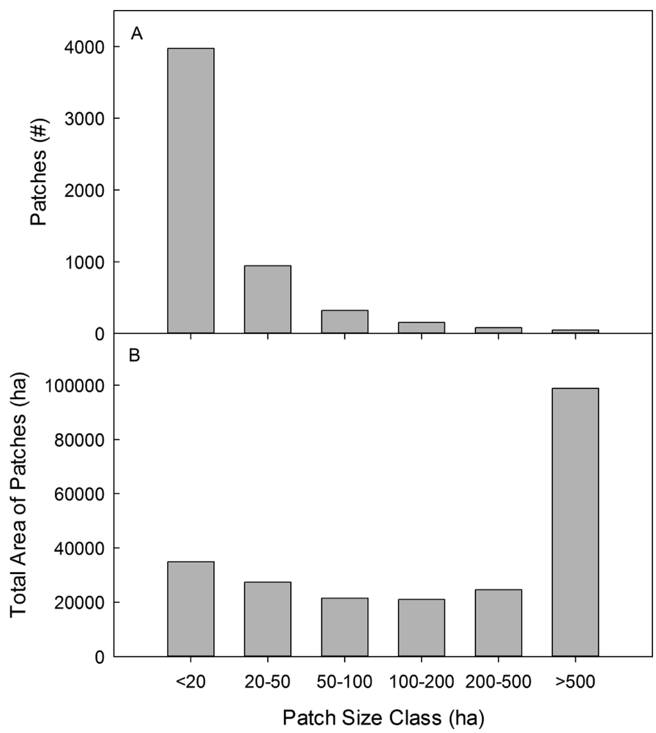

Fig. 4. (A) Number and (B) total area (ha) of high suitability patches for prescribed fire by patch size class on the Front Range. High suitability patches were determined using the 4-neighbor rule in Fragstats, whereby high suitability pixels adjacent in one of the cardinal directions were grouped together to define patches of high suitability.

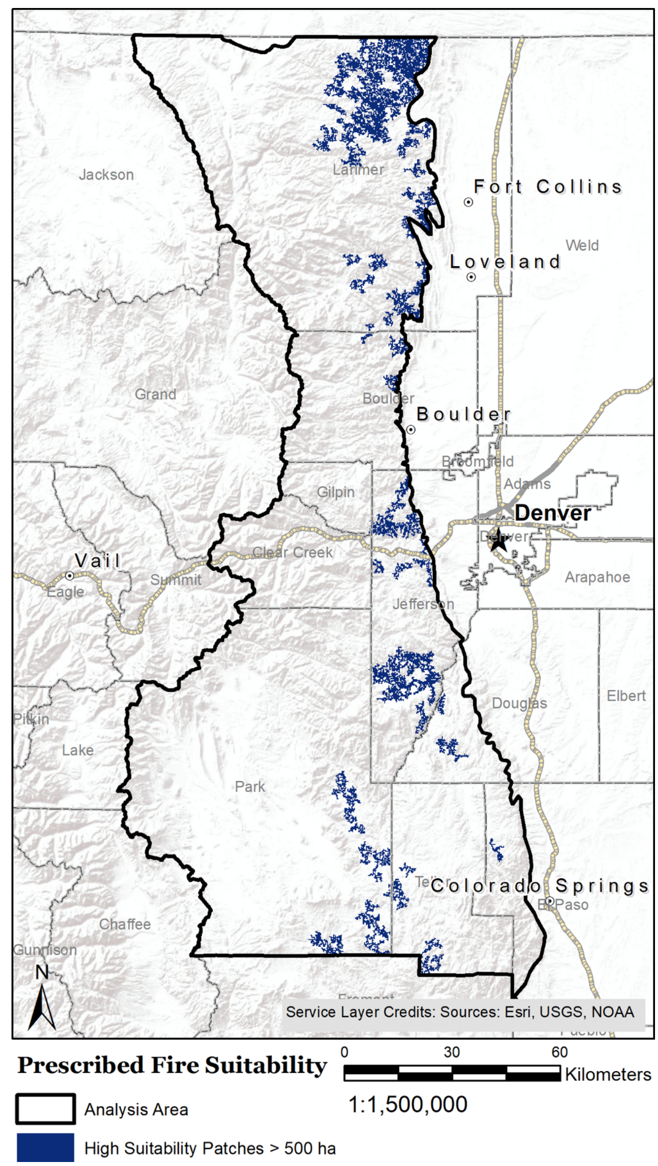

Fig. 5. High suitability patches for prescribed fire greater than 500 ha in size on the Front Range.

