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Modeling wildfire potential in residential parcels: A case study of the north-central Colorado Front Range

Rutherford V. Platt[a,*], Tania Schoennagel[b], Thomas T. Veblen[b], Rosemary L. Sherriff[c]

[a] *Department of Environmental Studies, Gettysburg College, Gettysburg, PA 17325, USA*
[b] *Department of Geography, University of Colorado at Boulder, Boulder, CO 80309, USA*
[c] *Department of Geography, Humboldt State University, Arcata, CA 95521, USA*

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ABSTRACT

This study evaluated if present-day wildfire potential (i.e. potential fireline intensity and percentage crown fire) differs for residential parcels developed at different time periods in the north–central Colorado Front Range. To answer this question, a model of wildfire potential was built based on 2001 fuels and vegetation and compared the output to actual fire severity of the 2002 Hayman and 2004 Picnic Rock fires (measured by satellite imagery). Except for low-load fuel types such as grass, the modeled wildfire potential corresponded well to observed fire severity. Wildfire potential was then evaluated within 7 classes: developed (1880–1944, 1945–1959, 1960–1974, 1975–1989, 1990–2005) and undeveloped (either zoned or not zoned for development). The results suggest that there is one class characterized by relatively low wildfire potential (developed 1880–1944) and three classes characterized by relatively high wildfire potential (developed 1960–1974 and the two undeveloped parcel classes). These results hold both for 99th percentile (extreme) and 50th percentile (average) fuel conditions. The results suggest that under current zoning regulations, future structures are likely to be built on parcels that, on average, have somewhat higher potential fireline intensity and higher percentage of crown fire compared to currently developed parcels. However, the location of future development may be influenced by forest changes, such as the visual degradation and perceived fire hazard of trees killed by the continuing mountain pine beetle outbreak. Overall, this study introduces an improved method for quantifying wildfire potential in the rapidly developing wildland–urban interface that could be applied to other areas.

1. Introduction

The wildland–urban interface (WUI) is the area where human-built structures intermix with or adjoin flammable wildland vegetation. A principal challenge in understanding wildfire in the WUI is quantifying the spatial and temporal variability wildfire hazard, defined as the wildfire potential of a fuel complex, independent of weather (Hardy, 2005). Many studies have attempted to delineate the WUI over large areas (see Platt, 2010 for a review and comparison of methods). For example, Radeloff et al. (2005) created the first consistent map of the WUI for the coterminous United States. Hammer, Radeloff, Fried, and Stewart (2007) extended this approach to map the change in the WUI from 1990 to 2000 in the Pacific Northwest. Wilmer and Aplet (2005), took a similar approach as in Radeloff et al. (2005), but refined the spatial extent of the WUI using information about public lands and vegetation type. Theobald and Romme (2007) estimated the extent of the WUI from 1970 to 2000 within fire hazard classes derived from vegetation type.

These studies have advanced the understanding of the extent and characteristics of the WUI over large areas, but they are limited by coarse source data and simple or nonexistent treatment of wildfire potential. In particular, most WUI maps depend on 2000 census block data that is spatially coarse in sparsely populated WUI areas. Vegetation, fuels, topography, development patterns, and zoning laws can all vary considerably within a single large census block. One example of a project that attempted to spatially refine housing density estimates is the Hazard–Risk–Value map of Colorado, which estimated housing density using a combination of parcel, well, and census data rather than census data alone (Edel, 2002). Another general limitation is that most WUI mapping methods focus on the recent history of the WUI (no further back than 1970) due to a dearth of historical data on development patterns. Finally, WUI models tend to over-simplify or omit the

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* Corresponding author. Tel.: +1 717 337 6078; fax: +1 717 337 8550.
E-mail addresses: rplatt@gettysburg.edu (R.V. Platt), Tania.Schoennagel@colorado.edu (T. Schoennagel), thomas.Veblen@Colorado.Edu (T.T. Veblen), rosemary.Sherriff@Humboldt.Edu (R.L. Sherriff).

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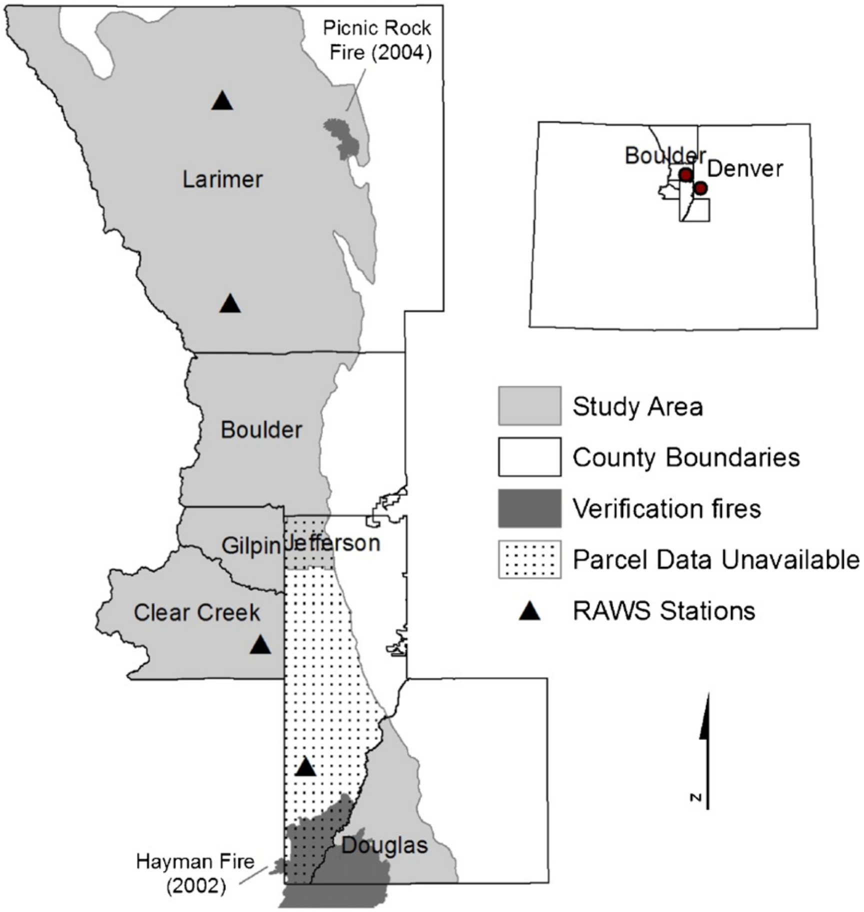

