fire

MDPI

SUPPLEMENTARY MATERIALS

The Application of Fire Behavior Modeling to Fuel Treatment Assessments at Army Garrison Camp Williams, Utah

Scott M. Frost, Martin E. Alexander and Michael J. Jenkins

Correspondence: scott.m.frost@gmail.com

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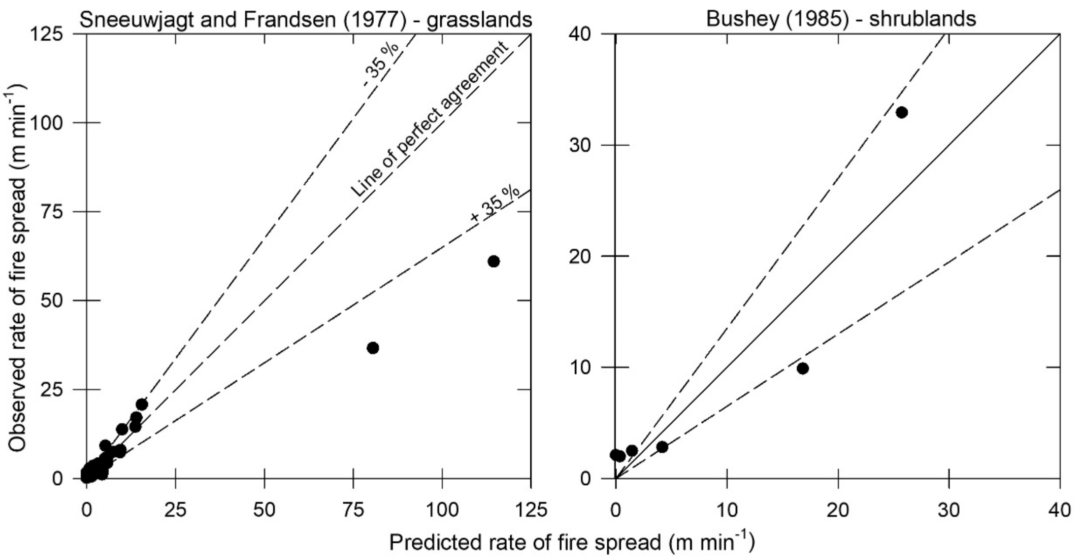

Figure S1. Observed versus predicted rates of spread for experimental fires and wildfires in grasslands by Sneeuwjagt and Frandsen [1] and experimental fires in sagebrush shrublands by Bushey [2] compared to predictions from Rothermel's [3] surface fire spread model.

Table S1. General fuel treatment methods and their pros/cons at Army Garrison Camp Williams.

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/moderately steep 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/moderately steep terrain
Herbicides	• Effective at controlling regrowth of woody plants and in vegetation state conversions • Can be used in areas with unexploded ordinance	• 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 escapes • Visual impact • Smoke production • Time required for planning efforts

Table S2. Maximum spotting distance (km) look-up table for non-canopied fuel types as a function of flame length (FL) and 10-m open wind speed (from Alexander [4]).

	Wind Speed (km/h)									
***FL* (m)**	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	1.0	1.1
4	0.3	0.4	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
5	0.3	0.5	0.7	0.8	1.0	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	1.0	1.2	1.3	1.5	1.7	1.8	2.0	2.1
9	0.5	0.8	1.0	1.3	1.5	1.6	1.8	2.0	2.2	2.3
10	0.5	0.8	1.1	1.3	1.6	1.8	2.0	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	1.0	1.3	1.5	1.8	2.0	2.2	2.4	2.6	2.8
13	0.6	1.0	1.3	1.6	1.9	2.1	2.4	2.6	2.8	3.0
14	0.7	1.1	1.4	1.7	2.0	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	3.0	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	2.0	2.4	2.7	3.0	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	1.0	1.6	2.1	2.5	3.0	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	5.0	5.4

Notes: Tabular values based on the output from BehavePlus for the maximum spotting distance from a wind-driven surface fire in non-canopied fuel types over level terrain as a function of continuous steady-state flame length and 10-m open wind speed. To approximate a 6.1-m (20-ft) open wind speed level, reduce the 10-m open wind speed by 15% as per Andrews [5].