Likewise, of the roughly 600,000 ha of private lands within the analysis area, over 105,000 ha were deemed highly suitable, representing 17.5% of the private lands area.

Patch size analysis showed that most of the high suitability patches were in smaller patches, less than 20 ha in size (Fig. 4A). There were 3974 patches less than 20 ha and 47 patches that were greater than 500 ha. Large patches (> 500 ha) totaled 98,830 ha of the analysis area (Fig. 4B), with 33,133 ha in one contiguous patch on the northern Front Range. In addition to the northern Front Range, the analysis also identified opportunities for larger-scale prescribed fire projects within the more highly populated areas of the central Front Range (Fig. 5).

4. Discussion

4.1. Factors affecting prescribed fire suitability

The factors in our analysis are meant to identify areas where prescribed fire could be used to meet fuel reduction goals as well as forest restoration goals, including reestablishment of mixed-severity fire regimes. While restoring the low-severity component of the fire regime is often the emphasis of prescribed fire efforts, some degree of moderate- and high-severity fire effects within burn perimeters is desirable as well during prescribed fire operations (Hunter et al., 2007; North et al., 2012; Stephens et al., 2012). Burn objectives often include tree mortality as a desired outcome to reduce tree density and to recruit snags for wildlife. Our use of Sherriff et al.'s (2014) layer, in conjunction with vegetation and fuel types, enabled us to prioritize areas historically characterized by low-severity fire but also include areas historically characterized by mixed-severity fire where prescribe fire may be used to achieve moderate- and high-severity fire effects. Additionally, our fire behavior modeling under prescribed fire weather conditions allowed for higher flame lengths (up to 2.44 m) necessary for achieving desired mixed-severity fire effects and tree mortality objectives. Because Sherriff et al.'s (2014) model also incorporates slope, it identifies areas in higher-elevation settings historically characterized by low-severity fire that may be priority for prescribed fire. This approach avoids using elevational cutoffs to determine appropriate zones for prescribed fire, but rather bases prescribed fire suitability on factors such as landscape features, forest types, and locally-derived ecological models.

Prioritizing areas where mechanical treatments have already occurred for prescribed fire is important as several studies have shown that mechanical treatments followed by prescribed fire are more effective in modifying wildfire behavior compared to those that are not followed by prescribed fire (Fulé et al., 2012; Kalies and Yocum Kent, 2016). While mechanical treatments may reduce the potential for active crown fire, they often leave heavy residual surface fuels that may increase surface fire intensity and can still lead to high-severity fire effects during wildfire (Agee and Skinner, 2005; Martinson et al., 2003; Hunter et al., 2007; Graham et al., 2012). Prescribed fire can be used to reduce surface and ladder fuels, as well as maintain open stand structures and reduce the potential for surface fire transitioning to crown fire in the event of a wildfire (Hunter et al., 2007; Vaillant et al., 2009). We also retained areas previously treated with prescribed fire in our analysis, with the intent of prioritizing these areas for maintenance via prescribed fire to prolong treatment effectiveness and increase treatment longevity (Hunter et al., 2007; van Mantgem et al., 2016). Fuel treatment longevity is variable based on local physiographic conditions and site productivity, but recent studies suggest that maintenance treatments should occur roughly every 10–15 years to avoid losing initial investments in treatments (van Mantgem et al., 2016; Francis et al., 2018).

