5-2015

Fire Environment Analysis at Army Garrison Camp Williams in Relation to Fire Behavior Potential for Gauging Fuel Modification Needs

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FIRE ENVIRONMENT ANALYSIS AT ARMY GARRISON CAMP WILLIAMS IN

RELATION TO FIRE BEHAVIOR POTENTIAL FOR GAUGING FUEL

MODIFICATION NEEDS

by

Scott M. Frost

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Forestry

Approved:

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Logan, Utah

2015

ABSTRACT

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Behavior Potential for Gauging Fuel Modification Needs

by

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Utah State University, 2015

Major Professor: Dr. Michael Jenkins
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Jordan, Utah. In 2010 and 2012, wildfires burned beyond the Camp's boundaries into the

wildland-urban interface. The political and public reaction to these fire escapes was

intense. Researchers at Utah State University were asked to organize a system of fuel

treatments that could be developed to prevent future escapes. The first step of evaluation

was to spatially predict fuel model types derived from a random forests classification

approach. Fuel types were mapped according to fire behavior fuel models with an overall

validation of 72.3% at 0.5 m resolution. Next, using a combination of empirical and semi-

empirical based methods, potential fire behavior was analyzed for the dominant

vegetation types at AGCW on a climatological basis. Results suggest the need for

removal of woody vegetation within 20 m of firebreaks and a minimum firebreak width

of 8 m in grassland fuels. In Utah juniper (*Juniperus osteosperma* (Torr.) Little), results

suggest canopy coverage of 25% or less while in Gambel oak (*Quercus gambelii* Nutt.)

stands along the northern boundary of the installation, a fuelbreak width of 60 m for

secondary breaks and 90 m for primary breaks is recommended.

(198 Pages)

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Large fires (400 ha +) occur about every seven to ten years in the vegetation types located at US Army Garrison Camp Williams (AGCW) practice range located near South Jordan, Utah. In 2010 and 2012, wildfires burned beyond the Camp's boundaries into the wildland-urban interface. The political and public reaction to these fire escapes was intense. Researchers at Utah State University were asked if a spatially organized system of fuel treatments could be developed to prevent future escapes. The first step of evaluation was to spatially predict fuel model types derived from a random forests classification approach. Fuel types were mapped according to fire behavior fuel models with an overall validation of 72.3% at 0.5 m resolution. Next, using a combination of empirical and semi-empirical based methods, potential fire behavior was analyzed for the dominant vegetation types at AGCW on a climatological basis. Results suggest the need for removal of woody vegetation within 20 m of firebreaks and a minimum firebreak width of 8 m in grassland fuels. In Utah juniper (*Juniperus osteosperma* (Torr.) Little), results suggest canopy coverage of 25% or less while in Gambel oak (*Quercus gambelii* Nutt.) stands along the northern boundary of the installation, a fuelbreak width of 60 m for secondary breaks and 90 m for primary breaks is recommended.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

Problem Statement and Objectives

Suburban development over the last 20 years has moved the proximity of
communities closer and closer to the boundaries of Army Garrison Camp Williams
(AGCW), a military base established in 1914 in northern Utah.[1] Due to the regular
occurrence of wildfire in the fuel types at AGCW and recent wildfires that have burned

Fig. 1.1. Current fuel modification activities employed at Army Garrison Camp Williams:
(A) primary road, (B) goat grazing on Gambel oak in order to establish a fuel break, (C)
prescribed fire, (D) primary 7.62 m (25 ft) fire breaks constructed and maintained by
bulldozer.

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[1] http://en.wikipedia.org/wiki/Camp_Williams

Fig. 1.2. Photos from the Pinyon Fire, July, 2012 at Army Garrison Camp Williams. (A) photo taken from helicopter looking to south, (B) fire in Gambel oak stopped by a road, (C) hand crew marching to the line, (D) extreme fire behavior in juniper, (E) water bucket drop to douse crown fire in juniper, (F) fire in grass/sage/juniper.

homes and structures (e.g., Machine Gun Fire 2010)[2], the need for large fire prevention is

becoming more obvious. Current efforts to contain large fires are primarily based upon

linear firebreaks and fuelbreaks involving roads (Fig. 1.1A) and constructed firebreaks

(Fig. 1.1D). Grazing by goats (Fig. 1.1B) have been used since the early 2000s to

establish a fuelbreak along the northern boundary, usually about 70 m wide (Clark 2009).

Cattle grazing and sheep grazing have been used to reduce grass and shrub cover.

Prescribed fire has been applied to Gambel oak on a trial basis. Hand-thinning treatments

have also been used on a limited basis in stands of Utah juniper (*Juniperus osteosperma,*

(Torr.) Little) to reduce stand density and increase canopy base height. The 2010

Machine Gun Fire[2] and the 2012 Pinyon Fire (Fig. 1.2)[3] burned into the adjacent

wildland-urban interface (WUI) areas around AGCW, demonstrating the need for a

rigorous evaluation of current fuel treatments and potential treatments that could increase

the likelihood of limiting the frequency of occurrence and final size of large fires.

The objective of this research was to address limitations of current fuel treatments

and to evaluate future alternative treatments for the fuel types located at AGCW based on

remotely sensed vegetation and fuel model maps, climatological records, topographic

steepness, and existing operational fire behavior models.

Research Questions

This research begins with analysis of the components of the AGCW fire

environment (i.e., fuels, weather, and topography) in Chapter 2, followed by a review of

the recent fire history of AGCW, including a case study summary of the 2010 Machine

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[2] http://en.wikipedia.org/wiki/Machine_Gun_Fire
[3] Photos in Figure 1.2 Obtained from AGCW at:
https://www.flickr.com/photos/utahnationalguard/7733983922/in/set-
72157630933741482, also, several YouTube video clips are available of the 2012 Pinyon
Fire: https://www.youtube.com/results?search_query=2012+pinyon+fire

Gun Fire in Chapter 3. Finally, in Chapter 4, empirical and semi-empirical models are used to assess potential fire behavior at AGCW.

Chapters 2 through 4 are directed at answering the following primary questions:

1. How is the distribution and quantity of vegetation and fire behavior fuel models (Anderson, 1982) arranged at AGCW? How are slope steepness and associated topographic conditions described? What are typical fire weather conditions during the fire season at AGCW in terms of temperature, relative humidity, wind speed, and fuel moistures? (Chapter 2)

2. What constitutes the fire regime at AGCW in terms of fire frequency, annual acreage burned, fire intervals, sources of wildfire ignition, and historical fire perimeters? What do modeled fire regime characteristics at AGCW indicate about future expectations regarding frequency and severity of wildfire? In a case study format, what was the vegetation and fuel composition and arrangement prior to the Machine Gun Fire of September 19, 2010? Using BehavePlus (Heinsch and Andrews 2010), how does predicted fire behavior compare to observed fire behavior for the Machine Gun Fire during its major run on September 19, 2010? (Chapter 3)

3. What are the fire behavior patterns associated with different combinations of fuel model, wind speed, percent slope, and live and dead fuel moistures using the BehavePlus fire modelling system (Heinsch and Andrews 2010)? (Appendix, Figs. A.1, A.2, A.3, A.4, A.5)

4. How can firebreaks be evaluated for their effectiveness at stopping the forward spread of a grass fire? How can fire behavior potential be assessed in juniper woodlands? (Chapter 4)

5. Using the FlamMap fire modelling system (Finney, 2006), how does treatment implementation affect fire behavior compared to current conditions? (Chapter 4)

The fifth and final chapter presents the summary and conclusions of the preceding three chapters. The thesis document is organized in the multiple paper format, with Chapters 2 and 3 formatted for *Fire Ecology* and Chapter 4 formatted according to the *Journal of Rangeland Ecology and Management.*

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Heinsch, F.A., and P.L. Andrews. 2010. BehavePlus fire modeling system, version 5.0: design and features. Fort Collins, CO, USA: USDA, Forest Service, Rocky Mountain Research Station. General Technical Report, RMRS-GTR-249. 111 p.

CHAPTER 2

FIRE ENVIRONMENT COMPONENTS[1]

ABSTRACT

Planning of fuel treatments for ecological or social purposes requires an in-depth understanding of the conditions associated with the occurrence of free-burning fire behavior for a given area of concern. An analysis of the fire environment at Army Garrison Camp Williams in north-central Utah has been completed as a prerequisite for just such an undertaking. Overall the terrain would be generally regarded as mountainous in nature. Topographic information was summarized using a digital elevation model (DEM) that allows for the determination of the land base to be expressed in terms of slope steepness, aspect, and elevation, as well as a visualization map. The majority of the landscape is characterized by slopes less than 40% with slightly more north and east aspects than south and west with elevations largely ranging from 1650 to 1950 m MSL. Fire weather data were compiled from the three nearest remote automatic weather stations (RAWS) within and adjacent to the military installation and summarized according to diurnal and seasonal (from March to October) trends in ambient air temperature, relative humidity, 6.1-m open wind speed, and in terms of 1-, 10-, and 100-h dead fuel moisture timelags. Average temperature maxima (32 °C) and relative humidity minima (12%) usually occurred from 1400 to 1500 hours daily and from July to August seasonally. The predominate vegetation type complex is grass followed by lesser amounts of Gambel oak, sagebrush and some juniper. A fire behavior fuel model map was

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[1] Coauthors: Martin E. Alexander; Michael Jenkins

predicted from using biophysical, vegetation type, and plot survey data using the random forests technique and resulted in an overall validation of 72%. The semi-arid climate of Army Garrison Camp Williams coupled with its corresponding preponderance of flashy fuel types and sloping terrain constitutes a formidable fire environment.

INTRODUCTION

Clive M. Countryman (1915-1998) was a pioneer wildland fire behavior scientist stationed initially at Berkeley and then at Riverside, California with the research branch of the USDA Forest Service from 1941 to 1977. Countryman considered one of the keys to the effective control of wildfires and successful use of prescribed fires in wildland management was the understanding of the interactions of fire and its environment (i.e. the surrounding conditions, influences or forces that influence or modify). To this end, it is believed that he was the first to coin the term "fire environment" to represent the synergy that occurs amongst fuel, topographic and air mass or weather factors that influence the inception, growth, and behavior of a fire, and wrote extensively on the subject (Countryman 1960, 1964, 1966, 1969, 1972, 1973; Countryman and Schroeder 1962).

The fire environment may be represented by an inverted isosceles triangle (Figure 2.1). The two lower sides of the triangle represent the fuel and topographic components of the fire environment. The top side represents the air mass or weather component of the fire environment. The current state of each of these environmental components and their interactions with each other and with the fire itself determine the characteristics and behavior of a fire at any given moment.

The objective of this chapter is to provide an analysis of the three individual components of the Army Garrison Camp Williams (AGCW) fire environment by assembling and processing the available data on terrain, weather, and vegetation (fuels) in the area. This constitutes a prerequisite for interpreting wildland fire behavior potential using existing model systems and guidelines. In this way, potential fire behavior characteristics can be estimated as functions of weather, fuel, and terrain slope (Ryan 1984).
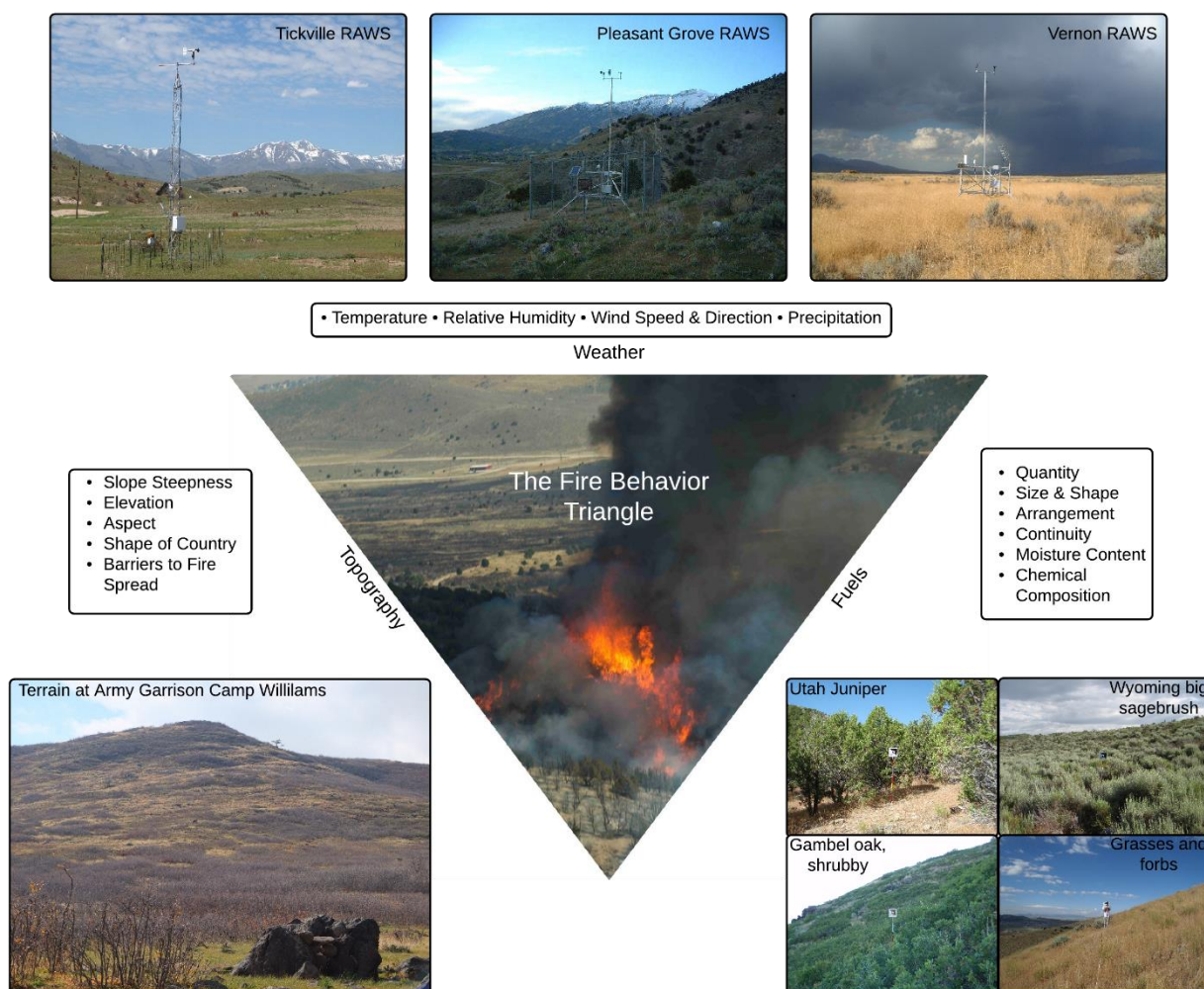
Figure 2.1. Photos of the fuels, weather, and topography at Army Garrison Camp Williams illustrating the components of the fire behavior environment triangle as outlined by Countryman (1972).

Brief Overview of the Three Fire Environment Components

Other factors important to fire behavior must always be considered in relation to fuels for "In short, no fuel, no fire!" (Brown and Davis 1973). Wildland fuels are created by living and dead plant materials through biological processes, photosynthesis, decomposition and accumulation (Keane 2015). Wildland fuels are only vegetation viewed from a particular standpoint of how they affect the behavior of wildfires and prescribed fires (Brown and Davis 1973). Certain individual vegetation types are commonly viewed as a "fuel type" – i.e. "an identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behavior under defined burning conditions" (Merrill and Alexander 1987). A "fire behavior fuel model" on the other hand is a simulated fuel complex for which all fuel descriptors (e.g. loading and surface area-to-volume ratio by fuel size, fuelbed depth) required for the solution of the Rothermel (1972) mathematical rate of spread model have been specified (Deeming and Brown 1975).

Weather is the most dynamic component of the fire environment, varying greatly, both temporally (in terms of months, days, hours, and minutes) and spatially. The influence of a weather element on fire behavior can be direct, as with the case of wind speed on fire spread rate and wind direction on the direction the fire is heading towards. It can also have an indirect influence as is the case in determining dead fuel moistures in which wetting and drying effects are controlled by past and present variations in air temperature, relative humidity, solar radiation and precipitation (Nelson 2001). Conversely, moisture levels in living plants are controlled by plant phenology and time of

year; they generally have very little to do directly with weather conditions, except in the case of extended droughts.

Changes in the moisture content of woody fuels is dependent on the particle diameter and the environmental conditions. The diameters of woody fuel particles have been classified according to their "time-lag" — i.e. the length of time required for a fuel particle to lose about 63% of the difference between its initial moisture content and its equilibrium moisture content (Fosberg 1970, Fosberg *et al.* 1981). Small diameter fuels respond relatively quickly to changing weather conditions whereas large diameter fuels require a longer drying or wetting trend to impact fuel moisture. The time-lag (TL) categories conventionally used in the U.S. for wildland fire modelling are specified as 1-, 10- , 100-, and 1000-h TL and correspond to round wood diameters size class ranges of 0-0.635, 0.635-2.54, 2.54-7.62, and 7.62-20.3 cm, respectively (Brown 1974, Deeming *et al.* 1977). Rothermel (1972) regarded the first three TL classes as "fine", "medium" and "heavy" fuels.

The term "topography" refers to the orientation of the land surface or exposure which is determined by the steepness or inclination of the slopes and by the aspect or the azimuth of the slope. It also includes elevation, barriers to fire spread (natural and man-made, water bodies), and shape of the country (Barrows 1951, Campbell 2005). These factors affect fire behavior in one or more ways. The effect of slope on fire spread is to increase the efficiency in preheating fuels and in turn the rate of the advancing flame front. All other things being equal with respect to the fire environment, a fire burning on a 20% slope will spread approximately two times faster than a fire on level ground (Van Wagner 1977). With the exception of the mechanical effect of slope steepness on rate of

fire spread the effects of topography on fire behavior depends largely on how it alters

both the meso- and micro-scale meteorological variables and how these influence

changes in dead fuel moistures and winds near the ground surface (Schroeder and Buck

1970, Cheney 1981, Whiteman 2006).

METHODS

Topography

To better understand the topography at AGCW, Light Detection and Ranging

(LiDAR) data obtained in 2011 was processed using QT Modeler 8.01 (QT Modeler

2013) into return categories and graphically displayed using a Geographic Information

System (GIS) via ArcGIS 10.1 (ESRI 2012). An important post-processing raster product

was a high resolution (0.5 m) digital elevation model (DEM), which is a representation of

the Earth's surface. From the DEM layer, slope and aspect rasters were also derived

(Figure 2.2). The areas involved with individual topographic characteristics were

calculated using the zonal statistics geoprocessing tool in ArcGIS 10.1 (ESRI 2012).

A wide variety of proposed slope steepness classifications can be found in the

wildland fire literature. (i.e. there appears to be no universal agreement of any kind on the

matter). For example, Barrows (1951) considered 0-20% as a gentle slope, 21-40% as a

moderate slope, 41-60% as a steep slope, and 60%+ as very steep. The decision was

made to use the five slope classes associated with the National Fire Danger Rating

System (NFDRS) (Bradshaw et al. 1983): 0-25, 26-40, 41-55, 56-75 and >75%. As for

aspect or slope exposure, the four major cardinal directions (north, east, south and west)

were selected as per Rothermel (1983). For elevation, five classes were delineated on the

basis of 150-m intervals starting at 1500 m MSL with the final class set at 2100 m MSL.