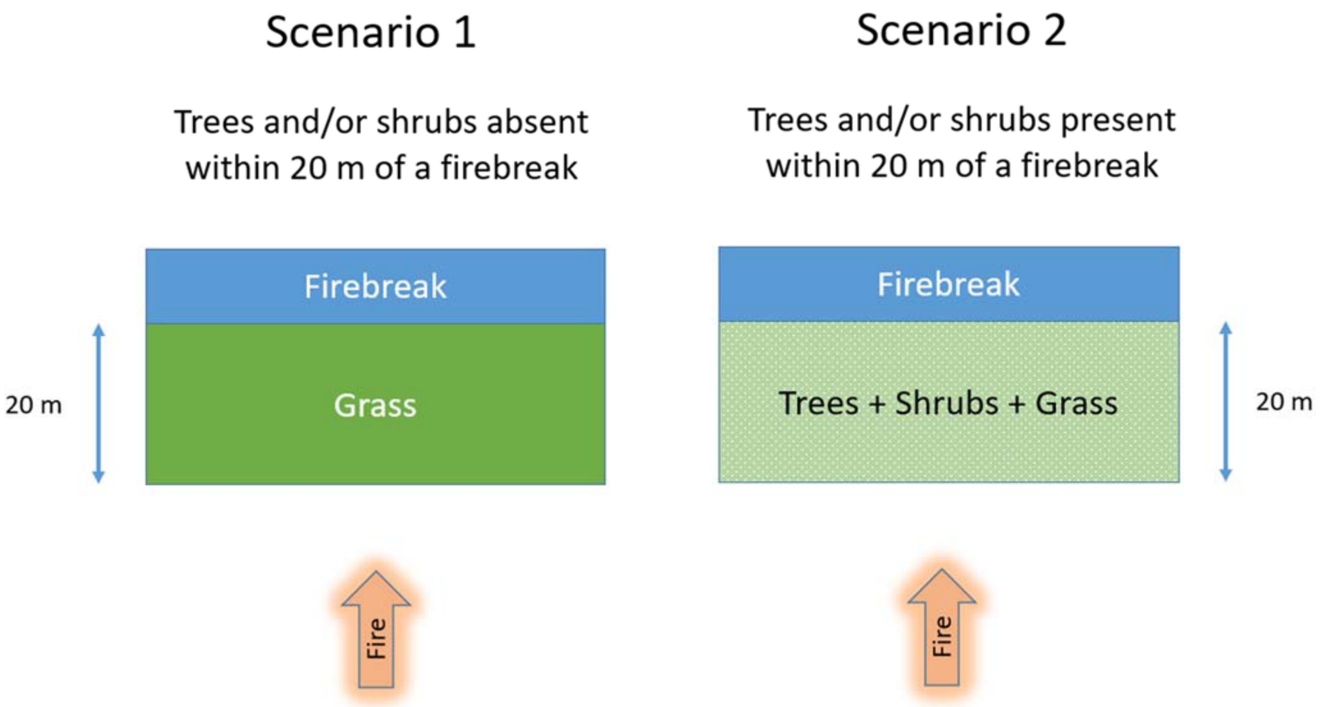

Figure S2. Conceptual representation of the two scenarios involved in the models of Wilson [6] for estimating the probability of grassland firebreak breaching.