Perhaps the greatest constraint to broadcast prescribed fire on the Front Range is exurban development in the wildland-urban interface. We used wildland-urban interface density as a proxy for several constraints that often accompany increased exurban development, including air quality regulations, smoke management, and more stringent burn permitting (Ryan et al., 2013; Stephens et al., 2016). Our analysis allows for some use of prescribed fire in less developed areas of the wildland-urban interface but decreases suitability as building densities increase above 123.55 buildings/km^2 (1 building per 0.81 ha) to reflect these constraints. Fuel treatments in densely populated areas of the wildland-urban interface may need to focus more heavily on mechanical treatments, but prescribed fire could be used in a larger landscape context to influence fire behavior of wildfires that may be transmitted from neighboring wildlands (e.g., National Forests) to wildland-urban interface communities (Ager et al., 2014; Stephens et al., 2016). Strategic placement of prescribed fire projects within less populated areas of the wildland-urban interface may be important in protecting more densely populated areas. Such an approach is consistent with core elements of programs such as the National Cohesive Wildland Fire Management Strategy aimed at promoting fire-adapted communities, enhancing wildfire response, and fostering larger landscape resilience (NCWFMS, 2014; Stephens et al., 2016). While we treated the wildland-urban interface as a constraint in our analysis, an alternative that deserves further evaluation would be to look more explicitly at opportunities for prescribed fire within the wildland-urban interface. Even if burns are at relatively small scales within the wildland-urban interface, they may serve as good opportunities for outreach and education about the role of prescribed fire in managing fuels, which may help to foster social acceptance.

4.2. Management applications

Our results have several direct applications to fuel treatments on the Front Range at both landscape and project scales. At a broad scale, our analysis can be used in landscape planning and prioritizations efforts to identify where opportunities for the use of prescribed fire are high. Data from our analysis can be tabulated at a range of scales and incorporated into relevant planning units such as watersheds (Fig. 6A). Given the close connections between forests and water resources on the Front Range (Venable et al., 2017), planning efforts have often taken a watershed-based approach to prioritizing fuel treatments (e.g., JWA, 2009). Sub-watersheds (e.g., 6th level watersheds, Hydrologic Unit Code (HUC)-12) have become important planning units in this context on the Front Range. Results can be scaled to these units and used in conjunction with landscape risk assessments to identify priorities for fuels reduction and opportunities for prescribed fire.

As opportunities for the use of prescribed fire are identified at a landscape scale, results can then be evaluated at a project scale to assist in designing individual prescribed fire projects. Such projects can use existing containment features such as roads and water resources to delineate burn unit boundaries (Fig. 6B). Incorporating land ownership as an overlay can help to identify areas where cross-boundary projects can be developed among agencies and organizations to create larger projects. These results can be used by collaborative prescribed fire initiatives such as the Fire Learning Network and associated Prescribed Fire Training Exchanges (TREXs) in codeveloping prescribed fire projects (Spencer et al., 2015; Stephens et al., 2016). Likewise, such projects can align burn unit boundaries with existing containment features to help with prescribed fire control, rather than creating new containment lines based on property boundaries (Fig. 6C). Using existing landscape features for containment may reduce resources required for unit preparation as well as staffing during burn operations and may also help to minimize the installation of new containment features such as dozer lines that can have adverse ecological effects.

Numerous studies point to the need to increase the scale of treatment to affect wildfire behavior and increase the likelihood of wildfire interacting with treatments (Agee and Skinner, 2005; Martinson et al., 2003; Collins et al., 2010; Barnett et al., 2016). Results of our patch size analysis showed several opportunities for the development of large-scale (> 500 ha) prescribed fire projects on the Front Range. These areas are spatially distributed throughout the Front Range and offer opportunities for the development of prescribed fire "anchors" that could be placed strategically throughout the landscape (Collins et al., 2010; North et al., 2015). Mechanical treatments to further facilitate the use of prescribed fire could be concentrated in these areas as well to increase the overall scale of treatment footprints (North et al., 2012).