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┌──────────────┐
│    LiDAR     │
└──────────────┘
       │
       ▼
┌──────────────┐
│   Digital    │
│  Elevation   │
│  Model (DEM) │
└──────────────┘
       │
       ▼
┌────────┐ ┌──────────┐ ┌────────┐
│ Slope  │ │Elevation │ │ Aspect │
└────────┘ └──────────┘ └────────┘
    │          │            │
    ▼          ▼            ▼
```

Slope → Area by NFDRS Slope Classes

Elevation → Area of Elevation by 150 m Classes

Aspect → Area of Aspect Exposure by Cardinal Direction
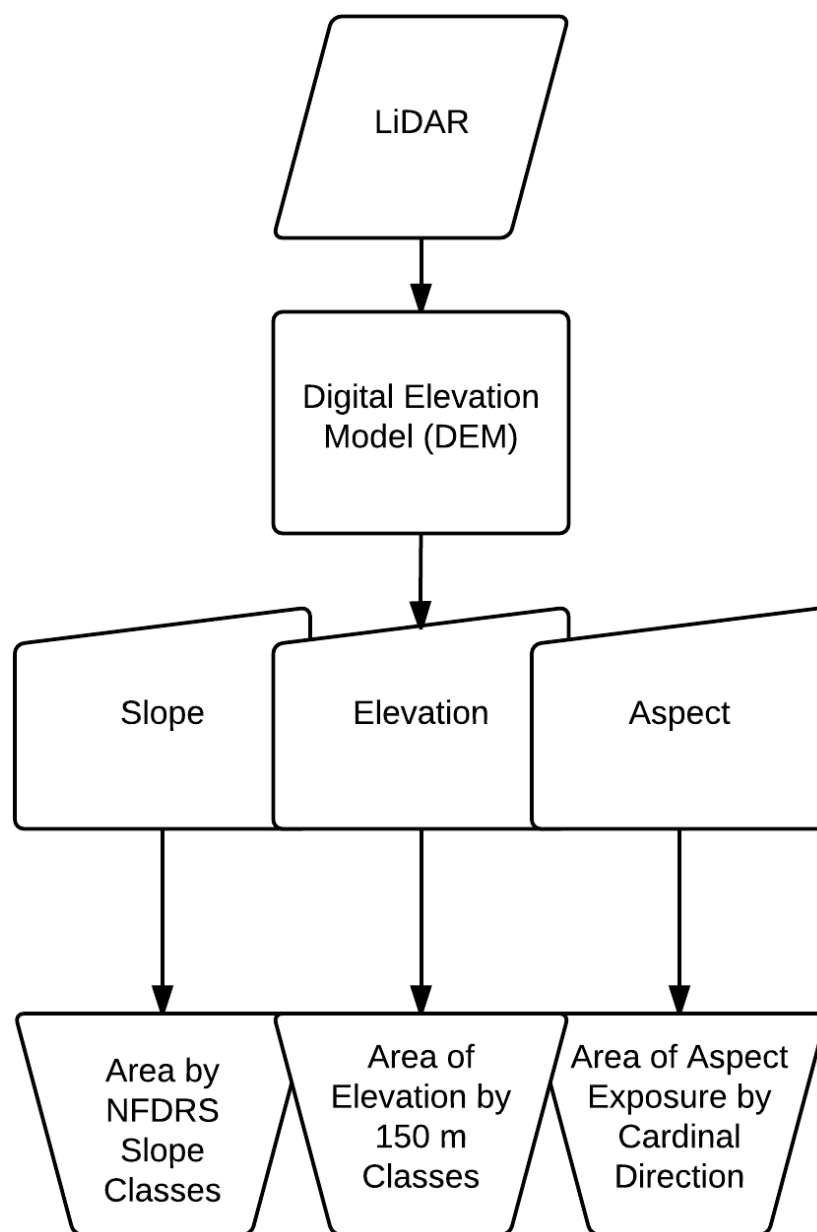
Figure 2.2. Methodology for the assessment of topography at Army Garrison Camp Williams. LiDAR = Light Detection and Ranging, NFDRS = National Fire Danger Rating System.

Weather information refers to the observations of meteorological variables made at a particular place and time. This is in contrast to climate, which represents the synthesis of weather observations to obtain a statistical description of conditions over a large area (Furman *et al.* 1984).

The location of AGCW is within the great basin fire climate region and is typified by cold winters, hot summers, and low annual precipitation, generally from 40 to 100 cm annually (Schroeder and Buck 1970). Climate is heavily influenced by the rain shadow effect of the Sierra-Cascade Ranges including wind patterns such as the Great Basin High. Wind patterns associated with this high typically come from Canada and the Northwest and warm adiabatically as air masses move from the high elevations of the Sierra and Cascade ranges to the drier and lower elevations of the Great Basin. Surface pressures tend to be flat in the Great Basin summer months, allowing for extended periods of high ambient air temperature, low humidity, and air mass instability (Schroder and Buck 1970). Precipitation occurs mostly in the winter months with a secondary maximum in the spring.

Weather data were gathered from the nearest available Remote Automatic Weather Stations (RAWS) to AGCW (Figure 2.3). Nearby weather stations from the Pleasant Grove RAWS and Vernon RAWS were used to provide a longer temporal window and to fill in missing time periods for the Tickville RAWS. Table 2.1 and Table 2.2 gives a detailed description of the three RAWS stations and the three sites for live fuel moisture data used, including their location, elevation, and range of data. Readings for weather data are initiated 15 min before the hour and represent 10 minute averages

(NWCG 2005) which are reported on the hour. Also, in Utah daylight savings begins in

March and ends in November. RAWS hourly data are recorded according to local

standard time (NWCG 2012b) with no time adjustment for changes in standard time

daylight savings time. Thus, no time adjustment for daylight savings was made in the

results reported in this research. If desired, the diurnal averages during the fire season

should be adjusted forward one hour.

Table 2.1 Characteristics of weather stations selected for analysis and available years of data.

Weather station	Latitude	Longitude	Elevation (m MSL)	No. of years of data	List of years
Tickville	40°24' N	112°00' W	1 582	11	2000-2001, 2004-2010, 2012-2013
Pleasant Grove	40°25' N	111°45' W	1 585	17	1997-2013
Vernon	40°05' N	112°25'W	1 676	23	1991-2013
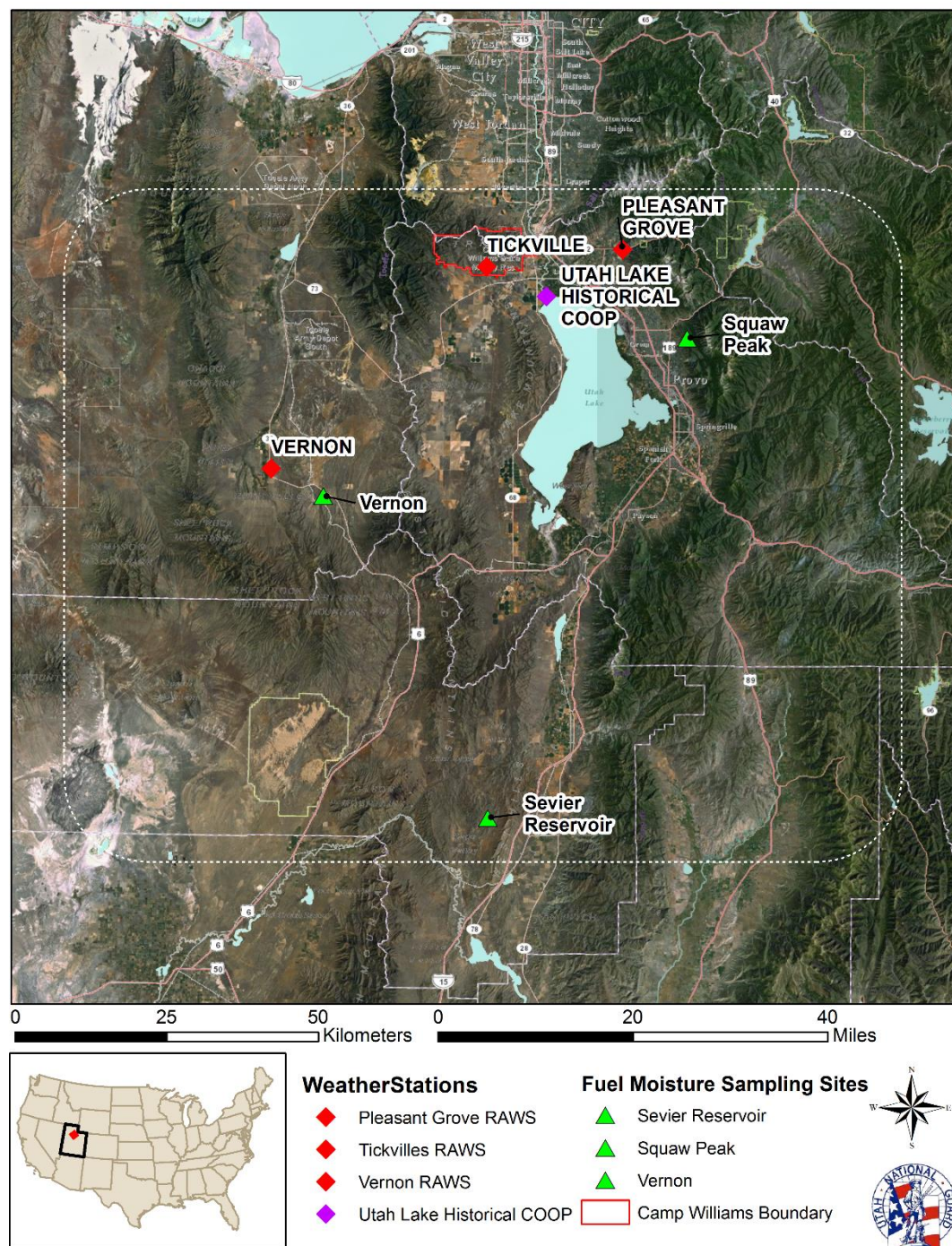
Figure 2.3. Location of remote automatic weather stations, long-term climatological weather station (1904-2013), and fuel sampling sites used in the fire weather component analysis at Army Garrison Camp Williams.

Historical weather data were obtained via the NOAA National Climatic Data

Center (NOAA 2014) from a nearby climatological station (elevation 1373 m MSL) on

the northern end of Utah Lake, approximately six miles south of AGCW (Figure 2.3).

The data ranges from 1904-2013 and were used to compare precipitation and ambient air

temperature trends over 30-year periods. The historical weather data at Utah Lake were

averaged by month for years 1904-1930, 1931-1960, 1961-1990, and 1991-2013 from

January to December.

Table 2.2 Characteristics of fuel moisture sampling sites selected for analysis and available years of data.

Site	Latitude	Longitude	Elevation (m MSL)	Fuel type sampled	List of years
Squaw Peak	40°18' N	111°37' W	2038	Gambel oak	2002-2013
Sevier Reservoir	39°35' N	112°00' W	1624	Cheatgrass	2002-2013
Vernon	40°03' N	112°19'W	1719	Utah juniper, W. big sagebrush	1997-2013

RAWS data were processed using FireFamily Plus (RMRS 2002) and the R

Statistical Package (R Core Team 2013) to summarize diurnal and seasonal trends during

the fire season (defined here as March 1 to October 31, 84% of the 27906 fires in Utah

from 1992 to 2012 occurred during this time frame (Short 2014)) for ambient air

temperature, relative humidity, 6.1 m open wind speed, 1-, 10-, and 100-h dead fuel TL

fuel moistures (Figure 2.4). For diurnal data, observations where averaged according to

month and hour of the day for the span of each RAWS station weather record. Seasonal

data were averaged by month for each weather station according to the same time-frame.

Wind Rose plots for this analysis were automatically generated from the Western

Regional Climate Center (WRCC) for each of the RAWS stations in Figure 2.3. Data for
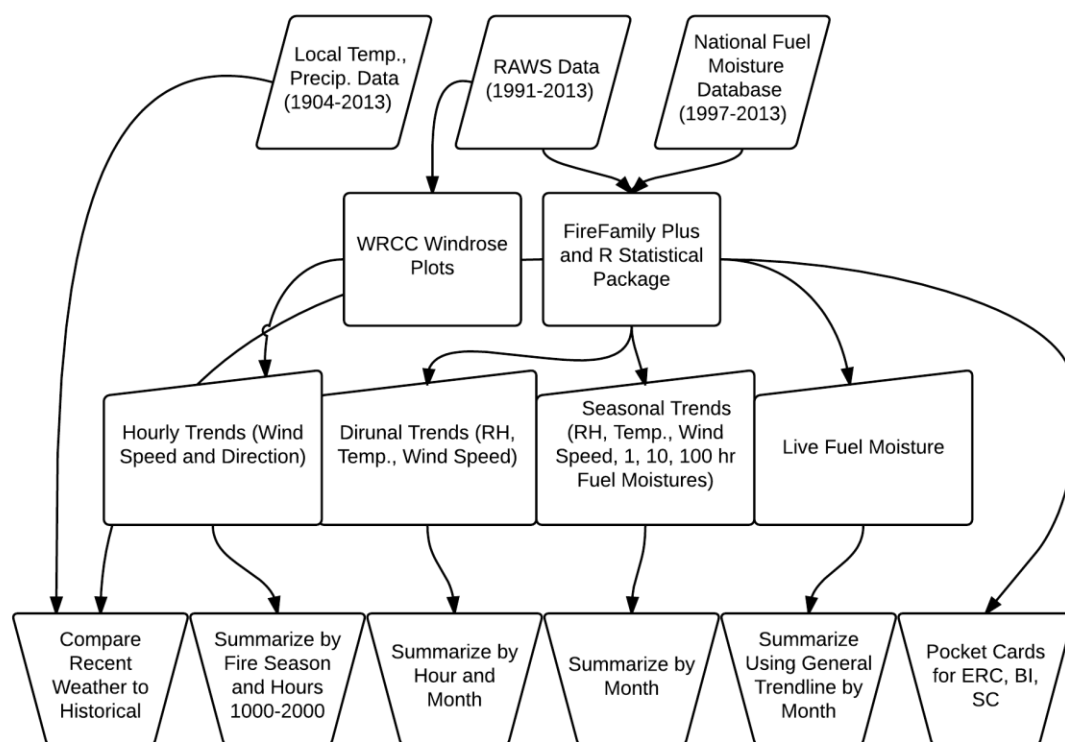
Figure 2.4. Flow chart of methodology used to summarize weather using remote automatic weather station (RAWS) data, local weather observation data, and National Fuel Moisture Database live fuel moisture content data. RH = relative humidity, ERC = energy release component, BI = burning index, SC = spread component, WRCC = Western Regional Climate Center.

the Wind Rose plots at each RAWS were queried to average observations that occurred

between 1000 to 2000 hours from March 1 to October 31. A Wind Rose diagram is

designed to show the distribution of wind directions experienced at a given location – it

thus shows the prevailing wind direction – the most common format is a circle from

which eight or 16 lines are estimated, one for each compass point with the percentage for

calm conditions noted in the center. Fire Danger Rating Pocket Cards (Andrews *et al.*

1998, RMRS 2002) were also produced for NFDRS index values of Energy Release

Component (ERC), Burning Index (BI), and Spread Component (SC). ERC is a measure

of the total heat release per unit area, BI is an indication of suppression difficulty related to flame length at the head of a fire, while SC is a rating of the forward rate of spread at the head of a fire (NWCG 2012a).

No sampling of live herbaceous and woody fuel moistures is carried out within AGCW. It was necessary to compile live fuel moisture data from the National Fuel Moisture Database (USFS-WFAS 2014)[4] for the dominant vegetation corresponding to dominant vegetation types occurring within AGCW located at adjacent sampling sites. Samples obtained for live fuel moistures are generally collected on a bi-monthly basis. Sample data were plotted according to vegetation type for all the years of record so as to determine seasonal trends.

Fuels

For fuels planning purposes, land managers frequently use data provided by the Landscape Fire and Resource Management Planning Tools (LANDFIRE). This dataset is nationally available at a 30 m resolution and provides geospatial data required by fire behavior and growth simulation software such as FARSITE (Finney 2004) and FlamMap (Finney 2006). Fire behavior fuel models (FBFM) are one component of the LANDFIRE suite of data products. Both the original set of 13 (Anderson 1982) and the newer set of 40 fuel models (Scott and Burgan 2005) are available. The FBFM predictions are derived from rule sets based on existing vegetation type, cover, height and environmental site potential (Reeves *et al*. 2009). Due to the large national scale of LANDFIRE data, its delivery is typically one to four years behind current conditions.

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[4] http://www.wfas.net/index.php/national-fuel-moisture-database-moisture-drought-103

Other efforts at local fuel model mapping have been attempted (Arroyo *et al.*
2008) to attain better spatial and temporal prediction accuracy. Different techniques have
been employed utilizing normalized difference vegetation index (NDVI) in combination
with an unsupervised classification (Van Wagtendonk and Root 2003), object based
image analysis (Arroyo *et al.* 2006, Gitas *et al.* 2006, Alonso-benito *et al.* 2013), machine
learning (Poulos 2009, Chirici *et al.* 2013, Jakubowksi *et al.* 2013), and data fusion
approaches with light detection and ranging data (LiDAR) (Mutlu *et al.* 2008, García *et
al.* 2011).

Using random forests to predict fuel model and dominant vegetation type. To
evaluate fuels at Army Garrison Camp Williams (AGCW), an inventory of current
conditions must first be obtained. The two sources of data on fuel model type and
location currently available at AGCW were derived from the national Landscape Fire and
Resource Management Planning Tools (LANDFIRE) classification system and a local
fuel typing based on vegetation (Rollins and Frame 2006). These two data sources have
several limitations, including limited verification and the assumption that vegetation type
represents a particular fuel model. It is common to base fuel model classifications on
descriptions of the fuel complex including vegetation type, structure and arrangement,
and physical descriptions of the fuels themselves, including surface area-to-volume ratio,
fuel load, fuel depth, and fuel size distributions. It is important to utilize experienced
judgment and familiarity with local burning characteristics in order to refine the
classifications to more accurately appraise fire behavior potential.

For fuel mapping, Keane *et al.* (2001) suggested a standard, termed the
"vegetation triplet" be followed. A vegetation triplet is comprised of a combination of (1)

biophysical data used to describe important governing environmental factors and context,

(2) species composition data describing typical vegetation type or cover, and (3) vertical

stand structure data, which describes the typical height and dimension characteristics of

the vegetation. Data used to map fuels and vegetation at AGCW (Figure 2.5) followed the

Keane *et al.* (2001) framework, using LiDAR derived biophysical data, LiDAR derived

vegetation height, high resolution orthoimagery (HRO) (15 cm), and a normalized

difference vegetation index layer (NDVI). Two sets of plot data were used for the

classifications. The first set were field data collected by AGCW resource management

personnel in 2012 on 91 plots using Natural Fuel Photo Series guides (Ottmar *et al.* 1998,

Ottmar *et al.* 2000*a*, 2000*b*, Ottmar *et al.* 2007) to classify vegetation strata. Additionally,

each plot was classified as a standard fuel model according to Scott and Burgan (2005).

Further plots were added to the original 91 using a geographic information system (GIS)

and visually interpreted from the same HRO layer used in the mapping process to

supplement under-represented fuel model categories. The second set of plot data were

derived by generating 1 000 random points in a GIS and were classified into dominant

vegetation type categories of either Gambel oak (*Quercus gambelii,* Nutt.), Utah juniper

(*Juniperus osteosperma,* (Torr.) Little), sagebrush (*Artemesia tridentata*), grass (common

species at AGCW include *Bromus tectorum, Hesperostipa comate, Poa bulbosa, Poa*

secunda, Pascopyrum smithii, Pseudoroegneria spicata, Stipa hymenoides) or bare earth.

      Utilizing the plot data, a spatially classified map of fire behavior fuel models and

vegetation types across the camp were produced using a random forests classification

scheme (Breiman 2001). The random forests classification recursively selects 60% of the

data to predict the remaining 40%. The remaining 40% is referred to as the out of bag

(OOB) data. Random forests constructs hundreds of decision trees and outputs the class

occurring predicted by the majority of the trees. The final model is then applied to the
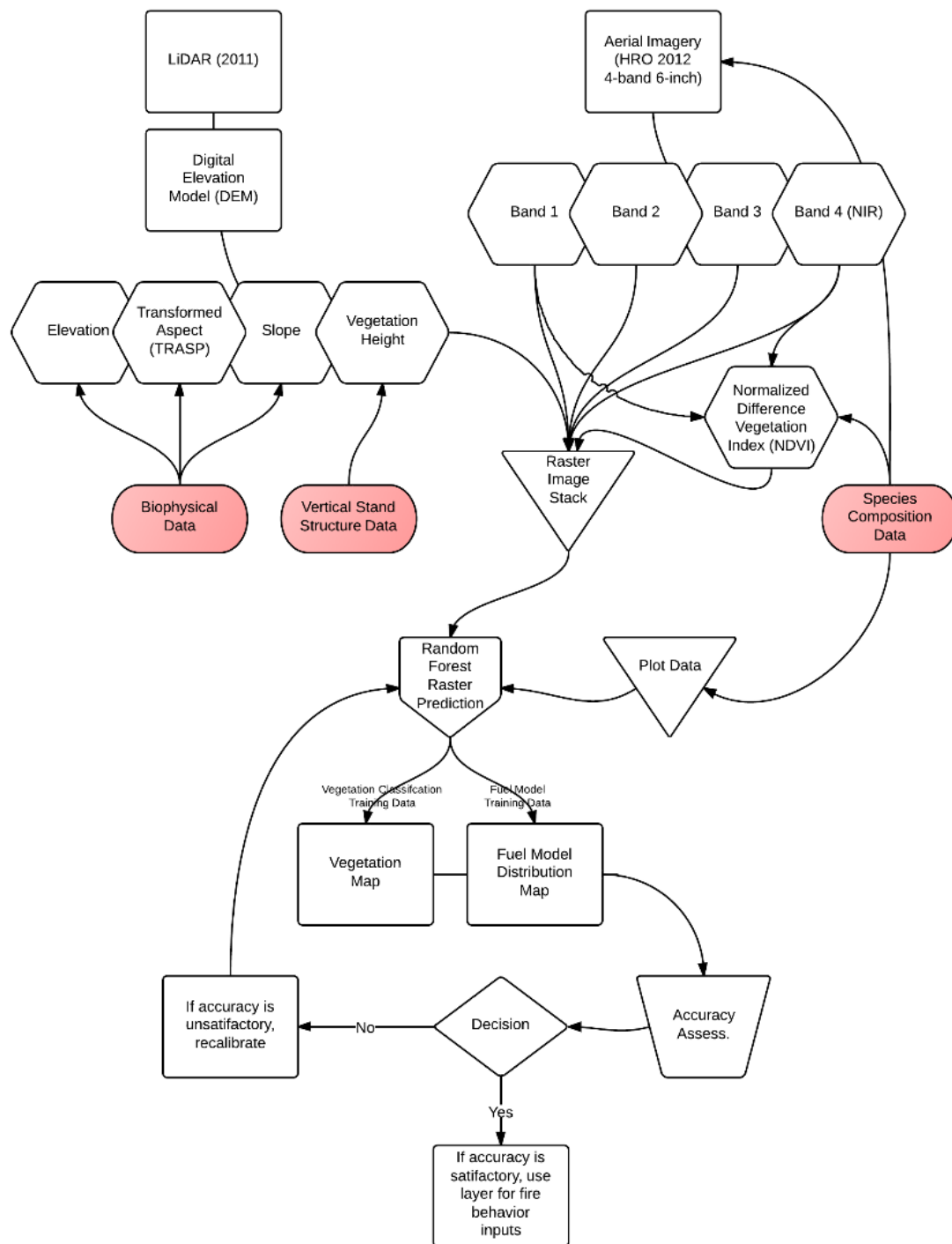
Figure 2.5. Flow chart of methodology used to map vegetation type and fuel models (Anderson 1982) at Army Garrison Camp Williams. Red boxes indicate the three vegetation triplet categories of Keane *et al.* (2001). LiDAR = light detection and ranging, HRO = high resolution orthoimagery, and NIR = near infrared.

spatial data on a per-pixel basis. This process has been referred to as 'voting' for classification. To produce the fuel model map, 500 trees were used for every prediction, with three variables used at each split. Two different random forests models were used in this process. The first was used to predict fire behavior fuel model type and the second to predict dominant vegetation type. The geospatial raster layers used for prediction in the random forests models were exactly the same, the only difference being the plot datasets specific to the fuel models and the dominant vegetation types. This method was employed to minimize error propagation from the vegetation output to the fuel model output and vice versa. Following production of classified dominant vegetation and fire behavior fuel model maps, tables were produced summarizing the area involved in relation to the NFDRS slope steepness classes.

RESULTS

Topography

The principal topographic characteristics of AGCW are summarized in Table 2.3 by area and percentage of total area in terms of NFDRS slope class, aspect, and elevation. Figure 2.6 presents a map of the DEM layer at AGCW, allowing for a quick visualization of landscape arrangement and form. Elevation at AGCW is highest on the western and northwestern boundaries at elevations near 2 100 m. The large valley running south-north across the middle of the base in the Tickville area often acts as a catalyst for upslope wind speeds blowing south to north during the day. In the context of wildland-urban-interface (WUI) fire protection, this configuration of topography with respect to weather patterns in the area is extremely problematic, as prevailing winds and the steepest slope

tend to align at the end of the valley along the northern ridgeline of AGCW. To further

complicate matters, this same area is dominated by shrubby Gambel oak on a southern

exposure. This is precisely the location where a fuelbreak maintained using goat grazing

was breached in 2010 by the Machine Gun Fire which subsequently burned multiple

structures in the community of Herriman UT.

Referring to Table 2.3, nearly all of the area at AGCW is characterized by slopes

from zero to 40% slope (78% of total area) and the remaining 22% is characterized by

steep slopes of 41% or greater. The breakdown of aspect categories reveals that a large

portion of the base has north- and east-facing aspects (62%) as opposed to south and west

aspects (38%). Elevation is most typically between 1650 to 1950 m MSL (85% of total

area), with the remaining 15 % on the two tail ends.

Weather and Climate

Weather and Climatic data are summarized according to three general categories:

(1) diurnal, (2) seasonal, (3) and 30-year historical trend comparisons.

Diurnal Variation. Trends in diurnal variation where averaged by hour and month

at the Pleasant Grove RAWS for March 1 to October 31 for the period 1997 to 2013.

While this station was not the closest in proximity to AGCW, it provided a longer record

of weather data. Ambient air temperature trends in diurnal variation report average

minima near 0900 hours and average maxima usually around 1500 hours (Figure 2.7).

Hourly temperatures are greatest from June to August, topping out at about 32 °C at 1500

hours in July. These hourly values are averages aggregated over multiple years and thus

do not capture large individual variations that may have been recorded. For example, the

Table 2.3. Area estimates of topographic and fuel characteristics incorporating 250 m buffer surrounding the Army Garrison Camp Williams boundary.

Fire environment characteristic	Area (ha)	Percent of total area (%)
NFDRS slope steepness class and range in percent		
1 = 0 – 25%	5976	53.70
2 = 26 – 40%	2734	24.57
3 = 41 – 55%	1670	15.00
4 = 56 – 75%	653	5.87
5 = > 75%	96	0.86
Aspect		
North	3540	31.81
East	3334	29.96
South	2046	18.38
West	2210	19.85
Elevation (m MSL)		
1500-1649	665	5.97
1650-1799	2619	23.53
1800-1949	4312	38.75
1950-2099	2529	22.72
>2100	1005	9.03
Vegetation type		
Gambel Oak	2027	18.21
Juniper	419	3.76
Sagebrush	1405	12.62
Grass	6529	58.66
Bare Earth	751	6.74
Fire behavior fuel model		
1—Short grass (0.3 m)	2008	18.04
2—Timber (grass and understory)	3815	34.28
5—Brush (0.6 m)	4073	36.60
8—Closed timber litter	199	1.79
Bare earth	1034	9.29
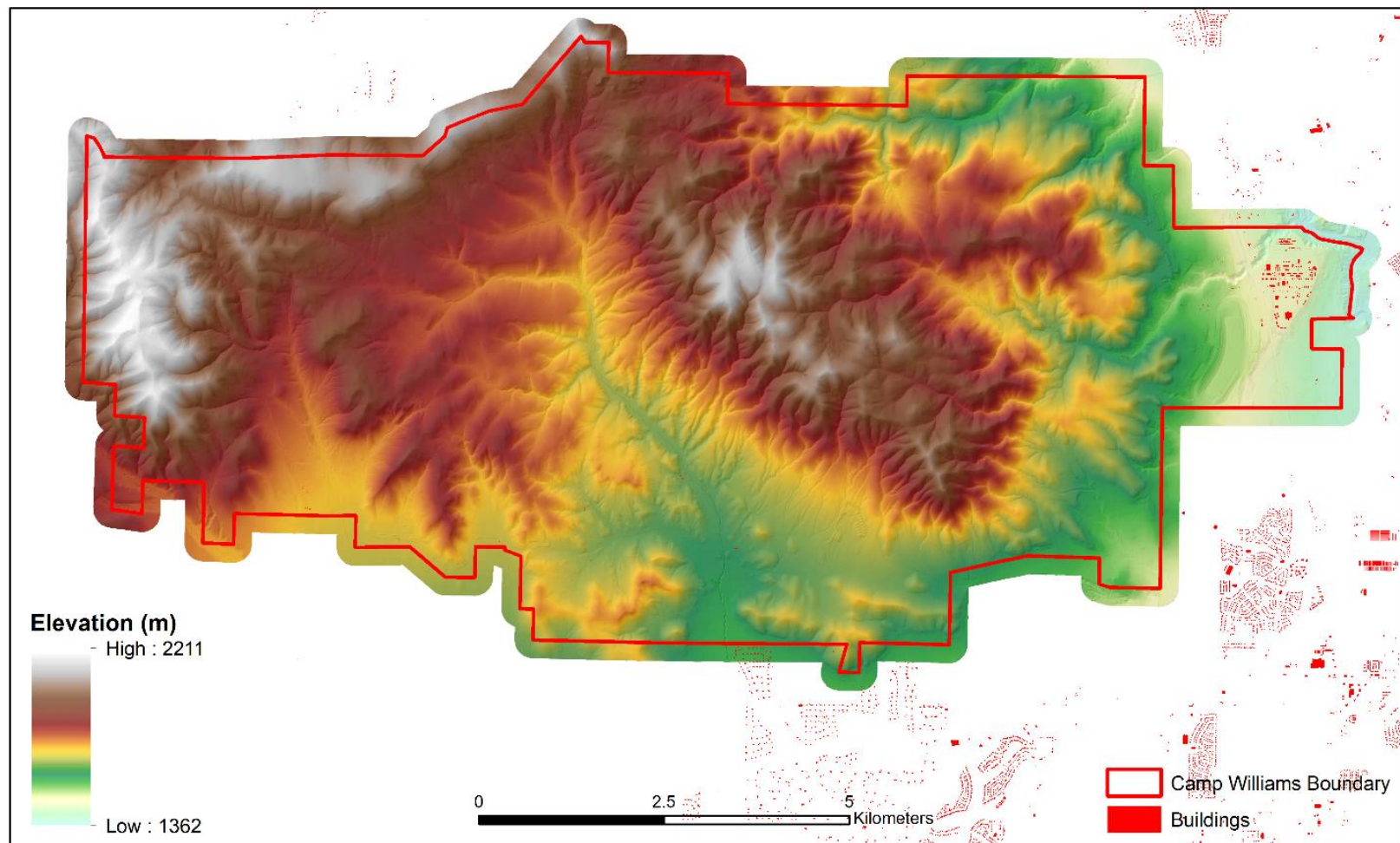
Figure 2.6. Digital elevation model (DEM) at Army Garrison Camp illustrating the general landscape features of the area.

maximum hourly temperature recorded between the three RAWS stations from the available data were 42°C in July of 2003. In terms of RH, months with the lowest values are those within the peak fire season from June to September (Figure 2.7). Daily variation of RH in July ranges from the average minimum of about 12% to the average maximum of about 23%. The largest dip in RH occurs during the daylight hours, typically in the afternoon around 1500 hours, corresponding to maximum daily temperatures at about the same time.

The diurnal variation in the 6.1 m open wind speed is dramatic in terms of maximum (19 km h^{-1}) and minimum (5 km h^{-1}) averages, but appears somewhat consistent by month (Figure 2.7). The lowest wind speeds during the day, around five km h^{-1}, occur in the morning at about 0900 hours regardless of month, except for March and April. Wind speeds typically increase throughout the day after the morning minimum until a short lull occurs at around 1800 to 2000 hours, followed by a further increase, reaching maximum wind speeds in the midnight hours.

Seasonal variation. Seasonal trends were computed for each RAWS weather station in the AGCW area and averaged. The fire weather variables analyzed were ambient air temperature, RH, 6.1-m open wind speed, and dead fuel moisture TL size classes. Temperature for the three RAWS stations peak in July near 32°C at the Vernon RAWS, 33°C at the Pleasant Grove RAWS, and 26°C at the Tickville RAWS (Figure 2.8). Corresponding RH values for all RAWS stations are lowest in June, July, and August, with the lowest values reached in July, near 15% at the Vernon RAWS (Figure

2.9). Maximum wind speeds for all three stations appear to average from 15 to 20 km h^{-1}

regardless of the fire season month.
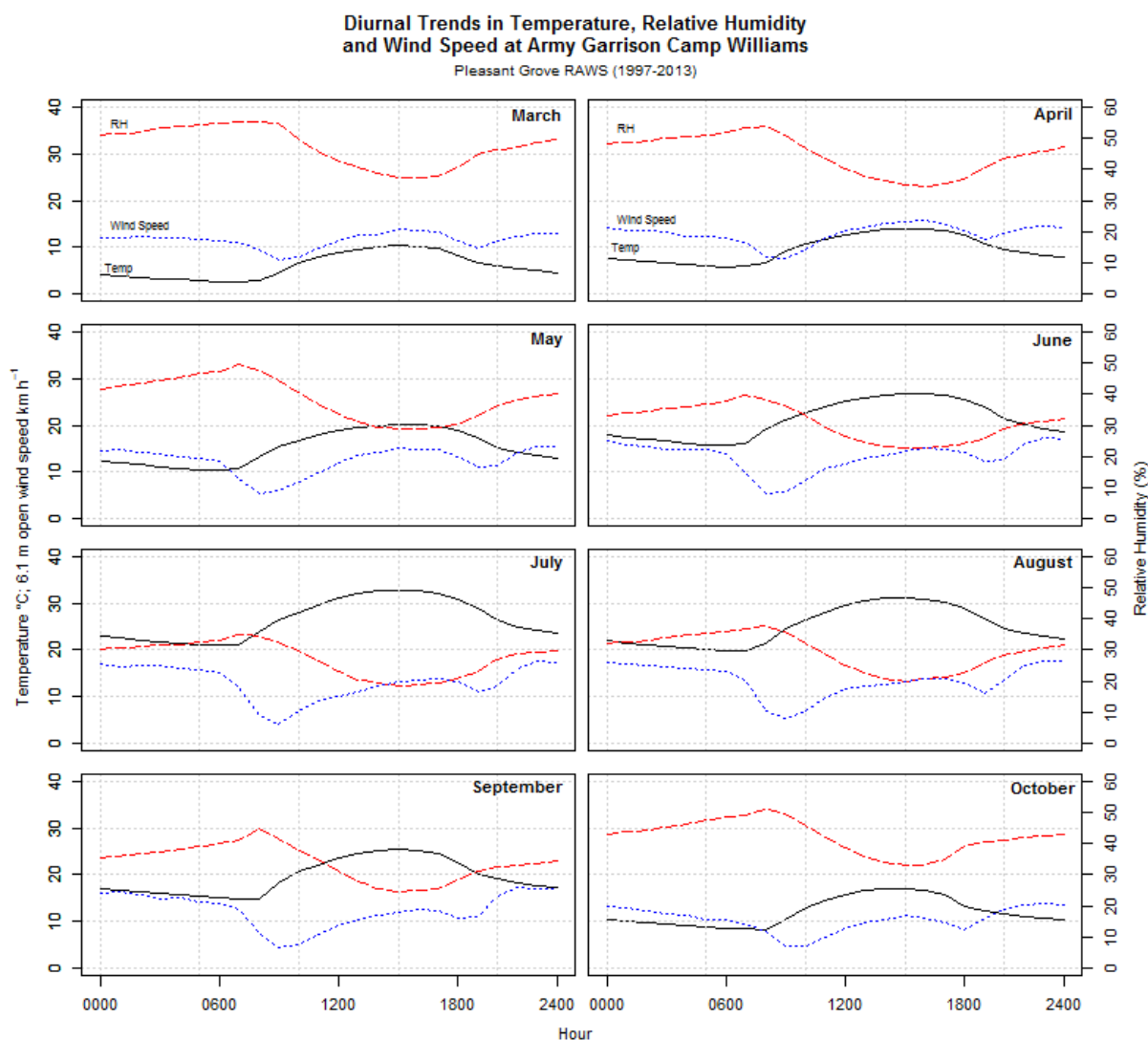
Figure 2.7. Graphical summary of diurnal variations in relative humidity (RH), ambient air temperature (Temp), and 6.1 m open wind speed by month during the fire season at Army Garrison Camp Williams based on the Pleasant Grove RAWS for the period 1997 to 2013.

Seasonal Trends in Temperature at
Army Garrison Camp Williams
Observations Averaged at 1300 hrs
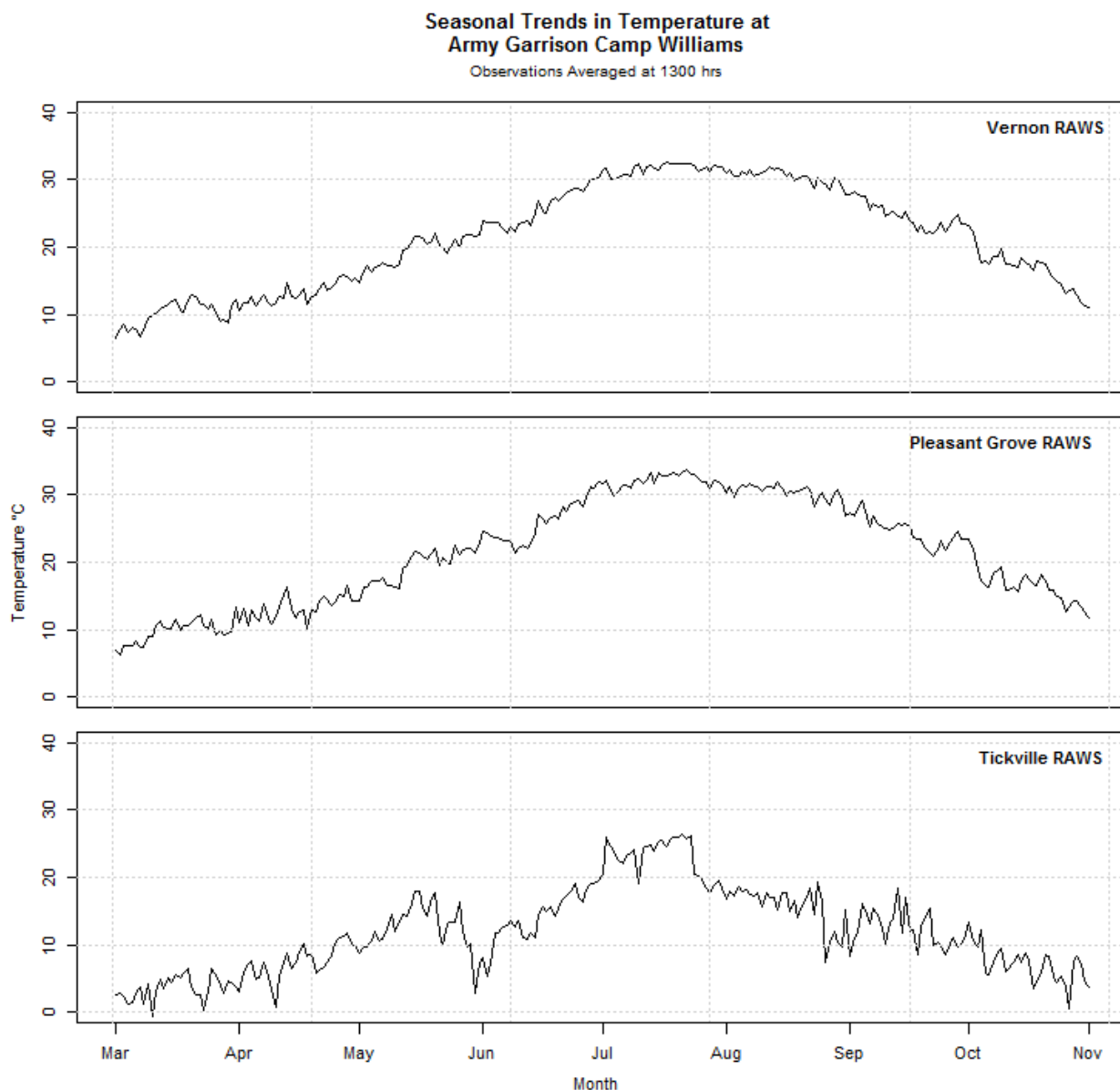
Figure 2.8. The seasonal variation in the daily ambient air temperature as recorded at 1300 hours from March 1 to October 31 at three remote automatic weather stations (RAWS) within and near Army Garrison Camp Williams.

The graphs of seasonal variations in the dead fuel time-lag size classes (1-, 10-, 100-h), indicate that dead moisture content starts out high in the spring (March, April, and May), and gradually decreases each month until seasonal lows are reached in July

and August (Figure 2.11). After August, moisture contents again begin to gradually rise

during the latter part of the fire season (September and October).
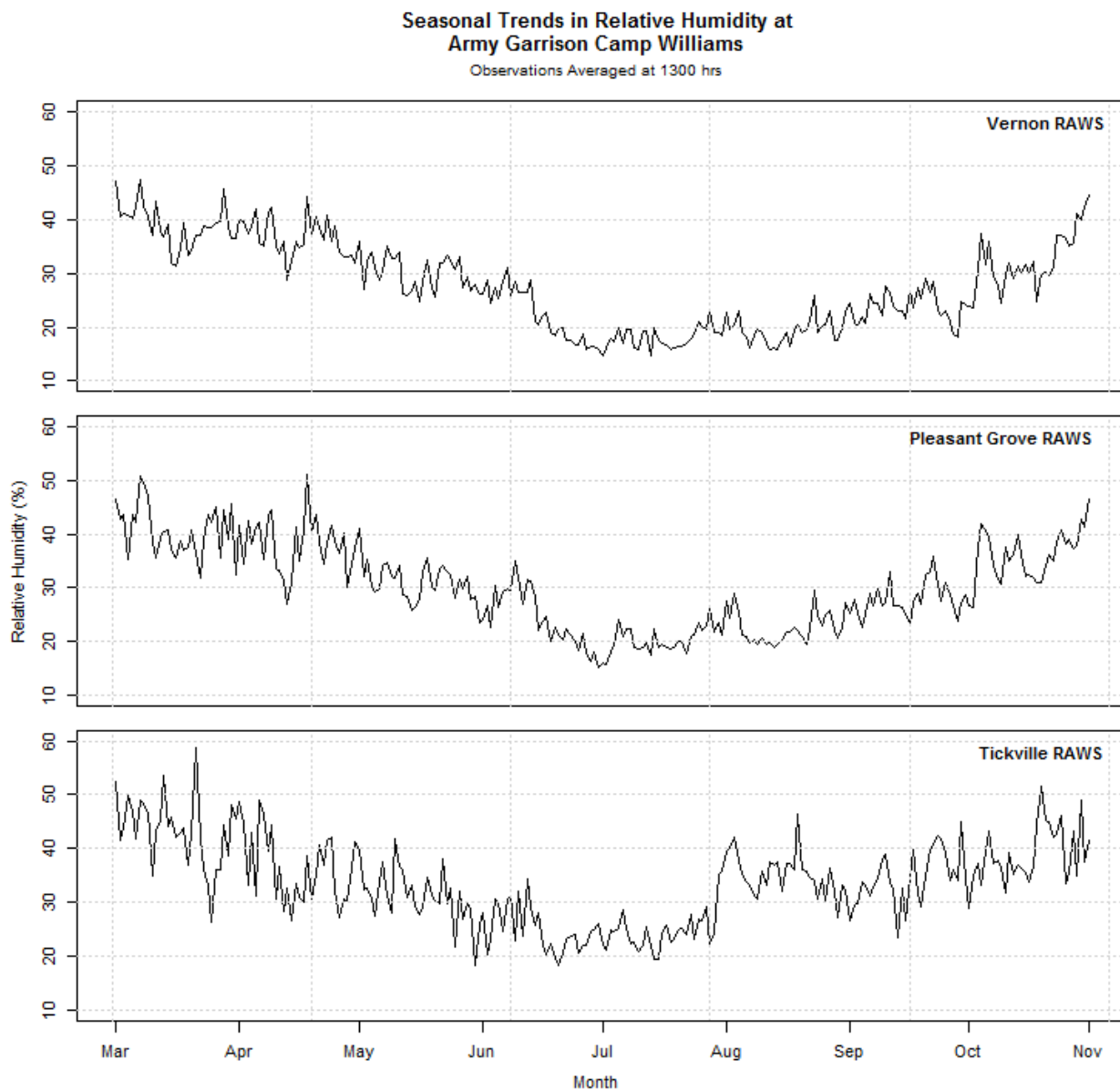
Figure 2.9. The seasonal variations in the daily relative humidity as recorded at 1300 hours from March 1 to October 31 at three remote automatic weather stations (RAWS) within and near Army Garrison Camp Williams.
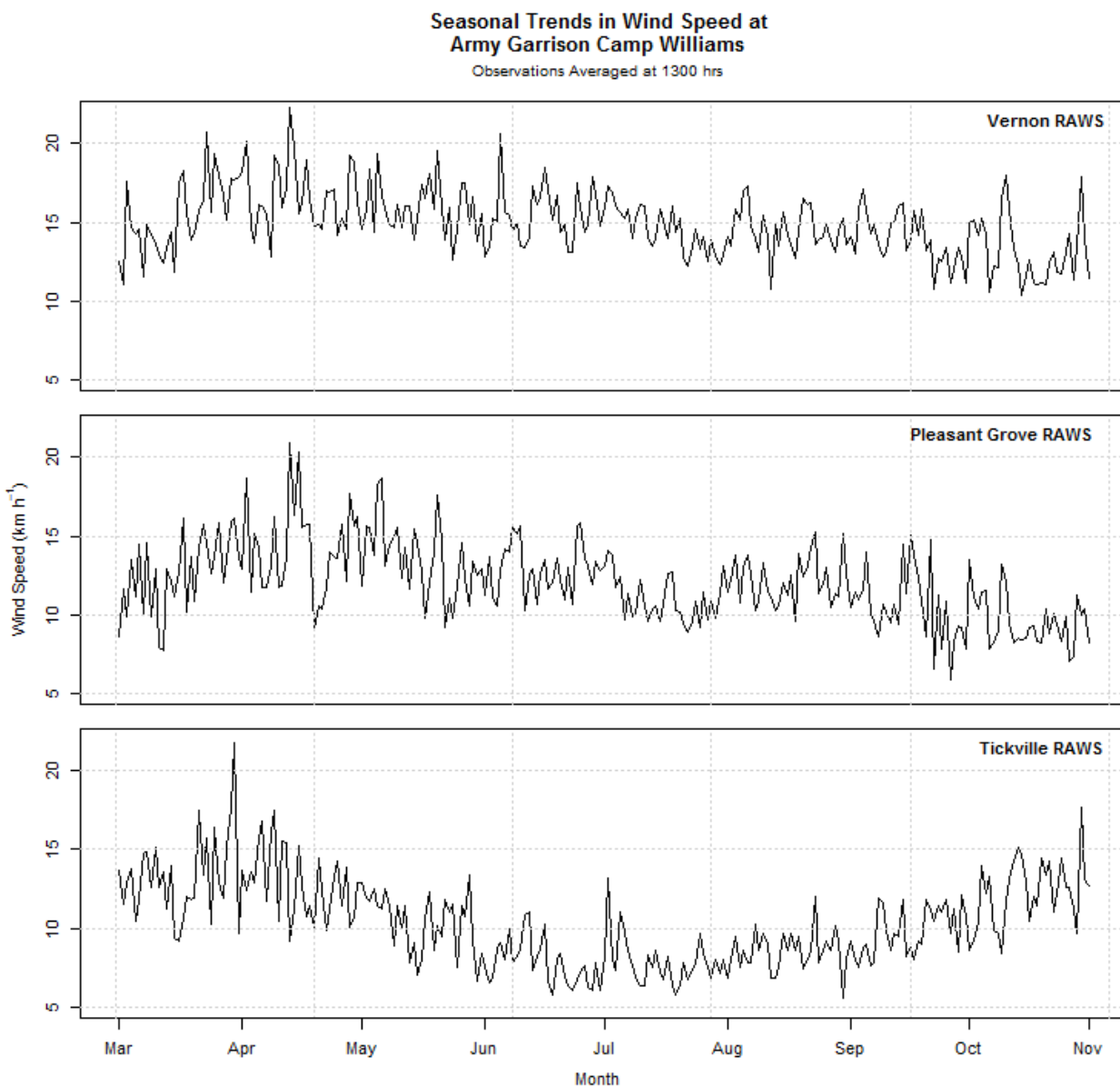
Figure 2.10. The seasonal variation in the daily 6.1-m open wind speed as recorded at 1300 hours from March 1 to October 31 at three remote automatic weather stations (RAWS) within and near Army Garrison Camp Williams.
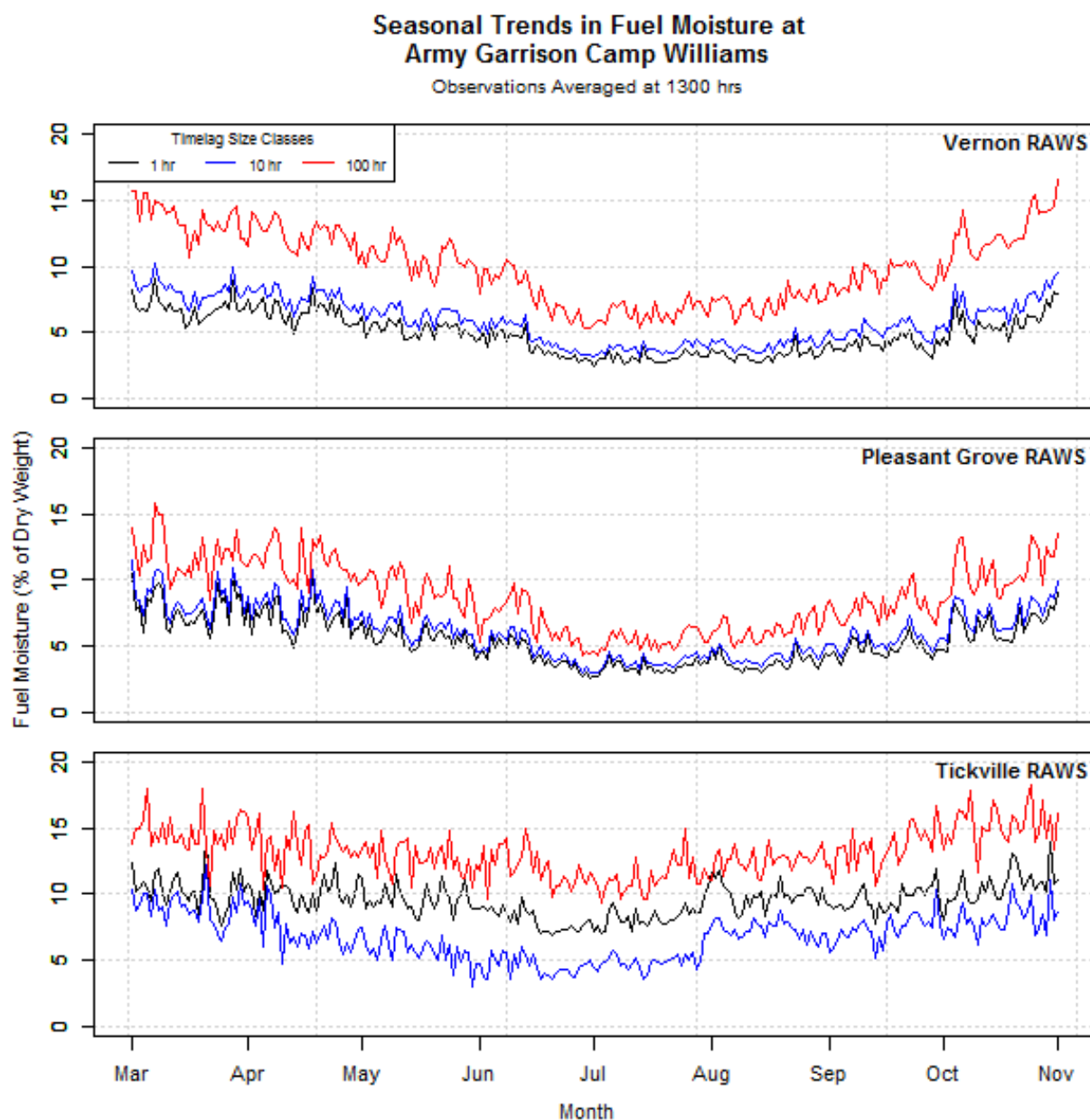
Figure 2.11. The seasonal variation in daily dead fuel moistures for 1-, 10- and 100-h time-lag size classes as computed for 1300 hours from March 1 to October 31 at three remote automatic weather stations (RAWS) within and near Army Garrison Camp Williams.

Wind Roses

The average 6.1 m open wind speed and direction available from the WRCC (2014) are summarized for the three RAWS locations within and adjacent to AGCW using wind rose plots, with wind speed ranges classified according to the Beaufort wind force scale (List 1951). Data for the wind rose plots were filtered to present a summary only for the main burning period each day (1000 to 2000 hours) from March to October (Figures 2.12, 2.13, 2.14).

Data at the Tickville RAWS (Figure 2.12) was only available from April 2012 to October of 2013 because the RAWS station residing at AGCW was not registered with the geostationary satellite server (GOES) network until sometime early in 2012. The Tickville wind rose diagram indicates winds primarily from the southeast, east, and north. Calm wind conditions (average wind speeds of less than 1.3 m s^{-1} or 5 km h^{-1}) prevail for 5.9% of the days recorded, while about 30% of the time there is an indication that winds from 1.8 to 3.6 m s^{-1} primarily occur from the east and southeast. Wind speeds from 3.6 to 5.8 m s^{-1} occur approximately 30% of the time, with wind direction typically from southeast, east, and north. Only about 3-5% of all days have average wind speeds from 8.55 to 14.4 m s^{-1}. The highest wind speeds are typically from the southeast, south, north, and northwest.
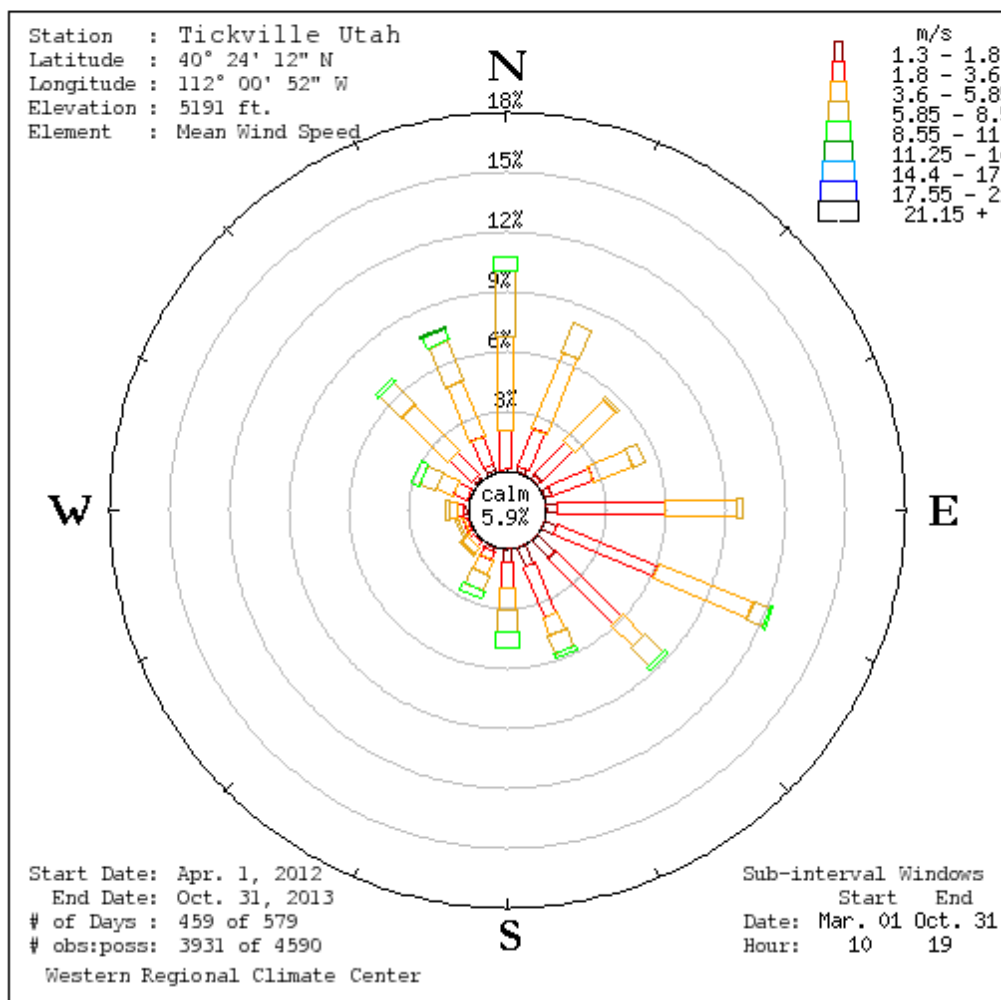
Figure 2.12. Wind rose diagram following the WRCC (2014) format for the Vernon remote automatic weather station southwest of Army Garrison Camp Williams.

The Pleasant Grove wind rose diagram (Figure 2.13) indicates calm conditions occur about 19% of the time, while about 20% of the time winds of 1.8 to 3.6 m s^{-1} occur primarily from the southwest, south and west. Approximately 15% of days exhibit wind speeds between 3.6 to 5.8 m s^{-1}, mostly from the south, west, and northwest. Wind speed maximums of 11.2 to 14.4 m s^{-1} are associated with winds from the south. The

predominant wind directions recorded by the Pleasant Grove RAWS are typically

south/southwest/west/northwest during the fire season.

   The wind rose diagram for the Vernon RAWS indicates that calm conditions

occur 6.3% of the time, while about 33% of the time winds from 1.8 to 3.6 m s^{-1} occur

from the southeast, west, and north (Figure 2.14). Wind speed from 3.6 to 5.8 m s^{-1} occur

about 30% of the time, almost equally distributed in between the south, southwest, west,
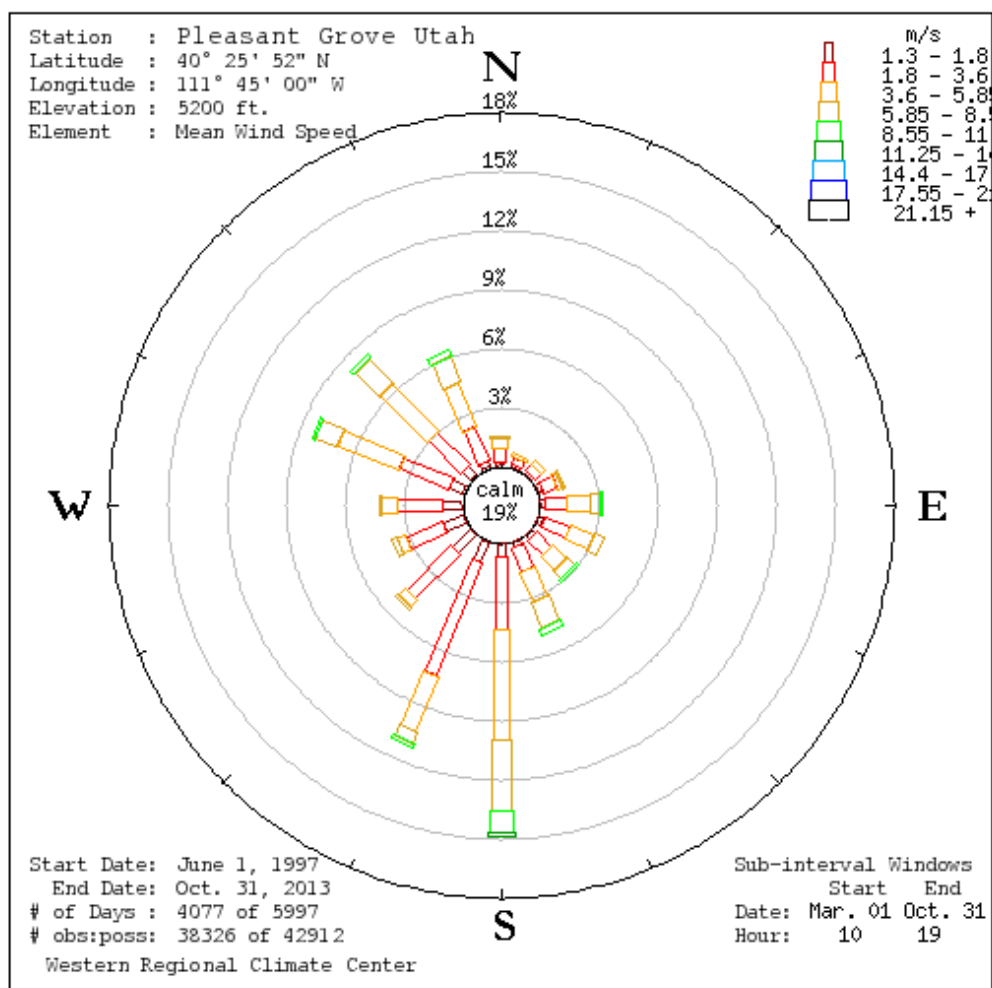
Figure 2.13. Wind rose diagram following the WRCC (2014) format for the
Pleasant Grove remote automatic weather station east of Army Garrison
Camp Williams.

northwest, and northern directions. Wind speeds of 5.8 to 8.5 m s^{-1} were recorded about

16% of the time with a similar directional distribution at 3.8 to 5.8 m s^{-1} interval winds.

Wind speeds of 11.2 to 14.4 m s^{-1} rarely occur but when they do they generally come

from the south, southwest, and north. The predominant wind directions recorded by the

Vernon RAWS are typically south followed by southwest.
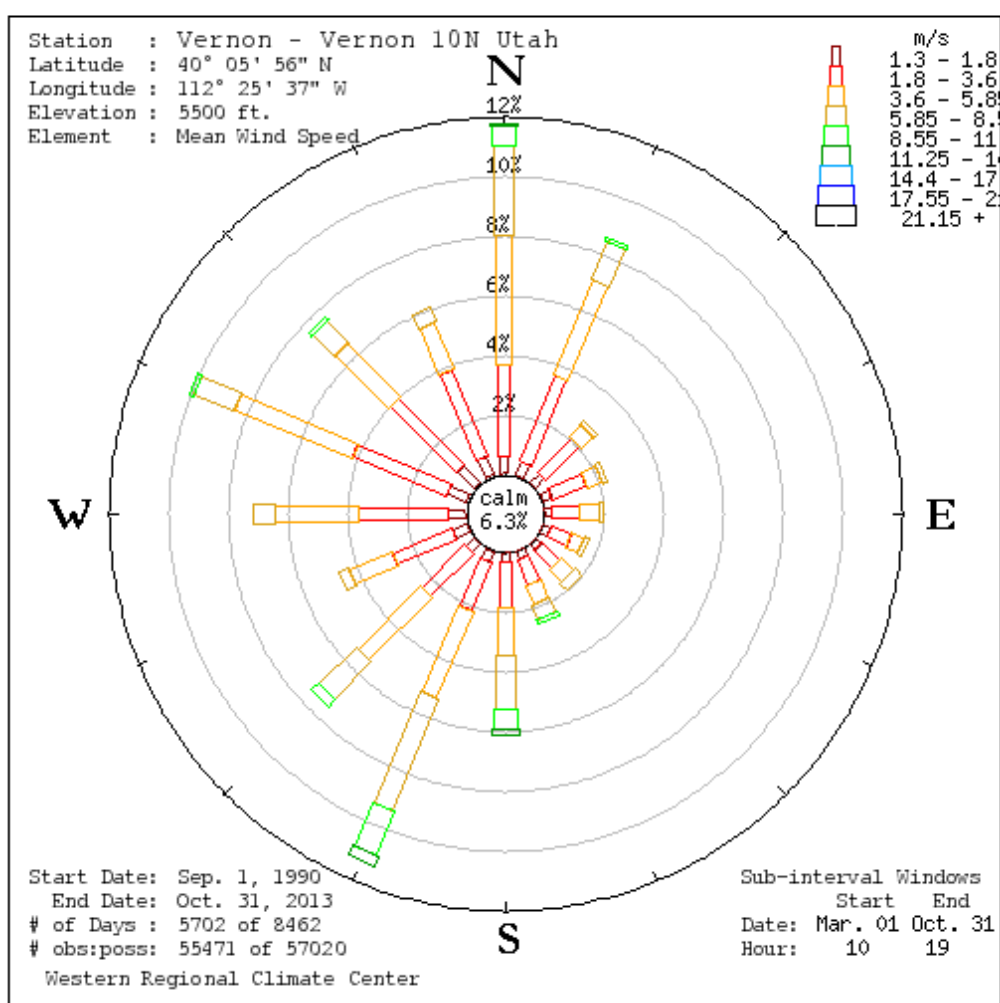
Figure 2.14. Wind rose diagram following the WRCC (2014) format for the
Vernon remote automatic weather station southwest of Army Garrison Camp
Williams.

The contrast in wind direction recorded at the Tickville RAWS and Pleasant Grove RAWS sites is likely due to the Vernon RAWS position in a valley bottom to the west of the Oquirrh Mountain Range (see Figure 2.1 for photos of each RAWS site). From the three wind rose graphs, it is evident that wind speed and direction are highly variable, depending mostly upon topographic position and proximity to diurnal wind flows associated with canyons and steep slopes.

Fire Danger Rating Pocket Cards

Fire danger rating pocket cards are visual aids developed to display NFDRS indices and thus encourage situational awareness and safety for local fire fighters (NWCG 2012). Pocket cards help fire fighters judge the severity of current weather conditions within the context of historical NFDRS ratings, which were developed from historical climatological data located in the geographic area. Typically, fire danger rating pocket cards are distributed to fire fighters at the beginning of the fire season for reference. Pocket cards usually display NFDRS indices such as burning index (BI), energy release component (ERC), and spread component (SC). The historical data used for pocket cards is plotted by month and averaged over the time period of the weather record (Figure 2.15). A red horizontal line is often plotted to represent a critical percentile threshold that once crossed, represents the likelihood of extreme fire behavior. In addition, specific NFDRS indice values corresponding to large fire events are plotted for quick reference (indicated as a star with the fire name in Figure 2.15). Fire danger rating

pocket cards are easily produced using local RAWS data through the FireFamily Plus

software package (RMRS 2002).
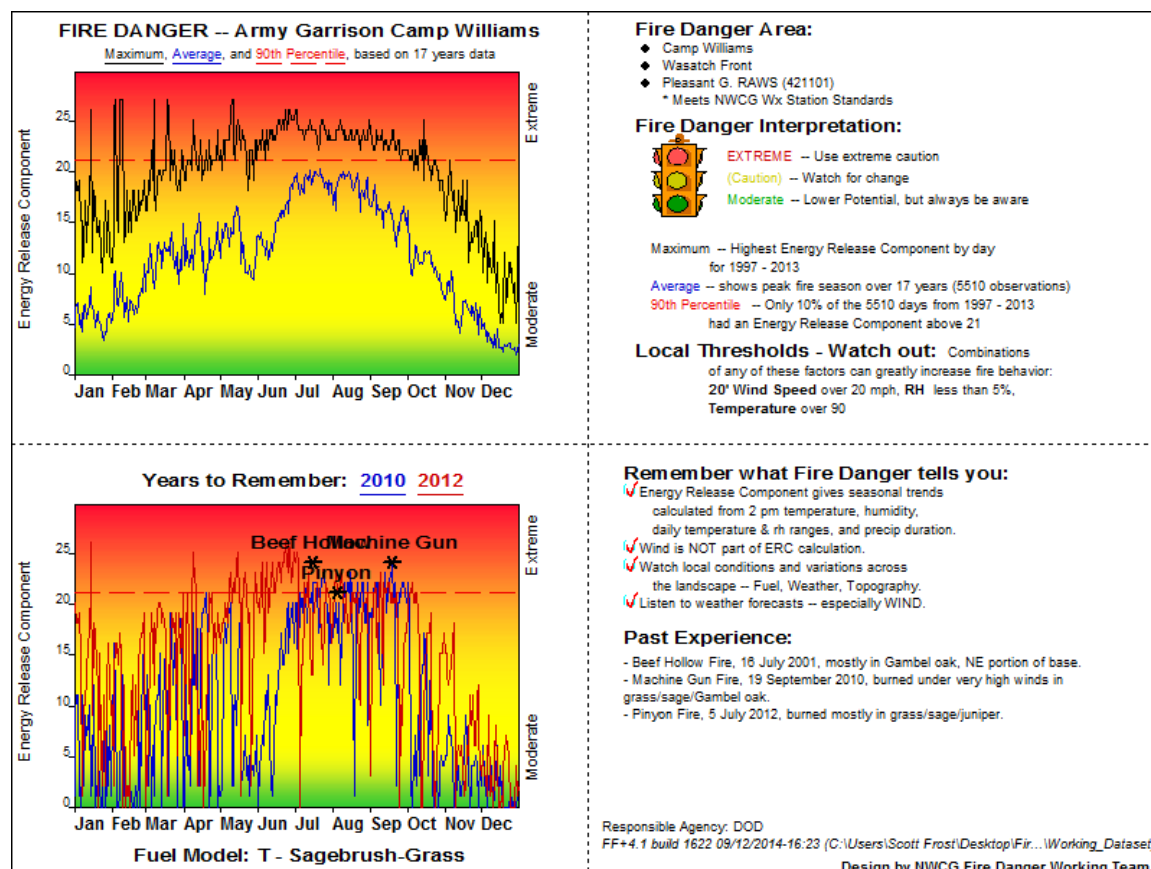
Figure 2.15. National fire danger rating pocket card example, produced from remote automatic weather station (RAWS) climatological data recorded near Army Garrison Camp Williams. Energy release component (ERC) is displayed here, the red-dotted line represents 90th percentile conditions for ERC and the bottom plot displays two specific years when large fires occurred in 2010 (Machine Gun Fire) and 2012 (Pinyon Fire).

Historical Climate Comparisons

Local historical climatic trends for 30-yr time periods obtained from a
climatological station located at the northern end of Utah Lake near Lehi, UT were
plotted in addition to three RAWS stations (Figs. 2.16, 2.17). The Pleasant Grove RAWS
station is located on the western slope of the Wasatch Range near American Fork, UT
and recorded a much larger amount of precipitation than did the other locations, except
for the Tickville RAWS in July and August. The Utah Lake weather station reports that
precipitation amounts from 1991-2013 are the second lowest of any of the 30-yr periods