Fig. 1. Study area of the north-central Colorado Front Range, bounded by the lowest extent of the montane zone (ca. 1830 m) to the east and by county boundaries.

spatial variation in wildfire potential. For example, Wilmer and Aplet (2005) distinguish only between wildland and non-wildland cover types. Hammer et al. (2007) employ a coarse-scale model of departure from historical fire regimes to infer wildfire potential (Schmidt, Menakis, Hardy, Hann, & Bunnell, 2002). Theobald and Romme (2007) evaluate wildfire hazard based on an association of vegetation type to a fire severity rating grounded in the literature. Few if any existing studies incorporate weather or climate in the evaluation of wildfire potential in the WUI. As a consequence of these limitations, existing models of wildfire potential in the WUI do not operate at the spatial scale at which residential development actually takes place; omit many of the most important factors that influence wildfire behavior, such as fuel moisture, forest structure, and wind; and do not allow for the assessment of how long-term development trends alter vulnerability to wildfire hazard.

This study of the north-central Colorado Front Range aims to address several limitations of previous attempts to map the WUI and evaluate wildfire hazard. To do so, historical development patterns from 1880 to 2005 were reconstructed based on detailed parcel data rather than census data. Historical development patterns were overlaid on a model of wildfire potential in 2001 derived from fuels, forest structure, topography and weather. Areas of “high wildfire potential” were defined as having relatively high fireline intensity and percentage of crown fire under particular reference fuel and weather conditions.

The history of residential development in the north-central Colorado Front Range indicates that valley bottoms at lower elevations were claimed first, followed by steeper slopes and higher elevations (Riebsame, Theobald, & Fagre, 2002). It was hypothesized that recently developed parcels may be characterized by higher wildfire potential than parcels developed earlier, and that parcels developed in the future (currently undeveloped) may be characterized by even higher wildfire potential. The goal of the study was to answer the following questions: (1) Does wildfire potential differ for parcels developed at different time periods? (2) Are undeveloped parcels characterized by different wildfire potential than developed parcels? If so: (3) which biotic or abiotic factors are associated with the differences in wildfire potential? Whether or not any particular structure is likely to burn is contingent on many factors – including roof type and defensible space – that are beyond the scope of this study. The focus here is on the wildfire potential within parcels rather than the flammability of particular structures.

2. Methods

2.1. Study area

The study area is located in the north-central Front Range of Colorado, bounded by the lowest extent of the montane zone (ca. 1830 m) to the east and by county boundaries (Fig. 1). Specifically, the study area includes all of Gilpin and Clear Creek counties, the mountainous western regions of Larimer, Boulder, and Douglas counties, and the northwestern portion of Jefferson County. Parcel data were not publically available for Jefferson County outside of the northwestern portion. The study area falls within the montane (1830–2740 m) and subalpine (2740–3400 m) zones. The lower montane zone comprises a mixture of ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), and grasses. Prior to fire exclusion, these areas were characterized by low-severity (primarily surface) fires that recurred within the same stand (c.

50–100 ha) at intervals of approximately 10–40 years (Sherriff & Veblen, 2007; Veblen, Kitzberger, & Donnegan, 2000). In the upper montane zone ponderosa pine and Douglas-fir dominate on south-facing slopes, and mix with lodgepole pine (*Pinus contorta*) and aspen (*Populus tremuloides*) on north-facing slopes. Prior to fire exclusion, these higher elevation areas were characterized by moderate to high-severity (largely stand-replacing crown fires) that recurred within the same stand (c. 50–100 ha) at intervals of 30 to over a 100 years (Sherriff & Veblen, 2008; Veblen & Lorenz, 1986). The highest elevations of the study area fall within the subalpine zone, which is characterized by lodgepole pine, aspen, as well as Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*), which burned at >100-year intervals by large, high-severity fires (Sibold, Veblen, & González, 2006). Although the north-central Front Range has experienced relatively few large fires since ca. 1920, when fire suppression became effective, wildfire potential is considered high throughout the study area. Actual fire hazard determined by fuels is spatially complex across the landscape (Krasnow, Schoennagel, & Veblen, 2009).

The study area is characterized by a long history of exurban development. The region had been inhabited by Native Americans at least from the end of the Pleistocene epoch 12,000 years ago (Larson & Francis, 1997). However, widespread permanent human settlements did not become established until the 1860s, when thousands of miners a week migrated to the southern Rocky Mountains of Colorado to search for gold and silver. Extensive road and trail building followed in the 1870s and 1880s (Wyckoff, 1999). By the 1870s, the Denver Pacific railroad arrived and surveyors had mapped the interior Rockies. Subsequently homesteaders claimed tracks of land, primarily along valley bottoms. Between the 1890s and 1940s, the Federal Government reserved and restricted the use of extensive areas of public land that had not yet been homesteaded. Located at the higher slopes, much of this land had been severely degraded by logging, mining, and grazing and is now administered by the US Forest Service (Riebsame et al., 2002). From 1940 to 1960, the population of the Front Range doubled while government spending, both civilian and military, led the economic expansion (Kendall, 2002). In the 1960s and 1970s the economy moved rapidly into technology, tourism, real estate and energy. By the 1970s oil prices had skyrocketed, leading to a boom and subsequent bust in oil and natural gas employment in many rural areas of the Rockies and the transportation hub of Denver. In the 1990s and 2000s, a sustained development boom took place based on an increase in service and technology jobs and amenity migration (Vias & Carruthers, 2005). Urban and rural areas shared in the development boom (Baron, Theobald, & Fagre, 2000), including mountainous areas within close proximity to the urban centers of the Front Range. In all eras, roads built for transportation of natural resources facilitated residential development in subsequent economic booms (Riebsame et al., 2002).