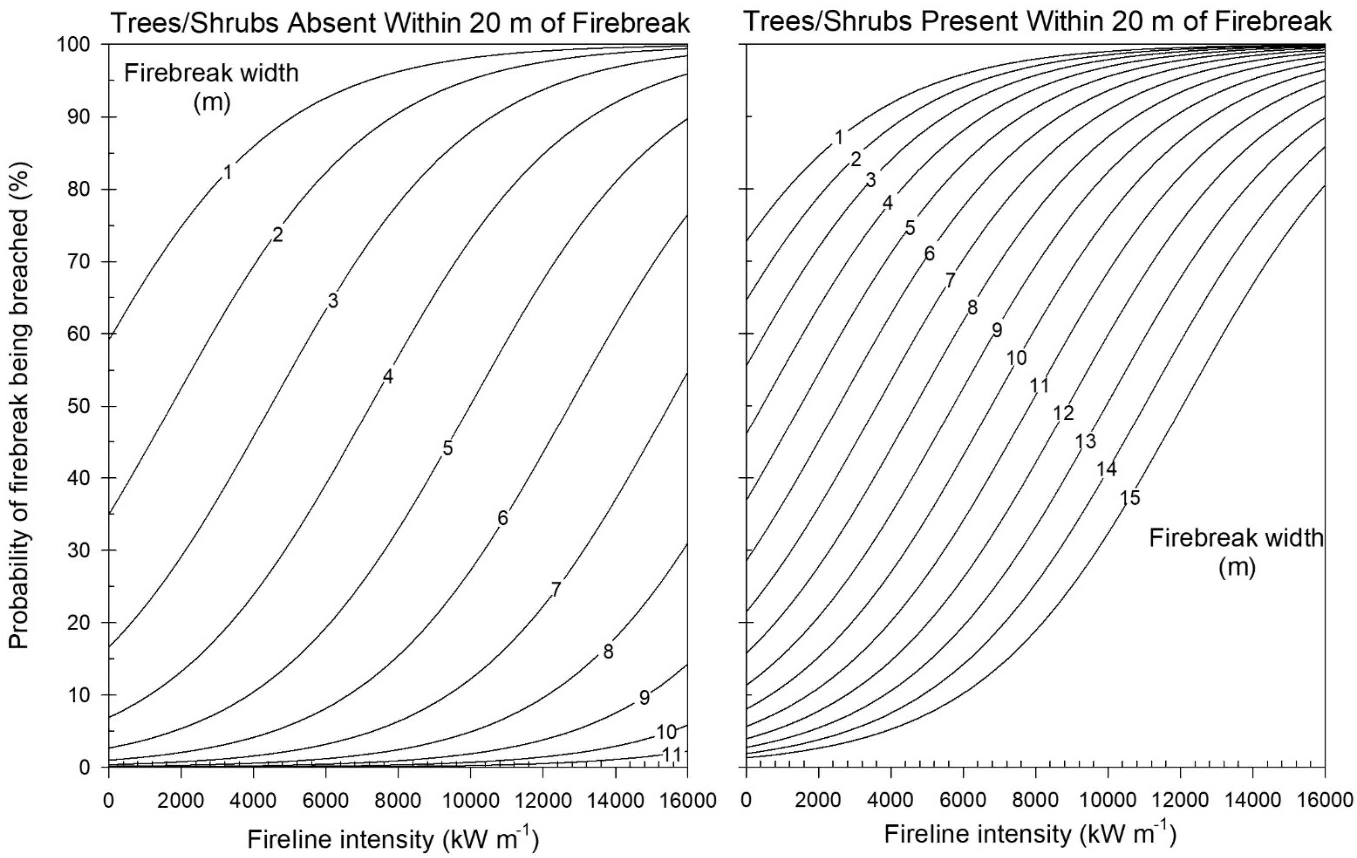

Figure S3. Graphical representation of the two probability of firebreak breaching models developed by Wilson [6] for grassland fires as a function of fireline intensity and firebreak width and whether or not trees and/or shrubs were present or absent within 20 m of the firebreak (after Alexander et al. [7]).

BehavePlus Fire Behavior Modelling System Predictions

Fire behavior predictions were made using BehavePlus [8] for rate of spread (*ROS*), fire-line intensity (*FLI*), flame length (*FL*) to illustrate potential fire behavior in relation to environmental conditions (i.e. fuels, weather and topography).

Slope steepness was held constant at zero percent (i.e. flat terrain) while four different scenarios of dead and live fuel moisture contents were selected and mid-flame wind speed was varied from zero to 40 km h^{-1}.

The Anderson [9] 13 fire behavior fuel model (FBFM) classification was used in lieu of the Scott and Burgan [10] 40 fuel models because grass fuel moistures in Anderson [9] fuel models are input as fully cured values and thus represent worst-case scenario burning conditions.

Table S2 outlines the dead and live fuel moisture values employed in the BehavePlus simulations as used for the 'very low', 'low', 'moderate', and 'high' fuel moisture scenarios per Scott and Burgan [10].

Maximum spotting distances for each of the FBFMs can be inferred from the predicted *FL* and open wind speed (Table S1). Fire suppression interpretations of *FLI* and *FL* outputs are given in Table S3.

Table S3. Four scenarios for combination of dead fuel moisture contents by time-lag (TL) size and live fuel moistures as used by Scott and Burgan [10] for making fire behavior simulations.

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 S4. Interpretation diagnostics for fire suppression tactics as outlined by Andrews and Rothermel [11] based on fire-line intensity and flame length.