on average. Precipitation from the period of 1904-1930 (27 yrs) recorded the lowest
annual average with a total of 159 mm compared to 176 mm from 1991 to 2013 (23 yrs).
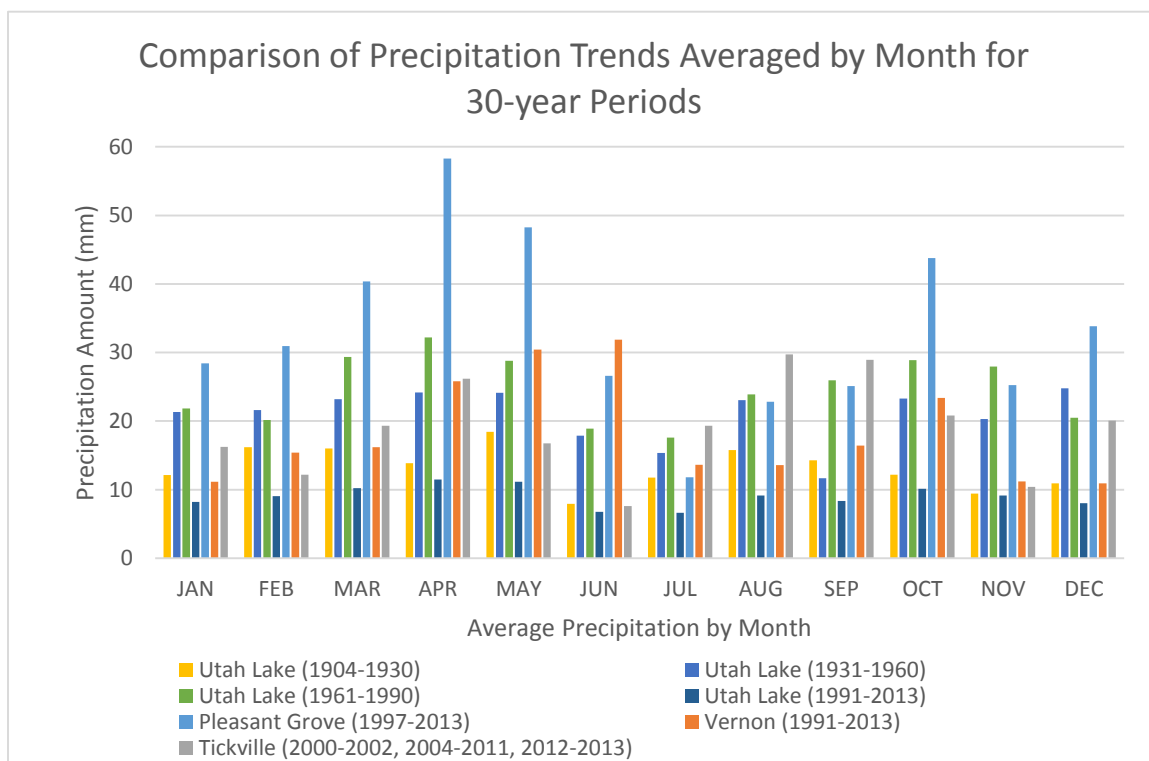
Figure 2.16. Monthly averages for precipitation of 30-year periods at local weather
station at Utah Lake, Pleasant Grove Remote Automatic Weather Station (RAWS) and
Vernon RAWS.

March to May are generally the wettest months, whereas June to August are the driest months in the Army Garrison Camp Williams area.

Ambient air temperature trends (Figure 2.17) are nearly the same per month between weather stations except for the Tickville and Pleasant Grove RAWS. With each successive 30-yr period, temperature increases gradually during the hottest months. For example from 1904-1930, the maximum average July temperature is about 31.5 °C, increasing to about 32°C from 1931-1990, and topping out at about 33.5°C from 1991-2013. This pattern of increasing temperature by 30-yr period is also true for June, August, and September.
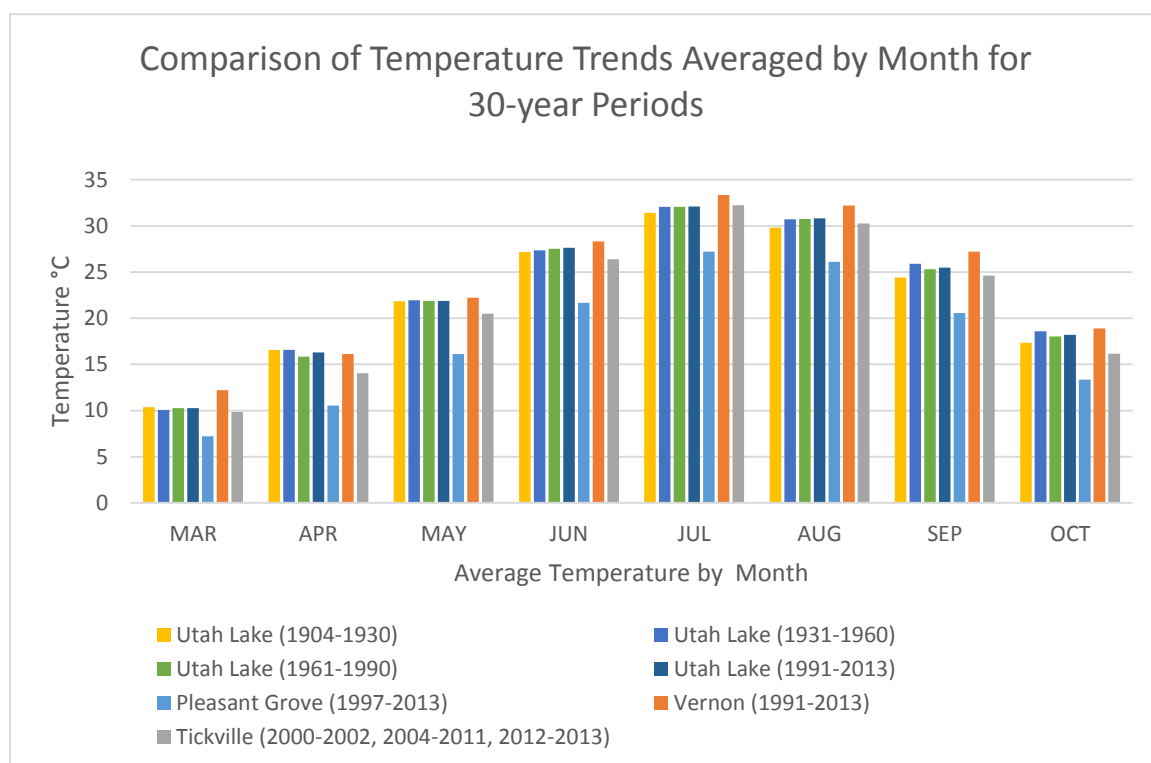
Figure 2.17. Monthly averages of ambient air temperature for 30-year periods at local weather station at Utah Lake in addition to Pleasant Grove Remote Automatic Weather Station (RAWS) and Vernon RAWS.

Precipitation Monthly and Daily Averages

Average monthly and daily precipitation was computed for the fire season (Mar. 1 to Oct. 31) at the Pleasant Grove RAWS, using 17 years of available data (1997-2013). Both the monthly and daily averages show a trend of higher average precipitation in the spring months of April and May. Precipitation on average is low in June, July, August, and September, with July averaging the overall lowest recorded amounts. Average precipitation rebounds in October, which is typically the end of fire season in northern Utah.
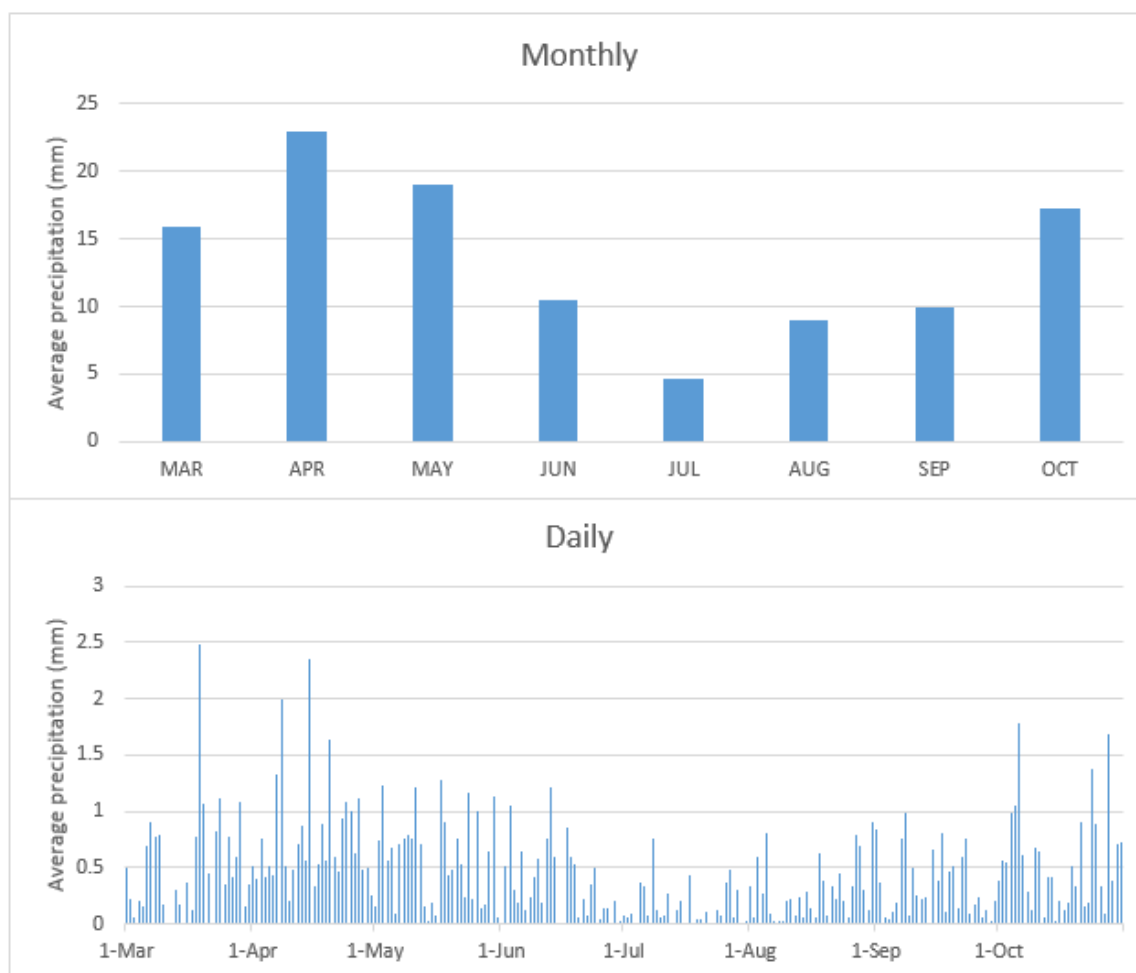
Figure 2.18. Computed monthly and daily precipitation averages recorded at the Pleasant Grove RAWS near AGCW, Utah, from 1997-2013.

Live Fuel Moistures

The seasonal trends in live fuel moistures for four different vegetation types available from the National Fuel Moisture Database applicable to Army Garrison Camp Williams for varying time periods are presented in Figure 2.19. This involves data for cheatgrass, Wyoming big sagebrush (*Artemesia tridentata* subsp. *wyomingensis*, Nutt.), Gambel oak and Utah Juniper. Live herbaceous fuel moistures can be extremely variable,
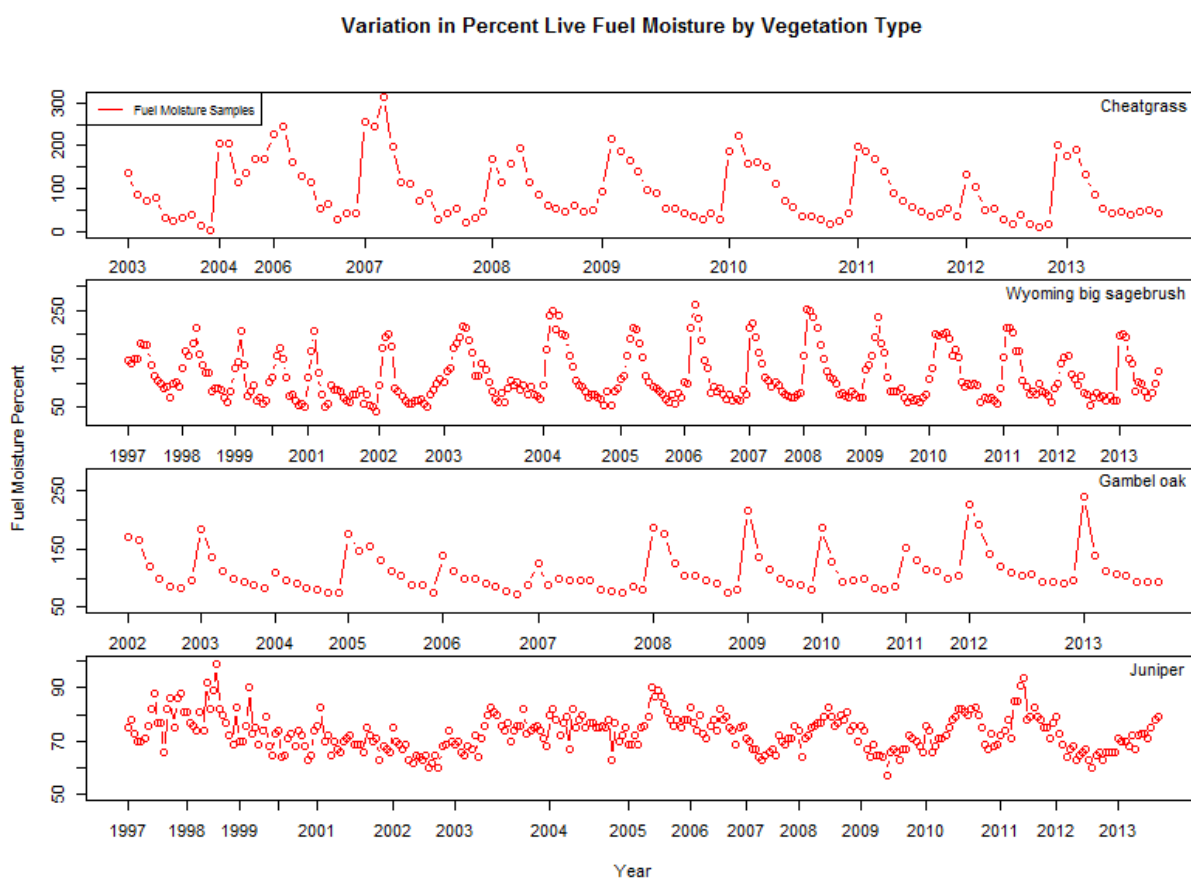
Figure 2.19. Yearly seasonal trends in sampled live fuel moisture extracted from the National Fuel Moisture Database for vegetation types applicable to Army Garrison Camp Williams.

however, sampled cheatgrass values were generally within one standard deviation of average. Wyoming big sagebrush live fuel moisture samples vary considerably throughout the fire season with values in the spring nearly 200% of dry weight and decreasing gradually to lows from 60 to 100%. Similar to Wyoming big sagebrush, Gambel oak fuel moistures start out very high in the spring at 150 to 220%, then decreases throughout the summer months, hitting low fuel moisture values from about 60 to 100% during the tail end of fire season from late August to October. Utah juniper fuel moisture exhibited the most variation outside of the one standard deviation range, but overall, fuel moisture levels generally vary much less (from about 63 to 85%) throughout the fire season than the other vegetation types.

Fuels

Fire is only possible where vegetation or fuel is present. At AGCW, the vast majority of the installation's land area is vegetated (10379 ha or 93.26%) as opposed to non-vegetated (751 ha or 6.74%) (Table 2.3). To map the vegetation at AGCW, five categories corresponding to dominant vegetation were used: bare earth, grass, sagebrush, juniper, and Gambel oak (Figure 2.22). Another map produced from this analysis mapped fire behavior fuel models according to Anderson's (1982) descriptions of fuel models or complexes (Figure 2.23). Anderson (1982) classifications were selected because live fuel moisture inputs for respective fuel models represented 'worst case' or driest possible conditions (Ziel and Jolly 2009). Therefore, in a conservative effort to avoid under prediction of fire behavior, Anderson (1982) fire behavior fuel models were mapped

rather than Scott and Burgan (2005) fire behavior fuel models. Table 2.8 at the end of the

results section gives a brief overview of each fire behavior fuel model mapped at AGCW

with representative photos.

Table 2.4. Accuracy metrics for random forests method applied to the development
of the fire behavior fuel model (FBFM) map based on the Anderson (1982)
classification.

	FBFM 1	FBFM 2	FBFM 5	FBFM 8	Bare earth	Row total	Users prec. (%)
FBFM 1	10	5	4	0	1	20	50.00
FBFM 2	2	23	9	0	1	35	65.71
FBFM 5	2	6	34	2	2	46	73.91
FBFM 8	0	0	3	17	0	20	85.00
Bare earth	0	0	2	0	18	20	90.00
Column total	14	34	52	19	22	141	
Producers prec. (%)	71.43	67.65	65.38	89.47	81.82		

Overall precision = 72.34%
Kappa = 57.15%

For mapping purposes, the random forests classification method was used because

it is ideally suited for non-linear and complex interaction variables employed for

classification (Cutler *et al.* 2007). Validation is not the same as accuracy. Just because the

model fits the out-of-bag data does not mean it will generate an accurate map. The overall

validation output is already cross-validated due to the repeated random recursive

selection process. Overall validation for the Anderson (1982) fire behavior fuel model

classification map (Tab. 2.4) was 72.3% with a Kappa coefficient (K-hat) of 57.1%,

while the vegetation classification overall accuracy (Tab. 2.5) was 64.0% with a K-hat of

47.3%. Overall validation for the vegetation classification map is low according to typical

remote sensing standards, while the fire behavior fuel model classification overall

validation is moderate. Jensen (2005) suggests that K-hat values between 40 and 80%

represent moderate agreement between the classification map and the ground reference

data. Despite moderate validation results, the mapped vegetation and fire behavior fuel

model prediction maps matched actual vegetation and fuel models well at a fine spatial

resolution (0.5 m), qualitatively speaking.

Table 2.5. Accuracy metrics for random forests vegetation classification map.

	Gambel oak	Juniper	Sage-brush	Grass	Bare-earth	Row total	Users prec. (%)
Gambel oak	124	8	63	1	19	215	57.67
Juniper	10	29	5	3	0	47	61.70
Sagebrush	17	3	77	85	1	183	42.08
Grass	21	0	30	376	14	441	85.26
Bareearth	3	0	7	70	34	114	29.82
Column total	175	40	182	535	68	1000	
Producers prec. (%)	70.86	72.50	42.31	70.28	50.00		

Overall precision = 64.00%
Kappa = 47.33%

In addition to the output classification maps, two matrices were produced that

express the vegetation (Table 2.6) and fuel model distribution (Tab. 2.7) by NFDRS slope

classes. By far, the largest proportion of vegetation classified as 'grass' (34.13%) is

located within the 0-25% NFDRS slope class, 13.63% in the 26-40% class, and 7.90% in

the 41-55% class. Fifteen percent of total vegetation is classified as Gambel oak, with

about five percent allocated within 0-25%, 26-40%, and 41-55% classes each

respectively. Gambel oak and grass have the most vegetation classified in the highest

slope categories, with both at about three percent of total vegetation where slope is 56%

and greater. For the fire behavior fuel model (Anderson, 1982) classification by NFDRS

slope class, fuel model 5 and 2 are the most abundant with 4073 and 3815 total hectares respectively. Fuel model 1 (2008 total hectares) is almost entirely allocated in slope classes 0-25% (12.83%) and 26-40% (3.28%). Fuel model 5 and 2 have the largest proportion of area classified into slope classes of 41% and greater with a total of 12.94% for fuel model 5 and a total of 4.44% for fuel model 2.

Gambel oak occurs primarily on higher elevation slopes and northern aspects, juniper is typically on higher elevation sites, but usually occurs more on exposed southern and western aspects. Sagebrush is mostly constrained to lower elevation sites, while grasslands occur both in low elevation and higher elevation areas. Fuel model 5 mostly corresponds to areas where Gambel oak and juniper are located, there is possible overlap of shrubby, immature Gambel oak into the fuel model 2 category. Fuel models 1 and 2 mostly indicates grass and sagebrush/grass fuel complexes in the lower elevations, while fuel model 8 occurs in limited areas in mature Gambel oak stands. Lastly, Table 2.7 was made to describe the amount of land area by NFDRS slope steepness associated with each fire behavior fuel model classification at AGCW.

Table 2.6. Matrix of vegetation class distribution within National Fire Danger Rating System (NFDRS) slope steepness classes.

Vegetation Type	NFDRS slope steepness class (%)					
	0-25 (%)	26-40 (%)	41-55 (%)	56-75 (%)	> 75 (%)	Area (ha)
Gambel oak	4.96	5.90	4.71	2.29	0.35	2027
Juniper	1.90	0.99	0.61	0.22	0.04	419
Sagebrush	7.86	3.05	1.22	0.41	0.08	1405
Grass	34.13	13.63	7.90	2.67	0.32	6529
Bare earth	4.84	0.99	0.55	0.28	0.08	751
Slope class percentage of total	53.70	24.57	15.00	5.87	0.86	11130

Table 2.7 Matrix of fire behavior fuel model (FBFM; as per Anderson 1982 classification) class distribution by National Fire Danger Rating System (NFDRS) slope steepness classes.

| FBFM | NFDRS slope steepness class (%) | | | | | |
	0-25 (%)	26-40 (%)	41-55 (%)	56-75 (%)	> 75 (%)	Area (ha)
1	12.83	3.28	1.50	0.40	0.03	2008
2	22.86	6.98	3.45	0.90	0.09	3815
5	11.47	12.19	8.50	3.83	0.61	4073
8	0.61	0.49	0.42	0.22	0.05	199
99	5.92	1.62	1.14	0.52	0.10	1034
Slope class percentage of total	53.69	24.57	15.00	5.87	0.86	11130

FBFM 99 = Bare earth

Variable importance is a metric that used with random forests classifications to explain the importance of each predictor variable for the classification. Two variable importance plots were generated, one for each map produced, along with another plot called the Gini Index. For variable importance plots, a large break between variables usually indicates the most important variables for selection. Variables highest on the y-axis are the most important. The mean decrease in accuracy on the x-axis is determined during the OOB error estimation. The more the accuracy decreases with the addition of a single variable, the more important the variable is deemed by the random forests model. The Gini index explains how each variable contributes to the homogeneity in the nodes and leaves of the results in the random forest classification. It is an attempt to describe which variables are best to use at nodes for splitting. The index goes from zero (homogenous) to one (heterogeneous) and has been multiplied here by 100 for ease of interpretation. If all possible entries at single nodes were classified the same (homogeneous), then the values of the Gini index would be zero. However, as with mean

decrease in accuracy, the greater the decrease in the Gini index, the more important the variable.

The vegetation map variable importance plot and Gini index plot (Figure 2.20) indicates no clear separation between variables for decrease, however hro_1 (high resolution orthoimagery, band 1) has the highest value for both plots followed by the lidar_ras_values (LiDAR raster values). The LiDAR raster values referenced here represent vegetation height (i.e. the difference from the first return data minus the bare earth data). For the fire behavior fuel model map, the mean decrease in accuracy for the variable importance plot and the Gini index (Figure 2.21) indicate that the

Variable Importance Plots for Mapping Dominant Vegetation Type
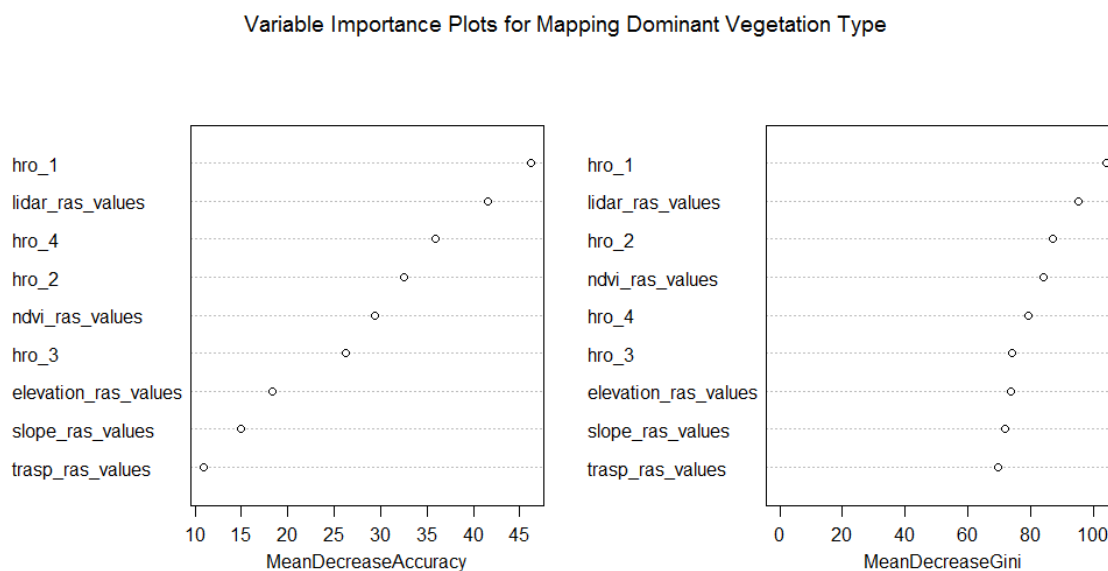
Figure 2.20. Mean decrease for variable importance and Gini impurity for the vegetation map product at Army Garrison Camp Williams. Lidar_ras_values = Height of vegetation from light detection and ranging values determined by taking first return values minus bare earth values, hro_1 = high resolution orthoimagery band 1, hro_2 = high resolution orthoimagery band 2, hro_3 = high resolution orthoimagery band 3, hro_4 = high resolution orthoimagery band 4, slope_ras_values = slope raster values, elevation_ras_values = elevation raster values, ndvi_ras_values = normalized difference vegetation index (NDVI) raster values, and trasp_ras_values = transformed aspect raster values.

lidar_ras_values are clearly the most important for prediction accuracy, followed by high

resolution orthoimagery (HRO) bands 1, 4, and the NDVI layer.

Figure 2.21. Mean decrease for variable importance and Gini impurity for the fire behavior fuel model map (Anderson 1982) product at Army Garrison Camp Williams. Lidar_ras_values = Light detection and ranging values, hro_1 = high resolution orthoimagery band 1, hro_2 = high resolution orthoimagery band 2, hro_3 = high resolution orthoimagery band 3, hro_4 = high resolution orthoimagery band 4, slope_ras_values = slope raster values, elevation_ras_values = elevation raster values, ndvi_ras_values = normalized difference vegetation index (NDVI) raster values, and trasp_ras_values = transformed aspect raster values.

Vegetation Type

- Gambel oak
- Juniper
- Sagebrush
- Grass
- Bare Earth

Camp Williams Boundary

Buildings
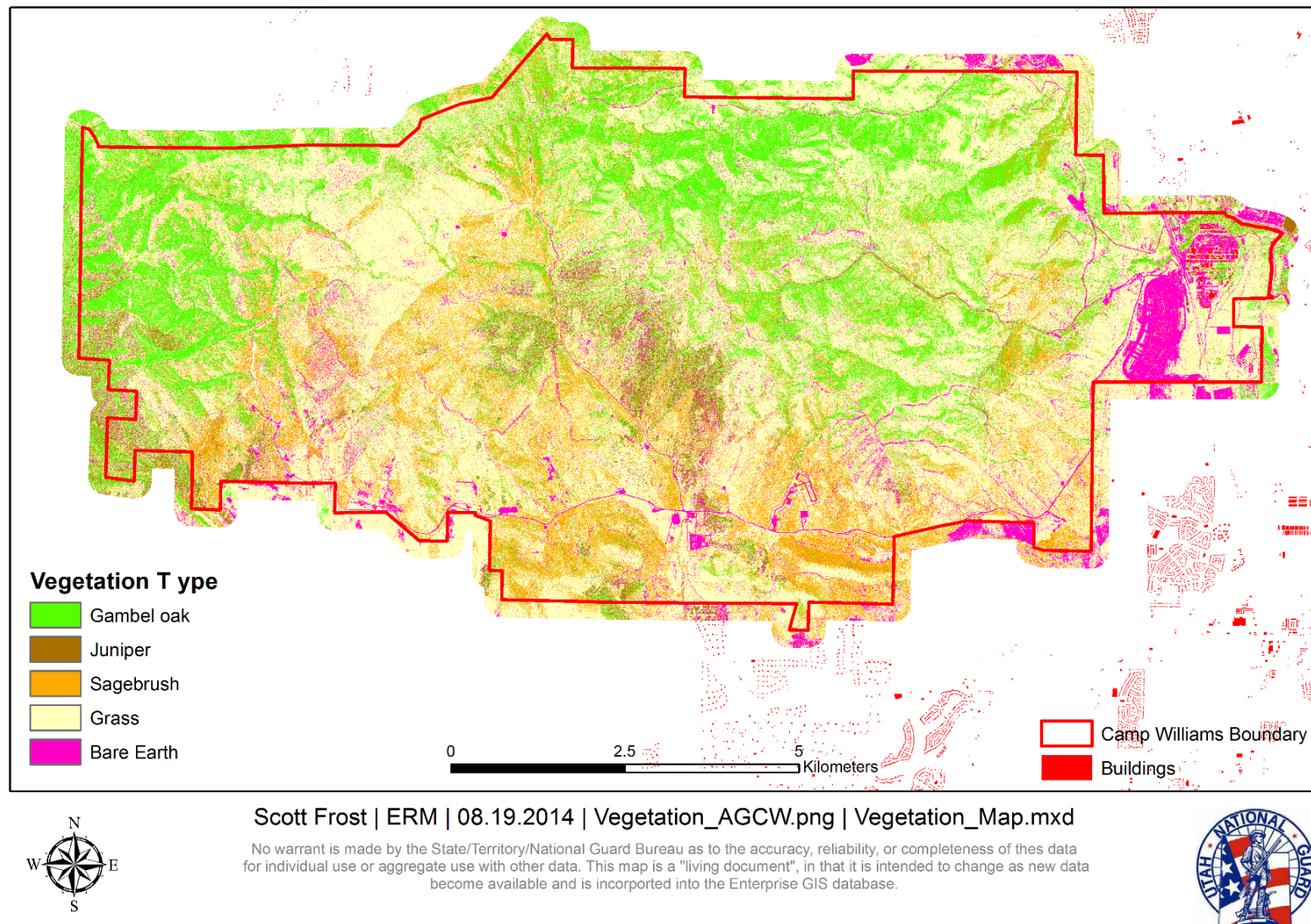
Figure 2.22. Vegetation at Army Garrison Camp Williams as predicted using random forests at 0.5 m resolution.

Fire Behavior Fuel Model (Anderson 1982)

- Bare Earth
- 8
- 5
- 2
- 1

0   2.5   5 Kilometers

☐ Camp Williams Boundary

■ Buildings

N
W E
S

Scott Frost | ERM | 08.19.2014 | FuelModels13_AGCW.png | FuelModel_Map.mxd

No warrant is made by the State/Territory/National Guard Bureau as to the accuracy, reliability, or completeness of thes data for individual use or aggregate use with other data. This map is a "living document", in that it is intended to change as new data become available and is incorported into the Enterprise GIS database.

Figure 2.23. Fire behavior fuel models (Anderson 1982) at Army Garrison Camp Williams as predicted using random forests at 0.5 m resolution.

Table 2.8. Typical fire behavior associated with the primary fire behavior fuel models (FBFM) as described by Anderson (1982) found at Army Garrison Camp Williams (AGCW) along with representative photos.

F B F M	Description of typical fire behavior and representative photos from AGCW
1	Fire spread is dictated by the fine, very porous, and continuous herbaceous fuels that have cured or are nearly cured. Fires are surface fires that move rapidly through the cured grass and associated material. Very little shrub or timber is present, generally less than one-third of the area.
2	Fire spread is primarily through the fine herbaceous fuels, either curing or dead. Surface fires where the herbaceous material, in addition to litter and dead-down stemwood from the open shrub lands contribute to the fire intensity. Open shrub lands that cover one-third to two-thirds of the area may generally fit this model.

5	Fire is generally carried in the surface fuels that are made up of litter cast by the shrubs and the grasses or forbs in the understory. Usually shrubs are short and almost totally cover the area. Young, green stands with no dead wood would qualify. Young green stands may be up to 2 m high but have poor burning properties due to live vegetation. The exception are in late seasons conditions with low fuel moistures and the combination of extreme fire weather and long term drought.
8	Slow-burning ground fires with low flame lengths are generally exhibited, although the fire may encounter an occasional "jackpot" or heavy fuel concentration that can flare up. Only under severe weather conditions involving high temperatures, low humidities, and high winds do the fuels pose fire hazards. Closed canopy stands of Gambel oak that have leafed out support fire in the compact litter layer.

DISCUSSION

The objective of the preceding analysis was to acquire an understanding of the

AGCW fire environment in order to gain a better perspective of the fire behavior

potential associated with this particular land mass. The overall approach might well constitute a model framework for future research and planning, regardless of geographic location. This systematic process will aid fire and fuels planners to establish an effective context before policies and treatments are implemented in earnest.

The results related to weather and climatic component of the AGCW fire environment suggest that the months from June to September are typically associated with critical fire weather conditions (i.e. high ambient air temperature and low relative humidities) and low dead fuel moisture levels that will allow for the development of high-intensity, spreading combustion given an ignition source. Daily wind speed patterns during the free season on average remained fairly constant regardless of month. In general, winds can be expected to increase in strength throughout starting at about 1000 hours and declining sharply shortly after midnight.

To our knowledge, little research has been attempted in the sage steppe to map fire behavior fuel model types at high resolution. The availability of LiDAR data are fairly recent and to-date has been used to estimate sagebrush height (Streutker and Glenn 2006; Bond 2011) and vegetation types (Bork and Su 2007). It has yet to be employed in mapping fire behavior fuel models in rangelands. Using a random forests classification scheme (Brieman 2001) to classify vegetation type and fire behavior fuel models was considered a novel approach to rangelands and yielded moderately accurate results. The greatest source of error in the two classifications came from distinguishing between bare earth and sagebrush and could likely be improved using additional layers and/or imagery flown on a different date. Accuracy could likely be improved using LiDAR as a component of other machine learning or data fusion approaches.

The matrices reporting vegetation type and fire behavior fuel model by NFDRS slope steepness class (Tables 2.6 and 2.7) reveal that Gambel oak, usually represented by fire behavior fuel model 5—brush (0.6) as described by Anderson (1982), occurs most frequently in association with grass on slopes of 41% or greater. Gambel oak typically exhibits high fuel moisture contents throughout the fire season until late July through September. Under extreme conditions (strong winds, high temperature, low relative humidity), Gambel oak can burn vigorously and when coupling wind flow (typically from the south) with the Tickville valley located in the central portion of the base at AGCW, extreme fire behavior can occur. Every attempt should be made to mitigate for the occurrence of this scenario through manipulation of fuels prior to a wildfire occurrence.

Data from the historical 30-yr ambient air temperature comparisons reveal a trend of increasing temperature. This is consistent with other research (Brown *et al.* 2004) which imply higher temperature, longer growing seasons, extended fire seasons, and more days of high fire danger as a result of a warming climate. Weather and fuels data at AGCW should be monitored closely to ascertain patterns in growth and senescence. Each individual season is likely to vary considerably, but an expectation of longer fire seasons should be incorporated into training considerations at AGCW. Warming trends also underscore the need for monitoring of live fuel moisture contents in the dominant vegetation/fuel types located on the AGCW grounds. Additional weather stations are recommended to supplement existing resources and to provide accurate data for localized areas at AGCW, which are highly influenced by topographic conditions. This data will

help further future fire and fuels planning efforts by providing the baseline data for vegetation responses related to climate.

The methodology presented here is an example of a new standard for fuels project evaluations, prior to implementation. A thorough understanding of the fire behavior environment will lead to more informed decision making and hopefully, more effective treatment implementation, ideally suited for the specific conditions of a geographic location.

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CHAPTER 3

RECENT FIRE HISTORY[1]

ABSTRACT

Large wildfire events at Army Garrison Camp Williams, a military base in
northern Utah, such as the Machine Gun Fire of September 19, 2010, have underscored
the difficulty of planning for and mitigating human and lightning caused sources of
ignition. Subsequent wildfires in grass and shrub fuels types (e.g. Gambel oak (*Quercus
gambelii*, Nutt.) burn frequently, from moderate to high severity. To protect nearby
adjacent communities and priority resources, effective fuel treatments, both spatially and
temporally, must be planned with an understanding of the fire regime—the pattern of fire
behavior over time for a given geographic area. Additionally, an understanding of how
modeled fire behavior compares to actual fire behavior provides critical interpretive
inference for predications of local fire behavior in future treatments. Fire report data from
1985-2012 was summarized from local records at Army Garrison Camp Williams,
indicating a fire occurrence interval of one to two years and large fire (> 400 ha)
occurrence once every four years. Mean fire return interval was calculated at 32 years. Of
the ignition sources on record, only 28% were ignited by lightning. Landscape Fire and
Resource Management Planning Tools (LANDFIRE) data were utilized to build context
of the fire environment. Maps from LANDFIRE data were developed to summarize mean
fire return interval, fire regime category, general vegetation type, and fire behavior fuel
model type. At Army Garrison Camp Williams, a wildfire has never to date been

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[1] Co-author: Martin E. Alexander; Michael J. Jenkins

documented and analyzed in a case study format. The Machine Gun Fire, which occurred

on September 19, 2010, was selected for a case study analysis due to its large size and

destructive fire behavior in relation to the wildland urban interface. Observed rate of

spread for different fire run segments was compiled by personnel at AGCW in a fire

progression map and were compared to predicted rate of spread using BehavePlus, with

inputs informed by the LANDFIRE fuel model classification map and weather data from

a nearby station on the day of the fire event. Of the seven different fire run segments

compared, three of the predicted segments were within 60% of the observed fire behavior

rate of spread values, while the other four segments were drastically different. This case

study analysis provides a format for future fire behavior analysis and documentation. A

portfolio of case study analyses will help to build a greater understanding of how

predictive fire behavior models can be interpreted in wildfire risk mitigation planning.

INTRODUCTION

Fuel management planning must necessarily consider the history of the

interactions between natural and anthropogenic ignitions and the fire environment on the

landscape of consideration. This concept is typically referred to as a "fire regime"

(Graham *et al.* 2004). While many definitions have come to exist (Krebs *et al.* 2010), it is

generally agreed that the term is intended to describe "The kind of fire activity or pattern

of fires that generally characterize a given area" (Merrill and Alexander 1987). Some

important elements or characteristics typically include the ignition source(s) or causal

agent(s), number, type, size, seasonality, frequency or recurrence interval, and the

intensity of fires. Several different approaches are commonly used in fire regime analyses

(e.g., Parisien *et al.* 2004, Tymstra *et al.* 2005). Some authors have elected to include consideration of fire severity, which describes the ecosystem responses or direct impacts following fire such as tree mortality and soil erosion resulting from the fire's energy release and duration (Keeley 2009).

Associated with the fire regime concept is the fire cycle or mean fire return interval (MFRI) which constitutes the number of years required to burn over an area equal to the entire area of interest; some areas within the whole may burn more than once during the cycle and others not at all (Van Wagner 1978).

Applying these concepts to Army Garrison Camp Williams (AGCW), the objective of this research is to provide clarity regarding the following questions: what is the typical pattern of fire in vegetation over time (i.e. fire regime) including historical fire perimeters and the total amount of hectares burnt per year? Under what circumstances of fuel and topography are fires most common? What are the known sources of fire ignition? And what is the predicted fire return interval? What data sources are available to researches or resource managers attempting to characterize fire history, frequency, and fire regime data?

In this chapter we describe the process and results of a fire regime analysis of AGCW based on fire report data and information gleamed from Landscape Fire and Resource Management Planning Tools (LANDFIRE) (Rollins and Frame 2006). Also included is a case study (Alexander and Thomas 2003*a*, 2003*b*) of a recent large wildfire incident at AGCW.

METHODS

Fire Report Information

Information on recent fire occurrences varies widely in the level of detail but at a minimum provides basic data on the date of occurrence, location, and approximate time of response to a newly reported fire. Fire report data can also contain information about the vegetation or fuel complex the fire is burning in, weather at the time of response, potential threats to nearby infrastructure, additional resources requested and their arrival times, and observed fire behavior, all generally for statistical reporting purposes (Donoghue 1982). In the analysis reported on here, local fire reports available for AGCW in association with a geographic information system (GIS) layer describing location and areas burned by past fires from 1978 to 2012 were used to summarize the recent fire history of AGCW. Some data were also available on ignition sources. Such information could prove useful for understanding where fire prevention efforts, for example, could be most effectively focused.