2.2. *Model of wildfire potential*

Wildfire potential across the landscape was estimated using FlamMap 3.0, a fire behavior mapping and analysis system that calculates potential wildfire behavior under constant weather and fuel conditions. To run the model, 30 m raster layers related to topography and fuels were acquired. Topography is characterized by layers of elevation, slope, and aspect. Fuels layers were developed by Landfire, an interagency project for mapping vegetation, fuel, and fire characteristics across the United States (Landfire, 2010). The fuel layers (valid for circa 2001) include percent forest canopy cover, stand height, canopy base height (CBH), and canopy bulk density (CBD), and Scott and Burgan (2005) fuel models (Table 1). Scott and Burgan (2005) fuel models comprise 40 distinct classes characterized by fire carrying type (i.e. grass, brush, timber litter, or slash), loading, fuelbed depth, dead fuel extinction moisture content, and fuel heat content. The Landfire layers were developed through predictive ecological models calibrated with remotely sensed imagery and land-based plots; a complete description of the layers is available at the Landfire website (Landfire, 2010). In two cases Landfire layers were modified from their original form: canopy cover and CBH values were adjusted downward following the suggestions in the December 2006 data product notification (Landfire, 2006) and a previous comparison of Landfire fuel layers with field-derived fuel layers in part of the study area (Krasnow et al., 2009). Two sets of model outputs were produced: one for analysis (described below) and one for verification (described in the next section). The modeling process took place in two steps: (1) fuel conditioning and (2) calculating wildfire potential.

Table 1
Raster layers used in model of wildfire potential.

Purpose	Name	Units or classes	Source
Input	Elevation	Meters	USGS
	Slope	Degrees	USGS
	Aspect	North, east, south, west	USGS
	Forest canopy cover	Percentage	Landfire
	Fuel model	Scott and Burgan (2005) fuel classes	Landfire
	Stand height	Meters	Landfire
	Canopy base height	Meters	Landfire
	Canopy bulk density	kg/m^3	Landfire
Output	Fireline intensity	kW/m	FlamMap
	Crown fire activity	Surface or crown fire	FlamMap

The first step was fuel conditioning, in which FlamMap adjusts fuel moisture based on the weather and wind conditions over a specified period of time. The wind/weather conditions include the daily minimum and maximum temperature and relative humidity, precipitation, wind velocity, and wind direction. For the analysis runs, fuels were conditioned for 28 days using average (50th percentile) or extreme (99th percentile) monthly wind/weather conditions during the primary fire season (June–September) (Table 2). The wind/weather variables were derived from four Remote Automated Weather Stations (RAWS) that span the study area and have the longest record: Redfeather (station 050505; 1964–2007), Estes Park (station 05050; 1964–2007), Corral Creek (station 051804; 1968–2007) and Bailey (station 052001; 1970–2007).

The second step was calculating wildfire potential in FlamMap based on the conditioned fuels, topography, and instantaneous wind velocity. To characterize wildfire potential, FlamMap employs several models: surface fire behavior (Rothermel, 1972), crown fire initiation (Van Wagner, 1977), crown fire spread (Rothermel, 1991), and dead fuel moisture (Nelson, 2000). In this step, the wind velocity data represent an instant in time rather than a conditioning period, and were made spatially explicit using WindNinja, a simple flow simulation program designed for this application that refines wind velocity within 500 m cells based on a 30 m digital elevation model (Table 2). For the analysis runs, the wind speed was fixed at 74 km/h (99.9th percentile daily wind conditions during the primary fire season, June–September, ca. 1964–2007). Wind data for the analysis runs came from the same four RAWS stations used for fuel conditioning. While wind direction along the Colorado Front Range is highly variable, for the purposes of the analysis runs it was fixed at southwest, which is the most common direction across the four RAWS stations. For each model run, FlamMap generated two fire behavior outputs:

1. *Fireline intensity*, a measure of energy released per unit length along the flaming front of a fire (kW/m).

Table 2
Summary of FlamMap model runs.

Model run	Hayman Fire	Picnic Rock Fire	Average fuel conditions	Extreme fuel conditions
Purpose	Verification	Verification	Analysis	Analysis
Location	Perimeter of Hayman Fire	Perimeter of Picnic Rock Fire	Study area	Study area
Conditioning wind/weather	Historical weather observations: May 13th–June 9th, 2002	Historical weather observations: March 5th–April 1st, 2004	28 days, based on 50th percentile of monthly RAWS data (ca. 1964–2007)	28 days, based on 99th percentile of monthly RAWS data (ca. 1964–2007)
Instantaneous wind/weather refined by WindNinja	72 km/h, observed June 9th, 2002	82 km/h, observed April 1st, 2004	74 km/h, 99.9th percentile of daily RAWS data (ca. 1964–2007)	74 km/h, 99.9th percentile of daily RAWS data (ca. 1964–2007)
Source of weather/wind data	Cheesman RAWS station, Bradshaw et al. (2003)	Bailey RAWS station, NOAA National Weather Service Observations	Mean of Redfeather, Estes Park, Corral Creek, and Bailey RAWS stations	Mean of Redfeather, Estes Park, Corral Creek, and Bailey RAWS stations

2. *Crown activity* (either surface fire or active/passive crown fire) using the Scott and Reinhardt (2001) method.