Results of our analysis may also inform the type of mechanical treatment most appropriate in a prescribed fire context. For instance, avoiding treatments such as mastication in areas suitable for prescribed fire may be important, as mastication leaves large amounts of surface fuels that can smolder for long periods (Kreye et al., 2014), making mop-up operations more difficult. Alternatively, treatments such as whole-tree removal may be desirable in areas slated for prescribed fire, as this technique typically leaves less residual surface fuel following treatment (Agee and Skinner, 2005; Stephens et al., 2012). While it may be challenging to implement prescribed fire at broad scales on the Front Range, these prescribed fire anchors may provide opportunity for the development of projects that could be implemented in phases over the course of several seasons, and then maintained through time with repeated burning. These areas may also provide opportunities to manage wildfire for resource benefits to achieve fuels reduction and forest restoration objectives, in conjunction with additional analyses such as potential operational delineations (PODs) and potential control lines (PCLs) aimed at identifying tactical points and strategies for wildfire containment (e.g., Thompson et al., 2016; O'Connor et al., 2017).

4.3. Limitations

While we feel we accounted for many of the most important spatial factors for prescribed fire suitability on the Front Range, our analysis

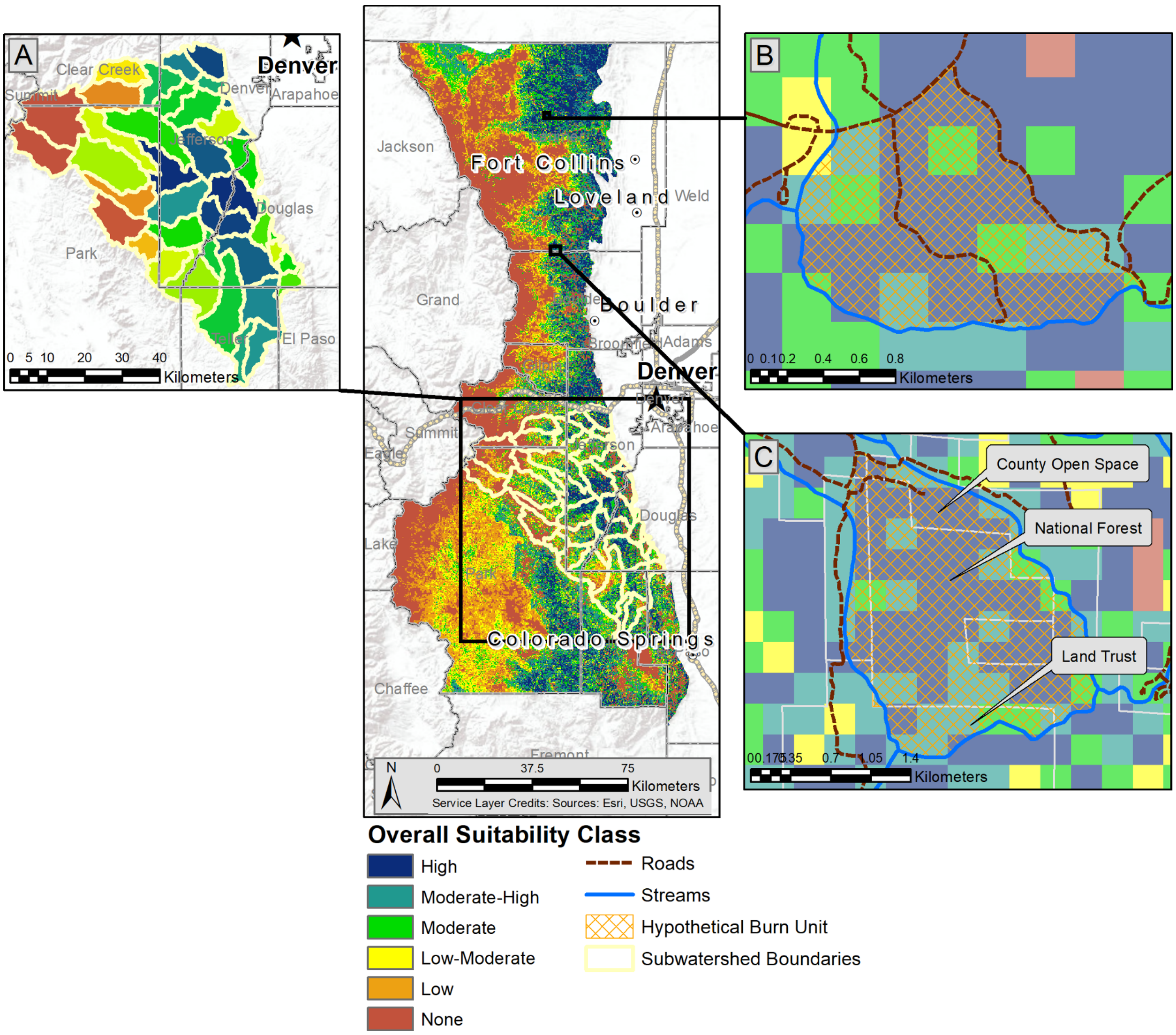

Fig. 6. Example applications of prescribed fire suitability output: (A) the suitability layer can be scaled to other planning units such as sub-watersheds and used in comprehensive forest management planning efforts to help identify treatment priorities based on opportunities for prescribed fire; (B) the suitability layer can be combined with containment features layer (e.g., roads and water features) to delineate individual burn units within a single land ownership; and (C) the suitability layer can facilitate cross-boundary and interagency planning of prescribed fire projects to avoid creating holding lines that coincide with property boundaries but rather are tied to landscape features.

has several limitations. First, we were unable to address temporal constraints to fire management based on factors such as weather conditions and fuel moistures. While these factors can be incorporated during the burn planning stage, it would be useful to spatially identify where prescribed burn windows may be longer in duration versus areas where weather and fuel moistures tend to be in prescription only for short periods each year (e.g., Chiodi et al., 2018). We were also unable to address factors such as social and policy barriers to the use of prescribed fire, as well as county permitting processes and agency resource capacity (Quinn-Davidson and Varner, 2012; Ryan et al., 2013; Schultz et al., 2019). Such