For the purposes of compiling the recent fire history of AGCW, fires were classified as either "small" or "large" according to the area burned.[2] Such a separation is obviously relative and therefore somewhat arbitrary (Gill and Allan 2008, Irland 2014) as evident by different thresholds selected by various authors over the years. Krueger (1961), for example, selected 40 ha whereas Headley (1940) 120 ha and Stocks *et al*.

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[2] The following wildfire size classes are presently recognized in the U.S. (after NWCG 2014): As to size of wildfire: Class A - one-tenth acre or less; Class B - more than one-tenth acre, but less than 4.0 ha; Class C – 4.0 ha or more, but less than 40 ha; Class D – 40 ha or more, but less than 120 ha; Class E – 120 ha or more, but less than 400 ha; Class F – 400 ha or more, but less than 2000 ha; and Class G – 2000 ha or more.

(2002) 200 ha. A value of 40 ha was selected to make this distinction and is presented in terms of two categorized as "small" fires, as Classes A-C (i.e., fires < 40 ha in size), and "large" fires, as Class D and higher (i.e., fires > 40 ha in size).

Modeled Spatial Fire Regime Characteristics

In addition to the fire history data compiled from records kept at AGCW, LANDFIRE data were obtained for information regarding the predicted MFRI and typical fire regime classes (Rollins 2009). LANDFIRE is a landscape-scale vegetation, wildland fuel, fire regime, and vegetation succession and departure from historical conditions mapping project designed to provide nationally consistent and seamless geospatial data (Rollins 2009). LANDFIRE uses field referenced data, workshop input from ecologists and fire managers, existing literature, satellite imagery, and qualitative descriptions of ecological systems as inputs into a myriad of different simulations and predictive models (Figure 3.1). LANDFIRE uses the following process to create geospatial data layers. First, a LANDFIRE reference database (LFRDB) is compiled from existing field reference databases. Plot data from the LFRDB are then assigned to vegetation map units based upon sequence tables produced by NatureServe (http://www.natureserve.org/explorer/ as described by Comer *et al.* 2003). Next, biophysical gradient data, Landsat imagery, and training data from the LFRDB are combined to create maps describing potential vegetation (PVT), existing vegetation (EVT), vegetation height (EVH), and canopy cover (EVC) (Rollins 2009). In addition, LANDFIRE uses two layers to describe potential vegetation: (1) Environmental Site Potential (ESP), and (2) Biophysical settings (BpS). ESP represents vegetation that could

be supported at a given area based upon the biophysical environment (Rollins 2009). ESP

maps represent the successional trajectory of natural plant communities in the absence of

disturbance. The BpS layer is similar to the ESP layer except that it incorporates the

presumed historical disturbance regime (Rollins 2009). Map units in the BpS layer

represent natural plant communities that would become dominant, given historical

disturbances (e.g. fire). LANDFIRE BpS maps are a derivative of EPS maps in that EPS

vegetation units are either divided or aggregated based upon disturbance characteristics

from the BpS layer.

From these base layers, the vegetation dynamics development tool (VDDT) and

LANDSUM tool simulate succession pathways and disturbances in a given area for

vegetation. VDDT uses state and transition modelling to predict pathways of rates of

vegetation succession through time and the probability and effects related to ecological

disturbances (Rollins 2009), but excludes fire disturbances. LANDSUM also uses a state-
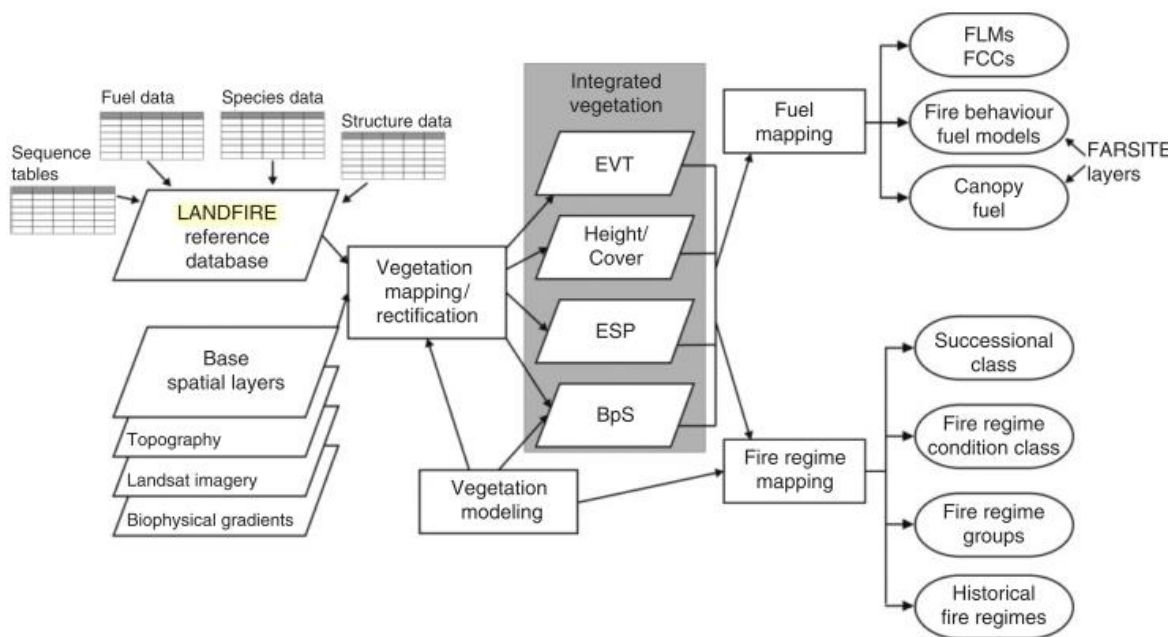
Figure 3.1. LANDFIRE flow chart for prediction of existing vegetation type (EVT), fire behavior fuel models (FBFM), and fire regime maps (from Rollins 2009).

and-transition approach, but integrates fire-related disturbance into successional simulations. Fire ignition, spread, and effects are modeled stochastically by annual time-steps. LANDSUM also uses succession classes (S-Class), which categorize vegetation into successional states, including those that describe uncharacteristic natural and uncharacteristic exotic states. Using Bps/S-class combinations, LANDSUM calculates low, moderate, and replacement severity maps which describe the severity type experienced by a given pixel (Rollins 2009). Fire severity is calculated as the total number of fires for a given severity type divided by the total number of fires experienced for a pixel, then multiplied by 100. Fire frequency is calculated by dividing the total number of simulation years by the number of fires that occurred for each given pixel. Fire frequency and fire regime maps are then synthesized to create a map of discretely classified fire regime groups. Fire frequency and fire regime maps were produced using LANDFIRE data to corroborate fire history data derived from past fire reports at AGCW.

Wildfire Behavior Case Study

A case study is presented for the major run of the Machine Gun Fire on September 19, 2010, which started within the confines of AGCW and spread beyond installation boundaries to the north, destroying three homes and requiring an evacuation of approximately 1600 more in an adjacent community. Alexander and Thomas (2003*b*) suggest that a wildland fire behavior case study should include, at the minimum, introduction remarks regarding the significance of the fire, fire chronology and development, detailed description of the fire environment (i.e., topography, fuels, and fire weather), an analysis of fire behavior, and concluding remarks regarding lessons learned

and significant contributions, if any, to the broader general fire behavior knowledge database. The chronology and development of the Machine Gun Fire was compiled from a combination of Historical Incident I-209 reports submitted by multiple incident commanders on scene throughout the wildfire event, a fire progression map with a timeline and narrative compiled by natural resources staff from observations by fire personnel, and remote automatic weather station (RAWS) hourly weather data from the day of the major run of the Machine Gun Fire on September 19, 2010.

RESULTS AND DISCUSSION

Recent Wildfire Occurrences

On the basis of local records held at AGCW for the years 1985 to 2012, a total of some 86 fires burned over an area totaling 12,279 ha during the time period (Figure 3.3). This represents an annual fire occurrence rate of about three fires on average per year. AGCW encompasses an area of 11,130 ha. Based on the annual area burned of 3.1%, this would mean a fire cycle or MFRI of 32 years. Information on the start date of each fire that occurred between 1985 and 2012 is not complete, nevertheless, the times of large fire activity during the fire season would appear to be from about mid-June to mid-September. The modern day record of fires occurring at AGCW indicates that over the course of the 28 years of data, 18 fires of 40 ha or greater have occurred. Six of those fires exceeded 400 ha in size (Table 3.1). Consequently, the frequency of fires about 40 ha in size is on average about one to two years, and for fires of about 400 ha, it is around four years. Ignition sources at AGCW since 1985 to present have been dominated (64%) by training caused and human related ignitions. Lightning-fire ignitions account for 28%

of the total number of fires for the same time period. Fires due to off-camp ignitions (3% of total) represent fires that were started (as a result of human-causes) outside of the boundaries of AGCW and eventually burned onto base grounds (Figure 3.2).

The "small fire" history map compiled for AGCW (Figure 3.4) indicates that while fires have occurred throughout the entire ACGW area, the preponderance of fire starts are located in the western half, near to areas of live-fire training. Also of note are the number of class C fires (i.e., 4-40 ha), about 11, that have occurred near the boundaries of AGCW. In qualitative terms, there does not appear to be any distinguishable pattern of wildfire occurrences related to elevation and aspect for small fires.
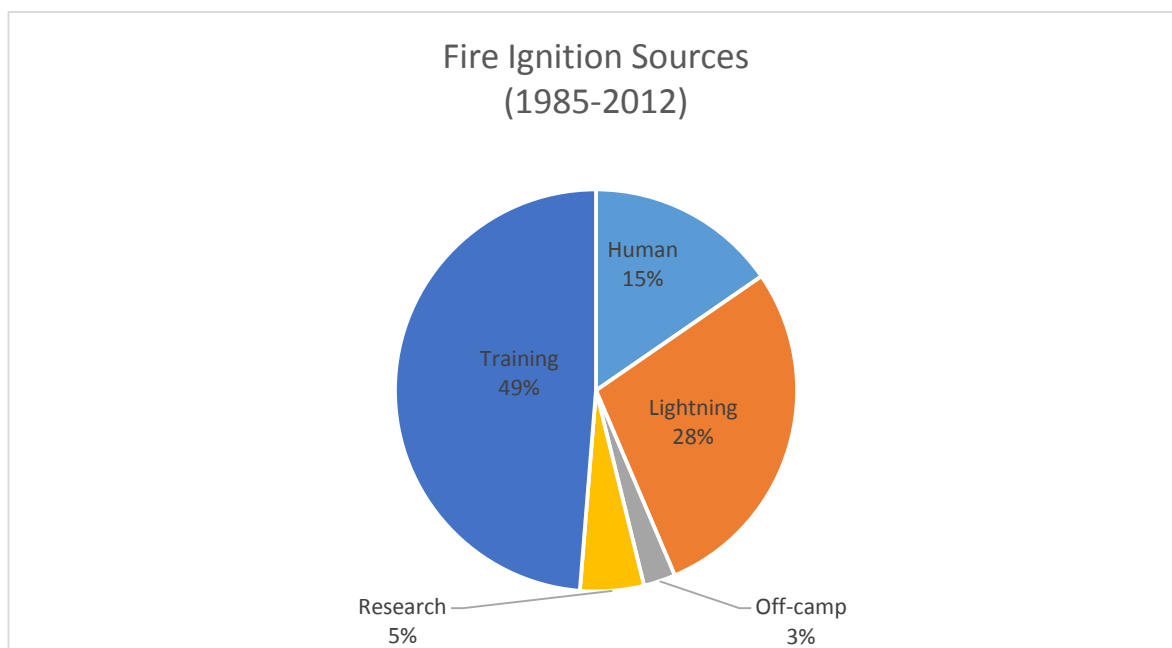
Figure 3.2. Percent of wildfires by ignition source (86 total fires) at Army Garrison Camp Williams from 1985 to 2012.

Hectares Burned and Ignitions Recorded by Year
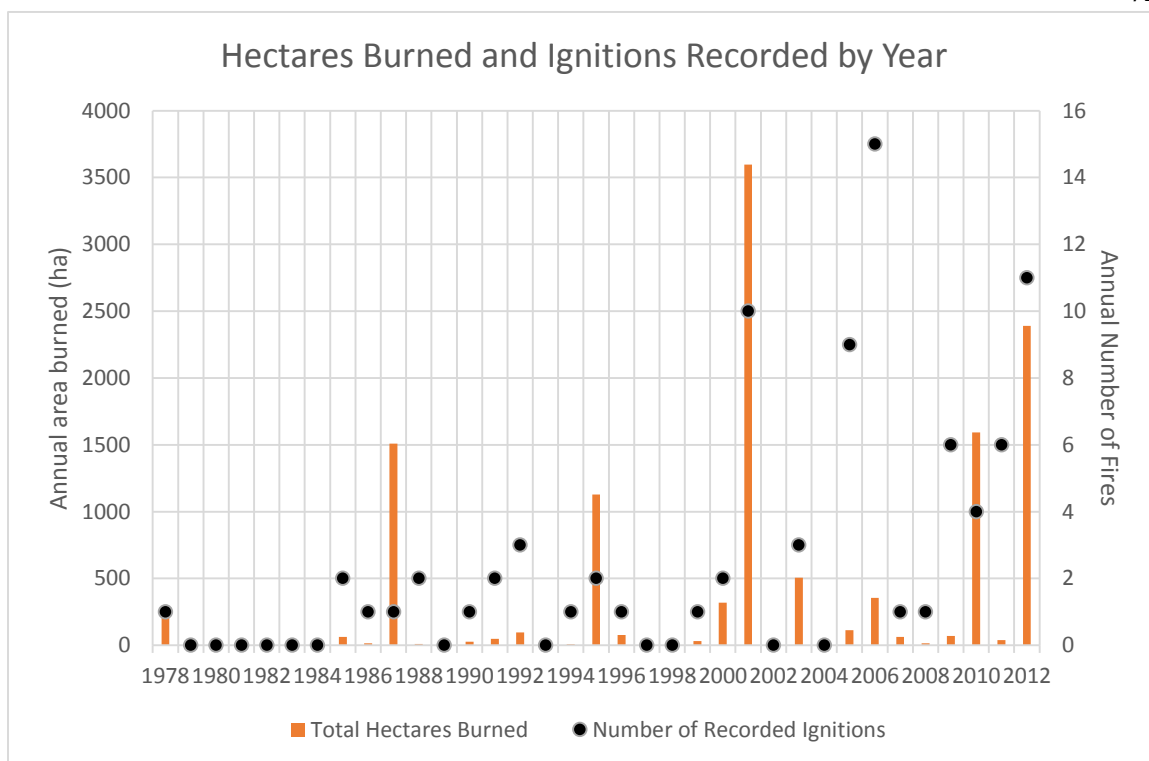
Figure 3.3. Total area burned by wildfires and number of incidents annually at Army Garrison Camp Williams from 1985-2012. Small fire ignitions from 1978 through the late 1990s were usually not reported (Johnson, Utah Army National Guard, Camp Williams, USA, personal communication).

Interestingly, the "large fire" history map (Figure 3.5) reveals that the eastern half of the AGCW base has most recently been susceptible to large fires (e.g., Big Fire of '87, the '95 Fire, Big Fire, Redwood Road, Welder's Fire, Mustang, Pinion Fire). Large fires certainly have occurred on the western portion of the base, most notably, the 2010 Machine Gun Fire. Large fires in the steep topography of the northeast portion of the base are typified by shrubby Gambel oak (*Quercus gambelii*, Nutt.) and drier climatic conditions relative to the western portion of the AGCW base. Gambel oak sprouts vigorously following fire and has reburned over identical areas in as few as six years, exemplified by the '95 Fire in August of 1995 and the Big Fire in July of 2001. In the

western area at AGCW referred to as the "impact area", overlapping fires have occurred in grassland and shrub fuel types in 1996 (Impact Area Sage), 2006 (Impact Area), 2010 (Machine Gun), and 2012 (Nacho). Average fire occurrence for this fuel type and geographic area is about once every four years.

The extreme western portion of the base contains some of the steepest topography and most mature stands of Gambel oak and Utah juniper (*Juniperus osteosperma* (Torr.) Little). This area is higher in elevation than the eastern portion of AGCW and resultant higher precipitation and cooler fuel temperature regimes appear to drive the growth and maintenance of these mature stands. This area has experienced very little fire since 1978, except for the 1978 Sheps Fire and the 1991 Shep's Ridge West Fire. Table 3.1 provides a partial summary of information regarding the large fires depicted in Figure 3.5. Low fire frequency in the extreme western portion of the base is likely linked to cool and moist climatic conditions experienced in the area coupled with the minimal live-fire training activity that occurs in this area.

Table 3.1. Listing of large fires by name, year of occurrence, start date (if available), area burned, ignition source, and any significant highlights associated with wildfires depicted in Figure 3.5.

Fire name	Year	Start date	Area (ha)	Ignition source	Significant highlights
Pre 1985 Tickville	1985	Unknown	56	Unknown	
Big Fire of '87	1987	Unknown	1508	Unknown	
Shep's Ridge-West	1991	Unknown	49	Unknown	
Impact Area-Sage2	1992	Unknown	88	Unknown	
The '95 Fire	1995	8 Aug.	1111	Lightning	Burned off base
Impact Area-Sage	1996	Unknown	78	Unknown	
Known Distance Range	2001	Unknown	48	Training	
Redwood Road	2001	17 June	271	Human	
The Big Fire	2001	16 July	3244	Training	Burned off base
Welders Fire	2003	8 July	478	Human	
South of Area 51	2005	Unknown	42	Lightning	
M31 Fire	2006	12 June	54	Training	
Impact Area Fire	2006	19 Sep.	278	Training	
Juniper Ridge Fire	2007	8 July	63	Lightning	
Mustang	2010	16 July	96	Human	
Machine Gun	2010	19 Sep.	1498	Training	Destroyed 3 homes off base
Nacho	2012	23 July	53	Lightning	
Pinion	2012	5 Aug.	2334	Lightning	Burned off base

Fire Size Class

- Class C (4-40 ha)
- Class B (0.10 - 4 ha)
- Class A (< 0.10 ha)

Camp Williams Boundary

Buildings

0   2.5   5
Kilometers

N
W   E
S
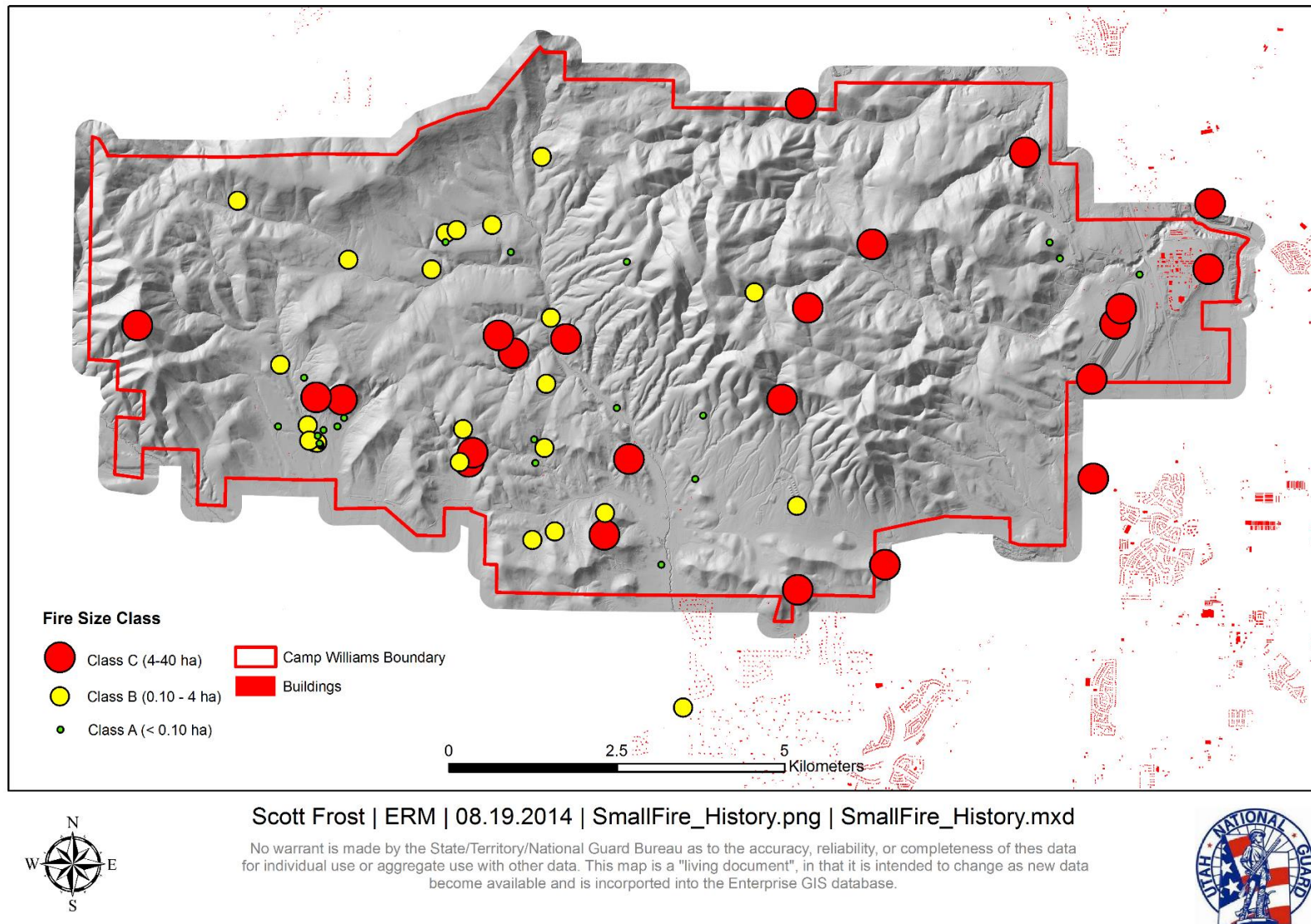
Figure 3.4. The "small fire" (classes A-C) history map for Army Garrison Camp Williams, 1985-2012.

Fire Name

M31 Fire	Impact Area-Sage	Known Distance Range	Mustang	Redwood Road	South of Area 51	Welders Fire
Big Fire of '87	Impact Area-Sage2	Machine Gun	Pinion	Shep's Ridge-West	The '95 Fire	Camp Williams Boundary
Impact Area Fire	Juniper Ridge Fire	Nacho	Pre1985Tickville	Sheps	The Big Fire	Buildings
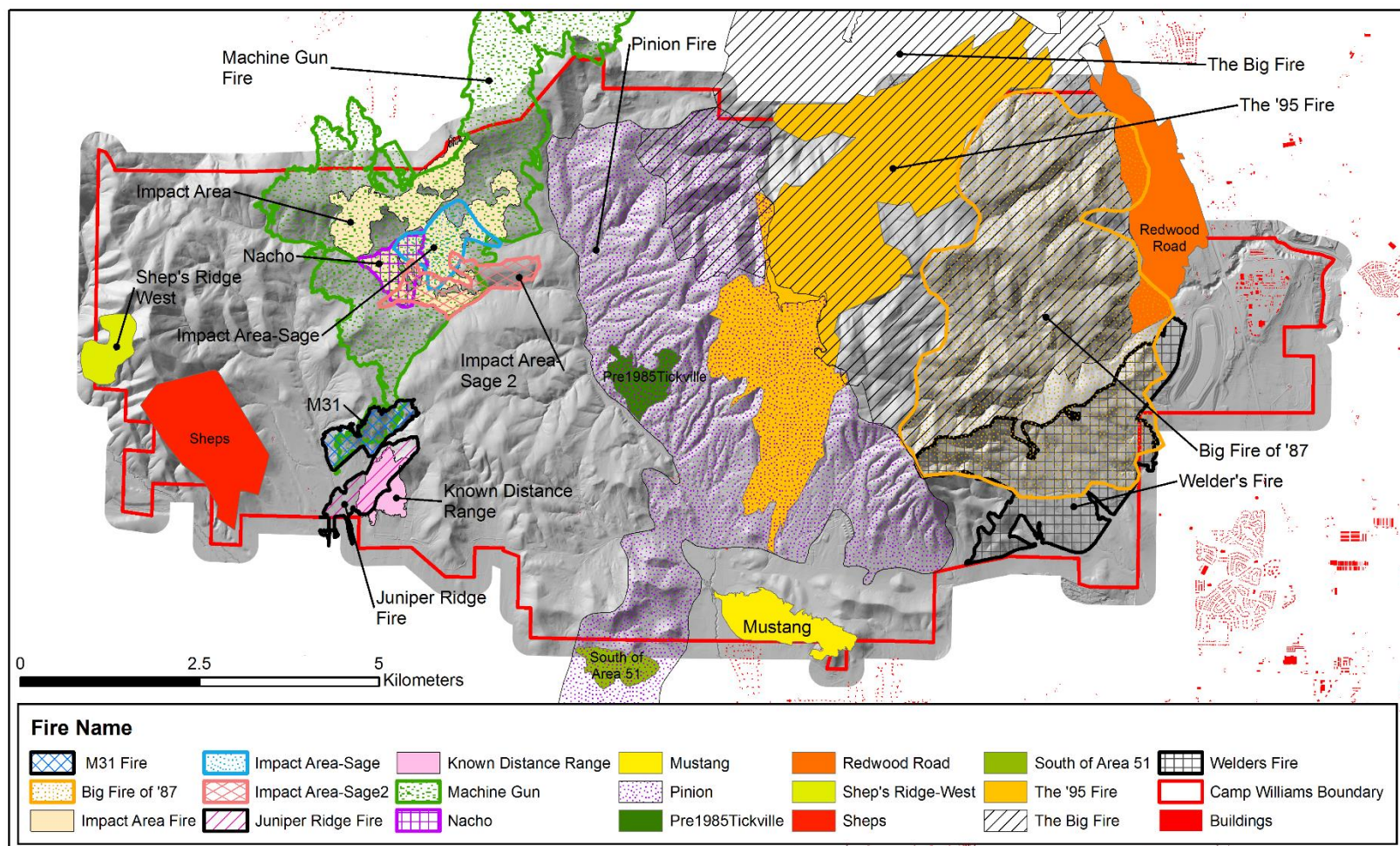
Scott Frost | ERM | 08.19.2014 | LargeFire_History.png | LargeFire_History.mxd

No warrant is made by the State/Territory/National Guard Bureau as to the accuracy, reliability, or completeness of thes data for individual use or aggregate use with other data. This map is a "living document", in that it is intended to change as new data become available and is incorported into the Enterprise GIS database.

Figure 3.5. The "large fire" (class D and above) history map for Army Garrison Camp Williams, 1985-2012.

The MFRI map produced by LANDFIRE (Figure 3.6), indicates return intervals ranging from five to about 22 years. The most widespread category is the interval from nine to 12 years. The map also indicates that along the northwestern boundary of AGCW, intervals are classified as predominantly in the range of five to eight years. Meanwhile, in the extreme western portion of AGCW the map corroborates the recent fire history data, indicating that the longest fire return intervals are from 18-22 years. Regardless of the MFRI class, the LANDFIRE map product suggests that wildland fire has and continues to be a frequent visitor across the AGCW landscape.

Data regarding fire regime categories as classified by LANDFIRE are interpreted as follows: (1) group one describes areas with a MFRI of less than 35 years of low to mixed severity, (2) group three describes areas with a MFRI from 35 to 200 years, also of low to mixed severity, (3) group four describes areas with a MFRI from 35 to 200 years with replacement severity (i.e., high severity), and lastly (4) group five describes areas with a MFRI of greater than 200 years of any severity type.

At AGCW, LANDFIRE classifies fire regimes into two predominant categories, namely Fire Regime groups three and four (Figure 3.7). There are small linear, mostly creek or valley bottom areas that are categorized into fire regime group five. The lower elevation terrain is categorized almost entirely as fire regime group four, indicating that fire is both frequent and of a replacement severity type. Meanwhile, higher elevation areas are typically categorized as fire regime group three, indicating frequent fire, but of low to moderate severity. Lastly, a small area on the western portion of the base, likely in mature Gambel oak and Utah juniper is categorized into fire regime group one. Thus,

only a small portion of the land area at AGCW is categorized into an exclusively low

severity category.

Return Interval (yrs)
- 5 - 8
- 9 - 12
- 13 - 17
- 18 - 22
- 23 - 132
- Camp Williams Boundary
- Buildings

Scott Frost | ERM | 08.19.2014 | MFRI_LANDFIRE.png | MeanFireReturnInterval_data.mxd

No warrant is made by the State/Territory/National Guard Bureau as to the accuracy, reliability, or completeness of thes data for individual use or aggregate use with other data. This map is a "living document", in that it is intended to change as new data become available and is incorported into the Enterprise GIS database.

Figure 3.6. Mean fire return interval as predicted by LANDFIRE (2010 data) reference and simulation data for Army Garrison Camp Williams.
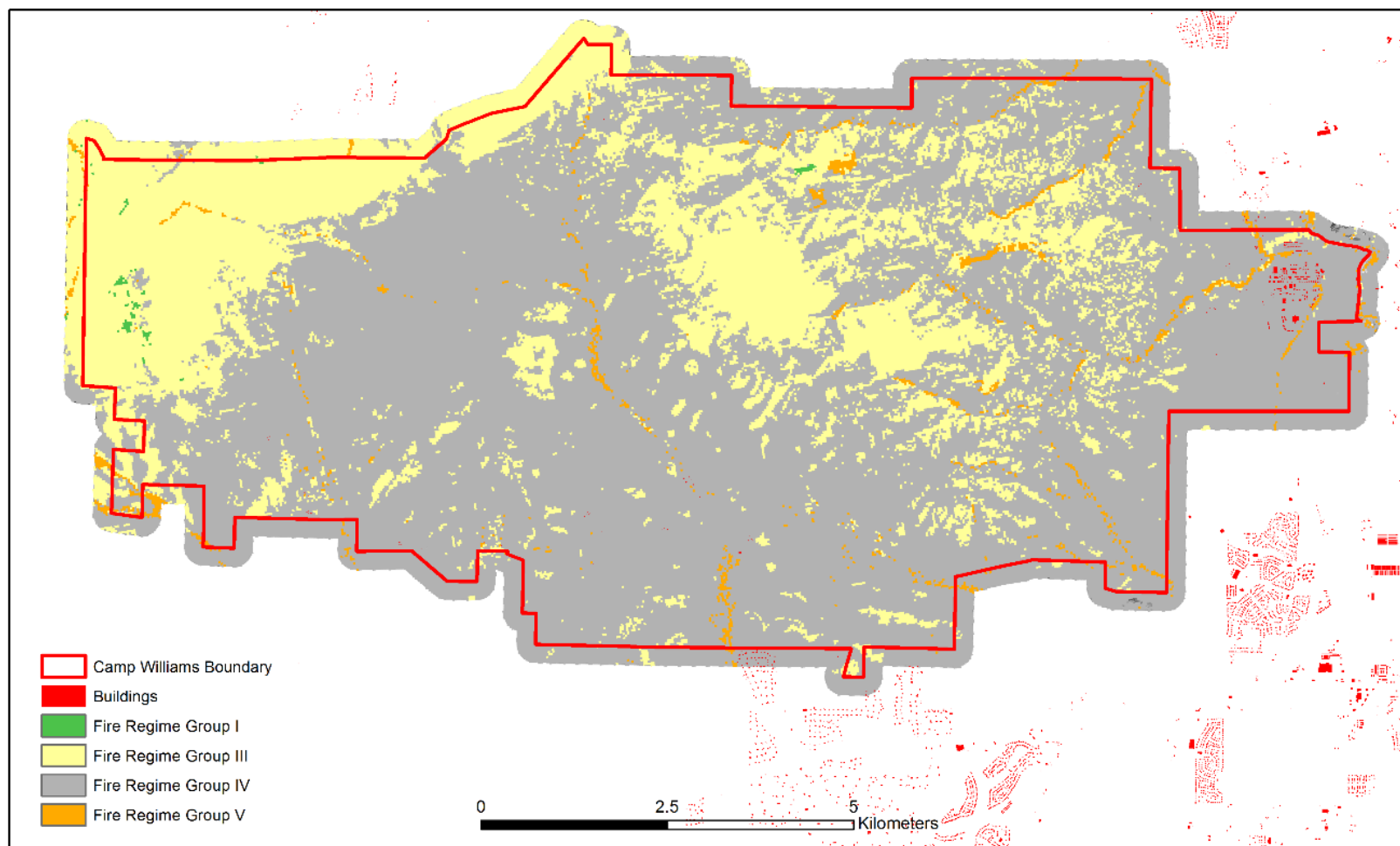
Scott Frost | ERM | 08.19.2014 | FRG_LANDFIRE.png | FireRegime_data.mxd

No warrant is made by the State/Territory/National Guard Bureau as to the accuracy, reliability, or completeness of thes data for individual use or aggregate use with other data. This map is a "living document", in that it is intended to change as new data become available and is incorported into the Enterprise GIS database.

Legend:
- Camp Williams Boundary
- Buildings
- Fire Regime Group I
- Fire Regime Group III
- Fire Regime Group IV
- Fire Regime Group V

0   2.5   5 Kilometers

Figure 3.7. Fire regime categories as predicted by LANDFIRE (2010 data) reference and simulation data for Army Garrison Camp Williams.

Fire Behavior Case Study of the Machine Gun Fire, September 19, 2010 Fire's Significance

Shortly after mid-day on September 19, 2010, a wildfire was ignited at AGCW lands near the Multi-Purpose Machine Gun (MPMG) Range (Figure 3.8) as a result of .50-caliber machine gun fire associated with a live-training, hence the name of the fire-exercise. Due to high winds and dry conditions at the time of ignition, the fire spread rapidly in a north to northeast direction, crossing over the northern boundary of AGCW onto private land about 6.5 hours later (Figure 3.9). The fire subsequently burned to the northeast, destroying three homes and causing the evacuation of some 1600 more in the community of Herriman, UT (Figure 3.9).[2] The fire eventually burned over an area of 1498 ha in total, representing the fourth largest fire to have occurred at AGCW in recent memory. The Utah National Guard admitted blame for the incident and for allowing the live-training exercise to proceed under critical fire weather conditions. The National Guard accepted claims for damaged or destroyed property. Resultant pressure from state and local government agencies and the public was understandably intense.

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[2] Several still photographic images of the Machine Gun Fire taken late during the evening of September 19, 2010, are available for viewing at *Google Images* and the Utah National Guard *Flickr* account. See for example:

- https://www.google.com/search?q=machine+gun+fire+camp+william+utah+2010&safe=active&biw=1280&bih=939&source=lnms&tbm=isch&sa=X&ei=W0SfVfPQN4KFyQSi0bLYDg&ved=0CAcQ_AUoAg
- https://www.flickr.com/photos/utahnationalguard/sets/72157625007005934

And similarly, on *YouTube* at:
- https://m.youtube.com/results?q=machine%20gun%20fire%20utah%202010&sm=3

Fire Chronology and Development

The Machine Gun Fire was estimated to have started at around 1237 hours (Figure 3.9)[3]. An initial attack fire suppression crew employed by the Utah National Guard stationed at AGCW were initially dispatched to the fire. Two distinct surges in the fire's forward advance subsequently occurred, the first at 1330 hours and a second at 1400 hours (Figure 3.9) were stopped at firebreaks in grass and sparse shrub cover northeast of the fire's point of ignition. Near 1500 hours, high winds gusting to at least 28 km hr^{-1} produced spot fires north of the firebreaks that had initially stopped fire spread. In 10 minutes, the fire propagated from the spotting activity, advanced 706 m and jumped yet another set of firebreaks in grass at 1530 hours (Figure 3.11a; Run 2). In the next 30 minutes, from 1530 to 1600 hours, the fire spread forward an additional ~800 m, and breached a trail at 1600 hours (Figure 3.9). From 1601 to 1625 hours, fire spread continued at a rapid pace until it jumped a set of trails at the EQA pad area (Figure 3.9). For the next 20 minutes (from 1626-1645), a large portion of the fire's edge propagated upslope in a northwesterly direction (Figure 3.9). At 1646, the fire jumped two sets of firebreaks, each approximately 8-m wide, and spread rapidly upslope in a north-northeast direction until running into a goat-maintained fuelbreak (Lovreglio *et al.* 2014) in Gambel oak. At 1656 hours, spot fires were observed developing on the other side of the fuelbreak that eventually spread beyond the northern boundary of AGCW. Meanwhile, the northwestern portion of fire continued on spreading from 1626-1645 (Figure 3.9), eventually breaching the same set of firebreaks at 1700 hours. From 1700to 2000 hours,

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[3] All times given in this chapter in Mountain Daylight Time (MDT)

the fire burned northward until spotting over the goat-maintained fuelbreak at 2000

hours. In addition, the fire burned along the fuelbreak towards the west and subsequently

hooked around the fuelbreak at 2045 hours, eventually convalescing with the spot fire

activity that developed at 2000 hours (Figure 3.9).
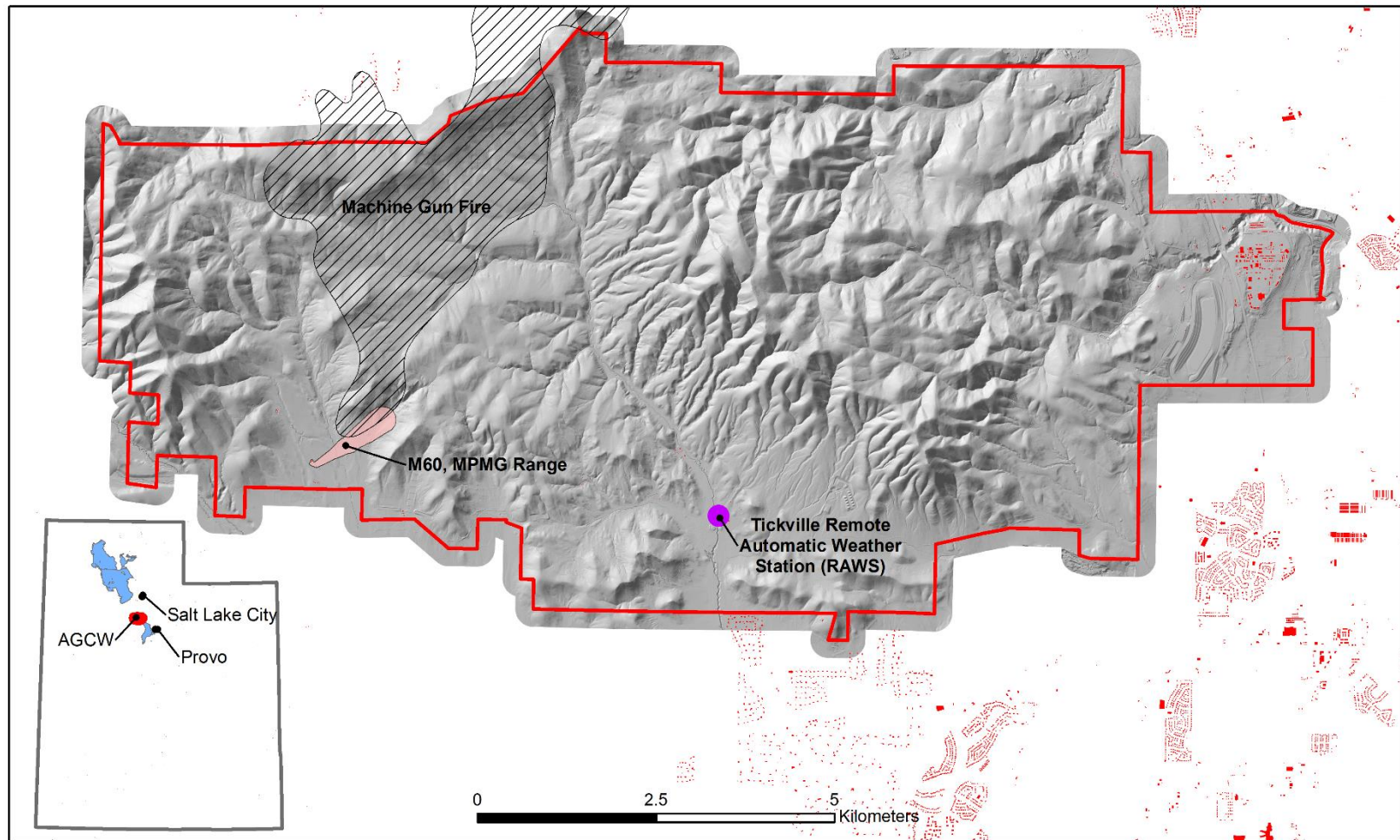
Machine Gun Fire

M60, MPMG Range

Tickville Remote
Automatic Weather
Station (RAWS)

Salt Lake City

AGCW

Provo

0   2.5   5
Kilometers

Figure 3.8. Map of the Machine Gun Fire's (19 Sept., 2010) final perimeter and location of the Multi-Purpose
Machine Gun (MPMG) Range, relative to the Army Garrison Camp Williams boundaries.

The fire then burnt farther northward, and consumed one home before being stopped along roads and property boundaries later the night of September 19.

In the northeastern portion of the fire, spread continued through the evening of September 19 and on into the morning of hours of September 20. According to the Incident Summary Report (ICS-209) submitted at 2100 hours on September 19, suppression planning for the next day was focused on structural point protection at the northern perimeter of the fire. On September 20, the fire spread farther northward, until reaching city roads and homes located in the community of Herriman, UT. Two homes were burnt in this area (Figure 3.10b) before the fire was finally contained and extinguished.

Details of the Fire Environment

The behavior of a wildland fire is influenced by its environment. This involves the complex interactions of inter-relationships associated with the spatial and temporal variations in topography, weather, fuels, and the fire itself (Countryman 1972). The topographic conditions during the different fire runs of the Machine Gun Fire are summarized in Figure 3.12. In addition, the fire perimeter, segmented by time step progressions are consistent with the colors of Figure 3.9 and in a three-dimensional perspective (Figure 3.11a) using Google Earth (https://www.google.com/earth/). The initial fire run advanced through moderately steep terrain (on average, 8.8% slope), gaining 113 m in elevation while advancing roughly 1284 m horizontally. Runs two and five actually decreased in slope steepness overall, while runs four and five advanced through undulating topography. Run six burnt through the steepest topography (Figures

3.11a and 3.12) near South Mountain on the northern boundary of AGCW before cresting

the ridge and burning downslope in run seven.
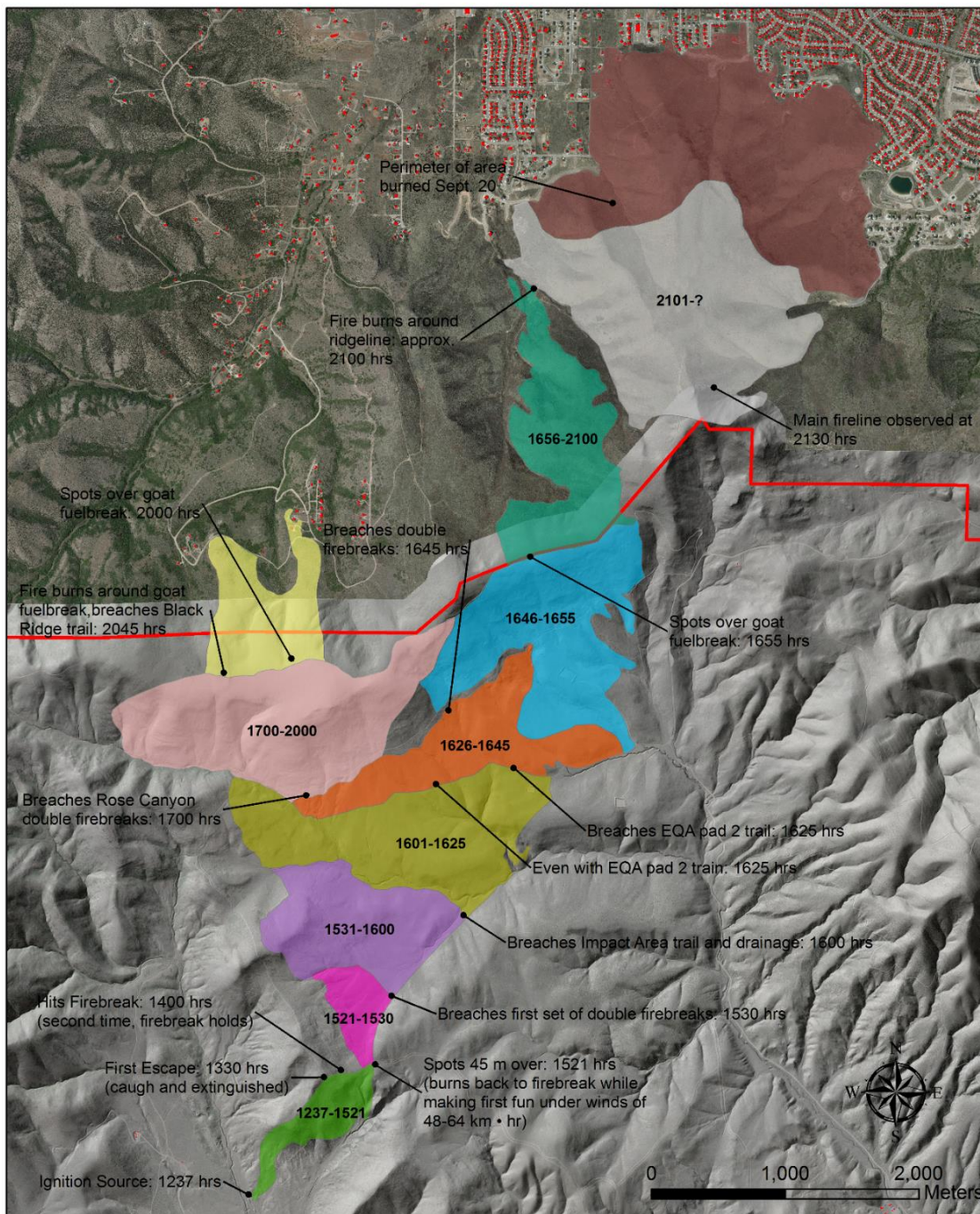
Figure 3.9. Progression map and narrative of events associated with the major run of the Machine Gun Fire on September 19, 2010. Color of progressions correspond to Figures 3.11a and 3.12.

Figure 3.10. Immediate aftermath of the 2010 Machine Gun Fire on the outskirts of Herriman, UT: (A) a burnt home and (B) burned ground adjacent to unimpacted structures. Photos courtesy of Tom Smart, Deseret News.
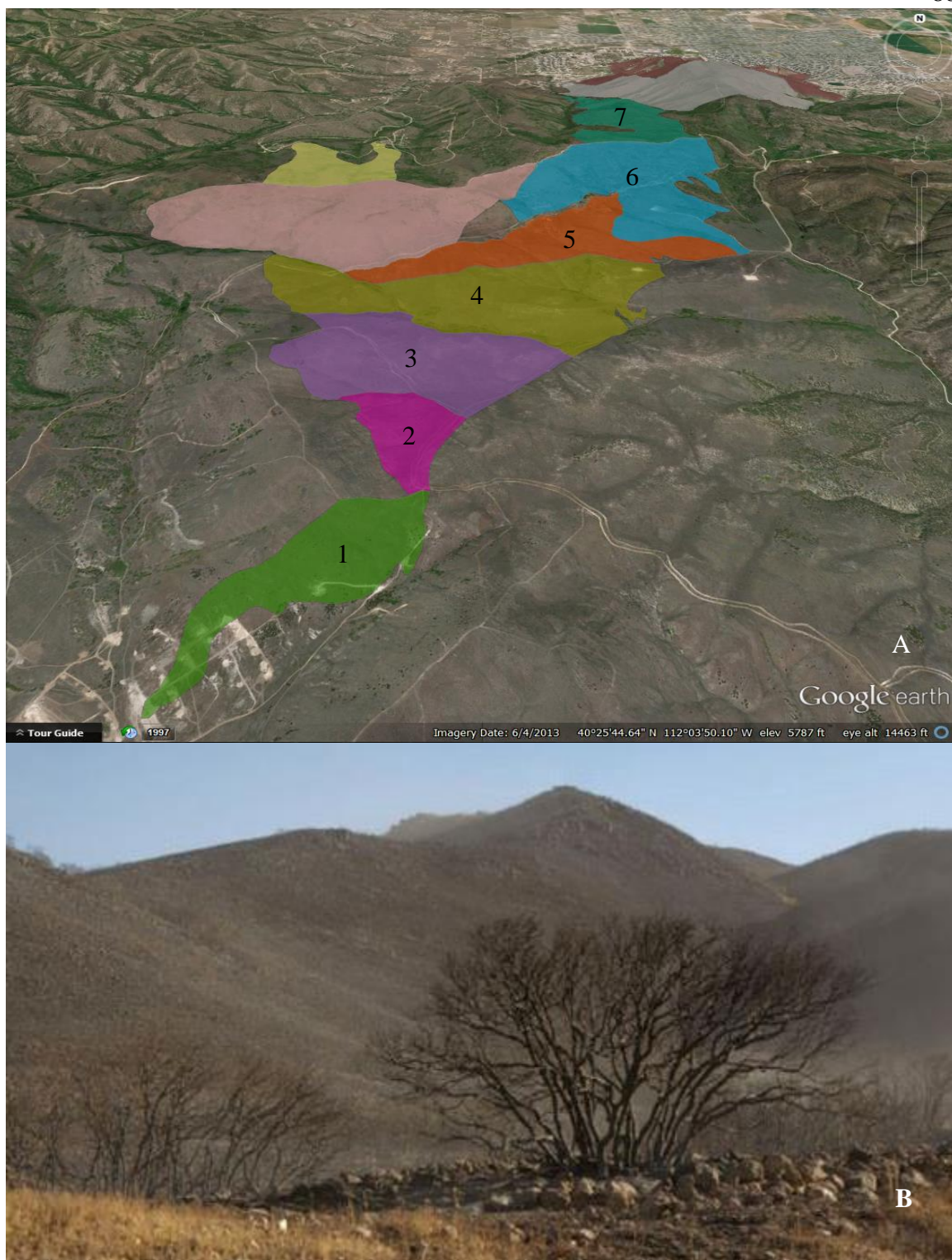
Figure 3.11. (A) Progression map for the Machine Gun Fire seen in a three-dimensional perspective using Google Earth and (B) topographic relief on the southern side of South Mountain; the northern boundary of Army Garrison Camp Williams is just over the ridgeline. Photo courtesy of David Williams.
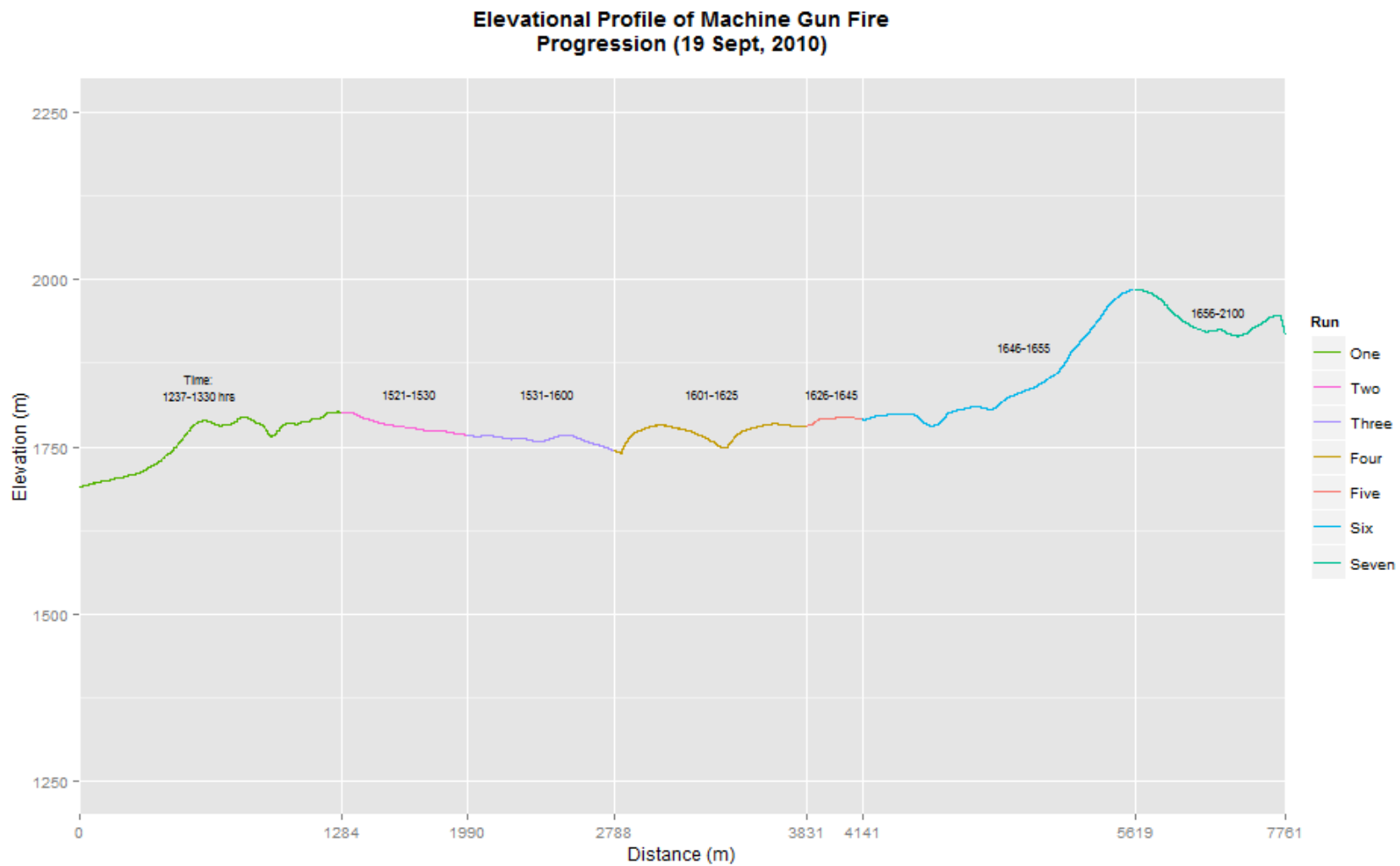
Figure 3.12. Elevation and horizontal progression of the Machine Gun Fire for seven progression sequences at Army Garrison Camp Williams.

Weather

The location of AGCW is within the great basin fire climate region and is typified by cold winters, hot summers, and low annual precipitation, generally from 40 to 100 cm annually (Schroeder and Buck 1970). Climate is heavily influenced by the rain shadow effect of the Sierra-Cascade Ranges including wind patterns such as the Great Basin High. Wind patterns associated with this high typically come from Canada and the Northwest and warm adiabatically as air masses move from the high elevations of the Sierra and Cascade ranges to the drier and lower elevations of the Great Basin. Surface pressures tend to be flat in the Great Basin summer months, allowing for extended periods of high ambient air temperature, low humidity, and air mass instability (Schroder and Buck 1970). Precipitation occurs mostly in the winter months with a secondary maximum in the spring.

The hourly weather data as recorded on September 19, 2010 at the Tickville RAWS located within AGCW is summarized in Table 3.2. The Tickville RAWS is located four km (east-southeast) from the point of origin of the Machine Gun Fire. While the Tickville RAWS is the closest weather station to the Machine Gun Fire, it was also the only weather station operating within AGCW at the time (Figure 3.8). Given that the land mass of AGCW spans a distance of 17.5 km from its western to eastern boundaries and 8.5 km from south to north, a single weather station is considered adequate for generating fire danger rating information from weather data (Lawson and Armitage 2008). A RAWS records weather observations for the 10 minutes prior to the hour. Samplings are recorded every five seconds during the 10-min sampling window ($n = 120$) and then averaged (NWCG 2005). This applies to the air temperature (Temp.), relative

humidity (RH), 6.1-m open wind speed (WS) and the wind direction (WD). The maximum gust or peak wind speed is obtained from samples taken every five seconds over the 60-min window (i.e., $n = 720$) prior to the hour, with the highest value being reported (NWCG 2005).

Upper air wind speed, direction (Figures 3.15 and 3.16), and temperature (Figures 3.13 and 3.14) were also summarized on September 19, 2010 at 0500 and 1700 hours MDT. Temperature in the first 2000 m of elevation at 0500 hours was within 5°C, above the 2000 m mark, air gradually cooled about 5-6°C per 1000 m of elevation gain. The second temperature reading at 1700 hours on September 19, 2010 indicates a dramatic increase in temperature from ground level until about 1000 m elevation, increasing from 20°C to 34°C. From the 1000 m elevation, air started to cool at a rate of roughly 8-9°C per 1000 m of elevation.
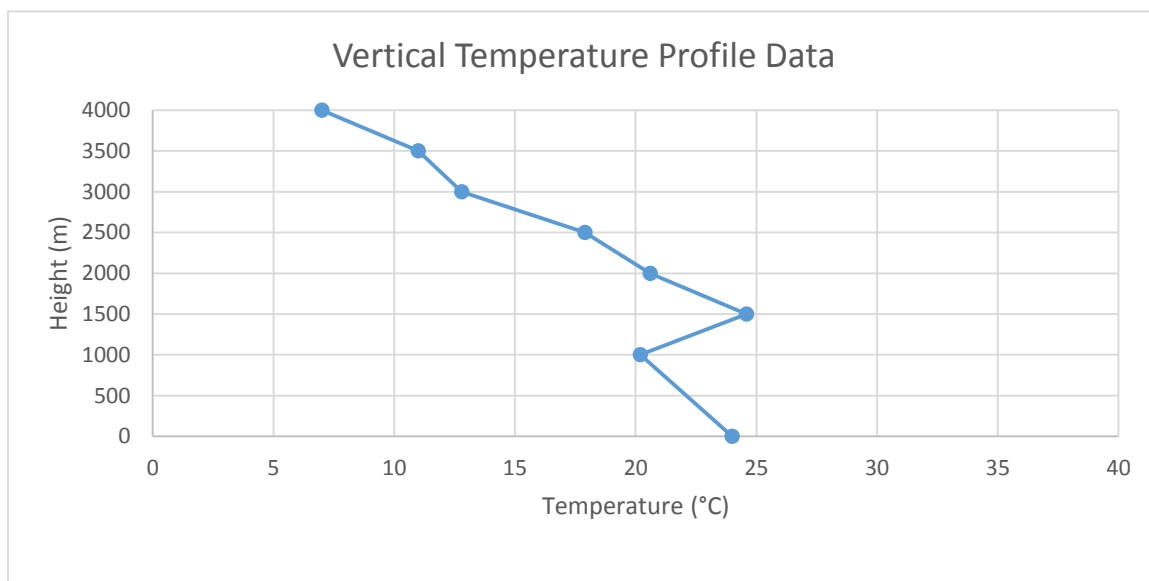
Figure 3.13. Vertical Temperature Profile Data on Sept. 19, 2010 at 0500 hours MDT at Salt Lake City Airport.
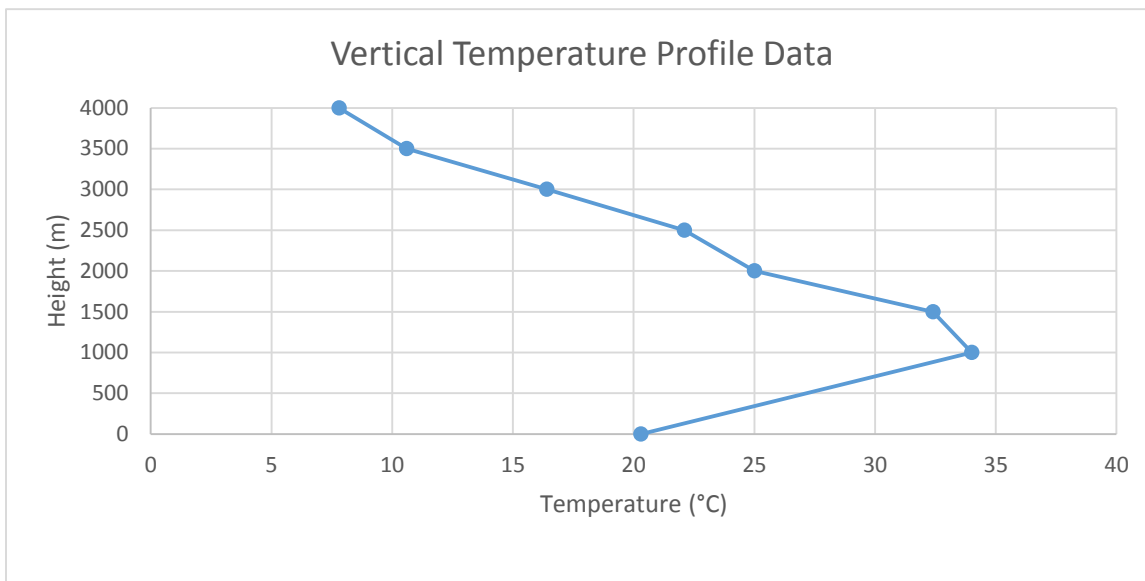
Figure 3.14. Vertical Temperature Profile Data on Sept. 19, 2010 at 1700 hours MDT, at Salt Lake City Airport.
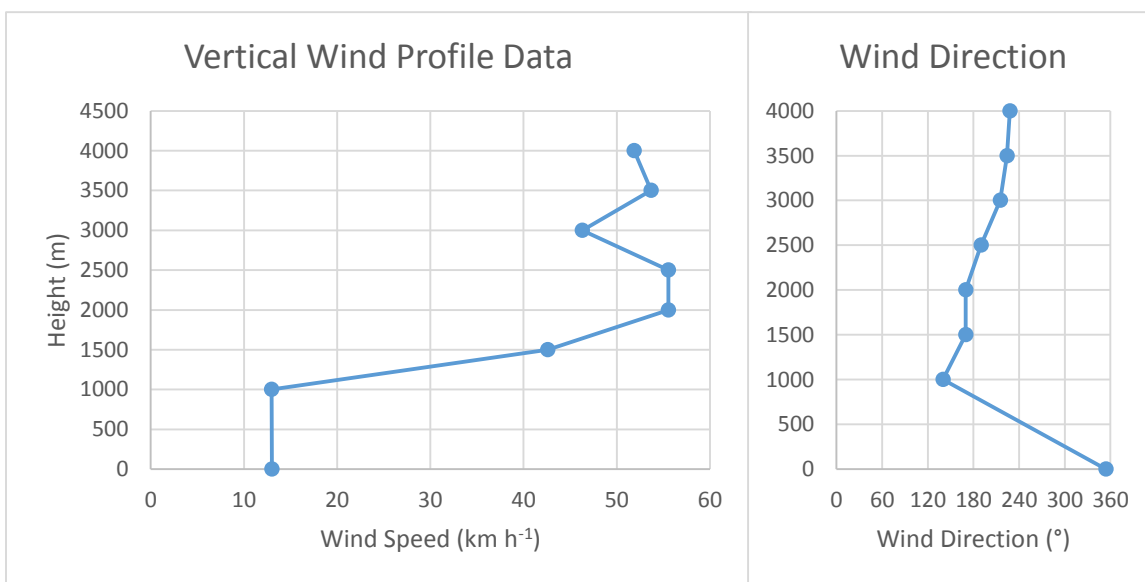
Figure 3.15. Vertical wind profile data at the Salt Lake City Airport on September 19, 2010 at 0500 hours MDT.

Wind speed for both readings was near 10 km h^{-1} at ground level and increased sharply within the first 1000 m of elevation gain. Wind speed continued to rise with increased elevation until about 2000-3000 m on both days, settling around 50 km/hr from