These fire behavior outputs were selected because they are widely used, interpretable, and general.

2.3. *Verification of wildfire potential*

True validation of FlamMap output based on historical fire behavior is not possible for several reasons. First, the model can only be validated on fires that have occurred since 2001 (the year for which fuel and vegetation conditions are valid). Secondly, FlamMap models potential fire behavior at an instant given an ignition source, yet actual fires play out over days or weeks during which fuel and wind/weather are constantly in flux. Third, burn severity – which can be measured for historical fires using remotely sensed imagery – is not the same as wildfire behavior, although the two are strongly related. Thus, model verification was sought—a simple check of the realism of the results rather than a comprehensive validation.

The model was verified using fire severity information from two significant fires in the region: the Hayman Fire of 2002 (the largest fire in recent Colorado history, characterized by extensive crown fires in montane forest), and the Picnic Rock Fire of 2004 (a wind-blown surface fire in grassland, Fig. 1). For the verification run, fuel moisture was conditioned based on the wind/weather conditions from the 28 days leading up to an intense day of burning for two fires (June 9th 2002 for the Hayman Fire, and April 1st 2004 for the Picnic Rock Fire, Table 2). Weather/wind conditions for the Hayman Fire fuel conditioning came from the Cheesman RAWS (station 053102), which is located within the perimeter of the fire. Winds with gusts up to 72 km/h were recorded at the Cheesman RAWS station on June 9th during the Hayman Fire, with prevailing wind coming from the Southwest (Bradshaw et al., 2003). Weather/wind conditions for the Picnic Rock fuel conditioning came from the Bailey RAWS (station 052001). The Bailey station is located at the same elevation as the Picnic Rock Fire, though it is 145 km south. (The closer Redstone RAWS (station 050508) is missing data for March 2004, and so could not be used.) Winds with gusts up to 80 km/h out of the south were observed by the NOAA National Weather Service on April 1st 2004 during the Picnic Rock Fire.

The two fire behavior outputs were compared to actual post-fire vegetation conditions from the USDA Forest Service's Burned Area Reflectance Classification (BARC) data set. BARC data has four burn severity classes: high, moderate, low, and unburned. These are based on a classification of the difference between the Normalized Burn Ratio (NBR) in Landsat satellite imagery taken before and after the burn. NBR was specifically developed to measure vegetation burn severity (Key et al., 2002; Lopez-Garcia & Caselles, 1991) and is derived as follows:

$$\mathrm{NBR} = \frac{\mathrm{NIR} - \mathrm{MIR}}{\mathrm{NIR} + \mathrm{MIR}}$$

where NIR is a near infrared band (in this case Landsat band 4, 0.76–0.90 μm) and MIR is a mid-infrared band (in this case Landsat band 7, 2.08–2.35 μm). In one study, NBR was found to be the most flexible, robust, and analytically simple of six approaches used to map fire severity using multi-temporal Landsat imagery (Brewer, Winne, Redmond, Opitz, & Mangrich, 2005). In another study, fire severity maps derived from change in NBR (dNBR) were compared to Composite Burn Index (CBI) data collected in the field (Cocke, Fule, & Crouse, 2005). The results showed that fire severity classes derived from NBR and CBI have an agreement of approximately 75%. An important limitation of dNBR is that it is sensitive to the pre-fire vegetation, complicating comparisons of dNBR between fuel types (Miller & Thode, 2007).

Within the perimeter of the Hayman and Picnic Rock Fires, a random sample of 3000 points was generated on land that burned. The burn severity class (low, moderate, or high) observed in the imagery was compared to the fireline intensity and crown activity class predicted by FlamMap. The distribution of fireline intensity within burn severity classes was compared using a Kruskal–Wallis test, a non-parametric ANOVA used to compare the distributions of groups with different variances or non-normal distributions. The percentage of crown fire within burn severity classes was compared using a Chi-Square test. Because NBR is sensitive to pre-fire vegetation, the comparisons were conducted separately for the three most common fuel types found within the burn perimeter of each fire. The three most common standard fire behavior fuel types (Scott & Burgan, 2005) found in the Hayman Fire perimeter were FM165 (very high load dry timber shrub, 37% of burn area), FM122 (moderate load dry grass–shrub, 32% of burn area), and FM161 (low load dry timber–grass–shrub, 19% of burn area). The three most common standard fire behavior fuel types found in the Picnic Rock Fire perimeter were FM122 (48% of burn area), FM141 (load dry climate shrub, 31% of burn area), and FM121 (low load dry climate grass–shrub, 8% of burn area). A model was considered a good approximation of reality if, within a given fuel type: (1) the mean fireline intensity and percentage crown fire are significantly different between dNBR classes and (2) the mean fireline intensity and percentage of crown fires get progressively larger from the "low" to the "high" dNBR classes.

2.4. *Construction of parcel dataset*

Once wildfire potential had been calculated and verified, a database of parcels (ca. 2005) was compiled for the six counties in the study area. All public land (e.g. land managed by federal, state, county, or city entities) and polygons that represent roads were then removed from the parcels. The boundaries between polygons that contain a common parcel number were then dissolved. Finally, zoning codes were assigned to each parcel based on current zoning data layers for the six counties. Based on two attributes – zoning code and year built – each privately owned ca. 2005 parcel was classified into one of seven classes based on a simplified characterization of development eras:

1. Developed 1880–1944 (Settlement era)
2. Developed 1945–1959 (Post war era)
3. Developed 1960–1974 (Era of rapid growth)
4. Developed 1975–1989 (Era of energy boom and bust)
5. Developed 1990–2005 (Technology and amenities era)
6. Undeveloped—not zoned for future development
7. Undeveloped—zoned for future development

In 2005 there were 29,500 parcels in the study area. Of these, 1324 parcels lacked a "year built" attribute and were removed. An additional 7857 parcels were comprised of primarily non-wildland vegetation and situated in densely settled small towns. These were also removed. The remaining private parcels had a median size of approximately 0.6 ha with an interquartile range of 1.6 ha.