Color Code	Fire-line Intensity ($kW\ m^{-1}$)	Flame Length (m)	Interpretation
(blue)	<346	<1.2	Direct attack possible by hand tools
(yellow)	346 – 1730	1.2 – 2.4	Direct attack possible by heavy equipment
(orange)	1730 – 3459	2.4 – 3.4	Aerial resources may be effective
(red)	≥3459	≥3.4	Direct suppression efforts generally not effective

Results for FBFM 1 – short grass (0.3 m) predictions (Figure S4) reveal that mid-flame wind speeds near 5 km h^{-1} are necessary before *ROS* will increase beyond about 20 m min^{-1} (Figure S4a). 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^{-1}, maximum rates of spread of about 50 m min^{-1} are reached. For 'low' fuel moisture conditions, again maximum rates of spread near 90 m min^{-1} can be reached at wind speeds beginning near 15 km h^{-1}. At 'very' low fuel moisture conditions, the highest rates of spread (~150 m min^{-1}) are achieved once wind speeds approach 20 km h^{-1}. *FL* estimates, regardless of fuel moisture scenario and wind speed are never greater than about 3.0 m (Figure S4b). 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 condition. The *FLI* output is similar to the *FL* results, with the 'very low' fuel moisture scenario topping out at near 3000 kW m^{-1} (Figure S4c), which can still potentially allow for suppression by aerial resources.

The results for FBFM 2 – Timber (grass and understory) (Figure S5) reveals it has the highest *ROS* potential of near 330 m min^{-1} for mid-flame wind speeds of near 40 km h^{-1}, at 'very low' fuel moisture levels (Figure S5a). The *ROS* predictions for all four fuel moisture scenarios remain below about 20 m min^{-1} until wind speeds of near 10 km h^{-1} are reached. Even under the 'high' fuel moisture scenario condition, the predicted *ROS* attained a value near 110 m min^{-1} at wind speeds of 35 to 40 km h^{-1}. FL predictions can reach extreme values (Figure S5b) whereby indirect attack is the only option at the 'very low' fuel moisture scenario when wind speeds near 27 km h^{-1} and at 35 km h^{-1} for a 'low' fuel moisture level. As wind speeds approach 20 to 28 km h^{-1}, 'moderate' and 'high' fuel moisture scenario 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 (Figure S5b) showed that fire suppression by aerial resources is the only possible option for wind speeds of 6 km h^{-1} in the "very low' fuel moisture scenario condition. Overall, *FLI* results for FBFM 2 (Figure S5c) indicate a much greater difficulty for fire suppression efforts than the *FL* results alone would suggest.