3000 m and above. Wind direction on September 19, at 0500 hours (Figure 3.15) was north at ground level, switching to a prevailing southwest and southeasterly direction from 1000 m elevation and higher. Wind direction at 1700 hours (Figure 3.16) was southeast at ground level and stayed south to southeast as elevation increased in the upper air layers.
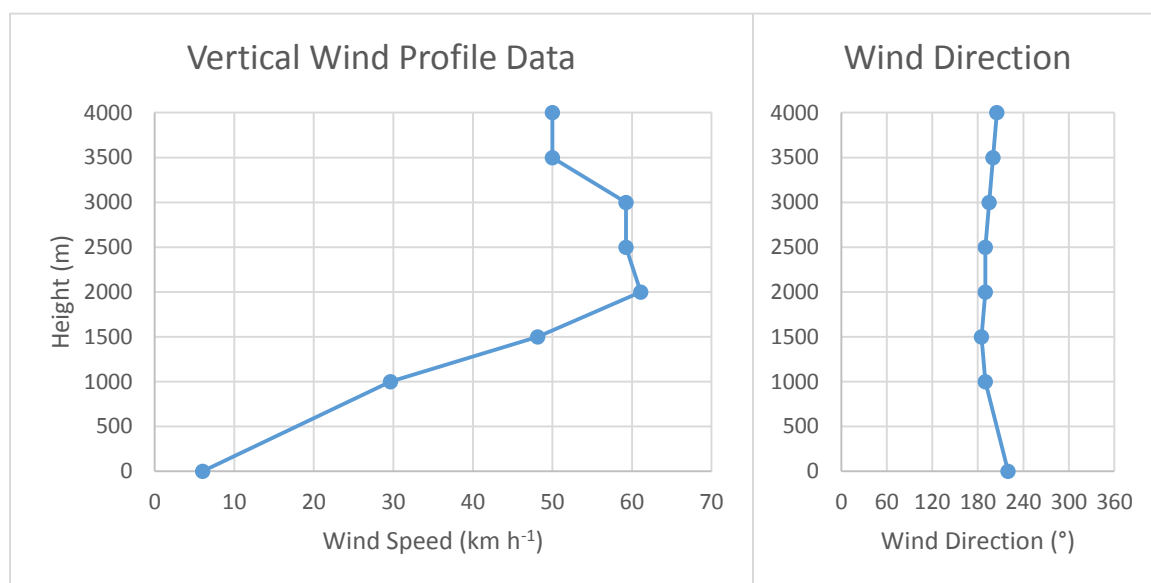
Figure 3.16. Vertical wind profile data at the Salt Lake City Airport on September 19, 2010 at 1700 hours MDT.

The ICS-209 report filed at 2100 hours MDT on September 19, 2010 briefly mentions a peak or gust wind speed observed at 56 km h^{-1} and rapid, wind-driven rates of fire spread. The RAWS hourly weather data indicates similar high wind speed observations with average 6.1-m open wind speeds of 22 to 32 km h^{-1} from 1400 to 2200 hours (Table 3.2). Wind speed in the morning hours on September 19, 2010, were fairly high with averages consistently between 12-15 km hr^{-1} from 2400 to 0900 hours. Average wind speed decreased slightly from 1000 to 1300 hours, varying from 6 to 14 km hr^{-1}. At approximately 1400 hours, peak temperatures for the day and relative humidity lows

coincided with a dramatic increase in average wind speed ranging from 22 to 32 km hr^{-1}

for all of the afternoon and evening weather observations. Relative humidity (RH)

dropped from a morning high of 34% at 0800 hours to 7% by 1400 hours. Wind direction

from 1000 hours onward was a constant southeast to south to southwest flow. The dead

timelag fuel moistures were very low throughout the day ranging from one to four

percent for 1-h fuels, two to six percent for 10-h fuels, and six to ten percent for 100-h

fuels.

Table 3.2. Weather conditions and associated dead fuel moisture time-lag (TL) classes as recorded at the Tickville RAWS at Army Garrison Camp Williams on September 19, 2010 before, during, and following the major run of the Machine Gun Fire.

Time (hours)	Temp (°C)	RH (%)	Mean WS (km h^{-1})	WD (°)	DFM TLs (%) 1-h	DFM TLs (%) 10-h	DFM TLs (%) 100-h
2400	13	22	14	354	4	4	6
0100	11	26	14	351	5	6	10
0200	9	30	8	354	5	6	9
0300	9	33	12	357	5	5	8
0400	8	29	15	352	5	5	7
0500	7	28	15	353	5	5	7
0600	7	30	11	347	5	5	7
0700	7	31	12	349	5	6	6
0800	6	34	14	352	5	5	6
0900	9	27	15	354	3	3	6
1000	21	14	9	159	2	3	6
1100	23	12	6	128	2	3	6
1200	24	13	11	115	2	2	6
1300	28	9	14	153	1	2	6
1400	30	7	22	189	1	2	6
1500	31	5	28	207	1	2	6
1600	32	6	32	195	1	2	6
1700	32	5	31	193	1	2	6
1800	32	5	32	194	1	2	6
1900	31	4	30	198	1	2	6
2000	29	6	26	177	2	3	6
2100	26	10	18	209	2	3	6
2200	26	11	23	220	2	3	6
2300	25	13	20	167	3	3	6

Timelag Fuel Moisture recorded at 1400 hours, live fuel moisture content of Wyoming big sagebrush was 74% and Gambel oak 81%. RH = relative humidity, WS = wind speed, WD = wind direction, DFM TLs= Dead fuel moisture time-lags

Fuels

Information on vegetation and fuel type at the time of the occurrence of the 2010

Machine Gun Fire was acquired via LANDFIRE (Reeves *et al.* 2009) for EVT and fire

behavior fuel model (FBFM) classifications as per Anderson (1982). As indicated earlier,

EVT is a baseline LANDFIRE data product that represents species composition at a

given site and is used for subsequent modelling of successional vegetation departures

from historical variation and for wildland fuel data products (Rollins 2009). EVT is

mapped from classification and regression tree (CART) algorithms using Landsat

imagery, biophysical gradients, and training databases developed through the LFRDB

(Rollins 2009). FBFMs are mapped using combinations of EVT, existing vegetation

cover (EVC), existing vegetation height (EVH), and ESP. Regional fire behavior experts

then evaluate the primary map products, with adjustments made as necessary (Reeves *et*

al. 2009).

The EVT map for AGCW is presented in Figure 3.17 with the perimeter of the

Machine Gun Fire overlaid onto LANDFIRE data compiled in 2008. Using general

vegetation groups, the EVT map indicates that while within the boundaries of AGCW,

the Machine Gun Fire burned predominantly through shrubland vegetation and small

patches of grassland. Once the fire crested Black Ridge on the northern boundary of

AGCW, the vegetation type transitions to hardwoods, which on the ground is represented

by Gambel oak. The FBFM map for AGCW at the time of the Machine Gun Fire in 2010

(Figure 3.18) indicates that the shrubland vegetation is primarily FBFM 5 and

secondarily FBFM 2. Grasslands are modeled as FBFM 1, while Gambel oak stands were

modeled as FBFM 8 and possibly FBFM 2.

Legend:
- Machine Gun Fire
- Camp Williams Boundary
- Buildings
- Unclassified
- Agricultural
- Conifer
- Developed
- Exotic Herbaceous
- Grassland
- Hardwood
- Non-vegetated
- Riparian
- Shrubland

0   2.5   5
Kilometers
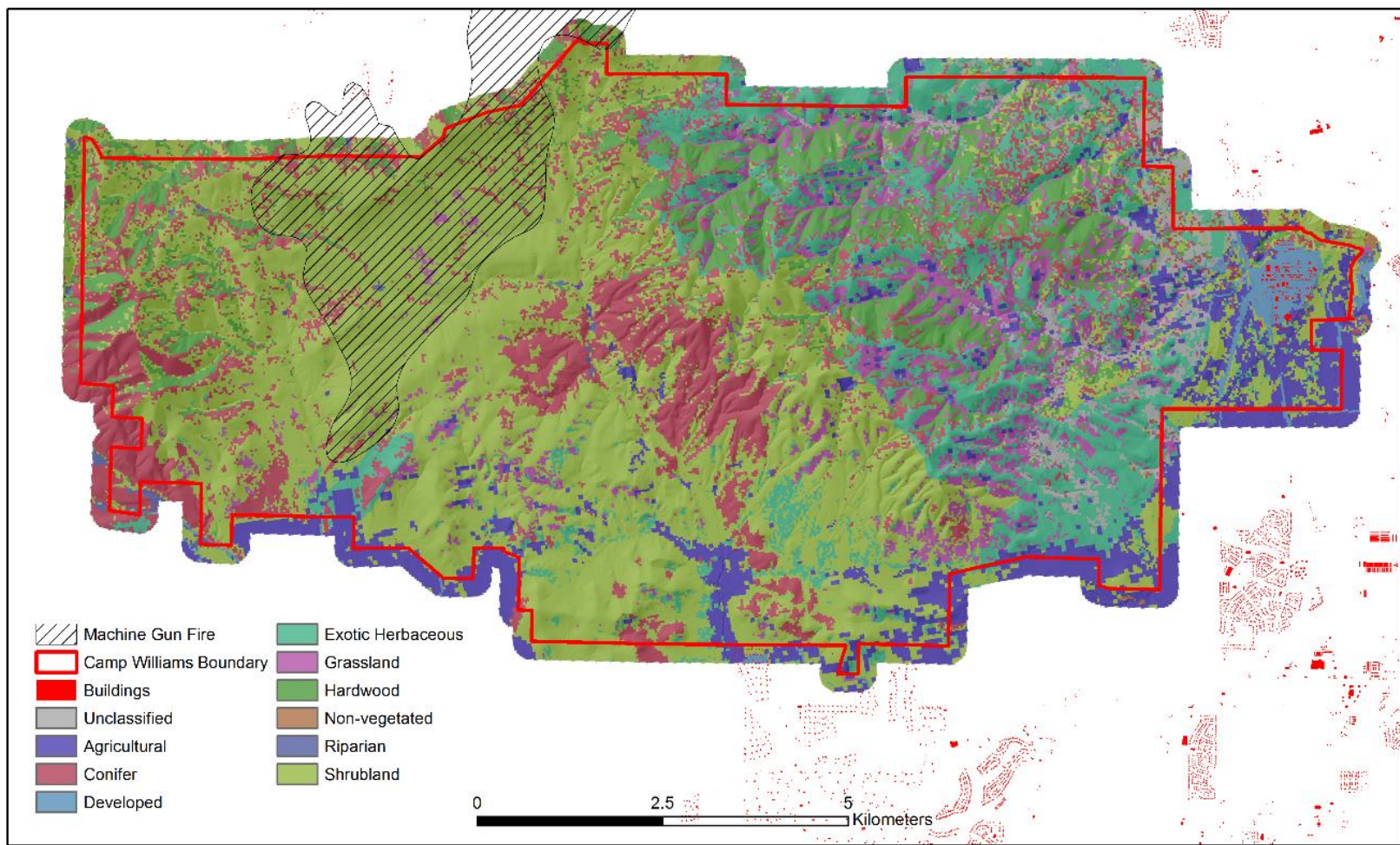
Scott Frost | ERM | 08.19.2014 | EVT_LANDFIRE.png | Vegetation2008_data.mxd

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Figure 3.17. Existing vegetation type (EVT) as classified by LANDFIRE (2008 data) at Army Garrison Camp Williams, grouped into general vegetation type categories.
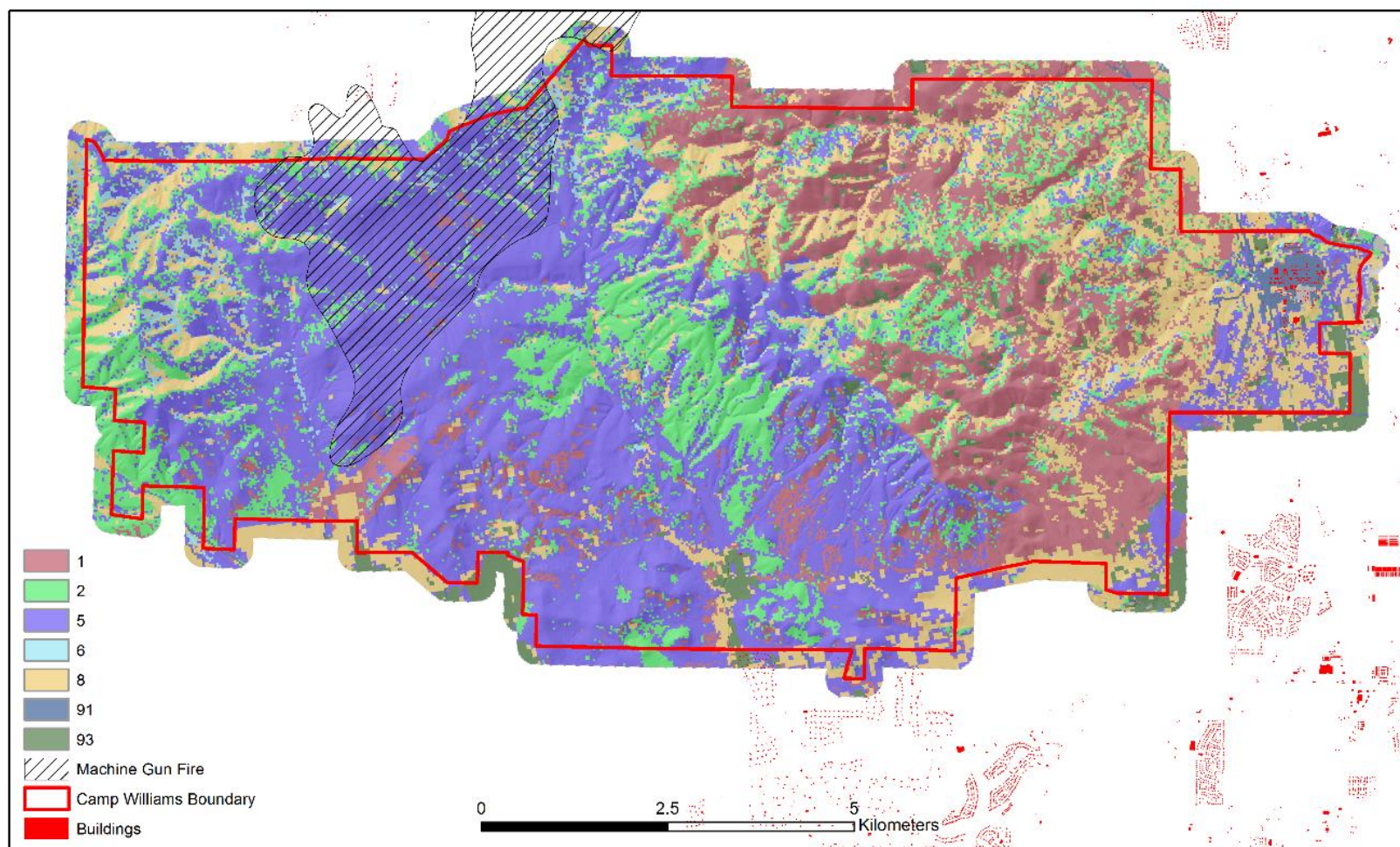
Legend:
- 1
- 2
- 5
- 6
- 8
- 91
- 93
- /// Machine Gun Fire
- Camp Williams Boundary
- Buildings

0   2.5   5 Kilometers

Figure 3.18. Fire behavior fuel models (FBFM) per Anderson (1982) as classified by LANDFIRE (2008 data) for Army Garrison Camp Williams.

Analysis of Fire Behavior

A rudimentary attempt was made to compare the fire's observed rate of spread (ROS) as reported via a fire progression map (Figure 3.9) compiled close to the time of incident versus predicted ROS values using BehavePlus fire modelling system software (Heinsch and Andrews 2010) and the weather data plus the computed dead fuel moisture contents from the Tickville RAWS (Table 3.4).

A sensitivity analysis patterned after the Butte Fire case study of Butler and Reynolds (1997) was conducted to understand the modeled differences in fire behavior for slight variations in 1-h and 10-h TL dead fuel moisture contents. A separate set of predictions tested different variations of live fuel moisture content (i.e., 64, 94, and 124%). BehavePlus fire behavior predictions were obtained using FBFM 5–brush (0.6 m) as per Anderson (1982) for ROS, heat per unit area, fire-line intensity (FLI), and flame length (FL) (Table 3.3). The live woody moisture content (LWMC) values used in the sensitivity analysis are very similar to spring (124%), early summer (94%), and late summer to fall (64%) levels observed in Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle & Young) and Gambel oak according to sampling carried out nearby to AGCW, except that 64% would be well below typical lows (usually about 80%). For a full description refer to Chapter 2. Other input variables to BehavePlus such as mid-flame wind speed and slope steepness were held constant.

The results indicate very slight differences in fire behavior when 1-h and 10-h dead fuel moisture TL size classes are adjusted from 1-2%. ROS maximum variation was 1.2 m min^{-1} and FL variation was minimal at 0.1 m. FLI and heat per unit area varied most, but still not enough to effect a major change in fire behavior. When LWMC was

varied, the results were very different. ROS changed from 26.0 to 14.8 m min^{-1} when the

LWMC was increased from 64 to 124%. Likewise, FL was reduced by 0.9 m, FLI by

1924 kW m^{-1}, and heat per unit area by 898 kJ m^{-2} when LWMC was increased from 64

to 124%. The drastic differences are nearly enough to change suppression options from

indirect and aerial attack only to direct attach using heavy machinery according to

Andrews and Rothermel (1982). Also of note, the Butler and Reynolds (1997) sensitivity

analysis was conducted for FBFM 2. Their results were nearly opposite to the results

presented here for FBFM 5, which indicated little sensitivity of FBFM 2 to variations in

live fuel moisture content, but extreme sensitivity to 1-h and 10-h dead fuel moisture TL

variations.

Table 3.3. BehavePlus model input and output values as patterned after Butler and
Reynolds (1997) BehavePlus model rate of spread (ROS) sensitivity analysis.

BehavePlus input Value	Sensitivity study[a]			Predicted spread rates[b]		
Fire Behavior Fuel Model	5	5	5	5	5	5
1-h TL fuel moisture (%)	**2**	**2**	**3**	2	2	2
10-h TL fuel moisture (%)	**3**	**4**	**5**	3	3	3
Live woody moisture (%)	74	74	74	**64**	**94**	**124**
Adjusted 6.1-m open wind speed (km h^{-1})	32	32	32	32	32	32
Wind adjustment factor	0.4	0.4	0.4	0.4	0.4	0.4
Mid-flame wind speed (km h^{-1})	12.8	12.8	12.8	12.8	12.8	12.8
BehavePlus output values						
Rate of spread (m min^{-1})	23.5	23.4	22.3	26	19.6	14.8
Heat per unit area (kJ m^{-2})	9010	8995	8612	9117	8866	8219
Fireline intensity (kW m^{-1})	3523	3511	3199	3957	2898	2033
Flame length (m)	3.3	3.3	3.2	3.5	3.0	2.6

[a]Sensitivity study of the predicted fire behavior compared to the dead fuel moisture
content, which is shown in bold.
[b]Comparison of predicted spread rates as a function of live moisture content, which is
shown in bold.

The observed ROS was derived from the fire progression map (Fig 3.9) by measuring the distance between points for each fire progression interval or segment and then dividing that value by the time for the fire to progress from one known location to another. Distances for each fire progression interval were calculated using GIS software. In addition, the elevation gained or lost as the fire advanced horizontally in space through time (Figure 3.12) was also derived to estimate the slope steepness associated with each run. If the slope steepness was less than 5%, then a zero percent slope was assumed. The observed ROS were then compared to the model predictions for the same fire progression segments which were paired with the Tickville RAWS weather data as inputs for FBFM 5 into BehavePlus (Table. 3.4). The outcome indicates that the observed versus predicted ROS values for progression segments 3, 4, and 5 are within 60% of the observed values. However, for progressions 1, 2, 6, and 7, the observed ROS values are drastically higher compared to the predictions.

Table 3.4. Observed versus predicted rates of spread tabulation for the major run of the Machine Gun Fire of September 19, 2010 patterned after Butler and Reynolds (1997). Predicted rates of spread were computed with BehavePlus using Fire Behavior Fuel Model 5 as per Anderson (1982). The live woody fuel moisture content was set as a constant at 69%, the value coming from a nearby live fuel sampling location for Wyoming big sagebrush on September 1, 2010.

Fire progression segment	Time interval (hours)	Slope steepness (%)	Spread distance (m)	6.1-m open wind (km h⁻¹) Avg.	Observed ROS (m min⁻¹)	Predicted ROS (m min⁻¹) from avg. wind speed
1	1231	8.8	1284	13	22	8
2	1521	-4.8	706	30	78	24
3	1531	-3.0	798	30	28	24
4	1601	3.5	1043	32	43	26
5	1626	3.2	310	32	16	26
6	1646	13.1	1478	32	164	27
7	1655	-3.2	2142	32	9	26

Butler and Reynolds (1997) in their wildfire behavior case study comparison of observed and predicted ROS values using BehavePlus found that, even in shrub fuel types, transition from a surface fire to crown fire was an abrupt occurrence and was under predicted by BehavePlus. However, once the fire reached a quasi-steady state in the crowns of the shrub fuels, the ROS predictions produced by BehavePlus were much more in alignment with the observed values. Major differences in ROS estimates in the present case study could be due to inaccuracies related to fire progression timelines and generalizations of slope and fuel model type when input into BehavPlus. Fire progression interval 6, which exhibited very high ROS, could be an example of this kind of inaccuracy or of a transition area from surface to crown fuels.

It is difficult to ascertain a definitive reason for the differences in observed and predicted ROS from the data available on the Machine Gun Fire. There could be any number of reasons (Alexander and Cruz 2013; Cruz and Alexander 2013). The present wildfire behavior case study represents the first such effort at AGCW. Findings from the present completed case study underscores the need for rigorous protocols to make fire behavior observations in the future in order to evaluate fire behavior models more thoroughly (Haines *et al.* 1986; Alexander and Taylor 2010) and ultimately to better evaluate fuel treatment effectiveness, amongst other purposes.

CONCLUSION

Fire reports compiled at AGCW from 1985 to 2012, were used to summarize past fire perimeters, acreage burned, and sources of ignition. LANDFIRE data were then used

to describe the vegetation type and FBFM per Anderson (1982). With the context of recent fire history, sources of widlfire ignition, and fire regime type in place, the analysis finished with a case study of the Machine Gun Fire, which occurred September 19, 2010, burning primarily in grass, sagebrush, and Gambel oak. In a comparison of predicted vs. observed fire behavior, BehavePlus (Heinsch and Andrews 2010) predicted ROS within 60% for three of the seven fire run segments. This analysis corroborates modeled fire regime products produced by LANDFIRE in that AGCW is typified by very frequent (1-4 years), high-intensity surface fires with rapid rates of spread.

The case study analysis follows the outline developed by Alexander and Thomas (2003*b*), and is intended to build a knowledge base that will reduce the probability of repeating past mistakes, provide evidence of fire behavior that will prepare wildland firefighters in future suppression events, and promote a learning organization—one intent on acquiring, interpreting, and retaining knowledge, and as a result, is willing to change protocol and behavior given new insight (Alexander and Thomas 2003*a*). Case study analyses are rarely attempted, thus the few that exist provide valuable data not only for local resources, but for the fire community at large, enabling empirical verification that can lead to improved understanding and modelling.

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CHAPTER 4

APPLICATION OF FIRE BHEAVIOR MODELS FOR FUEL TREATMENT

ASSESSMENTS[1]

Abstract

Large wildfires (40 ha + in size) occur about every three years in the vegetation types located at Army Garrison Camp Williams practice range located near South Jordan, Utah. USA. In 2010 and 2012, wildfires burned beyond the Camp's boundaries into the adjacent wildland-urban interface. The political and public reaction to these escaped fires was intense. Researchers at Utah State University were asked if a spatially organized system of fuel treatments could be developed to prevent future escapes. Using a combination of empirical and semi-physical based guidelines and models as well as fire behavior modelling systems, assessments of fire behavior potential for the dominant vegetation types in the area was undertaken. The results suggest the need for removal of woody vegetation within 20 m of firebreaks and a minimum firebreak width of 8.0 m in grassland fuels. In juniper (*Juniperus osteosperma* (Torr.) Little), a canopy coverage of 25% or less is recommended. In Gambel oak (*Quercus gambelii*, Nutt.) stands along the northern boundary of the installation, a fuelbreak width of 60 m for secondary breaks and 90 m for primary breaks is recommended.

Introduction

In 2010 and 2012, large wildfires occurring within the boundaries of Army Garrison Camp Williams (AGCW) located near South Jordan, Utah eventually burned

[1] Co-authors: Martin E. Alexander, Michael J. Jenkins

into the adjacent wildland-urban interface (WUI) areas, threatening members of the general public and destroying numerous homes. According to records for the period from 1991 to 2013, AGCW experiences large fires (i.e. > 40 ha in size) within installation boundaries roughly once every three years according to recent fire history records (see Chapter 3). Urban growth to the north and south of the camp's boundaries has made these large fires increasingly difficult to manage. Currently, a system of firebreaks and fuelbreaks are used at AGCW to protect valued resources within camp boundaries and the communities surrounding the base. Fuelbreaks, as defined by Green (1977), are areas, usually linear strips or blocks, where fuels have been modified to reduce the total available biomass for burning and to slow fire initiation and spread. In contrast, firebreaks are areas where all vegetation has been removed to bare mineral soil (Green, 1977). Firebreaks at AGCW are maintained by bulldozers on a one to two year basis. Fuelbreak treatments are maintained by goat and sheep grazing in the woody fuels on the northern boundary and by cattle in grass and shrubs on the southern boundary of the installation.

The overall aim of fuel treatments are to reduce public and private safety hazards (Cochrane et al., 2012), restore ecosystems to native conditions (Davies et al., 2014), increase resistance to fire (Agee and Skinner, 2005), and to provide habitat for wildlife (Connelly et al., 2014). For example, fuelbreaks have been implemented in juniper in southern Utah (Stratton, 2004) and in areas of sagebrush surrounding Carson City, Nevada (Smith et al., 2000) to protect communities adjacent to wildland fuels. Fuels management can facilitate timely initial attack, decrease the potential for extreme fire behavior, and reduce the economic and ecological costs of wildfires (Dellasala et al.,

2004; Cochrane et al., 2012). Effectively implemented, fuel treatments can reduce final wildfire size, slow fire spread, decrease emissions, allow fires to be managed for resource benefit, provide greater ecosystem resiliency, and reduce the need for post-fire rehabilitation while providing for increased firefighter safety (Washa, 2011). The goal of the analysis reported on in this paper is to evaluate fuel treatment alternatives and the effect of the treatments on reducing wildland fire ignition and spread within the boundaries of AGCW. This consisted of developing and analyzing fuel treatment alternatives for large fire mitigation. To evaluate expected fire behavior for the fuels at AGCW, a combination of empirically-based guidelines and models and fire model systems were utilized. Different alternative fuel treatments were modeled using an updated fuels layer input primarily via the fire behavior mapping and analysis program FlamMap (Finney, 2006).

Judging Treatment Effectiveness and Alternative Treatment Scenarios

Given the broad goals related to fuel treatments and the expense of implementation, how in turn can managers assess treatment effectiveness? Often, evidence for treatment effectiveness comes from model simulations of fire spread and fire behavior (Martinson and Omi, 2008). These simulations however are usually unverified and as such must be considered hypothetical until field evaluations can be undertaken. Ideal circumstances for validation of fuel treatments occur when wildfire burns through both untreated fuels and treated fuels, allowing for side by side comparisons of fire impacts and effects (Strom and Fulé, 2007). In the absence of a wildfire event, pre-treatment monitoring at the location of treatment followed by post-treatment monitoring compared to a non-treated control area is typical for treatment evaluation (Davies et al.,

2010). Experimental and/or prescribed fires have been used to monitor fire behavior at the time of burning (Bruner and Klebenow, 1979) to evaluate ideal weather conditions in which to implement treatments. Remote sensing techniques have also been utilized to evaluate burn severity (Eidenshink et al., 2007; Wang and Glenn, 2009). Burn severity can be used to compare fire effects such as fire severity from wildfire in treated plots to non- treated plots.

Typical fuel treatment methods are outlined in Table 4.1. At AGCW, the first fuel treatment alterative to consider is a no action approach. AGCW would continue using treatment practices currently in place with no additional modifications to fuel management procedures. This is an untenable course of action as potential fire behavior would continue at an elevated risk and fire suppression would remain difficult under extreme fire weather conditions. Another alternative, SPOTS/SPLATS as outlined by Finney (2001), is partially overlapping fuel treatments perpendicular to the direction of predominant fire spread. This treatment method requires about 20% of the entire land area to be treated and maintained. Treatment of large blocks that eventually incorporate 20% of the land area at AGCW would only be effective if implemented across the entire base. Treatment constraints in the Impact Area (where unexploded ordinance is present) would not meet the requirements of overlapping treatment blocks perpendicular to the prevailing direction of fire spread. In addition, to obtain the minimum of 20% land area treated, prescribed fire would likely be required. WUI concerns, smoke production, and aggressive use in the impact area limit the ability of management to use fire at the scale desired. Utilizing thinning treatments at such a scale would be very expensive. Further, the small land area and close proximity of AGCW to the WUI limit the potential

Table 4.1.

General fuel treatment methods and pros/cons at AGCW.

Treatment type	Pros	Cons
Hand thinning	• low impact • ideal in steep and rocky terrain • can be used near habitation where other methods are unfeasible	• expensive • slow • manpower intensive • leaves residual biomass
Mechanical thinning	• faster and cheaper than hand thinning • mastication of residual biomass possible	• high impact • visually unpleasant • leaves residual biomass • restricted to flat/moderate terrain
Grazing	• less impact than mechanical thinning • less residual biomass than thinning techniques • effective in Gambel oak stands	• expensive, but less than hand thinning • potentially manpower intensive • restricted to flat/moderate terrain
Herbicide	• effective at controlling regrowth of woody plants and in vegetation state conversions • can be used in areas with UXOs	• expensive • can have adverse impact on humans, vegetation and wildlife • controversial
Prescribed fire	• generally least expensive except when burning small areas • little to no soil disturbance • effective at treating large areas • less residual biomass after fire	• potential for escape • visual impact • smoke production • time required for planning efforts

UXO = unexploded ordinance.

effectiveness for SPOTS/SPLATS treatments to keep fire within AGCW and out of the adjacent WUI.

Due to the constraints of treatment at AGCW, the treatment alterative proposed is to connect firebreak and fuelbreak networks where no breaks are present or relocate them

to more ideal locations (e.g., along ridgelines). In addition, reduction of fuels surrounding ignition sources and implementation of landscape scale treatments, either by prescribed fire, grazing, or thinning to reduce fuel loads and continuity in areas of concern is desired where possible. Most often treatment types will be used in combination, for example hand thinning may occur in a treatment block followed by winter pile burning to remove the residual biomass. Considerations for treatment type should be based on safety, cost, man power commitment, ecological impacts (e.g. soil erosion), risk to the WUI, and training impact.

Limitation, Assumptions, and Uncertainties of Fire Behavior Decision Aids

Rothermel (1972) Fire Spread Model

Nearly all of the fire behavior modelling systems used in the United States for fire operations and planning, such as BehavePlus (Andrews et al., 2008) , FARSITE (Finney, 2004), NEXUS (Scott and Reinhardt, 2001), and FLAMAP (Finney, 2006), are based in part on the Rothermel (1972) surface fire spread model. These systems are thus subject to the same limitations and assumptions specified for the Rothermel (1972) model, namely (after Burgan, 1979; Andrews, 1986; Rothermel, 1983)[1]:

- The model was developed for a head fire spreading with the wind over level terrain or upslope.

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[1]The assumptions have been adapted from the Modelling Unit of version 5.0 of the BehavePlus fire modelling system "Surface Fire Spread and Intensity Lesson" dated October 23, 2009. Available for downloading at: https://www.frames.gov/partner-sites/behaveplus/tips-training/

- The model describes fire behavior in the flaming front, which is primarily influenced by fine fuels.

- The model is primarily intended to describe fires advancing steadily, independent of the source of ignition. The time that it takes for a point source ignition fire to reach a steady-state condition is not considered.

- Fuel, fuel moisture, wind, and slope are assumed to be constant during the time for which model predictions are to be applied.

- The model describes fire spreading through surface fuels. This includes fuel that is contiguous to and within about 1.8 m of the ground. Surface fuels are sometimes classified as grass, brush, timber litter, or slash. The model cannot be applied to timber crown fires, although tree regeneration might be considered as a surface fuel. Fires in shrubland fuel complexes are sometimes referred to as crown fires.

The performance of the Rothermel (1972) model has been subjected to comparisons against real-world fire observations in fuels similar to some of those occurring in AGCW. These include grass and sagebrush vegetation communities for which additional evaluation studies have been undertaken by Brown (1982), Rothermel and Reinhart (1983), and Butler and Reynolds (1997). It would appear from these evaluations that the fire modelling system applications of Rothermel's (1972) model are acceptable in a general sense for fire planning purposes in both grass and sagebrush fuels, at least up to certain spread rate levels. Figure 4.1 shows observed rates of spread for experimental fires in grasslands (Sneeuwjagt and Frandsen, 1977) and sagebrush (Bushey, 1985) versus predictions from Rothermel's (1972) surface fire rate of spread

model. The two fastest spreading fires associated with the Sneeuwjagt and Frandsen
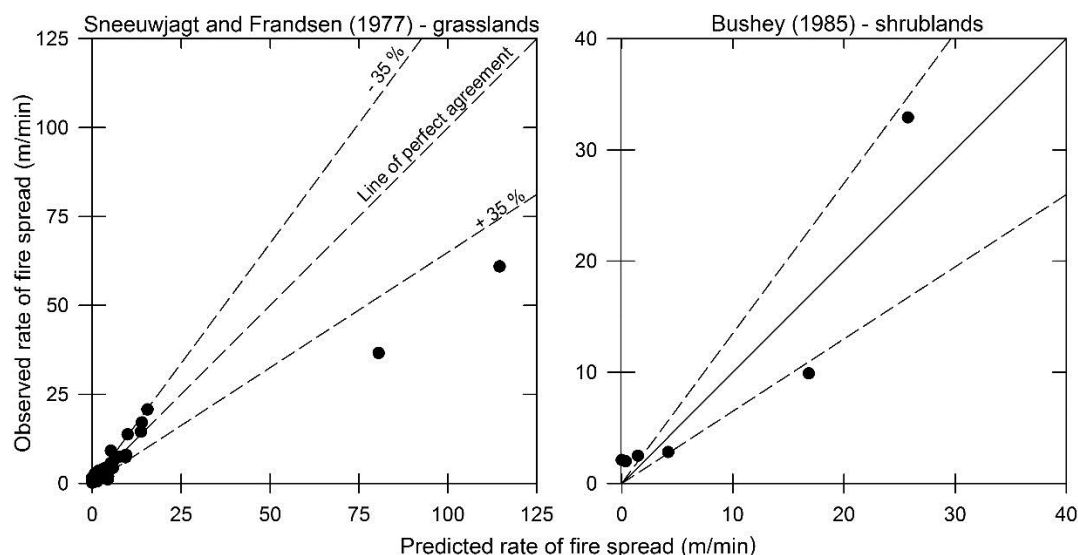
Fig. 4.1. Observed versus predicted rate of spread for experimental fires in grasslands and sagebrush, comparison of predictions is models using Rothermel's (1972) surface fire spread model. Courtesy of Miguel Cruz.

(1977) study are in fact wildfires. The dashed lines around the line of perfect agreement

indicate the ±35% error interval suggested by Cruz and Alexander (2013). Similar work