2.5. *Evaluation of wildfire potential and biotic/abiotic characteristics of parcels*

After compiling the parcel layers, the database was populated by assigning attributes to each parcel. Attribute values were assigned to parcels using the centroid method after applying a 5 × 5 majority filter to the integer raster layers and a 5 × 5 mean filter to the floating point raster layers. While parcel centroids are not an accurate representation of structure location in larger parcels, they provide an unbiased method of comparing the characteristics of developed and undeveloped parcels. To answer research questions 1 and 2, the three descriptors of wildfire potential – median fireline intensity, percentage of fireline intensity >40,000 kW/m, and percentage crown fire – were assigned to the parcel centroids (Table 1). Fireline intensity >40,000 is a binary variable used to identify the parcels with the most extreme wildfire potential, an order of magnitude greater than the 4000 kW/m "high intensity" threshold suggested by Alexander (1982). To answer research question 3, the following continuous attributes were assigned to the parcel centroids: elevation, slope, percent forest canopy cover, and the topographic position index (TPI), which represents the elevation difference between a given location and the surrounding area (Jenness, 2006). Also to answer research question 3, three binary variables were assigned to the parcel centroids: presence of north-facing slope, presence of fuel model 165 (high load dry timber shrub, Scott & Burgan, 2005), and presence of lodgepole pine (derived from existing vegetation type layer, Rollins & Frame, 2006). These variables were selected because of their relationship with wildfire behavior. North-facing slopes (i.e. slopes within 45° of due north) tend to be mesic and contain denser tree stands than south-facing slopes of the same elevation. Lodgepole pine stands are characterized by extensive ladder fuels and contiguous crowns that promote infrequent but high-severity crown fires (Schoennagel, Veblen, & Romme, 2004). Of the four most common fuel models in the study area (FM183—moderate load conifer litter, FM165—high load dry timber shrub, FM122—moderate load dry climate grass–hrub, and FM161—low load dry climate timber–grass–shrub), FM165 has the highest density of fine fuels and is associated with the highest flame length (Scott & Burgan, 2005). Summary statistics of attributes (mean for continuous variables, percentage for binary variables) were calculated within the seven development classes. Kruskal–Wallis tests (Kruskal & Wallis, 1952) and Tamhane multiple comparison tests (Tamhane, 1977) were used to evaluate whether the median values of the attributes were significantly different between classes.

3. Results

3.1. *Model verification*

Overall the models are consistent with what is generally known about the two fires; the model of the Hayman Fire predicted extensive crown fires while the model of the Picnic Rock Fire predicted extensive surface fires (Tables 3 and 4). Modeled fireline intensity generally ranges from 15 to 50,000 kW/m (and theoretically up to 100,000 in exceptional cases) with anything over 4000 considered to be "high intensity" and uncontrollable (Alexander, 1982). While both fires are dominated by "high intensity" values, the modeled fireline intensity values for the Hayman Fire – the largest and most destructive in recent Colorado history – are the highest overall.

The degree to which FlamMap output (mean fireline intensity and percentage crown fires) varies between dNBR classes depends on the fuel type. For high and moderate fuel types (FM165, FM122) in both fires, cells in the "high" dNBR severity class have the highest mean fireline intensity and percentage crown fire, cells in the "moderate" severity class have intermediate mean fireline intensity and percentage crown fire, and cells in the "low" severity class have the lowest mean fireline intensity and percentage crown fire (Tables 3 and 4). A Kruskal–Wallis test revealed that the distribution of fireline intensity is significantly different between dNBR classes at the $p < 0.05$ level. A Pearson Chi-Square test revealed that the frequency of crown fires is significantly different between dNBR classes at the $p < 0.05$ level. However, these tests also show that for low load fuel types (FM161, FM141, FM121) there is no significant difference in the distribution of fireline intensity or frequency of crown fires between dNBR classes in either fire. These results are not surprising, as dNBR is dependent on pre-fire vegetation type and necessarily has a narrower range of possible values for low load fuel types, which have less pre-fire biomass. Furthermore, a strong association between severity and percentage crown fires in the Picnic Rock Fire, which was a primarily wind-driven surface event in an open grass-dominated setting (i.e. predominately low load fuels), would not be expected.

Overall, these results suggest that within high and moderate load fuel types, the FlamMap model output corresponds well to severity measured by the dNBR index. However, for low load fuel types the FlamMap model output does not vary between dNBR classes, possibly due to limitations of the dNBR index itself.

3.2. *Research question #1: "Does wildfire potential differ for parcels developed at different time periods?"*

Both fireline intensity and crown activity class are heterogeneous across the study area (for example, Fig. 2 shows the output under extreme fuel conditions). In 2005, a total of 20,275 developed parcels and 15,820 undeveloped parcels contained wildland vegetation in the north-central Colorado Front Range (Table 5). Under both average and extreme fuel conditions, and all time periods, the median potential fireline intensity is over the 4000 kW/m "high intensity" threshold due to the high instantaneous wind speed of 74 km/h. However, a Kruskal–Wallis test revealed that the distribution of the three wildfire behavior descriptors – fireline intensity, percentage of fireline intensity >40,000, and percentage crown fire – are significantly different between development classes at the $p = 0.001$ level. On average, the 1880–1944 class has the low-

Table 4
Model verification of the Picnic Rock Fire. For each of the three most common fuels within the burn perimeter, the table summarizes fireline intensity and crown activity class within Burned Area Reflectance Classification (BARC) classes.