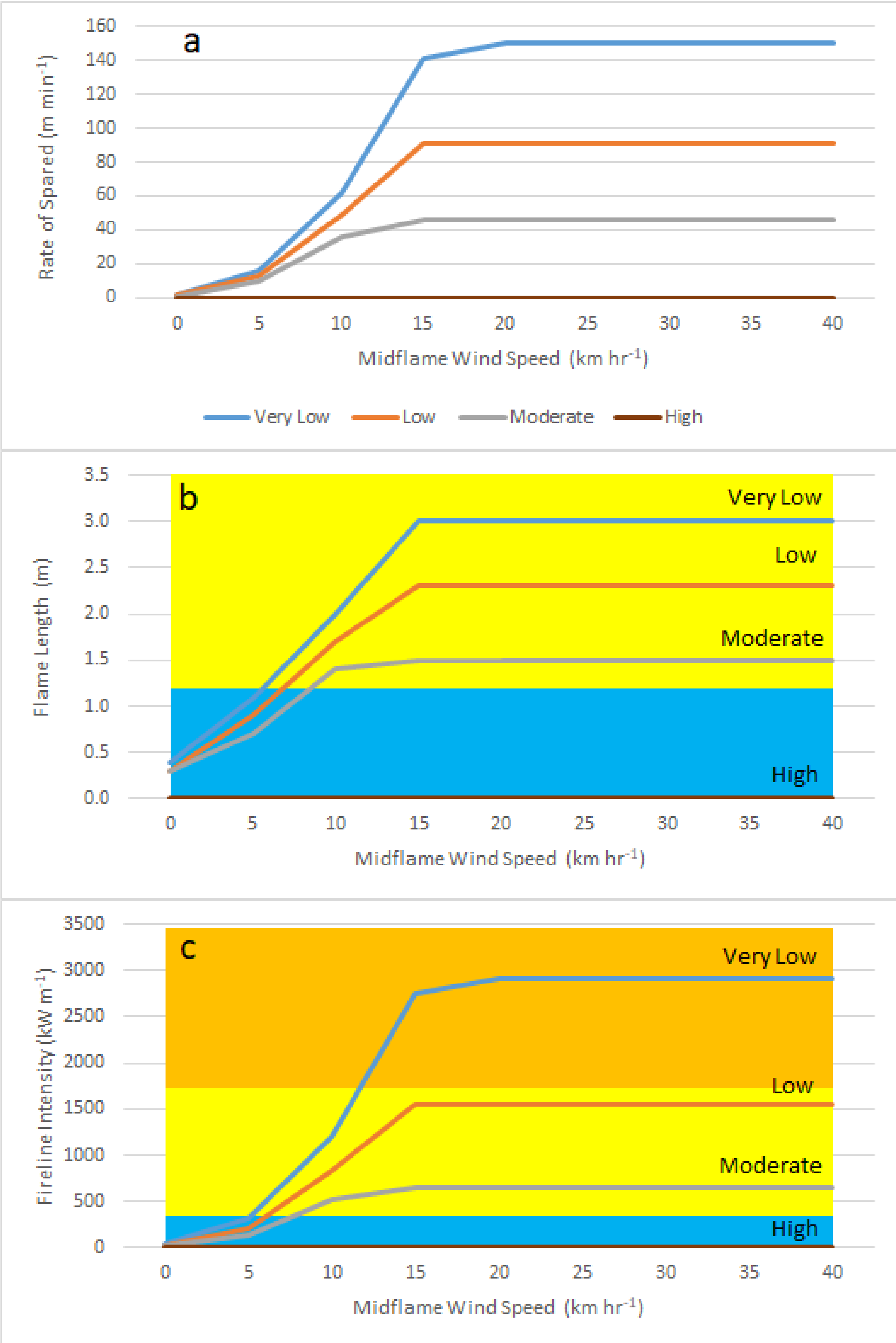

Figure S4. BehavePlus simulation results for 'very low', 'low', 'moderate', and 'high' fuel moisture scenario conditions and wind speed for the Anderson [9] Fire Behavior Fuel Model 1 – Short grass (0.3 m).