has not been undertaken to date in either pinyon-juniper or Gambel oak fuel complexes

and thus uncertainties naturally do exist.

Assessing wildland fire behavior potential involves numerous assumptions (Cruz

et al., 2015), such as the following, which in turn impose limitations on the relative

accuracy of the outcomes:

- The model or guide is applicable to the fuel conditions.

- The fuels are uniform and continuous.

- The fuel moisture values used are representative of the fire site.

- The topography is simple and homogeneous.

- Wind speed is constant and unidirectional.

- The fire is free-burning and unaffected by fire suppression activities.

Models and modelling are an integral component of modern day fire management practices (Alexander, 2009). Models and guides used for predicting fire behavior should obviously be sensitive to those parameters known to affect fire behavior, namely variations in live and dead fuel moistures, wind speed, and slope steepness, amongst other factors, for a given fuel complex.

Cruz and Alexander (2013) have shown how rate of fire spread can vary between model predictions and observed values. As Albini (1976) has pointed out, there are three principal reasons for disagreement between model predictions and observed fire behavior, no matter which models are being used (see Alexander and Cruz, 2013 for further discussion):

- The model may not be applicable to the situation.

- The model's inherent accuracy may be at fault.

- The data used in the model may be inaccurate.

The prediction of wildland fire behaviour invariably involves a number of uncertainties (Alexander and Cruz, 2013; Cruz and Alexander, 2013).

BehavePlus System

BehavePlus (Heinsch and Andrews, 2010) is a fire behavior modelling software program that uses fire behavior fuel models (FBFMs) (Anderson, 1982; Scott and Burgan, 2005) and associated inputs (fuel moisture, wind speed, slope steepness) to generate fire behavior output (rate of spread, fireline intensity, flame length). BehavePlus assumes static conditions of wind speed and continuous fuels in order to make fire

behavior predictions. In addition, FBFMs are a characterization of vegetation complexes based upon fuel load, surface area-to-volume ratios of live and dead fuels, fuel bed depth, and heat content. Lastly, BehavePlus utilizes Byram's (1959) fireline intensity equation to universally predict the relationship between flame length and fireline intensity. No adjustment to incorporate a geographic specific flame length-fireline intensity relationship (Alexander and Cruz, 2012) is made in this research. Thus, predictions are more generalized than exact.

<u>Maximum Spotting Distance</u>

The models contained within BehavePlus to predict the maximum spotting distance from single or group tree torching (Albini, 1979), burning piles of woody debris (Albini, 1981), and wind-driven surface fires in open fuel types such as grass, shrubs and slash (Albini, 1983; Morris, 1987) all involve many assumptions, the principal one being that firebrands are assumed to be sufficiently small to be carried some distance, yet large enough to still be able to cause an ignition once they reach the ground.

The other general assumptions with respect to these models center around:

- The availability of optimum firebrand material – the spotting models presume that at least one ideally suited firebrand particle exists. This is consistent with the intent to estimate the maximum potential spotting distance.

- The probability of spot fire ignition – for a spot fire to start, the firebrand must come into contact with easily ignited dry fuel. The spotting models do not deal with the chance of such contact or the probability that ignition will occur if contact is made. The models predict the maximum distance that a firebrand can travel and still retain the possibility of starting a spot fire but they do not predict

spot fire ignition probability. Other guides need to be consulted for such assessments (Rothermel, 1983; Weir, 2004).

- The number of spot fires – in keeping with the prediction of the maximum potential spotting distance, neither the spot fire density (i.e., number of spot fire ignitions per unit surface area) nor the exact location an ember will land are predicted, only the direction (assuming the wind is blowing steadily in one direction) and maximum distance an ember might possibly land.

None of the maximum spotting distance models have been rigorously tested or validated, yet they continue to be widely used by fire behavior analysts in the U.S. It is reported that they never under-predict (Albini et al., 2012). Perhaps the biggest limitation in their use is that the "worst case" situation is always predicted -- i.e., if a flaming source produces 100 firebrands, 99 of which fall within 100 m of the source and one travels 1.0 km, it is that "one" that travels the 1.0 km that the model predicts. Any deviation from the ideal assumed in the model only serves to decrease the maximum spot fire distance predicted.

The output of the maximum spotting distance model for wind-aided surface fires in non-tree canopied fuel complexes contained in BehavePlus in relation to the flame length and wind speed is given in Table A1.3. Note that in the case of fire behavior fuel model 1 –short grass (0.3 m) as per Anderson (1982) it is specifically assumed that some woody material would need to exist for spot fire distances given in the spotting table to occur.

Fuel Treatments in the Sage-Steppe

The four primary vegetation or fuel types in AGCW are (Figure 2.21 and Table 2.3):

- Grasslands, comprised chiefly of cheat grass (*Bromus tectorum*), bulbous bluegrass (*Poa bulbosa,* L.), bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh), Á.Löve), western wheatgrass (*Pascopyrum smithii* (Rydb.), Á.Löve), Sanberg bluegrass (*Poa secunda*, J.Presl), and Great Basin wild rye (*Leymus cinereus* (Scribn. & Merr.), A.Löve)
- Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis,* Beetle and Young) and basin big sagebrush (*Artemisia tridentata* (Nutall) subsp. *tridentata*)
- Gambel oak (*Quercus gambelii,* Nutt.)
- Juniper (*Juniperus osteosperma* (Torr.), Little)

Both regenerating and mature stands of Gambel oak can be found within AGCW. Most of these fuel and vegetation types are viewed as extraordinarily fire-prone or as a great fire hazard (Hester, 1952; Mutch, 1967; Wright et al., 1979; Ogle, 1989). Fire spread during the winter is possible under certain weather conditions in some fuel types (Neuenschwander, 1980). Late spring frosts that kill the leaves of Gambel oak can lead to extreme fire behavior later in the summer (Jester et al., 2012).[2] Bare ground or unburnable areas occupies 6.74 % of AGCW (Fig. 2.15 and Tab. 2.2).

There are several documented cases of wildfires spreading in grass and sagebrush fuel types at rates in excess of around 100 m · min over level to gentling undulating terrain (Traylor, 1961; Butler and Reynolds, 1997). This would equate to fireline intensities greater than 10,000 kW · m^{-1}. Crown fire spread has been observed in Gambel oak on steep terrain at rates of at least 175 m · min (Butler et al., 1998).[3]

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[2]Such an incident occurred July 17, 1976 on the Battlement Creek Fire in western Colorado in which three firefighters were overrun and killed (http://www.fireleadership.gov/toolbox/staffride/library_staff_ride10.html). A fourth firefighter was severely burned but did recover from his injuries.

[3] For further information on the South Canyon Fire in western Colorado in which 14 firefighters were killed on July 6, 1994, see: http://www.fireleadership.gov/toolbox/staffride/library_staff_ride9.html

Hudak et al. (2011) assert that there are *no* examples in the literature of wildfires that had been stopped by or burned over areas where fuel treatments had previously been conducted in rangelands of the western U.S. Owing to this lack of information regarding fire history (Baker and Shinneman, 2004), fire regimes, and post-disturbance successional patterns, a multidisciplinary research effort, called SageSTEP (McIver et al., 2010) was initiated to evaluate methods of sagebrush steppe restoration in the Great Basin. The results from SageSTEP have greatly enhanced the ability of land managers to make informed decisions about fuel treatment implementation on rangelands. The following is a brief review, much of it derived from the SageSTEP program literature, of the fuel treatments implemented in the dominant fuel types found at AGCW.

Pinyon-Juniper

Fire exclusion and grazing following European settlement have led to pinyon (*Pinus edulis*, *Iuniperus* spp.) and juniper encroachment (Miller and Tausch, 2002) into areas previously occupied by sagebrush and grasslands in the western U.S. As a result, most treatments in pinyon-juniper woodlands aim to restore areas of woody encroachment back to grasslands and/or sagebrush (Davies et al., 2014) using a variety of fuel treatment methods. In Nevada, Bruner and Klebenow (1979) examined the role of prescribed fire in restoring pinyon-juniper woodlands to grasslands for grazing and wildlife benefit. In southwestern Idaho, Bates et al. (2011) used partial cutting treatments in mature western juniper (*Juniperus occidentalis* ssp. *occidentalis* Hook) to increase fuel loads to promote subsequent prescribed fire initiation and spread. First year, post-fire herbaceous recovery was dominated by native annuals and forbs, but by year three, native perennial grass seedlings had become well-established. Baker and Shinneman (2004)

evaluated 46 different studies across the western US regarding fire and pinyon-juniper restoration. Contrary to common rhetoric, they found that nearly all of the available evidence indicate that low-severity surface fire in pinyon-juniper was uncommon (except possibly in southwest U.S. states) and is most likely typified by high-severity crown fire.

Gambel Oak

The preponderance of research regarding fuel treatments in Gambel oak pertain to thinning (Strom and Fulé, 2007) and combinations of thinning with low-severity understory burning (Fulé et al., 2001; Stevens-Rumann et al., 2013) in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws) forests of the southwestern US. In ponderosa pine forests, Gambel oak is the most prominent early successional species (Strom and Fulé, 2007) following disturbance. However, in northern Utah where Gambel oak is often the dominant overstory species, there is a paucity of fuel treatment research. One known method of treatment has been livestock grazing, especially by goats in woody fuels. Goats have been used in wildfire prevention primarily in the European Mediterranean and the United States. Grazing as a fuel treatment method is cost-effective, nontoxic, carbon neutral, and most importantly, ecologically sustainable (Lovreglio et al., 2014). However, the timing of treatment, intensity of treatment, target plant species, social structure of the herd, availability of expert herdsmen, and fencing materials (Lovreglio et al., 2014), are essential details that must be considered when using grazing for achieving the desired fuel treatment outcomes.

<u>Sagebrush and Grass</u>

Past fuel treatments in sagebrush ecosystems have typically focused on type conversions from shrubs or woodlands to grass (Ralphs and Busby, 1979) for restoration and grazing purposes. In southeastern Oregon, Davies et al. (2010) compared the effects of moderately grazed plots to control plots where grazing had not occurred for 70+ years. Results indicated that moderately grazed plots had reduced grass height, fuel continuity, and total available biomass compared to ungrazed plots. In northwestern Nevada, Diamond et al. (2009) compared targeted spring grazing treatments in cheatgrass invaded sites, with follow-up prescribed fire in the fall to non-grazed sites with burn and no-burn treatments. They found that the combination of grazing and prescribed fire treatments significantly reduced fire behavior in the grazed plots. Finally, Strand et al. (2014) found that moderate grazing (i.e., less than 50% utilization) in sagebrush dominated ecosystems can reduce fuel loads, fire ignition and spread potential, without encouraging the proliferation of annual invasive species. However, they note that under extreme fire behavior conditions (high wind, high air temperature, low relative humidity, low fuel moisture), grazing has less influence, with fire behavior mostly driven by climate and fuel continuity (Cheney and Sullivan, 2008; Diamond et al., 2009; Strand et al., 2014).

Methods

The base at AGCW is located along the Wasatch Front, south of South Jordan, UT. The installation covers approximately 10 018 hectares, ranging from 1 363 m to 2 211 m in elevation. The dominant vegetative cover in order of prominence are grassland (59%), Gambel oak (18%), sagebrush (13%), bare earth (6.7%), and juniper (3.7%).

Annual precipitation, according to a nearby climatological station, has averaged 22.6 cm

based on records kept from 1904 to 2013.

Empirically-based Fire Behavior Guides/Models and Fire Modelling Simulations

Wilson (1988) Firebreak Breaching Models for Grasslands

      Firebreaks were tested in the Northern Territory of Australia in July-August of

1986 for their performance in halting the spread of head fires (Davidson, 1988; Wilson,

1988) as part of a larger study of fire behavior in grasslands (Cheney et al., 1993; Cheney

and Sullivan, 2008). A total of 113 plots ranging from one to four ha in size were burned.

The downwind firebreak widths varied from 1.5-15 m. The resultant fireline intensities
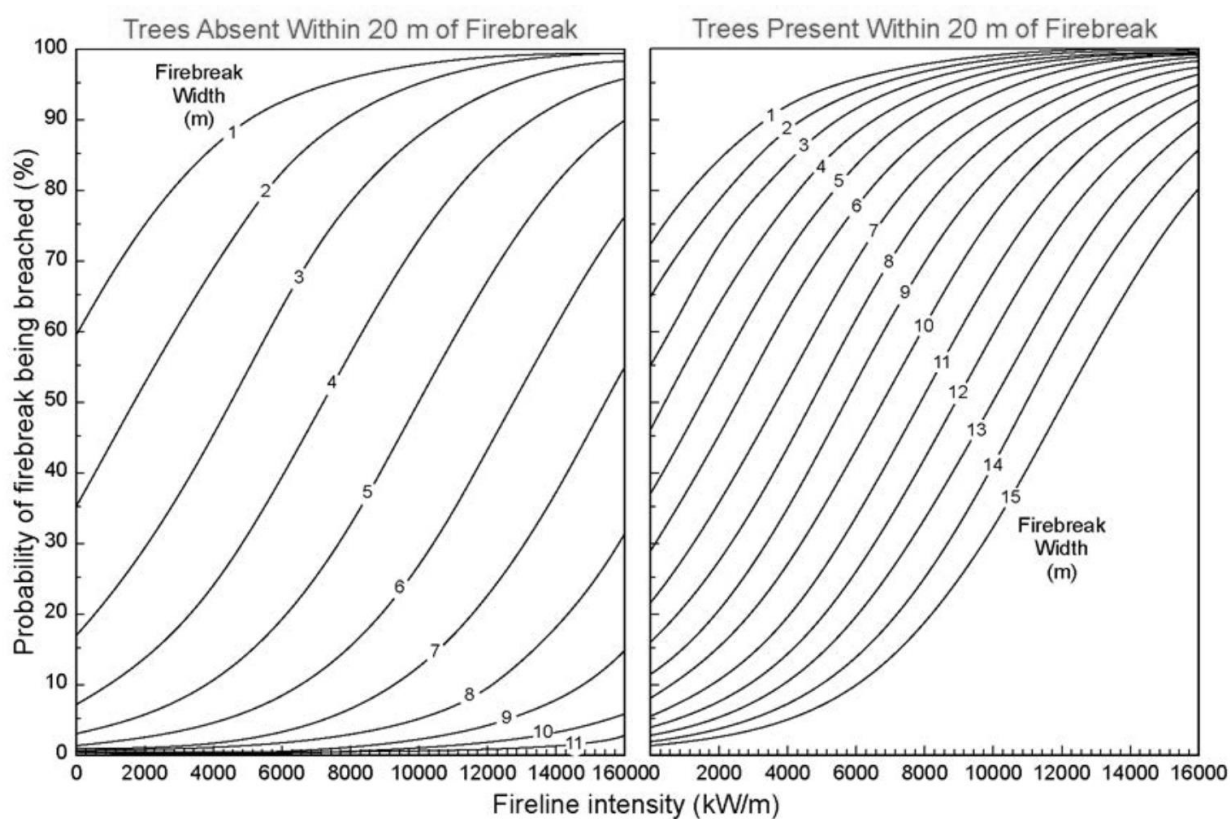
Fig. 4.2. Graphical representation of the probability of firebreak breaching models developed by Wilson (1988) for grass fires as a function of fireline intensity and firebreak width (from Alexander et al. 2013).

ranged from 70 to 17 000 kW · m^{-1}. The firebreaks were breached by 62 of the 133 fires.

A logistic response function was fitted to the data on firebreak breaching by Wilson

(1988). The equation for predicting firebreak breaching was found to increase with

increasing fireline intensity and the presence of trees (and/or shrubs) with 20 m of the

firebreak and to decrease with increasing firebreak width (Figs 4.2 and 4.3). The equation

used to produce Figure 4.2 is as follows (after Wilson 1988):

[1]
$$P = \frac{exp(1.36 + 0.00036 \times I - 0.99 \times FW) \times 100}{1 + exp(1.36 + 0.00036 \times I - 0.99 \times FW)}$$

where P = probability of a firebreak being breached by a grass fire where trees and shrubs

are absent within 20 m of the firebreak (%), I = fireline intensity (kW · m^{-1}), and FW =

firebreak width (m). The equation for the case where trees are present within 20 m of the

firebreak is the same as the above, except the coefficient 0.99 is replaced by 0.38.

Using the weather records available for AGCW, existing firebreak widths

occurring on the base (e.g., 4.0 and 8.0 m) in addition to two larger widths (10 and 15 m)
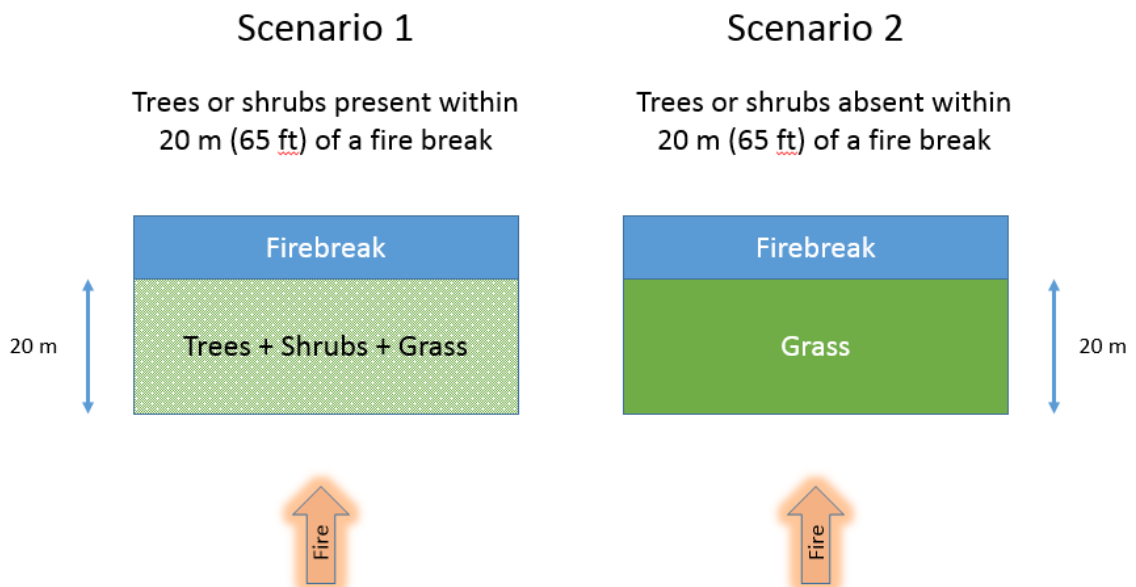
Fig. 4.3. Graphical representation of the two scenarios used by Wilson (1988) to test firebreak breach probability in Australia.

were evaluated for breaching probabilities under a broad range of conditions.

Observational data were assembled from the nearest available remote automatic weather

station (RAWS) for each day of record during the months of March to October from 1991

to 2013. Data for live fuel moisture content were collected from the National Fuel

Moisture Database (USFS-WFAS, 2014) from local cheatgrass (years 2003-2013) and

Wyoming big sagebrush (1997-2013) fuel moistures to represent the live herbaceous and

woody fuel moisture categories (NFMD: http://www.wfas.net/index.php/national-fuel-

moisture-database-moisture-drought-103). Using FireFamily Plus (RMRS, 2002), fuel

moisture content was computed for the 1-, 10-, and 100-h timelag size classes (Bradshaw

et al., 1983). The dead and live fuel moistures and wind speed for each day served as

input and were processed in the NEXUS (Scott, 1999) modelling system which uses the

Rothermel (1972) equations, as does BehavePlus, to predict ROS, FL, and FI for three

slope steepness conditions (0, 25, and 50%) for the most common FBFMs (1, 2, 5, 8)

(Anderson, 1982) at AGCW (Table 4.2). Anderson (1982) classifications were selected

because live fuel moisture inputs for respective fuel models represented 'worst case' or

Table 4.2.
Inputs required for the four most common fire behavior fuel models (FBFMs) from the
classification scheme described by Anderson (1982) utilized in the fire behavior
analyses at Army Garrison Camp Williams along with their associated dead (woody
fuel moisture time-lag (TL) size classes) and live fuel components.

FBFM number	Typical fuel complex	1-h TL	10-h TL	100-h TL	Live
1	Short grass (0.3 m)	x			
2	Timber (grass and understory)	x	x	x	x
5	Brush (0.6 m)	x	x		
8	Closed timber litter	x	x	x	

driest possible conditions (Ziel and Jolly, 2009). Therefore, in a conservative effort to avoid under prediction of fire behavior, Anderson (1982) fire behavior fuel models were utilized rather than Scott and Burgan (2005) fire behavior fuel models.

The fireline intensity output was then inserted into the logistic regression equation developed by Wilson (1988), to determine the probability of grassland firebreak breaching (Fig. 4.2). In addition to fireline intensity as an input the equation also required additional inputs: firebreak width and the presence or absence of shrubs or trees within 20 m of the firebreak, input as 0 or 1, respectively.

Using a survey of aerial imagery at AGCW (HRO 2012), typical widths of primary (7.8 m) and secondary roads (3.4 m) and firebreaks (7.8 m) were determined. Four values of firebreak width were tested (4.0, 8.0, 10, 15 m) for FBFMs 1 and 2 as per Anderson (1982) using a selection of conditions from the weather record (1991 to 2013). The probability of breaching for FBFMs 1 and 2 were then computed for each day of the weather record and plotted as a cumulative frequency distribution (CFD) function. In addition to the firebreak breaching probabilities, a CFD was compiled for each day of the weather record for ROS, FL, FI, and maximum spotting distance for FBFMs 1, 2, 5, and 8.

Cumulative Frequency Distributions for Comparison of Fire Behavior Characteristics

Fire behavior calculations were made using NEXUS batch processing software (Scott, 1999) for each day of the weather record for FI, ROS, and FL. Maximum spotting distance was also added for each day using a look-up table (Tab. A.3) patterned after Alexander (2006) and based upon BehavePlus (Heinsch and Andrews, 2010) output for wind-driven surface fires. Those values were then plotted in the same manner as the

Wilson (1988) probability of firebreak breaching CFD graphs (Figs. 4.4 and 4.5) with the

value of the fire behavior metric on the x-axis and the percent of total days plotted on the

y-axis.

Bruner and Klebenow (1979) Prescribed Burning Guide for Pinyon-Juniper Woodlands

Bruner and Klebenow (1979) prescribed burning guide is an empirically-based

study of fire behavior in pinyon-juniper woodlands. In this study, 30 prescribed burns

were attempted out of the main fire season (i.e., July-September) from the fall of 1974 to

the fall of 1976 at three different sites in Nevada. These attempts were made during

varied atmospheric conditions and in several pinyon-juniper communities, all on level

terrain. Ambient air temperatures and relative humidities ranged from 2-25 °C (36-78 °F)

and 5-90%, respectively, while maximum eye-level winds ranged from calm conditions

up to 56 km/h (35 mi/h). Percent vegetation cover in turn varied from 42-66%.

Table 4.3.
General rules of thumb associated with the score values in the prescribed burning guide
for pinyon-juniper woodlands developed by Bruner and Klebenow (1979).

Score value	Prescribed fire behavior interpretations
< 110	Burning conditions are such that fires will not carry.
110 - 125	Fires will carry but continual retorching will be necessary.
125-130	Burning conditions are optimal for a self-sustaining fire following ignition, creating "clean burns".
> 130	Burning conditions are too hazardous for prescribed burning.

Only 12 of the 30 attempts were successful (i.e., self-sustaining fire spread

following ignition with a hand-held drip torch). Fires were found to be most successful in

dispersed, scattered and dense pinyon-juniper stands but less successful in open and

closed stands. An analysis of the outcomes showed that a successful prescribed fire could

be predicted quite accurately (89% of the cases in this study) using the following simple

formula and associated interpretive guide for the results "Score" (Tab. 4.3):

Score = Maximum Wind Speed (mi/h) + Air Temperature (°F) + Vegetative Cover (%)

The authors acknowledged that there appeared to be a very narrow separation between

conditions for successful prescribed burning and those that would result in an

uncontrollable high-intensity wildfire that could easily escape the confines of the

prescribed burn unit, a fact that is substantiated by general field observations of wildfires

in the pinyon-juniper fuel type (Hester, 1952).

Using the RAWS weather data for 1991 to 2013, a score value for each day was

determined using the Bruner and Klebenow (1979) formula for vegetation coverages of

20, 30, 40, 50, 60, 70, and 80% and plotted using a CFD.

FlamMap Fire Behavior Comparisons

Prior to simulation, a fuel model layer was developed using a random forests

classification scheme (Breiman, 2001) to describe existing conditions and served as input

into the FlamMap spatial fire behavior modelling system (Finney, 2006). The fuel map

was classified according to the four Anderson (1982) FBFM types found on AGCW and

was resampled from an initial resolution of 0.5 m to 30 m to reduce time requirements for

simulation. The performance of three different weather scenarios were evaluated for pre-

and post-fuel treatment landscapes. For the pre-treatment landscape, fire behavior outputs

such as ROS, FL, and FLI were predicted for fuels as currently constituted. The area

where the Pinyon Fire (July, 2012) burned was primarily converted to FBFM 1 to

represent the most recent conditions. For post-treatment simulations, the first scenario

only implemented an expansion and connection of existing firebreaks and fuelbreaks and

left the rest of the fuel conditions the same. The second group of post-treatment

simulations implemented the expansion of the firebreak and fuelbreak network in

addition to large scale fuel reduction treatments. The third post-treatment scenario

simulated modification of the FBFMs surrounding the Multiple Purpose Machine Gun

(MPMG) Range, a common source of ignitions. The weather conditions of the three

scenarios used in simulations were: 1) Machine Gun Fire (Sept, 2010) weather conditions

with 6.1-m open winds simulated at 48 km · hr, from SE to NW, 2) Pinyon Fire weather

conditions, with 6.1-m open winds at 26 km · hr from N to S, and 3) Machine Gun Fire

weather conditions (the same as scenario 1) with fuels surrounding the MPMG Range

converted to FBFM 1. All of the fires were simulated using 1 000 randomly placed fires

using the minimum travel time (MTT) function (Finney 2002) with the exception of the

MPMG Range simulation which was simulated for a single ignition source.

Results

Empirically-based Fire Behavior Guides/Models and Fire Modelling Simulations

Wilson (1988) Firebreak Breaching Models for Grass-Tree/Shrubland Mixtures

Output is plotted as a CFD and arranged from highest to lowest values. To

interpret a curve, a given value of x indicates the probability of firebreak breaching on the

x-axis and the percent of days that exceed that value on the y-axis. For FBFM 1 when

shrubs and trees are *present* within 20 m of a firebreak, the probability of breaching a

firebreak width of 4.0 m, regardless of slope, ranges from about a 42 to 83% of the time

given an ignition (Fig. 4.4). At a firebreak width of 8 m, with trees *present,* breaching

probability ranges from near 18 to 58% of the time, regardless of slope. The probability

of breaching continues to decrease as firebreak width increases, with 10 m firebreaks

with trees/shrubs *present* ranging from near 10 to 40%. For firebreaks of 15 m wide,

probability of breaching with trees/shrubs *present* is nearly obsolete, ranging from 0.0 to

10%. When trees/shrubs are *absent* within 20 m of a firebreak, a width of 4.0 m has

about a 10 to 33% percent probability of being breached for all slope steepness classes.

When trees/shrubs are *absent* within 20 m of a firebreak at widths of 8.0 m and greater,

there is less than near a 2.0% probability of being breached.
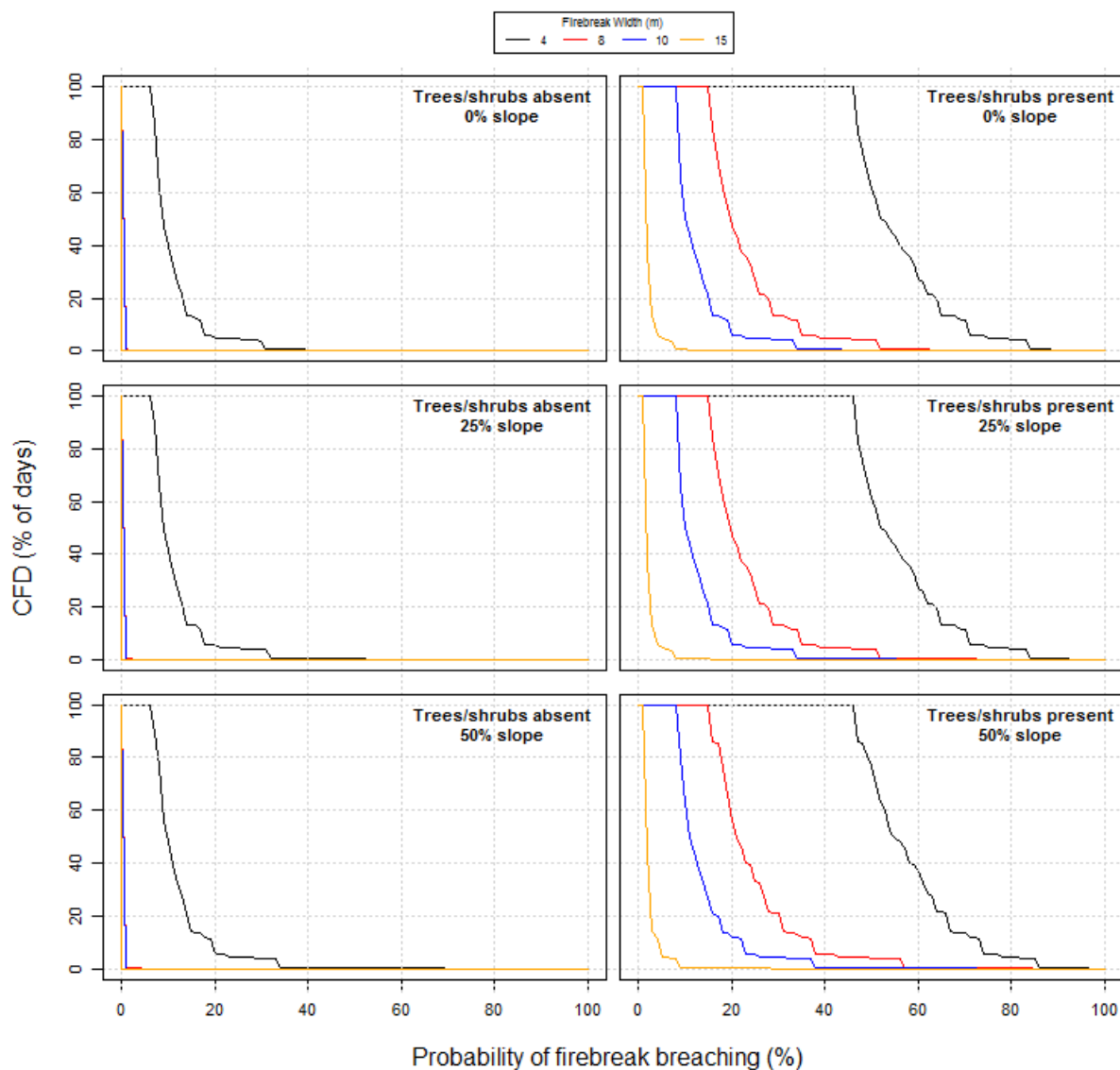
Fig. 4.4. Cumulative frequency distributions (CFD) for breaching grassland firebreaks of different widths where trees/shrubs are absent or present within 20 m of the firebreak during the fire season (March-October) according to Wilson (1988) for Fire Behavior Fuel Model 1 and three different slope steepness classes, based on 23 years of weather records from the Tickville, Vernon, and Pleasant Grove RAWS.

For FBFM 2 with trees/shrubs *present,* for all slope steepness classes, the breaching probability ranges from near 42 to 100% (Fig. 4.5). Even at a zero percent slope, a breaching probability is 60% or greater for 58% of the days at AGCW. Firebreak widths of 8.0 m, with trees/shrubs *present,* range from near 18 to100% probability of breaching. However, a breaching probability of 60% or greater occurs on only about 20% of the total days of record with a firebreak width of 8.0 m. Breaching probability continues to decrease as firebreak width increases with trees/shrubs *present*, but both firebreak widths of 10 and 15 m can have breach probabilities as high as 100%. When trees/shrubs are *absent* from within 20 m of a firebreak, a width of 4.0 m has from near 5 to 100% probability of being breached. Firebreak breaching is reduced dramatically as a breach probability of 60% or greater occurs on only about 18% of the time. An increase in firebreak width to 8.0 m decreases the overall probability of breaching from near 0.0 to 70%. Breach probabilities of 20% or greater occur about 7.0% of the time for a firebreak width of 8.0 m. A very small group of values within the 8.0 m width can still have high firebreak breach probabilities, which are likely associated with extreme fire behavior fire weather events. As firebreak width increases to 10 m, breach probability ranges from 0.0 to about 30%, regardless of the slope steepness. Firebreak widths of 15 m have a near 0.0% probability of being breached.