Scott and Burgan (2005) Fuel model	BARC class (percent of FM)	Mean fireline intensity (kW/m)	Crown activity class count (percentage)
FM122:		*	**
Moderate load dry grass–shrub, 48% of burn area	Low (54%)	6185	83 (12%)
	Mod (40%)	8192	58 (11%)
	High (5%)	8643	1 (2%)
FM141:			
Low load dry climate shrub, 31% of burn area	Low (92%)	2406	15% (3%)
	Mod (8%)	2471	1 (1%)
	High (0%)	–	–
FM121:			
Low load dry climate grass–shrub, 8% of burn area	Low (66%)	4169	57 (42%)
	Mod (34%)	4791	24 (34%)
	High (0%)	–	–

* A Kruskal–Wallis test indicates that the overall distribution of fireline intensity is significantly different between BARC classes at the $p < 0.05$ level.
** A Pearson Chi-Square test indicates a significant difference in the frequency of surface and crown fires within BARC classes at the $p < 0.05$ level.

Table 3
Model verification of the Hayman Fire (2002). For each of the three most common fuels within the burn perimeter, the table summarizes fireline intensity and crown activity class within Burned Area Reflectance Classification (BARC) classes.

Scott and Burgan (2005) Fuel model	BARC class (percent of FM)	Mean fireline intensity, kW/m	Crown activity class count (percentage)
FM165:		*	**
Very high load dry timber shrub, 37% of burn area	Low (22%)	19,415	113 (50%)
	Mod (61%)	26,291	401 (64%)
	High (18%)	43,711	169 (93%)
FM122:		*	**
Moderate load dry grass–shrub, 32% of burn area	Low (10%)	28,108	44 (52%)
	Mod (28%)	33,577	170 (68%)
	High (62%)	39,472	544 (99%)
FM161:			**
Low load dry timber–grass–shrub, 19% of burn area	Low (35%)	5126	24 (13%)
	Mod (61%)	5314	44 (14%)
	High (1%)	22,751	6 (34%)

* A Kruskal–Wallis test indicates that the overall distribution of fireline intensity is significantly different between BARC classes at the $p < 0.05$ level.
** A Pearson Chi-Square test indicates a significant difference in the frequency of surface and crown fires within BARC classes at the $p < 0.05$ level.

est median fireline intensity and mean percentage of crown fire of all developed classes, while the parcels developed during the 1960–1974 period have the highest median fireline intensity and mean percentage crown fire of all developed classes (Table 5). In terms of the percentage fireline intensity >40,000, the 1880–1944 class still had the lowest value, but the 1860–1974 class is not high compared to other time periods (Table 5). Contrary to expectations, the most recent development class (1990–2005) was not characterized by a high wildfire potential relative to other classes. These results hold under both 50th and 99th percentile fuel conditions.

3.3. *Research question #2: "Are undeveloped parcels characterized by different wildfire potential than developed parcels?"*

The Tamhane multiple comparison tests show which classes are significantly different from the undeveloped (zoned for development) class in terms of median fireline intensity, percentage fireline intensity >40,000, and percentage crown fire (Table 5). Under 50th percentile fuel conditions, undeveloped (zoned for development) has higher values than all developed classes for all three

Table 5
Wildfire potential within parcel development classes. Dark gray: significantly greater than "undeveloped (zoned for development)" at $p = 0.05$, multiple comparison Tamhane test. Bold: significantly less than "undeveloped (zoned for development)".

Class	Number of parcels	Fireline intensity median (kW/m)		Percentage fireline intensity > 40,000 (kW/m)		Percentage crown fire	
		99th %	50th %	99th %	50th %	99th %	50th %
Developed 1880–1944	2608	**17,472**	**10,096**	**15**	**10**	**35.5**	**22.6**
Developed 1945–1959	1926	**22,085**	**14,020**	**19**	**13**	44.1	**29.2**
Developed 1960–1974	4791	23,474	**14,087**	**21**	**13**	47.5	31
Developed 1975–1989	4941	**21,598**	**12,976**	**20**	**12**	44.2	**28.4**
Developed 1990–2005	6009	**21,160**	**12,954**	**21**	**13**	**41.3**	**29**
Undeveloped (not zoned for development)	4804	23,709	19,244	25	18	44.6	39.9
Undeveloped (zoned for development)	11,016	23,157	15,171	24	16	43.8	32.9