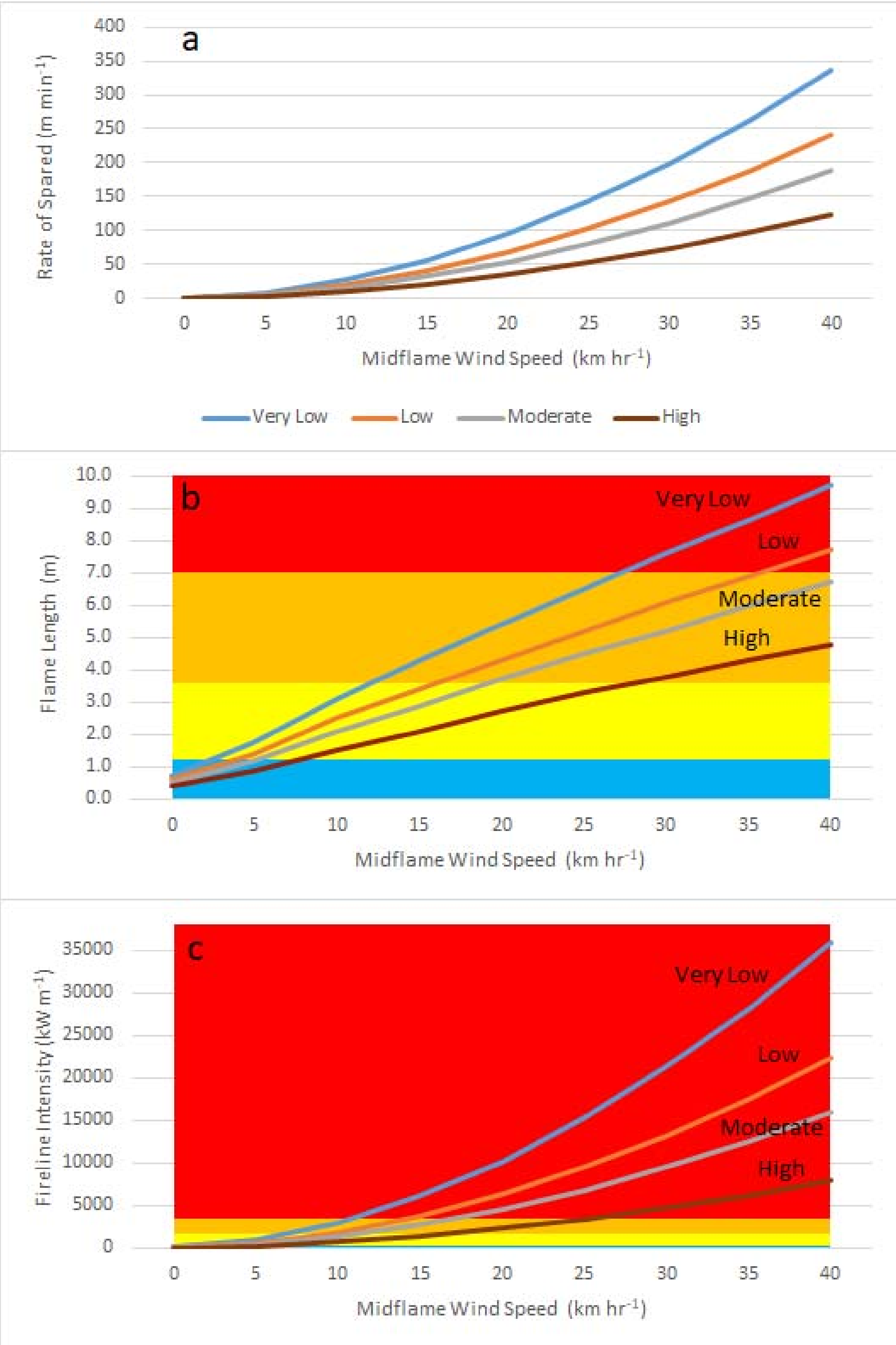

Figure S5. BehavePlus simulation results for 'very low', 'low', 'moderate', and 'high' fuel moisture scenario conditions and wind speed for the Anderson [9] Fire Behavior Fuel Model 2 – Timber (grass and understory).

The BehavePlus results for FBFM 5 – Brush (0.6 m) (Figure S6) 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 5.0 m min^{-1}, regardless of the mid-flame wind speed (Figure S6a). At 'very low' and 'low' fuel moisture scenarios, fire behavior potential begins to increase at winds speed near 5 km h^{-1} and increase in an almost linear manner, with *ROS* topping out at near 120 m min^{-1} at winds of 40 km h^{-1} at the 'very low' fuel moisture scenario and near 80 m min^{-1} at winds of 40 km h^{-1} 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 (Figure S6b). At wind speeds near 14 and 20 km h^{-1} for 'very low' and 'low' fuel moisture scenarios, respectively, fire suppression using aerial resources is considered 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^{-1}. As would be expected, *FLI* values for FBFM 5 follow the same general trends as for the *FL* results, with the 'high' and 'moderate' moisture scenarios never reaching levels high enough to rule them out of the direct attack category (Figure S6c). The 'low' fuel moisture scenario reaches the aerial attack only category for wind speeds near 18 km h^{-1}. The very 'low' fuel moisture scenario is associated with the aerial attack only category at wind speeds near 11 km h^{-1}.

The BehavePlus outputs for FBFM 8 – Closed timber litter (Figure S7) was the lowest of any of the four FBFMs examined. Even under wind speeds of near 40 km h^{-1} and 'very low' fuel moisture, *ROS* was only a maximum of 3.0 m min^{-1} (Figure S7a). Also, regardless of the fuel moisture scenario for *FL* and *FLI*, 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 (Figure S8) 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 fuel moisture content time-lag (TL) inputs, unlike FBFM 5 which requires 1- and 10-hour dead TL fuel moisture and live woody fuel moisture content values. These inputs drive fire behavior simulation results which indicate that the upper range of fire behavior for *ROS*, *FL*, and *FLI* are all greater for FBFM 5 than for FBFM 6. The interesting difference is that for 'moderate' and 'high' fuel moisture scenario conditions, FBFM 6 exhibits much higher values than FBFM 5 due to an absence of live woody biomass. *FL* results for FBFM 6 (Figure S8b) indicate that 'moderate' fuel moisture conditions are on the verge of requiring only the aerial attack 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.