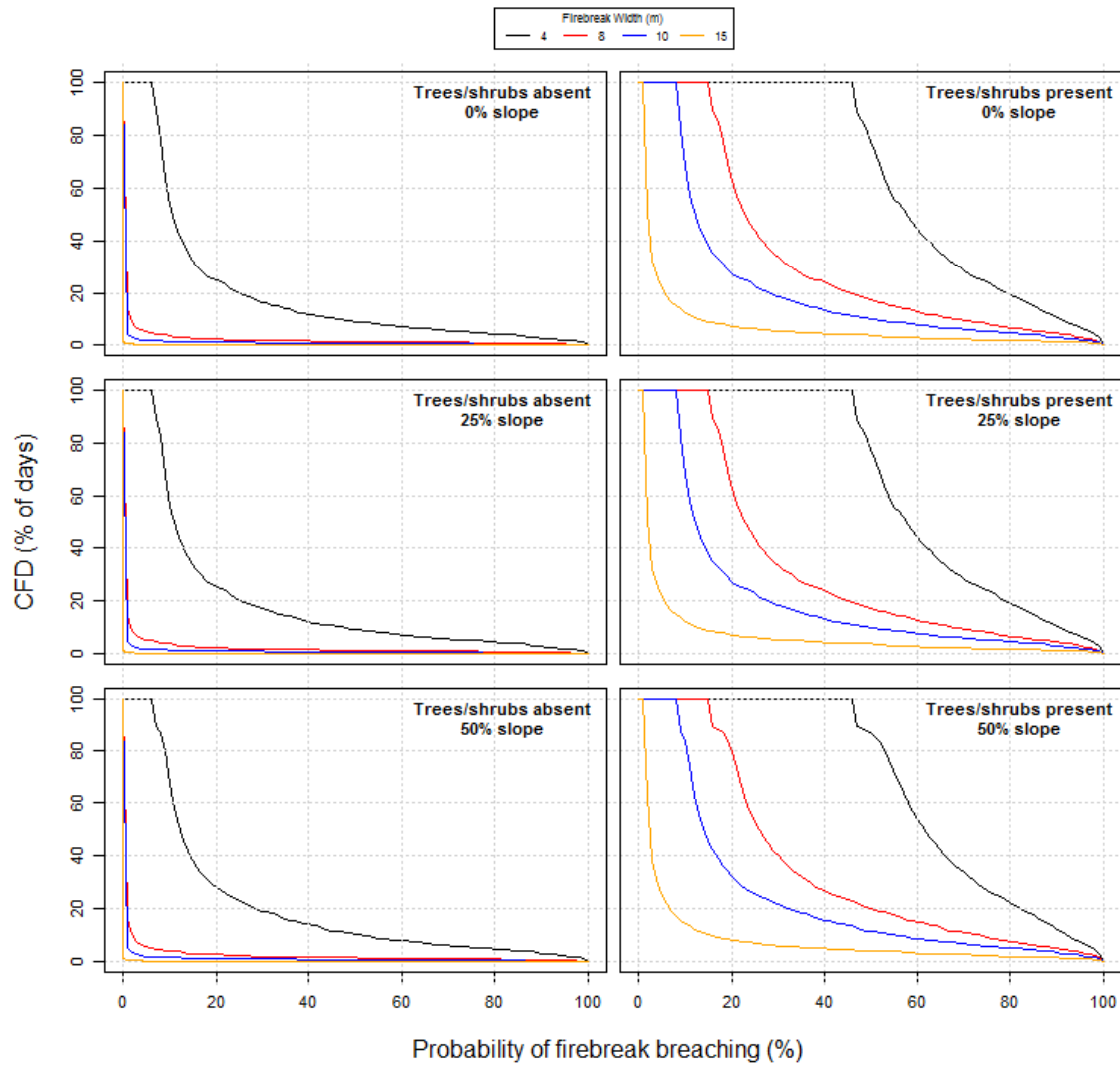
Fig. 4.5. Cumulative frequency distributions (CFD) for breaching grassland firebreaks of different widths where trees/shrubs are absent or present within 20 m of the firebreak during the fire season (March-October) according to Wilson (1988) for Fire Behavior Fuel Model 2, three different slope steepness classes, and 23 years of weather records from the Tickville, Vernon, and Pleasant Grove RAWS.

Cumulative Frequency Distributions for Fire Behavior Characteristics

Overall results for FBFM 1 FI values ranged from 0.0 to about 5 100 kW · m^{-1} for all slope classes (Fig. 4.6A). Direct attack with hand tools is possible at around FI values of 346 kW · m^{-1} or less (Andrews and Rothermel 1982) (Tab. A.2), which occurs on about 72 to 90% of the time. Direct attack is still possible with heavy equipment at values of 1 730 kW · m^{-1} or less, which occurs on about 22 to 35% of the time. FL values ranged from about 0.0 to 4.0 m for all slope steepness classes (Fig. 4.6C). At a 50% slope, about 90% of all days have FL values greater than 1.2 m, which is the upper limit for direct attack with hand tools. At a FL of 2.4 m, only about 20% of total number of days were deemed beyond control by direct attack with heavy equipment. About 5.0% of days have a FL At higher than 3.4 m, a level of fire behavior suggestive of critical fire weather conditions. Potential maximum spotting distances were found to range from near zero to 3.0 km (Fig. 4.6D). At terrain slopes of zero and 25%, 90% of days reported a maximum spotting distance of up to 1.8 km. At a 50% slope, the results are similar to zero to 25% slopes, with 88% of the time having a potential maximum spotting distance up to 1.8 km. ROS ranged from zero to about 220 m · min for all slope steepness classes (4.6B).
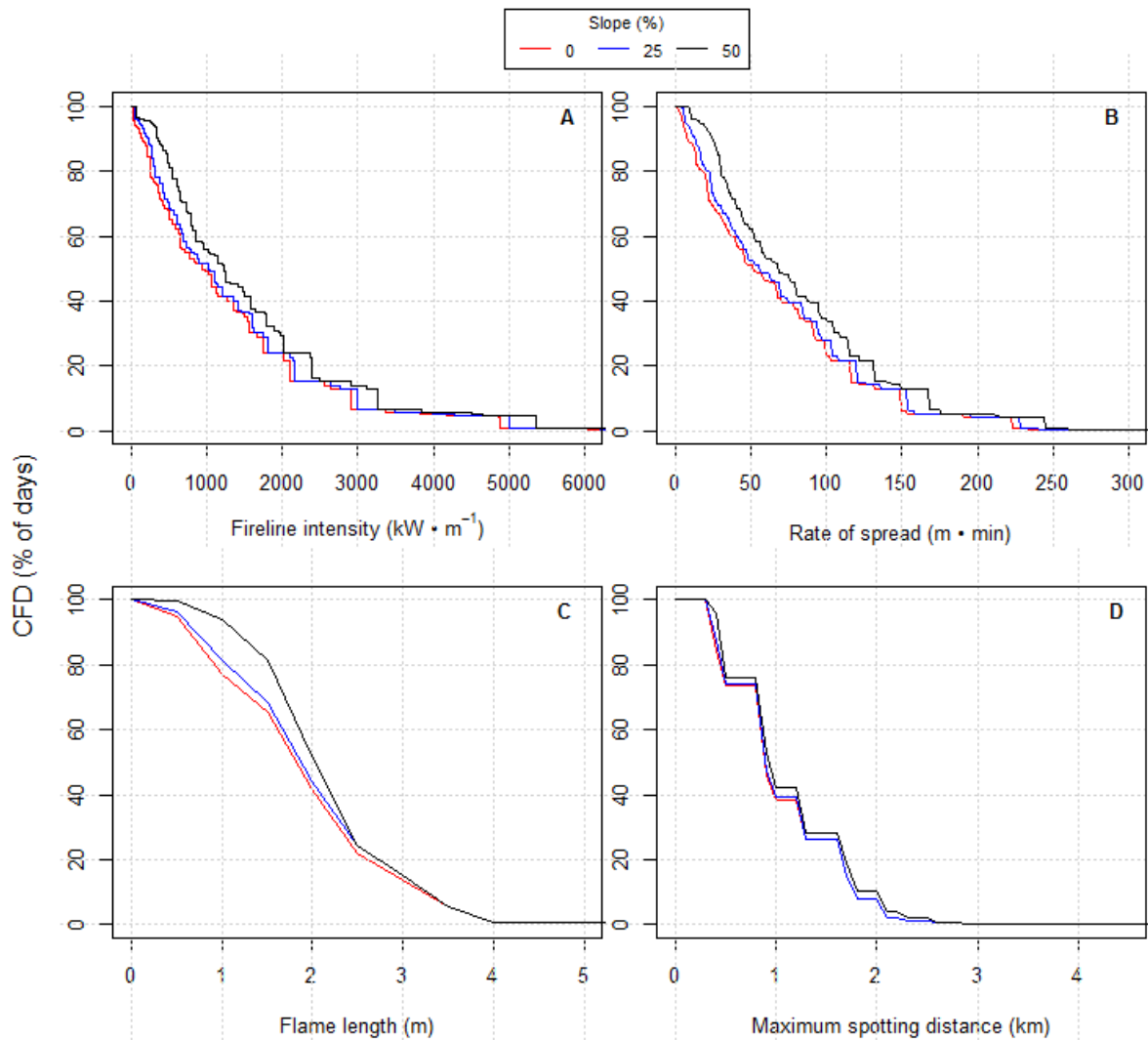
Fig. 4.6. Cumulative frequency distributions (CFD) for four fire behavior characteristics during the fire season (March-October) based on Fire Behavior Fuel Model 1, three different slope steepness classes, and 23 years of weather records for the Tickville, Vernon, and Pleasant Grove RAWS using the NEXUS fire modelling system.

For FBFM 2 FI values ranged from zero to about 25 000 kW · m^{-1} (Fig. 4.7A). About 95% of all days reported FI values of 346 kW · m^{-1} or greater, thus only 5% of total days are considered within the range of direct attack with hand tools. About 40% of total days were *greater* than 1 730 kW · m^{-1}, meaning that 60% of the time direct attack

by heavy equipment is possible. About 23% of the time, FI values exceed 3 459 kW · m^{-1}, limiting fire suppression tactics to indirect attack. FL values ranged from near zero to about 8.0 m (Fig. 4.7C). About 30% of total days have FL values greater than 3.4 m and therefore requiring indirect attack strategies. Potential maximum spotting distances ranged from near zero up to 5.0 km (Fig. 4.7D). Regardless of slope steepness, about
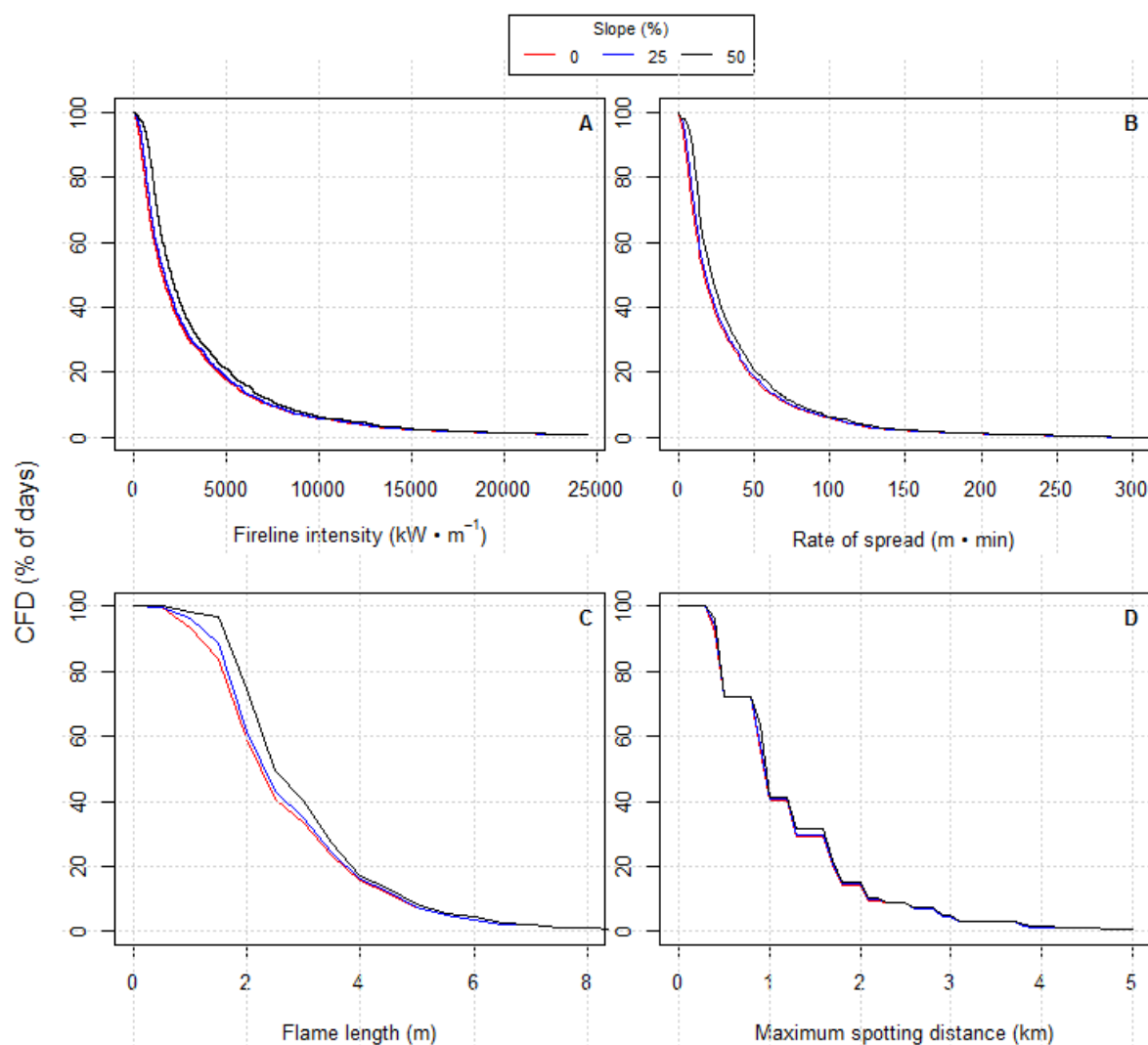
Fig. 4.7. Cumulative frequency distributions (CFD) for four fire behavior characteristics for the fire season (March-October) based on Fire Behavior Fuel Model 2, three different slope steepness classes, and 23 years of weather records for the Tickville, Vernon, and Pleasant Grove RAWS using the NEXUS fire modelling system.

90% of days reported maximum spotting distances of about 2.1 km or less. FI and FL

values for FBFM 2 were greater than FBFM 1, however ROS values were slightly less.

Spread rates ranged from zero or no spread to about 230 m · min (Fig. 4.7B).

For FBFM 5, FI values ranged from zero to about 10 000 kW · m^{-1} (Fig. 4.8A).

About 50% of all days reported FI values of 346 kW · m^{-1} or greater, therefore 50% of

the total number of days are considered within the range of direct attack with hand tools.
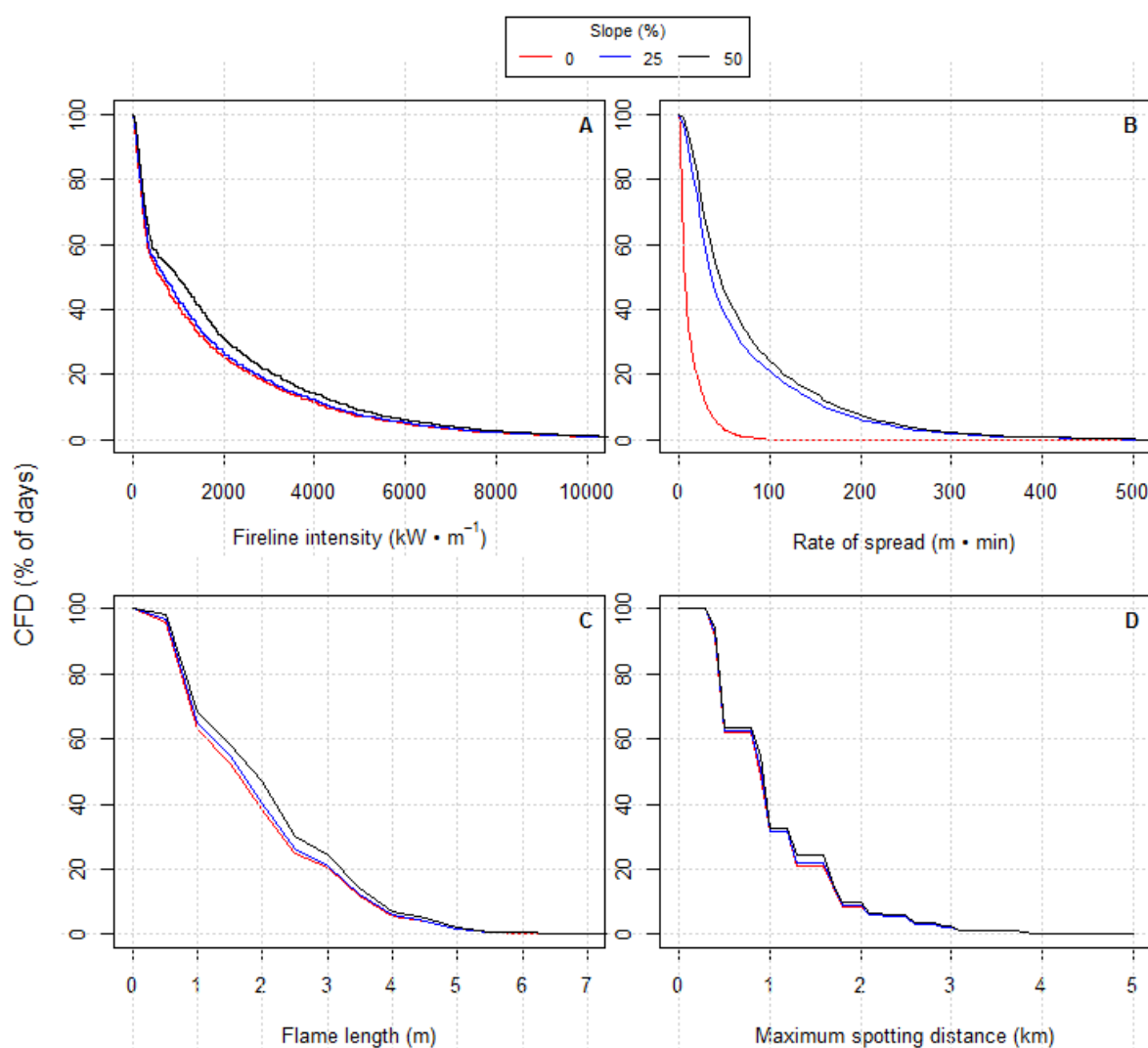
Fig. 4.8. Cumulative frequency distributions for four fire behavior characteristics during the fire season (March-October) based on Fire Behavior Fuel Model 5, three different slope steepness classes, and 23 years of weather records for the Tickville, Vernon, and Pleasant Grove RAWS using the NEXUS fire modelling system.

In contrast, only about 25% of the time were *greater* than 1 730 kW · m⁻¹, meaning that 75% of the total number of days are at least within the category of direct attack by heavy equipment. About 17% of the time, FI values were greater than 3 459 kW · m⁻¹, when direct attack is deemed ineffective. FL values ranged from near zero to about 7.0 m (Fig. 4.8C). FL values of greater than 3.4 m occur about 18% of the time, thereby requiring indirect attack strategies. Potential maximum spotting distances ranged from near zero to 5.0 km (Fig. 4.8D). Regardless of slope steepness, about 95% of days reported maximum spotting distances up to 2.1 km. ROS and FI values for FBFM 5 were much less than FBFM 2 compared to FBFM 1, ROS was less but FI and FL values were both higher. Spread rates ranged from near 0.0 to about 100 m · min (Fig. 4.8B).

For FBFM 8, fire behavior potential was minimal across the board (Fig. 4.9), never greater than the upper limits of allowing for direct suppression with hand tools. FI values ranges from 0.0 to about 200 kW · m⁻¹ (Fig. 4.9A). All output reported FI values of 346 kW · m⁻¹ or less. FL values ranged from near zero to about 1.0 m (Fig. 4.9C). Again, 100% of the days are still within the category of direct suppression using hand tools given an upper limit of 1.2 m. Maximum potting distance ranged from near zero to 1.0 km (Fig. 4.9D). ROS, FL, FI, and maximum spotting distance values for FBFM 8

were drastically less than for all other FBFMs. Spread rates ranged from near zero to
about 6.0 m · min (Fig. 4.9B).
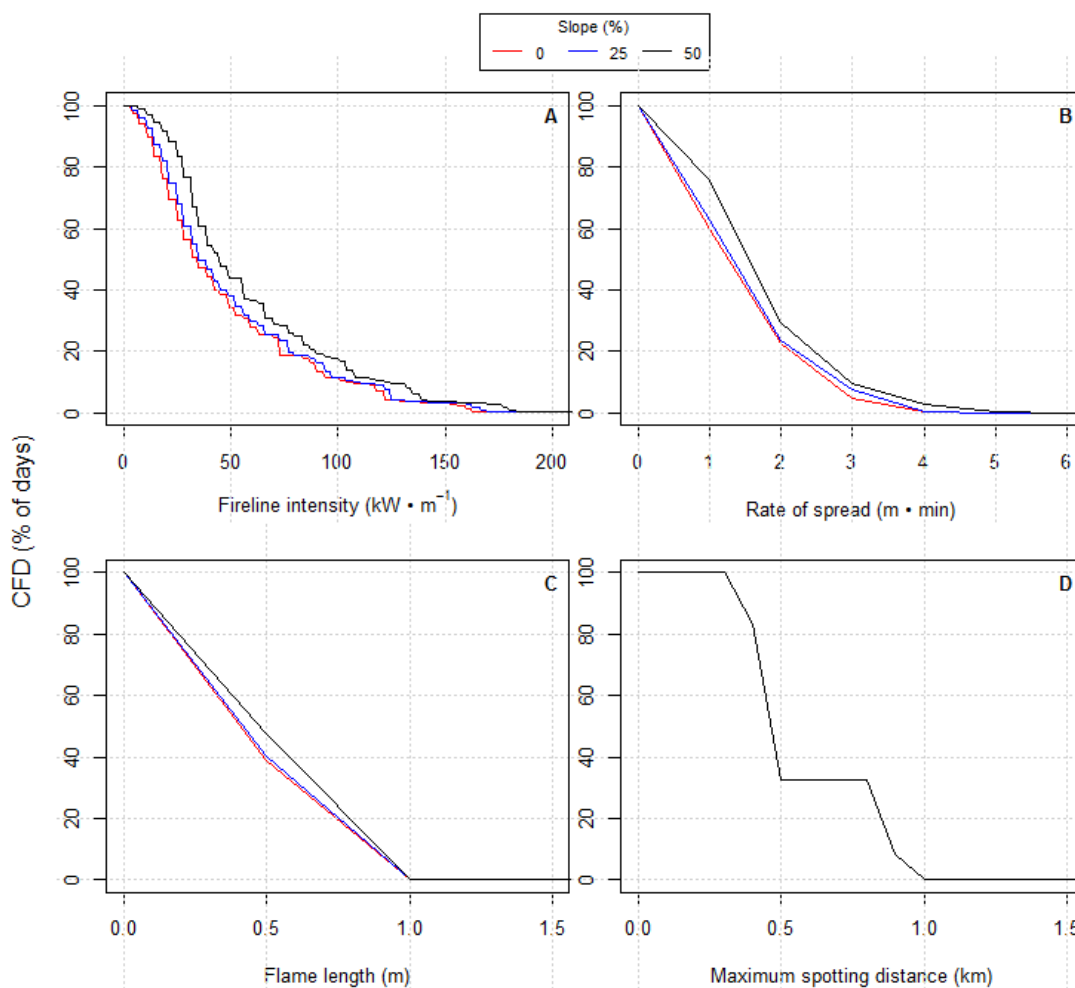
Fig. 4.9. Cumulative frequency distributions for four fire behavior characteristics
during the fire season (March-October) based on Fire Behavior Fuel Model 8, three
different slope steepness classes, and 23 years of weather records for the Tickville,
Vernon, and Pleasant Grove RAWS using the NEXUS fire modelling system.

A summary of the 25th, 50th, 75th, 90th, 97th, 99th percentiles and for the maximum
computed value for each of the four fire behavior characteristics by FBFM is presented in
Table 4.4.

Table 4.4.
Summary of various percentiles for four fire behavior characteristics by Fire Behavior Fuel Model (FBFM) as per Anderson (1982) for 1400 h daylight saving time for at least 17 years of weather records.

Fire behavior characteristic	Percentiles							
	25	50	75	90	95	97	99	Max
Fireline intensity (kW · m⁻¹)								
FBFM 1	242	713	1 741	2 911	3 365	4 884	4 884	23 424
FBFM 2	519	1 288	3 378	6 793	10 455	12 895	21 766	53 483
FBFM 5	180	564	1 980	4 240	5 951	7 160	9 792	17 574
FBFM 8	21	35	69	104	121	156	163	294
Rate of spread (m · min)								
FBFM 1	13	45	92	150	153	223	223	741
FBFM 2	6	15	36	70	104	124	201	368
FBFM 5	3	7	15	31	43	51	70	131
FBFM 8	1	1	2	2	3	3	4	5
Flame length (m)								
FBFM 1	1	2	2	3	3	4	4	8
FBFM 2	2	2	3	5	5	6	8	12
FBFM 5	1	2	2	4	4	5	5	7
FBFM 8	0	0	1	1	1	1	1	1
Maximum spotting distance (km)								
FBFM 1	0.5	0.8	1.6	1.8	2.1	2.1	2.6	4.3
FBFM 2	0.5	1.0	1.6	2.1	2.9	3.1	4.3	5.6
FBFM 5	0.5	0.8	1.3	1.8	2.6	2.9	3.7	4.7
FBFM 8	0.5	0.5	0.8	0.8	1.0	1.0	1.0	1.3

<u>Bruner and Klebenow (1979) Fire Behavior Guide for Pinyon-Juniper Woodlands</u>

A CFD was again used to plot the distribution of data from highest to lowest.

Results (Fig. 4.10; Tab. 4.5) suggest that vegetation coverages below 30% produced

scores that were almost always less than 130. For vegetation coverages of 50% and

greater, scores above 130 were common. Lines in bold (20, 30, 40, and 50%) indicate

percent juniper vegetation cover typical at AGCW. Table 4.5 provides a summary of the

area occupied by ranges of percent juniper cover. More than half of the juniper cover at

AGCW is between 20-40% (57% of total area), however, a large proportion of the

remaining acreage represent areas of cover from 40% and greater (43%). Overall, there is

little juniper cover remaining at AGCW after the Pinion Fire in 2012 (474 total ha),

which likely burnt more than half of the juniper vegetation on the base. A map of percent

juniper cover (Fig. 4.11) was also produced to provide spatial guidance for the natural

resource managers at AGCW.
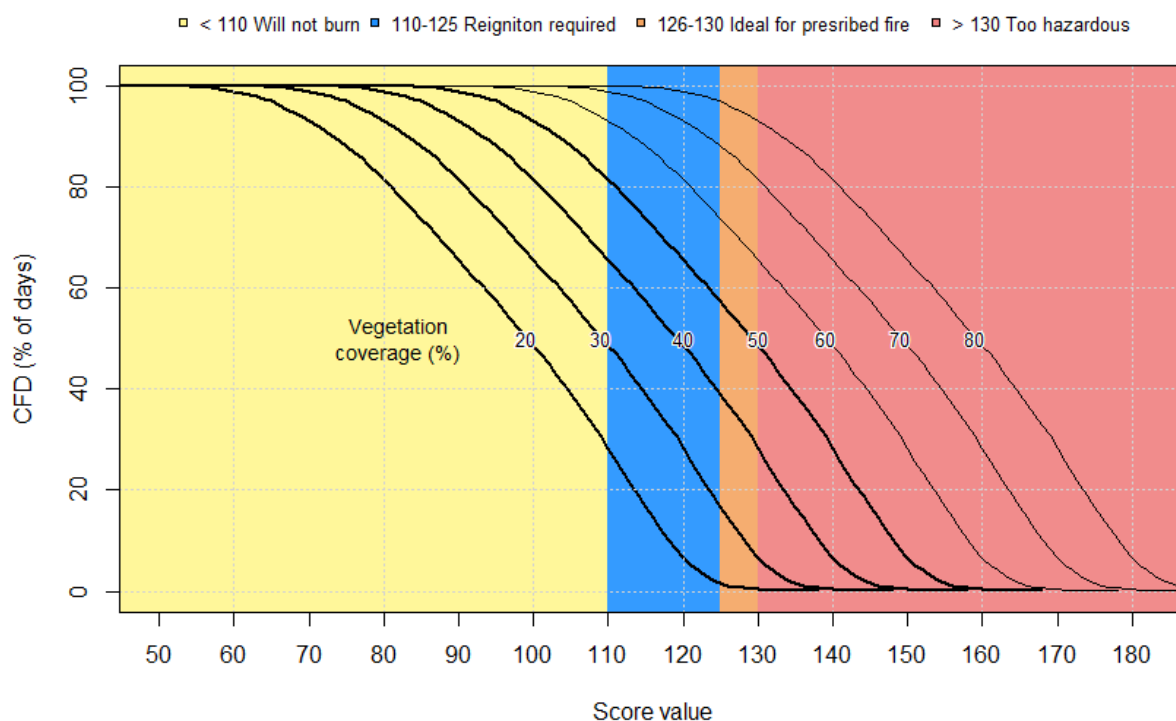
Fig. 4.10. Cumulative frequency distribution (CFD) for climate at AGCW from 1991-2013 processed according to the equation to predict fire behavior in pinion-juniper woodlands developed by Bruner and Klebenow (1979). Lines in bold indicate the typical percent vegetation cover of juniper at Army Garrison Camp Williams (20, 30, 40, and 50%).

Table 4.5.

Area of juniper cover at AGCW and percent of total area breakdown by percent juniper canopy cover classes.

Percent juniper cover	Hectares	Percent of total area
20-30%	145	30%
30-40%	128	27%
40-50%	65	14%
50-60%	60	13%
60-70%	37	8%
70-80%	18	4%
80-100%	22	4%

FlamMap Fire Behavior Comparisons

The results of the FlamMap simulations are summarized in Table 4.6 and Figure 4.12. The weather conditions of the 2010 Machine Gun Fire were the most severe, whereas the 2012 Pinyon Fire weather represented conditions ranging between moderate and severe. For both circumstances, fire behavior was reduced through treatment implementation.

The firebreak and fuelbreak expansion plus the landscape treatment was the most successful at reducing fire behavior for each simulation scenario. FL values exceeded 1.2 m, except in the case of the 2012 Pinyon Fire, where FL values were reduced on average to 1.2 m in the firebreaks plus landscape treatment scenario. For the 2012 Pinion Fire, with conditions exhibiting less severe fuel moisture values in Gambel oak and lower wind speeds, the simulations predicted that fire behavior would potentially be reduced enough to allow for direct suppression action. For the treatments surrounding ignition sources as exemplified by the MPMG Range simulation, the ROS actually increased for the fuelbreaks only treatment and the FL remained nearly the same. Conversion to FBFM 1 assumes near continuous grass, thus supporting an increased rate of fire spread.
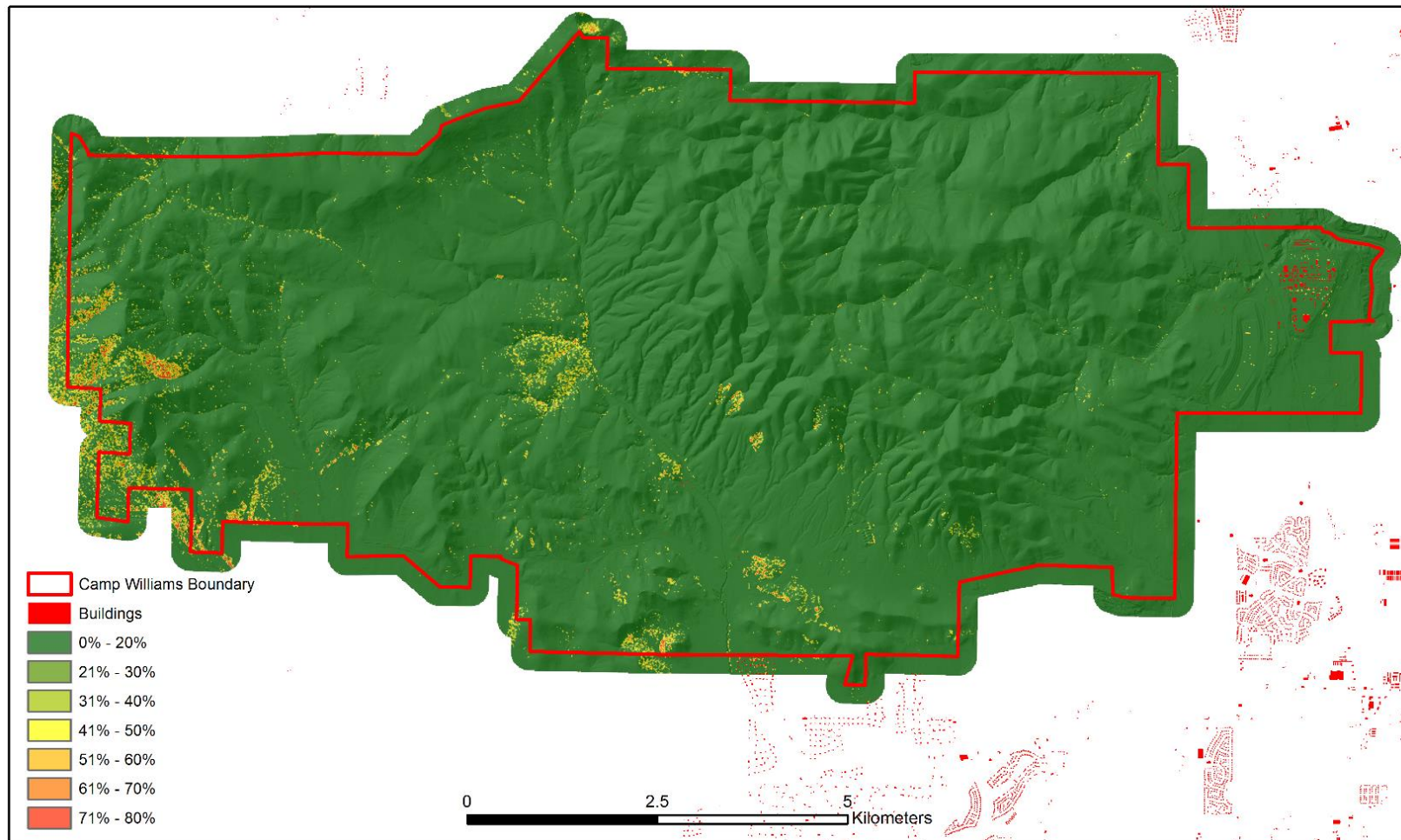
Fig. 4.11. Map of percent juniper canopy cover at Army Garrison Camp Williams, updated to reflect post Pinyon Fire vegetation coverage of juniper.

However, as discussed earlier in the Wilson (1988) firebreak evaluations, if woody vegetation was removed within 20 m of firebreaks surrounding the MPMG Range, with a firebreak width of 8.0 m, the probability of breaching in grass and tree/shrub conditions is typically less than 5.0%. The likely reduction in fire behavior after treatments would usually be expected to be much lower than the results indicate here. This is likely due to the resolution of simulation (30 m), and the difficulty of capturing linear break features of smaller resolution (4.0, 8.0, 10, 15 m) through simulations in FlamMap. Therefore, it is likely that fire behavior projections would indicate a more dramatic reduction in fire behavior for the breaks only and the landscape treatments plus breaks scenarios if linear breaks were better recognized.
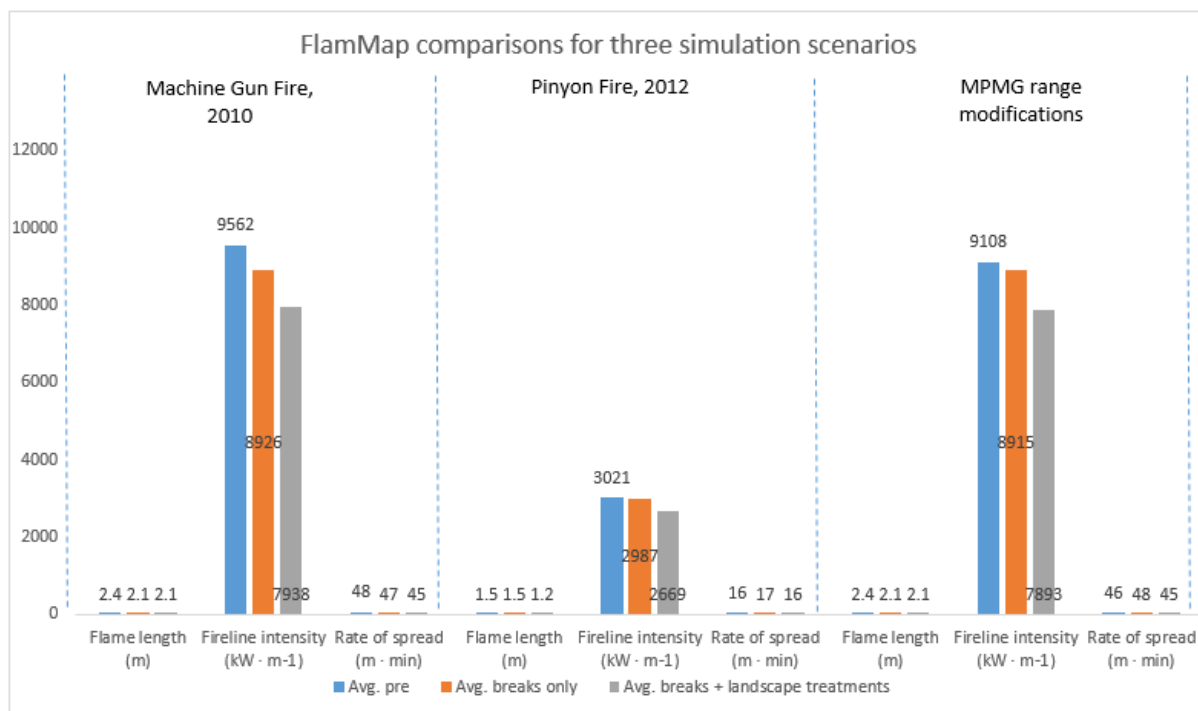
Fig. 4.12. FlamMap (Finney 2006) simulations for three different weather condition and fuel ignition scenarios at Army Garrison Camp Williams.

In addition to the fire behavior predictions, the probability that a given pixel will burn was simulated (Tab. 4.6, Fig. 4.13), also employing the MTT function in FlamMap. The simulation also used 1 000 randomly placed fires within the boundaries of AGCW to obtain this probability. Burn probabilities were not obtained for the MPMG scenario because FlamMap does not allow for calculation of single point source ignitions. Burn probability for both of the treatments was drastically reduced (especially for the Machine Gun Fire weather conditions, reduction of 89%) compared to the pretreatment landscape.

Table 4.6.
Comparison of results for potential fire behavior from pre- and post-treatment scenarios as simulated using FlamMap (Finney 2006).

Machine Gun Fire, 2010	Avg. pre	Avg. breaks only	Avg. breaks + landscape treatments
Flame length (m)	2.4	2.1	2.1
Fireline intensity (kW · m^{-1})	9562	8926	7938
Rate of spread (m · min)	48	47	45
Burn probability (per pixel)	0.1972	0.0289	0.0213

Pinyon Fire, 2012	Avg. pre	Avg. breaks only	Avg. breaks + landscape treatments
Flame length (m)	1.5	1.5	1.2
Fireline intensity (kW · m^{-1})	3021	2987	2669
Rate of spread (m · min)	16	17	16
Burn probability (per pixel)	0.0114	0.0131	0.0111

MPMG Range, modified fuels	Avg. pre	Avg. breaks only	Avg. breaks + landscape treatments
Flame length (m)	2.4	2.1	2.1
Fireline intensity (kW · m^{-1})	9108	8915	7893
Rate of spread (m · min)	46	48	45
Burn probability (per pixel)	Burn probability cannot be computed for a single point source ignition		

m = meters, kW = kilowatt, Avg. = Average.
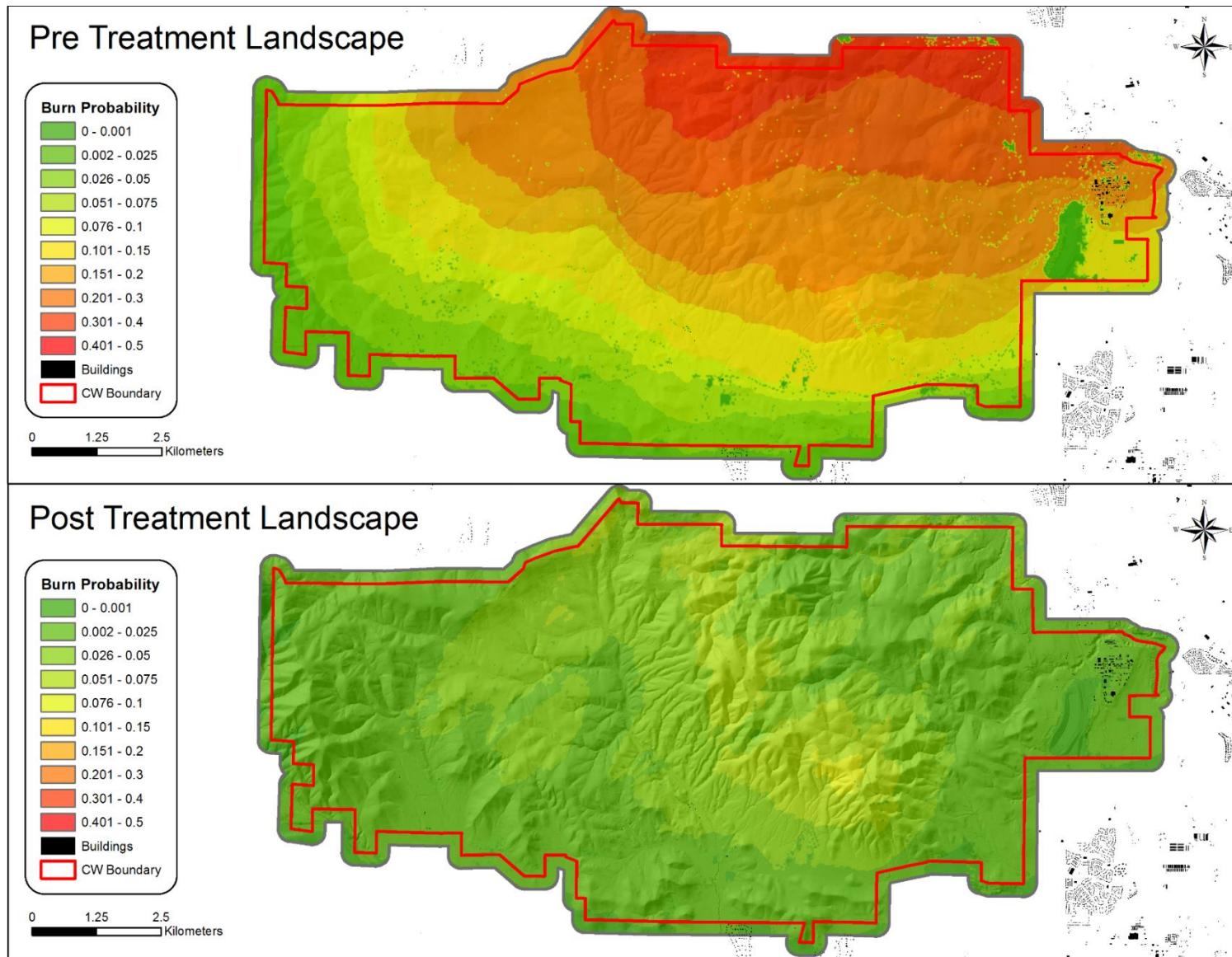
Fig. 4.13. Comparison of pre- and post-treatment burn probability at Army Garrison Camp Williams according to Machine Gun Fire weather conditions on the day of 19 September 2010.

Discussion

The desired condition at AGCW is a fuel type mosaic modified to reduce ROS, FL, FLI, and probability of firebreak breaching via direct flame contact or spotting. This could take the form of an organized network of firebreaks, fuelbreaks, and fuel treatments that reduce the probability of large wildfires escaping installation boundaries. The firebreak and fuelbreak network at AGCW is already extensive and an expansion of the network would only need to occur in a few strategic areas. Firebreaks, where vegetation is removed to bare mineral soil, should have a minimum width of 8.0 m with woody vegetation removed within 20 m on both sides of the firebreak. For small firebreaks and roads, a good general test for estimating firebreak breach by flame contact (in the absence of spotting) is to use Byram's rule of thumb, which suggests minimum firebreak width should be equal to flame length times 1.5 (Byram, 1959). Results also suggest that the ROS in pinyon-juniper stands can be reduced by maintaining stand densities at vegetation coverages of near 30% or less. Due to past large wildfires, especially the 2012 Pinyon Fire, the presence of juniper vegetation has become quite sparse at AGCW. Treatment priority in juniper should typically be low for the next 10 to 20 years, except in WUI areas of concern. It is important to note that the equations of Wilson (1988) were developed in grasslands with scattered shrubs and trees, and applying it to the other vegetation types such as pinyon-juniper and Gambel oak at AGCW would in all likelihood lead to erroneous conclusions. Likelise, the Bruner and Kelebnow (1979) guide was developed to predict general fire behavior potential in pinyon-juniper and should not be applied to other vegetation types on the base.

There is evidence to suggest that roads can act as disturbance corridors that promote invasion by annual exotics (Gelbard and Belnap, 2003). Land Cover Trend Analysis plots (Loveland et al., 1999) already in place at AGCW could be used to monitor potential vegetation changes as a result of firebreak maintenance. Fuelbreaks at AGCW are primarily located along the northern boundary in Gambel oak vegetation. During late fire season conditions, typically from August to October, once the foliar moisture content of Gambel oak is less than 120 percent the potential for extreme fire behavior is likely under extreme fire weather conditions (Romero, personal communication, February, 2014). This scenario occurred during the 2010 Machine Gun Fire when live fuel moisture content was 81% (NFMD, citation). Fires in Gambel oak under these dry conditions can behave much like fire in oak during the South Canyon Fire fatalities (Butler et al., 1998), Price Canyon Fire entrapment (Carpenter et al., 2002) and chaparral fuel complexes in southern California.

Following the recommendations for fuelbreak development by Green (1977) in California, fuelbreaks should be organized in a connected system of primary and secondary fuelbreaks. The recommended width for a secondary break is 60 m and 90 m for a primary break. This network of breaks would ideally segment land area at Camp Williams into 1 000 ha blocks or parcels that would facilitate suppression access and burnout operations if required. The arrangement of training areas and the associated roads and breaks currently in place at AGCW is already close to achieving this condition. Combining a firebreak/fuelbreak network with landscape treatments will increase the likelihood of success when managed in a systematic manner including scheduling updates as needed. Considerations for treatment type should be based on safety, cost, man

power commitment, ecological impacts (e.g., soil erosion), risk to the WUI, and the effect of vegetation modification on military training operations. Most often treatment types will be used in combination, for example hand thinning may occur in a treatment block followed by winter pile burning to remove the residual biomass.

Implications

Applying semi-empirical models that are applicable to local fuel types to predict fire behavior in combination with processing climatological data to create a distribution of predicted fire behavior is a novel approach in non-forested ecosystems like the sage steppe. Modelling fire behavior through spatial fire spread software programs akin to FlamMap (Finney, 2006) are valuable tools to explore alternative treatment options but are difficult to validate. This approach used semi-empirical models where possible (e.g. Wilson (1988), Bruner and Klebenow (1979), and combined them with fire behavior predictions with from FlamMap (Finney, 2006) and BehavePlus (Heinsch and Andrews, 2010). This approach is recommended for future fire behavior evaluations given the assumptions and limitations inherent in fire behavior models (Alexander and Cruz, 2013).

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CHAPTER 5

SUMMARY AND CONCLUSIONS

Introduction

Recent large wildfire occurrences at Army Garrison Camp Williams (AGCW) has resulted in the destruction of private property, including homes and structures. Fuel treatment prevention measures at AGCW as currently constituted have proven insufficient to prevent fires from running into adjacent wildland urban interface areas.

This thesis provides authoritative answers to the five primary research questions were based upon extensive analysis of the available data at AGCW. This chapter presents a summary of the results arranged by chapter. The primary research questions were posed in Chapter 1 and the principal results for the succeeding three chapters are summarized in Box 5.1.

Chapter 2 Summary:—Fire Environment Components

Using the framework outlined by Countryman (1972), the fuels, weather, and topography were evaluated at AGCW to establish context for fire behavior evaluation and prediction. Topography was modeled using Light Detection and Ranging (LiDAR) data, subsequently processed into digital terrain model (DTM) data. Slope steepness was summarized by National Fire Danger Rating System (NFDRS) percent slope classes, aspect or slope exposure by the four cardinal directions, and elevation by 150 m intervals. Slopes of 0-25% were most common (53.7% of total area), followed by slopes of 26-40% (24.5%), 41-55% (15.0%), 56-75% (5.87%), and rounded out by slopes of greater than 75% (0.8%). The predominate aspects were northerly (31.8%) and easterly aspects

(29.9%), followed by westerly (19.8%) and southern (18.3%) aspects. Elevation above

mean sea level was typically between 1650 to 1800 m (23.5% of total area), 1800 to 1950

m (38.7%), and 1950 to 2100 m (22.7%).

Weather component was characterized according to three temporal categories, 1)

diurnal, 2) seasonal, and 3) historical. Diurnal data were acquired from the three nearest

Remote Automatic Weather Station (RAWS) (Pleasant Grove, Tickville, Vernon) to

AGCW (about 25 km). Weather record duration for hourly data analyzed spanned from

1997-2013 for Pleasant Grove, 2001-2002 and 2004-2013 for Tickville, and 1991-2013

for Vernon. Diurnal trends were presented for each month of the active fire season,

namely March to October. The relative humidity (RH) minima and ambient air

temperature maxima occur from about 1400 to 1600 h regardless of month. The highest

average hourly temperatures (around 32 °C) occur in July, while the lowest RH values

(around 12%) also occur in July. Wind speeds at 6.1-m open height range from about 5 to

18 km/h on average, with minimums typically occurring around 0800 to 0900 h at 5 to 9

km/h. Wind speed increases throughout the day after the morning low, reaching

maximum values near 2000 h until close to 2400 h. Seasonal data revealed RH minima

and temperature maxima occurring in July and August. Dead woody timelag fuel

moisture content size classes (1, 10, and 100 hr) followed similar trends, with high fuel

moisture content in the spring months gradually decreasing with lows being reached in

July and August, followed by gradually increasing moisture contents in September and

October. Examination of historical data reveal that precipitation patterns were highly

dependent on geographic location and had slightly increasing temperature over the past

100 years. Live fuel moisture data were acquired from the National Fuel Moisture

Database for Wyoming big sagebrush (*Artemesia tridentata* subsp. *wyomingensis*, Nutt.),

Gambel oak (*Querqus gambelii*, Nutt.), Utah juniper (*Juniperus osteosperma* (Torr.)

Little) and cheatgrass (*bromus techtorum,* L.). Live woody fuel moistures for sagebrush

and Gambel oak both exhibited springtime highs around 180% and gradually decreased

throughout the summer, reaching lows of near 60% towards the end of the fire season in

late September and October. Juniper live woody fuel moistures did not vary drastically,

with springtime highs around 90% and lows of about 60%. Cheatgrass live herbaceous

fuel moisture levels peaked in late May and early June from around 200 to 300%, curing

rapidly thereafter to about 100-120% in late June, and continued to decrease in live fuel

moisture content to lows of around 50-80% by the end of the fire season. Lastly, wind

direction was summarized for each of the three RAWS stations for the span of available

data listed earlier. The Pleasant Grove RAWS, situated on the west slope of the Wasatch

Range near a canyon mouth and east of AGCW exhibited winds primarily from the south

to southwest. The Tickville RAWS, within the boundary lines of AGCW, situated on flat

terrain, recorded predominately southeast winds. Predominant winds recorded for the

Vernon RAWS, situated west of AGCW and the Oquirrh Mountains, came from the west,

southwest, and north.

Vegetation and fuels data were classified using random forests methodology

(Breiman, 2001), with precision for vegetation cover at 64% and 72.3% for fire behavior

fuel model (FBFM) classifications of Anderson (1982) at a resolution of 0.5 m. Accuracy

was moderate, but adequate for input into fire behavior simulation programs where

resolution was later resampled to 30 m. Results indicate that grassland dominated fuel

Box 5.1.
Summary of the conclusions and implications for the primary research questions of this thesis.

How are the distribution of vegetation types and fire behavior fuel models (as per Anderson 1982) arranged at AGCW? How are topographic conditions described? What are typical fire weather conditions during the fire season at AGCW in terms of ambient air temperature, relative humidity (RH), 6.1-m open wind speed, and fuel moisture? **Conclusions:**

- The random forests vegetation and fire behavior fuel model (FBFM) maps were produced with overall accuracies of 64.0 and 72.3%, respectively.
- The most common dominant vegetation type at AGCW is grasslands (58.6%) followed by Gambel oak (18.2%), sagebrush (12.6%), and juniper (3.7%). FBFM 5 is most abundant (36.6%), followed by FBFM 2 (34.2%), FBFM 1 (18.0%), and FBFM 8 (1.7%).
- Topographic slope steepness is typically varies up to 55% slope. Most of the land area is between 0-25% slope (53.7% of total area), 26-40% slope (24.5%), and 41-55% slope (15.0%). Slopes of 56% and greater occurred on only 6.7% of total area at AGCW.
- Diurnal trends in weather variables revealed RH minima and ambient air temperature maxima occur around 1500 h. Wind speeds measured at a 6.1-m open height about ground are lowest near 0800 h and are fairly constant throughout the remainder of the day on average.
- Examination of seasonal variations in weather variables revealed RH minima and ambient are temperature maxima in July and August. Wind speed is variable throughout the fire season.
- ACGW is a semi-arid environment. Fuel moistures for 1-h, 10-h, and 100-h dead woody timelag size classes are highest in March and April, and decrease gradually until August, after which they begin to increase gradually into the fall.

Implications: The steep slopes, high ambient air temperatures and low RHs and limited rainfall experienced during the fire season, coupled with the flammable fuel types at AGCW, make for a highly fire-prone landscape.

What did the case study analysis of the eight and a half hour major run of the Machine Gun Fire on September 19, 2010 reveal about wild fire behavior at AGCW? **Conclusions:**

- Due to very low fuel moistures and strong winds, the extensive network of firebreaks and goat-maintained fuel breaks at AGCW proved insufficient at stopping the forward advancement of fire spread. Similar burning conditions occur frequently at AGCW during the course of a fire season.

Implications: Further research is needed on the requirements (and limits) of fuel management measures in relation to days of critical fire weather conditions. Live-fire training exercises on days of red flag warning involving strong winds appears to be a recipe for disaster.

What is the fire behavior potential for the four fire behavior fuel models (as per Anderson 1982) found at AGCW using different combinations of wind speed and fuel moisture as modeled by BehavePlus (Heinsch and Andrews 2010)*?*
Conclusions:

- Rate of spread, flame length, and fireline intensity are consistently highest for fire behavior fuel model (FBFM) 2 – timber (grass and understory) followed by FBFM 5 brush (0.6 m), FBFM 1 – short grass (0.3 m) (with the sole exception of rate of fire spread which is higher than FBFM 5, but lower than FBFM 2), and lastly FBFM 8 – closed timber litter.
- Maximum spotting distances are greatest for FBFMs 2 and 5 (~5 km), followed by FBFM 1 (~3 km), and FBFM 8 (~1 km).

Implications: FBFMs 2 and 5 are by far the most abundant fuel model types (70.8% of total area) in AGCW. They both display rapid fire spread rates, long flame lengths high fireline intensities, and long-distance spotting. Complete containment of large wild fires will be extremely difficult to control under severe fire weather conditions.

How can firebreaks be evaluated for effectiveness at stopping the forward spread of grass fires? How can fire behavior potential be predicted in juniper woodlands?
Conclusions:

- Using the Wilson (1988) grass firebreak breaching model, with 8-m wide firebreaks when shrubs and trees are *absent* within 20 m, there is less than about 2.0% probability of breach for FBFM 1, breach probabilities of 20% or greater occur on only about 7.0% of total days when firebreak width is 8.0 m when shrubs and trees are *absent* within 20 m for FBFM 2.
- Using the model developed by Bruner and Klebenow (1979) for gauging fire behavior pinyon-juniper woodlands, stands of concern should be maintained at near 20 to 30% vegetative cover to avoid problematic fire behavior.

Implications: Implementation of Wilson's (1988) modeled outcomes will vastly improve firebreak performance in mitigating against the likelihood of large wild fire events, while adhering to the Bruner and Klebenow (1979) equation will reduce the probability of sustained crown fire runs in juniper stands.

Using FlamMap (Finney 2006) fire spread simulation software, how does treatment implementation affect potential fire behavior compared to current conditions? **Conclusions:**

- Results indicate that rate of spread, flame length, and fireline intensity were all reduced, albeit minimally, through treatment implementation. Results likely underpredict the impact of new treatments due to the difficulty of FlamMap to recognize linear features of less than 30 m resolution.
- Burn probability was drastically reduced for the 2011 Machine Gun Fire area (89.1% reduction), but was reduced very little for area burned by the 2012 Pinion Fire (2.6%).

Implications: Fuel treatments will result in reduced fire behavior in terms of rate of spread, flame length, and fireline intensity, although it is difficult to ascertain the exact amount. Burn probability was greatly reduced for more

> **severe weather conditions such as occurred during the Machine Gun Fire compared to moderate fire weather conditions associated with the Pinion Fire.**

types are by far the most abundant at AGCW (58.6% of total area), followed by Gambel oak (18.2%), sagebrush (12.6%), and juniper (3.7%). FBFM 5 – brush (0.6 m) was found to be the most abundant (36.6%), followed by FBFM 2 – timber (grass and understory) (34.2%), FBFM 1 – short grass (0.3 m) (18.0%), and FBFM 8 – timber (grass and understory) (1.7%). There is an apparent discrepancy between modeled grassland vegetation (58.6%) and FBFM 1 (18%) which corresponds to a grassland fuel complex. This is likely due to the random forest groupings. Grassland is not grouped into a fuel complex when modeled as a vegetation type, however, when the area at AGCW is modeled as fuel types, much of the grassland area is grouped together with other vegetation (e.g. juniper, sagebrush, Gambel oak) as an understory component. This effort represents the first attempt to classify and map vegetation and FBFMs at high resolution for the AGCW landscape. The moderate accuracy could likely be improved using a different machine learning classification approach or an object-based image analysis segmentation process.

Chapter 3 Summary:—Recent Fire History

Following the wildfire case study format outlined by Alexander and Thomas (2003), the fire history and fire environment were first summarized, followed by a case study analysis of the Machine Gun Fire, a large wildfire event which started at AGCW and eventually burned into the adjacent wildland urban interface. Recent fire history was summarized from records available at AGCW and vegetative type and FBFM were summarized using Landscape Fire and Resource Management Planning Tools

(LANDFIRE) data. Summary of the recent fire history data at AGCW indicated frequent large fire events of a minimum of about 40 ha, occurring once every three years on average. Ignition sources were primarily a result of human and training related activities (68%). Recent wildfire perimeters from 1985 to 2012 were mapped according to small and large size categories using the National Fire Danger Rating System (NFDRS) size classification. LANDFIRE maps modelling mean fire return interval and fire regime types overall indicated wildfire occurrence at high frequencies (~5 to 12 years) which typically burned from moderate to high severity.

The narrative of events and associated fire behavior and fire environment conditions were examined for the major run of the Machine Gun Fire that occurred on September 19, 2010. Fire ignition occurred as a result of military training exercises at the Multi-Purpose Machine Gun (MPMG) Range at around 1237 h on a red-flag warning day with high winds. It appeared that fire spread has been stopped at around 1330 to 1400 h until such time that winds again picked up and produced spot fires beyond the firebreak containment line. Following spot fire breach at 1521 h, rapid fire spread coupled with spotting activity accounted for the breaching of trails, double-wide firebreaks, and fuelbreaks created from goat grazing from 1530 to 1645 h. Fire behavior output was compared using time and distance from a fire progression map produced shortly after the fire to predications using BehavePlus (Heinsch and Andrews 2010). Results indicate that better documentation in needed during fire events to positively ascertain observed conditions from predicted fire behavior conditions. This is the first attempt to document a case-fire study at AGCW. For future fire events, standards for fire documentation during

the fire are recommended in order to evaluate the efficacy of fuel treatment and

suppression measures.

Chapter 4 Summary:—Application of Fire Behavior Models for Fuel Treatment Assessments

In Chapter 4, four different sets of fire behavior analyses were conducted using a

combination of semi-empirical models and fire spread simulation software. The first set

of analysis utilized BehavePlus fire modelling system (Heinsch and Andrews 2010) to

predict rate of spread (ROS), flame length (FL), and fireline intensity (FI) using wind

speed and fuel moisture combinations for FBFMs 1, 2, 5, and 8 per Anderson (1982).

ROS was the most extreme for FBFM 2 (up to 330 m · min), followed by FBFM 1 (150

m · min), FBFM 5 (122 m · min), and FBFM 8 (about 3 m · min). The FL output results

also indicated that the highest values were associated with FBFM 2 (up to 9.5 m),

followed by FBFM 5 (7.1 m), FBFM 1 (3 m), and FBFM 8 (0.7 m). The FI results were

again highest for FBFM 2 (up to about 37 000 kW · m^{-1}), followed by FBFM 5 (18 100

kW · m^{-1}), FBFM 1 (3 000 kW · m^{-1}) and FBFM 8 (125 kW · m^{-1}). Overall, ROS, FL, and

FI are highest for FBFM 2, closely followed by FBFMs 5 and 1. Based upon the

calculated FL and FI values, FBFM 8 was never extreme enough to exclude direct attack

suppression using either hand tools or heavy machinery.

The second fire behavior analysis undertaken used a logistic regression equation

developed by Wilson (1988) to predict the probability of firebreak breaching in

grasslands with tree/shrubs absent or present based on experimental fires carried out in

the Northern Territory of Australia. Each day of weather record from 1991-2013

available for AGCW was examined for the likelihood of firebreak breaching probability

for ROS, FL, FI, and maximum spotting distance. FBFMs 1, 2, 5, and 8 were analyzed at zero, 25, and 50% slope steepness. FBFMs 2, 5, 8 differed from FBFM 1 in that the years of weather data were constrained to those with available data for live herbaceous (2003-2013) and live woody (1997-2013) fuel moisture content. After weather was acquired on an hourly basis from RAWS data, a batch processing tool, NEXUS (Scott 1999), was used to calculate ROS, FI, and FL for each hour. Using a lookup table procedure, maximum spotting distance was added for each day of record based on the observed wind speed and calculated flame length. Cumulative frequency distribution (CFD) graphs for, ROS, FI, FL, and maximum spotting distance were constructed for each of the four FBFMs selected.

The CFDs for each FBFM represent valuable tools for discerning the percent of days in which extreme fire behavior could potentially have occurred historically given an ignition or fire start. For FBFM 1 at zero percent slope, about 20% percent of days reported flame lengths of 2.4 m or greater and FI values of 1 730 or greater, thus indicating fire behavior too extreme for direct attack. ROS is never greater than 250 m · min. Maximum spotting distance ranged from 0.4 to 3.0 km. FBFM 2 exhibited the most extreme fire behavior of any FBFM. At zero percent slope, about 39% of days were predicted to have FLs of 2.4 m and FIs of 1 730 or greater. Eighty percent of days reported a ROS of 50 m · min or less, with the maximum value near 250 m · min. Maximum spotting distance ranged from 0.4 to about 8 km. Interestingly, the data indicate that while fire behavior is more extreme in FBFM 2 than 1, high ROS values are more common in FBFM 1 – short grass (0.3 m), than FBFM 2 – timber (grass and understory). The output for FBFM 5 on level terrain indicates that about 22% of days

have FLs greater than 2.4 m and FIs greater than 1 730. ROS is the lowest thus far, ranging from near zero to 100 m · min. Maximum spotting distance ranged from 0.4 to about 3.8 km. Lastly, FBFM 8 fire behavior output indicates very low values for ROS, FL, FI, and maximum spotting distance. FL is never greater than 1.0 m, FI is never greater than 180 kW · m^{-1}, ROS is always less than 6 m · min, and maximum spotting distance is always less than 1 km. Thus, direct attack using hand tools would always remain an option in FBFM 8.

The Wilson (1988) probability of firebreak breach, batch out values for FI were used in combination with the daily weather record to assess the probability of firebreak breaching for FBFMs 1 and 2 at slopes of zero, 25, and 50% in the presence and absence of trees or shrubs within 20 m of the firebreak. For FBFM 1, slope zero, in the presence of trees or shrubs within 20 m of the firebreak, 4-m wide firebreaks have a 45 to 85% probability of being breached. The probability of breaching is from 17 to 50% for 8-m wide firebreaks, nine to 36% for 10-m wide firebreaks, and zero to 10% for firebreaks of 15-m in width. When trees or shrubs were absent within 20 m of the firebreak, 4-m wide firebreaks had five to 35% probability of being breached and less than about two percent for all other firebreak widths.

The firebreak breaching results for FBFM 2 were similar, except for an overall higher probabilities. With trees or shrubs present within 20 m of the firebreak at slope zero, the probability of breaching for 4-m wide firebreaks ranged from 44 to 100%. The breaching probability was 18 to 100% for 8-m wide firebreaks, 10 to 100% for 10-m wide firebreaks, and 1 to 100% at breaks for 15-m wide firebreaks, but only about eight percent of days have a breaching probability of 20% or higher. When trees or shrubs are

absent within 20 m of the firebreak on level terrain the probability of breaching for 4-m wide firebreaks ranged from 5 to 100%. However, only about 25% of days have a breaching probability of 20% or greater. With firebreak widths 8-m, the probability of breaching ranges from zero to about 70%. Only about 2% of days have a breaching probability of 20% or greater. With firebreaks of 10 and 15 m wide, the probability of breaching is below 20% on about 99% percent of days. As a general rule, 8-m wide firebreaks are probably sufficient, except during critical fire weather days at the 97[th] percentile and above. If a firebreak is located in an area of steep topography and vulnerable to high winds, increasing firebreak widths to 10 m or more is considered highly advisable.

The third set of fire behavior analyses undertaken involved an equation and guide developed by Bruner and Klebenow (1979) to gauge fire behavior potential in pinyon-juniper woodlands based on 30 prescribed fires carried out in Nevada. The equation inputs included ambient air temperature (°F), gust wind speed (m · ph) and vegetation cover (%). The sum of the three values constituted a "score" that allowed for interpretation of fire behavior potential following ignition. Score values were computed from daily weather records covering the period from 1991-2013 for different vegetative covers. The results were then summarized in a CFD. Results indicated that when vegetation cover is above 30%, a large proportion of the fire season exhibits values of 130 or great (i.e. conditions that support crown fire spread). Typical vegetation cover in juniper at AGCW is from 20-50%, and in stands close to the wildland urban interface (WUI), a density of 20-30% is recommended to reduce the likelihood of crown fire occurrences.

The fourth and final set of fire behavior analyses utilized the FlamMap (Finney 2006) fire behavior and spread simulation software to compare expected fire behavior between current conditions and hypothetically implemented fuel treatments. Simulations were run for the weather conditions at the time of the 2010 Machine Gun Fire and the 2012 Pinyon Fire using 1 000 randomly placed fires in the Minimum Travel Time (MTT) function of FlamMap. A third simulation was run for a single point fire ignition near the MPMG range using the weather conditions associated with the Machine Gun Fire. Three different fuel conditions were simulated: (1) current conditions, (2) current conditions in addition to an expansion of the firebreak and fuelbreak network, and (3) the expanded firebreak and fuelbreak network in addition to large landscape level treatments. Results indicate that fire behavior is indeed reduced when fuel treatments are implemented, with the greatest reduction in fire behavior occurring in the breaks plus the landscape treatment scenario. The results do not, however, indicate a large enough reduction in fire behavior to allow for direct attack, either by hand-tools or heavy machinery, except for the burning conditions associated with the Pinion Fire. A reduction in fire behavior potential is likely under-predicted due to the inability of the FlamMap software to recognize linear fuel treatments (e.g. firebreaks and fuelbreaks) on the landscape.

Conclusions

Based upon the research presented in this document, at a minimum, firebreaks established should be at least 8 m wide, with trees and shrubs removed from within 20 m of the firebreak. Circumstances of high concern may warrant firebreaks of 10 to 15 m wide. Juniper cover should be maintained below 20-30% in stands within close proximity to the WUI.

This research has established the narrative of the climatological record over the past 20 years or so in addition to the expected fire behavior for the hourly data observed within the same time frame. To fully address the temporal and spatial pattern of fire for the fuel types located at AGCW, more research is necessary. An example of note is research needed to ascertain growth response of Gambel oak to different disturbances and fuel treatments over time. Concerning documentation of fires that occur on base, standard forms and procedures should be developed to record observations and photograph/film fire behavior in terms of flame height, rate of spread, spotting, and any other notable characteristics of fire behavior. Suppression tactics and decision making should also be recorded. Documentation of fire events will provide valuable criteria for evaluating fuel treatment in relation to suppression measures and will improve the likelihood of correcting possible oversights of current fire management policy. Lastly, fire weather documentation requires multiple, well-maintained weather stations, thus a strong priority should be placed on devoting budget and time to ensure that weather stations are operating to standard.

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APPENDIX

Table A.1. Four scenarios of the dead fuel moisture content time-lag (TL) values and two live fuel moistures used by Scott and Burgan (2005) to make fire behavior predictions.

Fuel moisture content (%)	Very low	Low	Moderate	High
1-h dead TL	3	6	9	12
10-h dead TL	4	7	10	13
100-h dead TL	5	8	11	14
Live herbaceous	30	60	90	120
Live woody	60	90	120	150

Table A.2. Interpretation diagnostics for fire suppression tactics as outlined by (Andrews and Rothermel 1982) using flame length and fireline intensity.

	Flame length	Fireline intensity	Interpretation
	Meters	kW/m	
	< 1.2	< 346	Direct attack possible by hand tools
	1.2 - 2.4	346 to 1730	Direct attack possible by heavy equipment
	2.4 - 3.4	1730 to 3459	Aerial resources may be effective
	> 3.4	> 3459	Direct suppression efforts generally not effective

Fire behavior predictions were made using BehavePlus (Heinsch and Andrews 2010) for rate of spread (ROS), flame length (FL) and, fireline intensity (FI) to illustrate potential fire behavior in relation to environmental conditions. Slope steepness was held constant at zero percent while four different scenarios for fuel moisture contents were selected and mid-flame wind speed was varied from zero to 40 km/h. The Anderson (1982) 13 fire behavior fuel model (FBFM) classification was used in lieu of the Scott and Burgan (2005) 40 fuel models because grass fuel moistures are input as fully cured

values and thus represent worst-case scenario burning conditions. Table A1.1 outlines the fuel moisture scenarios employed for the BehavePlus (Heinsch et al. 2010) simulations as used by Scott and Burgan (2005) for very low, low, moderate, and high moisture scenario conditions.

Fire suppression interpretations of FL and FI outputs are given in Table A1.2. Maximum spotting distances for each of the FBFMs can be inferred from the predicted FL and the 6.1-m open wind speed.

Results for FBFM 1 – short grass (0.3 m) predictions (Fig. A1.1) reveal that mid-flame wind speeds near 5 km/h are necessary before ROS will increase beyond about 20 m/min (Fig. A1.1a). Under high fuel moisture conditions, FBFM 1 will not yield any fire spread regardless of the wind speed. With moderate fuel moisture conditions, at wind speeds near 15 km/h, maximum rates of spread of about 50 m/min are reached. For low fuel moisture conditions, again maximum rates of spread near 90 m/min can be reached at wind speeds beginning near 15 km/h. At very low fuel moisture conditions, the highest rates of spread (~150 m/min) are achieved once wind speeds approach 20 km/h. FL estimates, regardless of fuel moisture scenario and wind speed are never greater than about 3.0 m (Fig. A1.1b). Thus, for FBFM 1, direct attack, albeit by heavy equipment for moderate, low, and very low fuel moisture scenarios remains in play regardless of the scenario. The FI output is similar to the FL results, with the very low fuel moisture scenario topping out at near 3000 kW/m (Fig. Al.1C), which still can potentially allow for suppression by aerial resources.
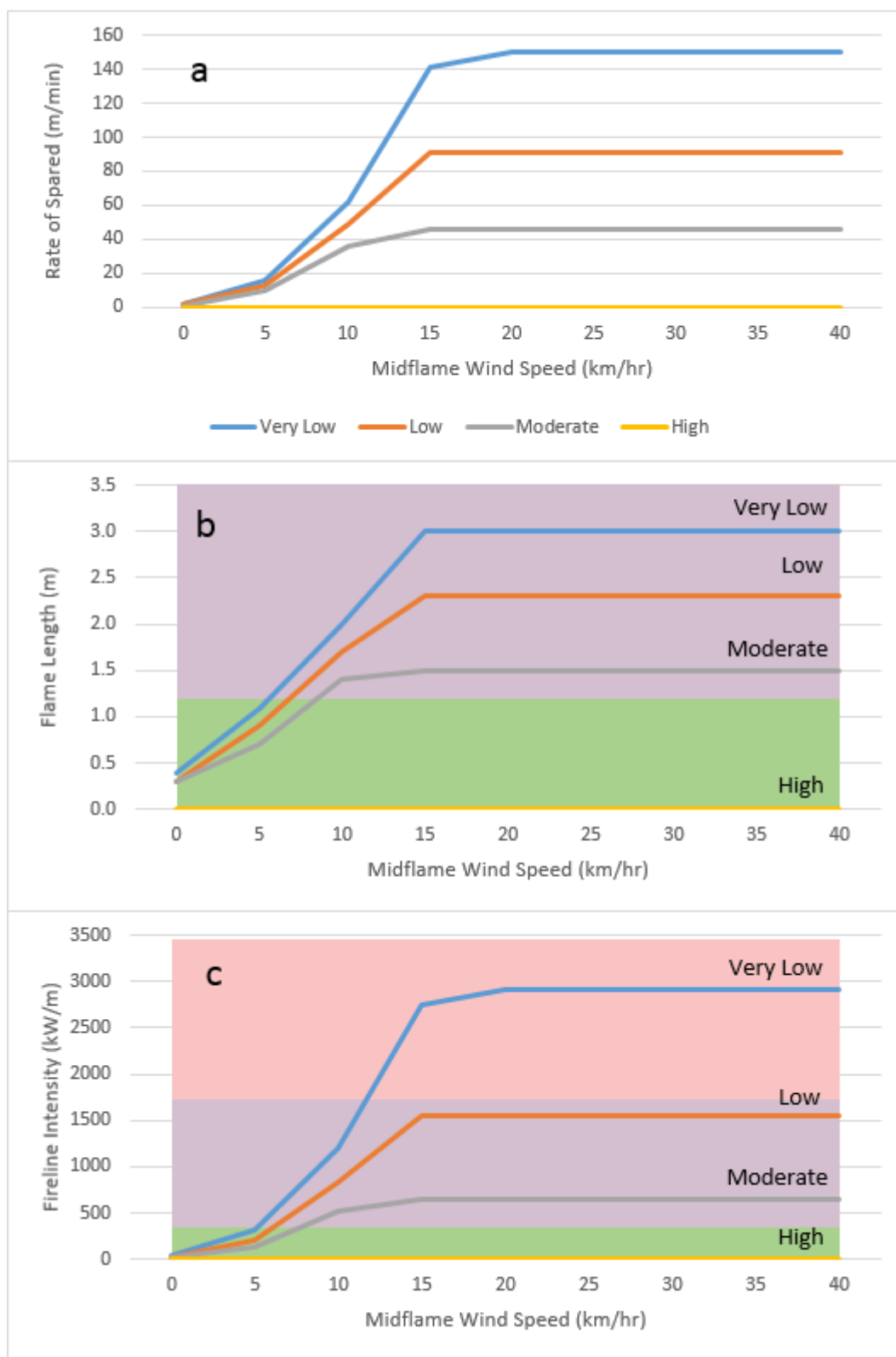
Figure A.1. BehavePlus results for very low, low, moderate, and high fuel moisture and wind speed combinations (Tab. A1.1) for fire behavior fuel model 1 (Anderson 1982).

The results for FBFM 2 – timber (grass and understory) (Fig. A2.2) reveals it has the highest ROS potential of near 330 m/min for mid-flame wind speeds of near 40 km/h, at very low fuel moisture levels (Fig. A1.2A). The ROS predictions for all four fuel moisture scenarios remain below about 20 m/min until wind speeds of near 10 km/h are reached. Even under the high fuel moisture scenario condition, the predicted ROS attained a value near 110 m/min at wind speeds of 35 to 40 km/h. FL predictions can reach extreme values (Fig. A1.2B) where by indirect attack is the only option at the very low fuel moisture scenario when wind speeds near 27 km/h and at 35 km/h for a low fuel moisture level. As wind speeds approach 20 to 28 km/h, moderate and high fuel moisture conditions are considered to be severe enough that only aerial fire resources are able to contain fire spread. FI results for the four fuel moisture conditions (Fig. A1.2C) showed that fire suppression by aerial resources is the only possible option for wind speed as soon as 6 km/h in the very low fuel moisture condition. Overall, FI results for FBFM 2 indicate a much greater difficulty for fire suppression efforts than the FL results alone would suggest.

The BehavePlus results for FBFM 5 – brush (0.6 m) (Fig. A1.3) are overall less severe than FBFM 2, but more severe than FBFM 1. The ROS for high and moderate fuel moisture scenarios never increases above 5 m/min, regardless of the mid-flame wind speed. At very low and low fuel moisture scenarios fire behavior potential begins to increase at winds speed near 5 km/h and increase in an almost linear manner, with ROS topping out at near 120 m/min at 40 km/h for the very low fuel moisture scenario and
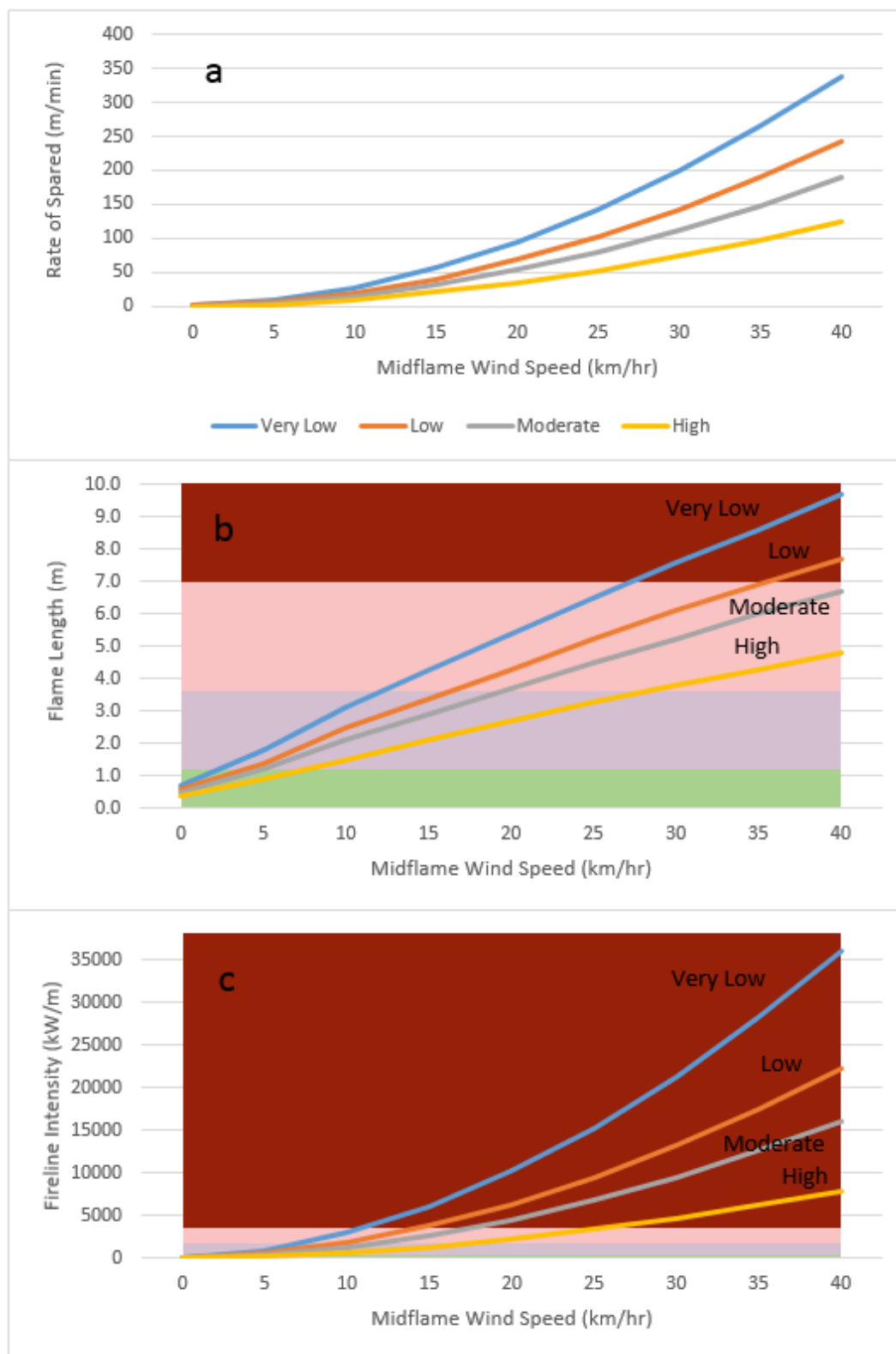
Figure A.2. BehavePlus results for very low, low, moderate, and high fuel moisture and wind speed combinations (Tab. A1.1) for fire behavior fuel model 2 (Anderson 1982).

near 80 m/min at 40 km/h for the low fuel moisture scenario. Regardless of wind speed, FL values were never greater than 1.0 m for high and moderate fuel moisture scenarios. At wind speeds near 14 and 20 km/h for very low and low fuel moisture scenarios, respectively, fire suppression using aerial resources is required. The very low fuel moisture scenario condition is barely able to be considered for indirect attack at predicted FL values of 8.0 m for wind speeds of around 40 km/h. As would be expected, FI values for FBFM 5 follow the same trend lines as for the FL results with the high and moderate moisture scenario categories never reaching levels high enough to rule them out of the direct attack category. The low fuel moisture scenario reaches the aerial attack only category for wind speeds near 18 km/h. The very low fuel moisture scenario is associated with the aerial attack only category at wind speeds near 11 km/h.

The BehavePlus outputs for FBFM 8 – closed timber litter (Fig. A1.4) was the lowest of any of the four FBFMs examined. Even under mid-flame wind speeds of near 40 km/h and very low fuel moisture, ROS was only a maximum of three m/min (Fig. A1.4A). Also, regardless of fuel moisture scenario for FL and FI, fire behavior was never great enough to merit more than direct attack with hand tools.

Output from FBFM 6 – dormant brush was also generated using BehavePlus (Fig. A1.5) in order to gain a better understanding of the possible consequences or impact of frost kill on Gambel oak. Input values for FBFM 6 only require 1-h, 10-h, and 100-h dead timelag fuel moisture inputs, unlike FBFM 5 which requires 1-, and 10-hour dead TL fuel moisture and live woody fuel moisture. These inputs drive fire behavior prediction results which indicate that the upper range of fire behavior for ROS, FL, and FI are all greater for FBFM 5 than for FBFM 6. The interesting difference is that for moderate and high

fuel moisture conditions, FBFM 6 exhibits much higher values than FBFM 5 due to an absence of live woody biomass. FL results for FBFM 6 (Fig. A1.5B) indicate that moderate fuel moisture conditions are on the verge of requiring the aerial attack only suppression category, with the high fuel moisture scenario not far behind. This is very different from FBFM 5, which for the same fuel moisture scenarios, is never high enough to go beyond the suppression by direct attack using hand tools option. Thus, in frost killed Gambel oak vegetation, even under moderate and high moisture conditions, fairly extreme fire behavior still remains a possibility.

Figure A.3. BehavePlus results for very low, low, moderate, and high fuel moisture and wind speed combinations (Tab. 4.3) for fire behavior fuel model 5 (Anderson 1982).
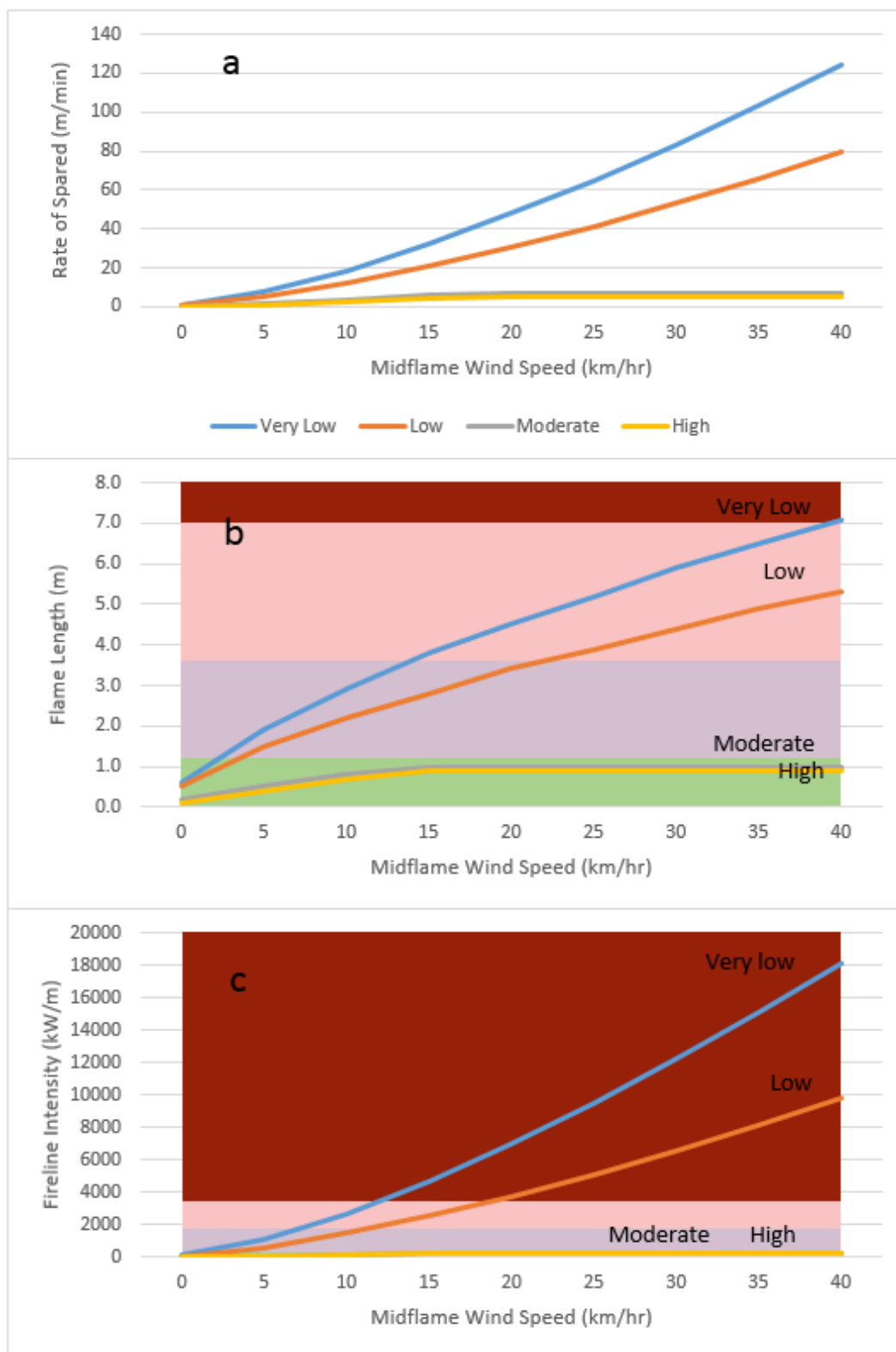
Figure A.4. BehavePlus results for very low, low, moderate, and high fuel moisture and wind speed combinations (Tab. 4.3) for fire behavior fuel model 8 (Anderson 1982).
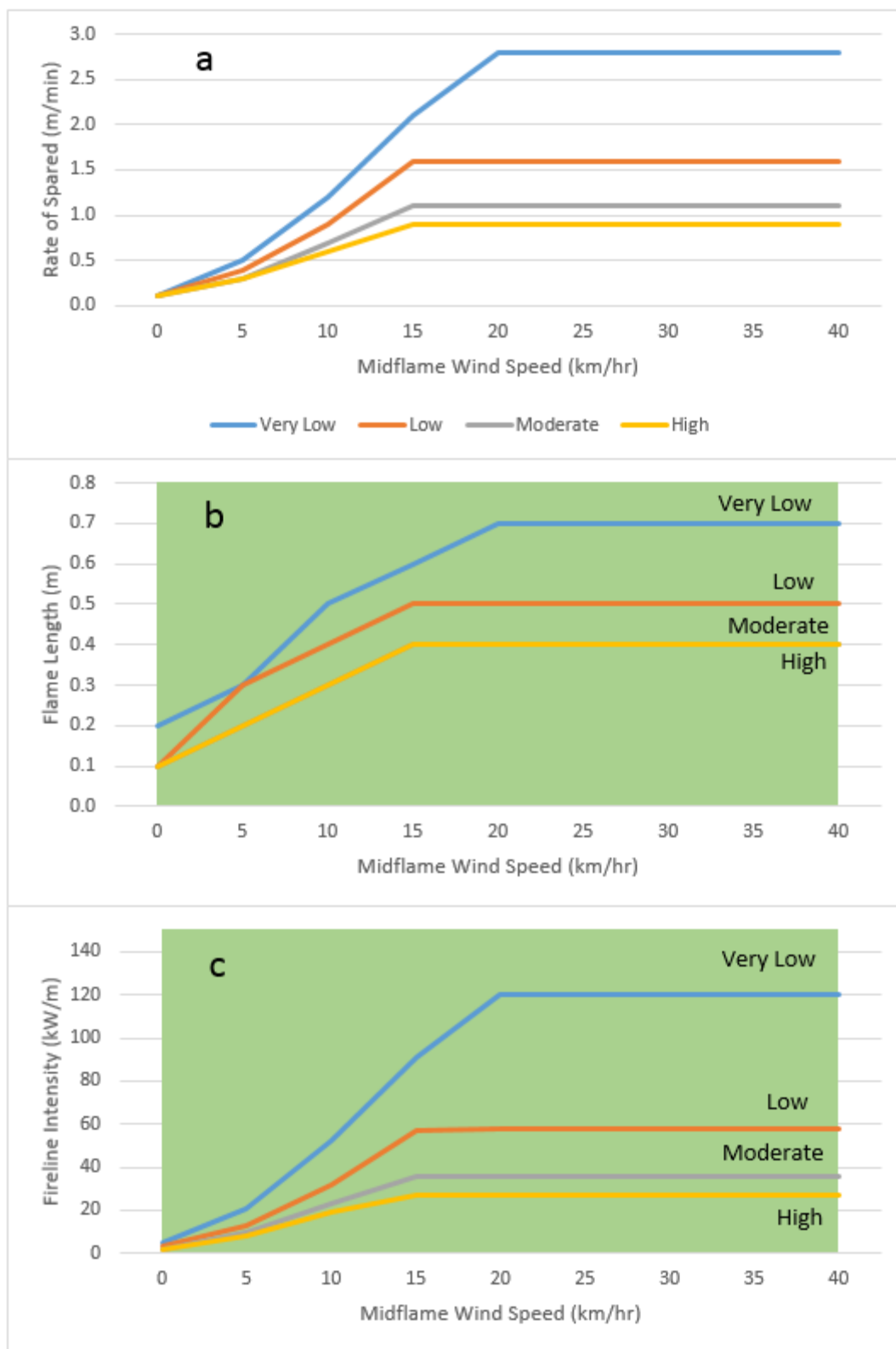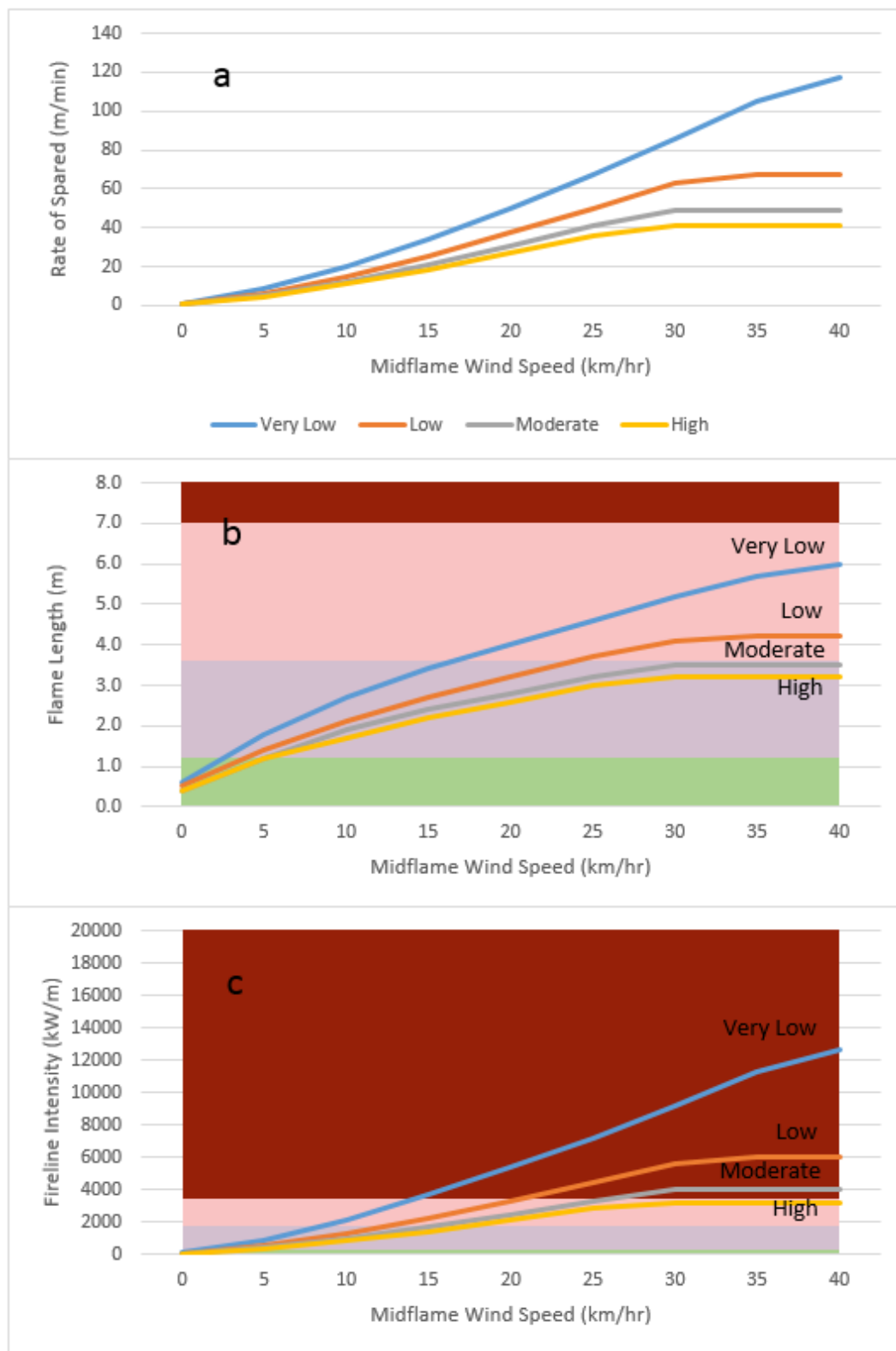
Figure A.5. BehavePlus results for very low, low, moderate, and high fuel moisture and wind speed combinations (Tab. 4.3) for fire behavior fuel model 6 (Anderson 1982).

Table A.3. Maximum spotting distance look-up table for non-canopied fuel types, per Alexander (2006). Spotting distance is measured in km.

FL (m)	Wind speed (km/h)									
	5	10	15	20	25	30	35	40	45	50
1	0.1	0.2	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5
2	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.8
3	0.2	0.4	0.5	0.6	0.7	0.8	0.8	0.9	1	1.1
4	0.3	0.4	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3
5	0.3	0.5	0.7	0.8	1	1.1	1.2	1.3	1.4	1.5
6	0.4	0.6	0.8	0.9	1.1	1.2	1.4	1.5	1.6	1.8
7	0.4	0.7	0.9	1.1	1.2	1.4	1.5	1.7	1.8	1.9
8	0.5	0.7	1	1.2	1.3	1.5	1.7	1.8	2	2.1
9	0.5	0.8	1	1.3	1.5	1.6	1.8	2	2.2	2.3
10	0.5	0.8	1.1	1.3	1.6	1.8	2	2.2	2.3	2.5
11	0.6	0.9	1.2	1.4	1.7	1.9	2.1	2.3	2.5	2.7
12	0.6	1	1.3	1.5	1.8	2	2.2	2.4	2.6	2.8
13	0.6	1	1.3	1.6	1.9	2.1	2.4	2.6	2.8	3
14	0.7	1.1	1.4	1.7	2	2.2	2.5	2.7	2.9	3.2
15	0.7	1.1	1.5	1.8	2.1	2.3	2.6	2.9	3.1	3.3
16	0.7	1.2	1.5	1.9	2.2	2.5	2.7	3	3.2	3.5
17	0.8	1.2	1.5	1.9	2.3	2.6	2.8	3.1	3.4	3.6
18	0.8	1.3	1.7	2	2.4	2.7	3	3.2	3.5	3.8
19	0.8	1.3	1.7	2.1	2.4	2.8	3.1	3.4	3.6	3.9
20	0.9	1.4	1.8	2.2	2.5	2.9	3.2	3.5	3.8	4.1
25	1	1.6	2.1	2.5	3	3.3	3.7	4.1	4.4	4.7
30	1.1	1.8	2.4	2.9	3.4	3.8	4.2	4.6	5	5.4

BehavePlus option for spotting distance from a wind driven surface fire in non-canopied fuel types over level terrain as a function continuous steady flame length and wind speed. Input wind speed was at a 10-m height, a 15% reduction adjustment in wind speed must be made to make comparisons to 20-ft wind speed inputs.

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