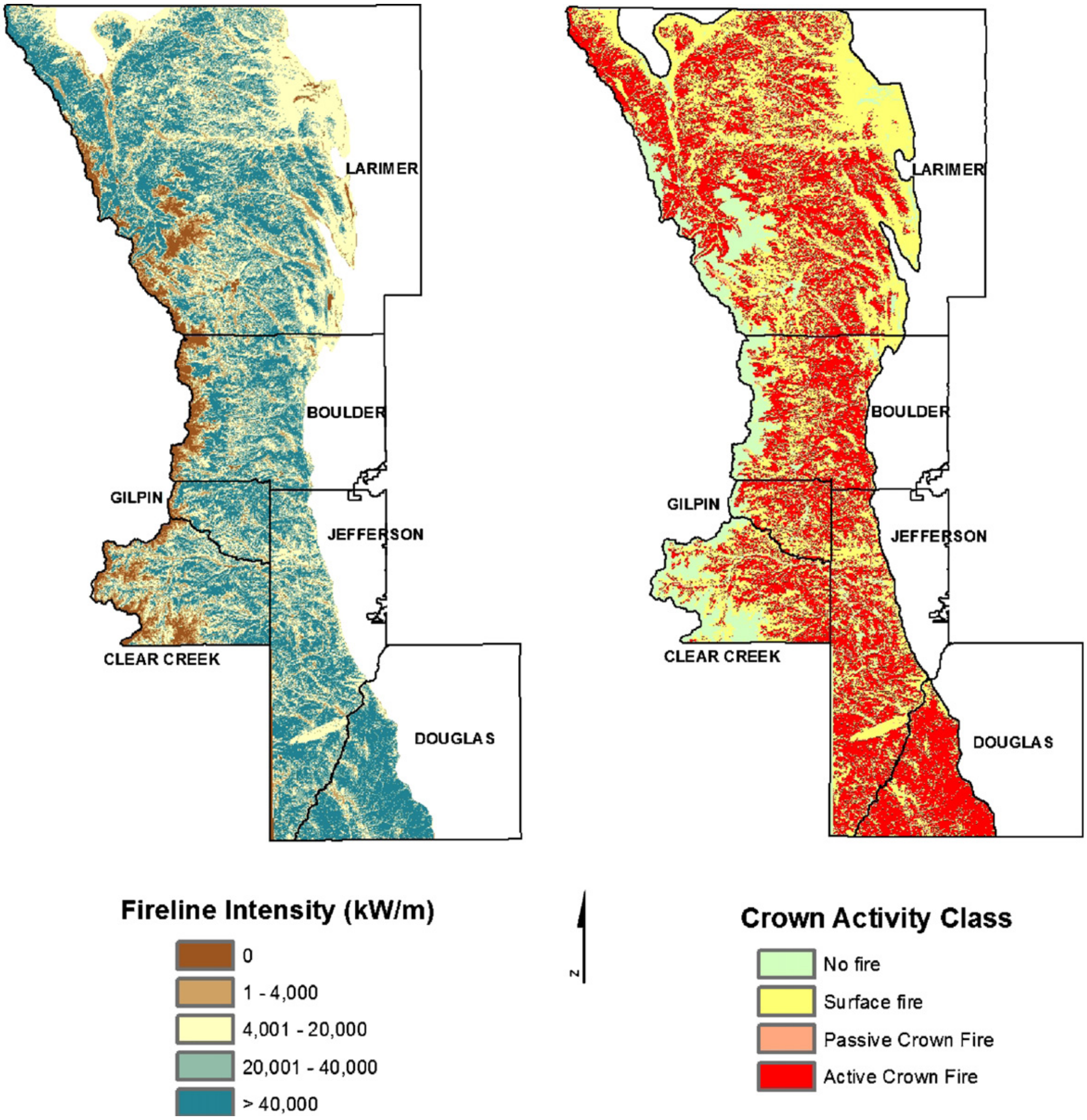

Fig. 2. Wildfire potential in the north-central Colorado Front Range under extreme (99th percentile) fuel conditions and 74 km/h instantaneous winds.

variables. The difference was statistically significant in all cases except percentage crown fire 1960–1974. Under 99th percentile fuel conditions, the differences between undeveloped (zoned for development) and developed classes are less pronounced. Undeveloped (zoned for development) has higher median fireline intensity and percentage fireline intensity >40,000 than developed classes, with the exception of the median fireline intensity of the1960–1974 class. Under 99th percentile fuel conditions, the percentage crown fire of undeveloped (zoned for development) is not high relative to other classes. Regardless of the fuel conditions, the 1880–1945 class has the lowest value for all three variables in all classes, developed or undeveloped.

3.4. Research question #3: "Which biotic or abiotic factors are associated with the differences in wildfire potential?"

The Tamhane multiple comparison tests show which classes are significantly different from the undeveloped (zoned for development) class in terms of seven topographic and fuel attributes (Table 6). Overall, developed parcels are either significantly lower or no different from undeveloped (zoned for development) in terms of elevation, slope, percent forest canopy cover, percentage of north facing slope, percentage of FM165 (very high load dry timber shrub, the most "hazardous" of the four most prevalent fuel models in the study area), and TPI. Several factors may contribute to the lower wildfire potential of the 1880–1944 class. Compared to other classes, parcels developed 1880–1944 have the same or lower percent forest canopy cover, have the lowest percentage of lodgepole pine, and have the same or lower percentage of FM165. Consideration of topographic influences provides additional insights. The TPI for the study area as a whole has a median value of −14, suggestive of flat and mid-slope areas. Parcels developed 1880–1944 and 1945–1959 have a negative TPI farther from zero, suggesting they contain more wide valleys and canyon bottoms, which may be less hazardous than mid-slope areas and ridgetops. Several factors may contribute to the higher wildfire potential of the undeveloped classes. It was found that undeveloped parcels tend to be higher in elevation than developed parcels and have the same or higher percent forest canopy cover. Undeveloped parcels have higher percentage of lodgepole

Table 6
Evaluation of biotic and abiotic variables within parcel development classes. Dark gray: significantly greater than "undeveloped (zoned for development)" at $p = 0.05$, multiple comparison Tamhane test. Bold: significantly less than "undeveloped (zoned for development)".

Class	Elevation	Slope	Percentage forest canopy cover	Percentage north facing slope	Percentage lodgepole pine	Percentage FM165	Topo Position Index
Developed 1880–1944	**2389**	11	**38**	27%	**14%**	**27%**	−**44.16**
Developed 1945–1959	**2391**	11	46	28%	**20%**	32%	−**32.94**
Developed 1960–1974	**2374**	11	45	26%	**20%**	30%	−**19.1**
Developed 1975–1989	**2348**	11	**40**	**23%**	**18%**	**27%**	−10.94
Developed 1990–2005	**2345**	12	**38**	**25%**	**19%**	**28%**	−8.23
Undeveloped (not zoned for development)	2731	18	45	**22%**	23%	43%	−**16.57**
Undeveloped (zoned for development)	2410	12	45	29%	24%	32%	−10.99

pine and the same or higher percentage of FM165 than developed parcels.

4. Discussion

This study presents a novel method for mapping and evaluating wildfire potential in the WUI that: (1) is spatially detailed, (2) incorporates historical data on development patterns, (3) accounts for wind/weather conditions in estimating wildfire potential, and (4) can be applied to other areas now that parcel data are commonly available. In evaluating the wildfire behavior model output, it was found that the models of fireline intensity and percentage crown fire were well associated with observed severity for high and moderate load fuels, but not for low load fuels largely comprising grass and shrubs.