constraints are difficult to quantify spatially but are important limitations to the implementation of prescribed fire on the Front Range (Gass, 2008). Large-scale burns that are developed collaboratively across agencies and boundaries may help to alleviate some of these constraints, such as agency resource capacity, by enabling agencies to pool resources for prescribed fire (Schultz et al., 2019). Projects that are cross-boundary and include private landowners may also help to foster social acceptability of prescribed fire. More work is needed to further quantify these constraints and depict them spatially to the extent possible.

We also chose to give the input layers in our analysis equal weights but point out that our analytical framework allows for weighting of individual layers based on specific objectives of fire planners and practitioners. For example, fire planners could increase the weight of the vegetation-fuels-historical fire layer to emphasize opportunities for more restoration-based use of prescribed fire in addition to fuels reduction. Similarly, the treatment history layer could be weighted within the analysis to highlight priorities for treatment maintenance with prescribed fire. Lastly, it is important to note that our analysis and associated data product have shelf lives based on the vintage of spatial layers used in the analysis and will need to be updated as the landscape changes due to treatment implementation and factors such as wildfire.

5. Conclusions

Increases in wildfire activity are expected to continue throughout the western United States with climate change and associated warmer temperatures, drought, and longer fire seasons (Westerling et al., 2006; Abatzoglou and Williams, 2016). Prescribed fire has been shown by numerous studies to be one of the most effective management practices in reducing fuels and modifying subsequent wildfire behavior, especially when coupled with mechanical treatments (Fulé et al., 2012; Walker et al., 2018). In landscapes as large as the Colorado Front Range, there is a need to prioritize forest management efforts, including the use of broadcast prescribed fire, to achieve desired outcomes at scale and to make best use of limited funding resources (Vaillant et al., 2009; Collins et al., 2010). Our analysis can be used to identify areas of high suitability for prescribed fire, where opportunity for prescribed fire is high and implementation constraints are low. Our results can be used in developing interagency, cross-boundary fuel treatment strategies that incorporate the use of prescribed fire, including identifying where mechanical treatments could be applied on the landscape to facilitate the use of prescribed fire over broad scales, as well as where prescribed fire may be a viable tool for long-term treatment maintenance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2019.117655.

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