A complex but significant relationship exists between the era of development and wildfire potential. Overall, undeveloped parcels are predicted to have higher fireline intensity and percentage crown fire than developed parcels. The earliest developed parcels (1880–1944) have the lowest wildfire potential of all classes, while parcels developed 1960–1974 have the highest wildfire potential of all developed parcel classes. These differences in wildfire potential can in part be explained by parcels developed 1960–1974 having higher elevation, percent forest canopy cover, percentage of FM165 (very high load dry timber shrub), all of which tend to be positively correlated with high wildfire potential. It was found that fireline intensity and percentage crown fire were higher under 99th percentile fuel conditions compared to 50th percentile fuel conditions. At the same time, the differences between development classes were less distinct under 99th percentile fuel conditions than 50th percentile fuel conditions. These findings are consistent with previous studies which suggest that under extreme weather conditions, geographical variations in fuel types become less important in explaining fire behavior, thus limiting the effectiveness of fire mitigation treatments under extreme weather conditions (Schoennagel et al., 2004). This was observed in the high-severity Fourmile Canyon Fire of 2010, the costliest and most destructive wildfire in Colorado history, which burned 169 structures in Boulder County under extreme weather conditions. While the dependence of predicted fire behavior on moderate rather than extreme fire weather is well understood within the fire-behavior modeling community, the general public and the planning community need to be informed about the dramatic reduction in effectiveness of mitigation treatments under the most extreme fire weather conditions. This is particularly important in the Rocky Mountain region because warm-dry episodes that were considered extreme during the 20th century are predicted to become average conditions during the mid-21st century (Hoerling & Eischeid, 2007).

One important caveat to the current study is that the fuel and vegetation layers represent conditions circa 2001. Clearly vegetation and fuels have changed since 1880 in both developed and undeveloped parcels. Mining, grazing, logging, development, road-building, and forest management have all had important impacts on the Front Range landscape (Fornwalt, Kaufmann, Huckaby, & Stohlgren, 2009; Theobald, 2000; Veblen & Lorenz, 1986; Veblen et al., 2000). While fire suppression has resulted in only minor vegetation changes over most of the study area at mid- to higher-elevations, in the lower 20% of the montane zone there have been significant increases in tree densities in formerly open woodlands or grasslands leading to a significant build-up of woody fuels (Mast, Veblen, & Hodgson, 1997; Platt & Schoennagel, 2009; Sherriff & Veblen, 2007; Veblen & Lorenz, 1986). Also, vegetation changes in the relatively near future may significantly affect both fuel types and future development plans. Since 1996, mountain pine beetles (MPB; *Dendroctonus ponderosae*) have inflicted severe mortality in subalpine lodgepole pine forests over millions of hectares in northern Colorado, and currently MPB activity in ponderosa pine-dominated forests in the Front Range is at an elevated level. Tree mortality due to MPB clearly is altering fuel profiles in the affected forests but the consequences for fire behavior are uncertain. Although the dry dead fuels associated with MPB kill are intuitively expected to increase wildfire potential, analysis of past outbreaks, post-MPB fuel measurements, and fire behavior modeling suggest that wildfire potential will not necessarily increase following MPB outbreaks (Jenkins, Hebertson, Page, & Jorgensen, 2008; Klutsch, Beam, Jacobi, & Negron, 2008). Despite uncertainty about the relationship between fire hazard and MPB outbreaks, the current high level of MPB activity in Colorado is increasing funding and public support for fire mitigation treatments which will alter fuel types in the short-term and potentially in the long-term. Furthermore, the perception of increased fire hazard due to MPB kill as well as its aesthetic impact may affect demand for housing in the WUI. For example, one study calculated that property values decline by $648 for each tree killed by MPB within a 0.1 km buffer (Price, McCollum, & Berrens, 2010). Moreover, climate change is bringing uncertain but potentially profound effects on fuel types, wildfire potential and the perception of vulnerability to fire hazard in forest landscapes (Millar, Stephenson, & Stephens, 2007; Westerling, Hidalgo, Cayan, & Swetnam, 2006).

5. Conclusions

What are the implications of the findings for planners? Under the status quo newly developed parcels are likely to have a higher wildfire potential on average than developed parcels, especially under average (50th percentile) fuel conditions. This result applies only to development of currently undeveloped parcels, not to the further subdivision of developed parcels. Some of the factors contributing to this elevated level of hazard are fixed (e.g. elevation), while other characteristics (e.g. percent forest canopy cover, fuel model) potentially could be changed by fuel management strategies such as thinning and prescribed fire (Reinhardt, Keane, Calkin, & Cohen, 2008; Wimberly, Cochrane, Baer, & Pabst, 2009). However, under current land use and fire mitigation policies, extensive and recurring thinning is unlikely to take place on private land, which is the focus of this study, and which constitutes a significant portion of the WUI across the West(Schoennagel, Nelson, Theobald, Carnwath, & Chapman, 2009). As there is considerable variability in wildfire potential, incentives to develop less hazardous parcels or less hazardous areas within parcels, have the potential to reduce the incremental increase in wildfire potential. However, given that in the short-term land use regulations and hazard zoning are likely to be politically unpalatable and fuel treatments are unlikely to greatly alter wildfire potential at a landscape scale, county planning authorities should expect wildfire potential in newly developed parcels to be greater on average than in currently developed parcels. Since many areas of the Rocky Mountains experienced historically analogous patterns of development in biophysically similar environments (i.e. early colonization of valley bottoms, of upslope areas later, and reservation of federal lands at the highest elevations and slopes), these findings may apply broadly to the U.S. Rocky Mountain region.

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