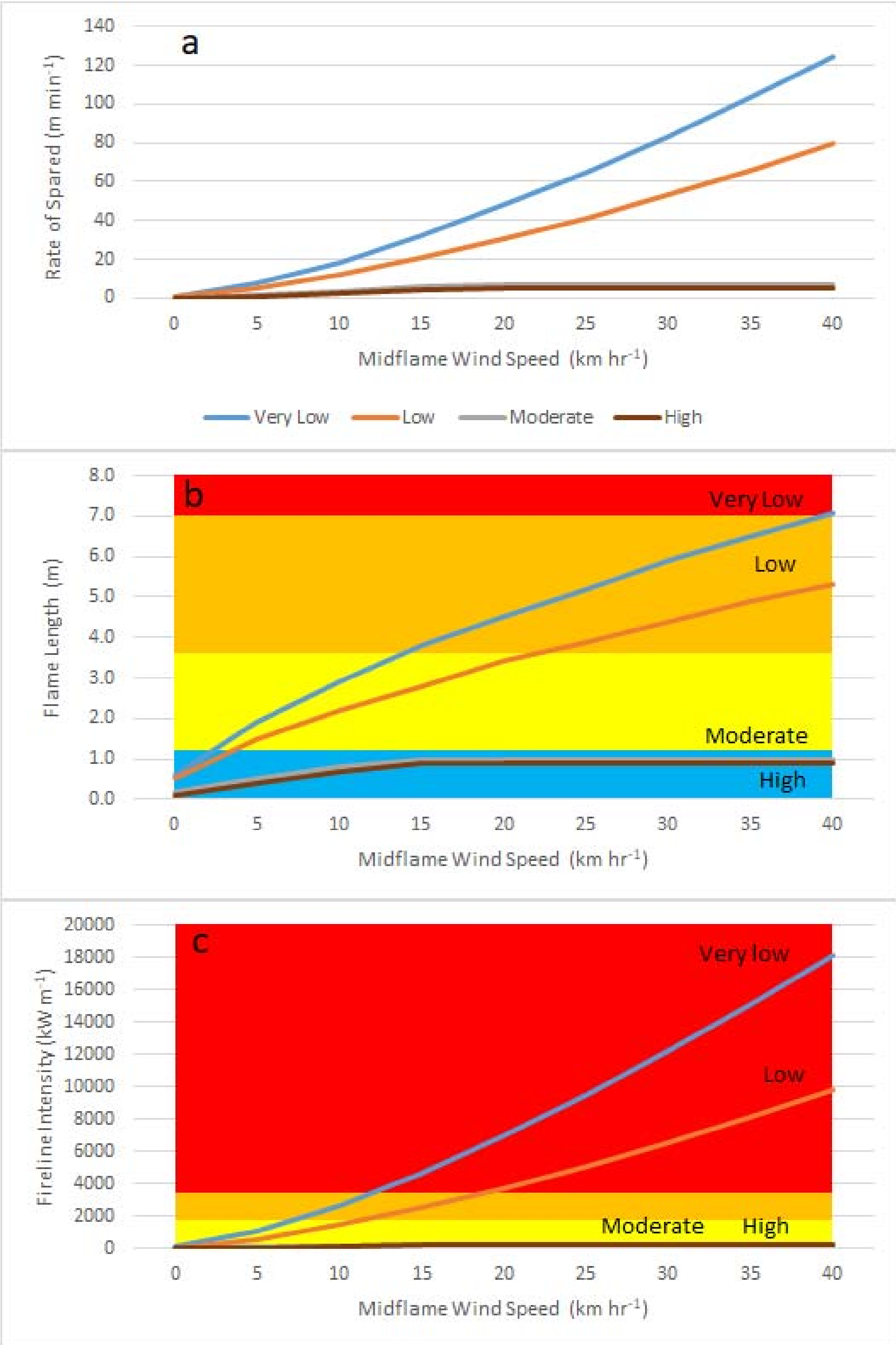

Figure S6. BehavePlus simulation results for 'very low', 'low', 'moderate', and 'high' fuel moisture scenario conditions and wind speed for the Anderson [9] Fire Behavior Fuel Model 5 – Brush (0.6 m).

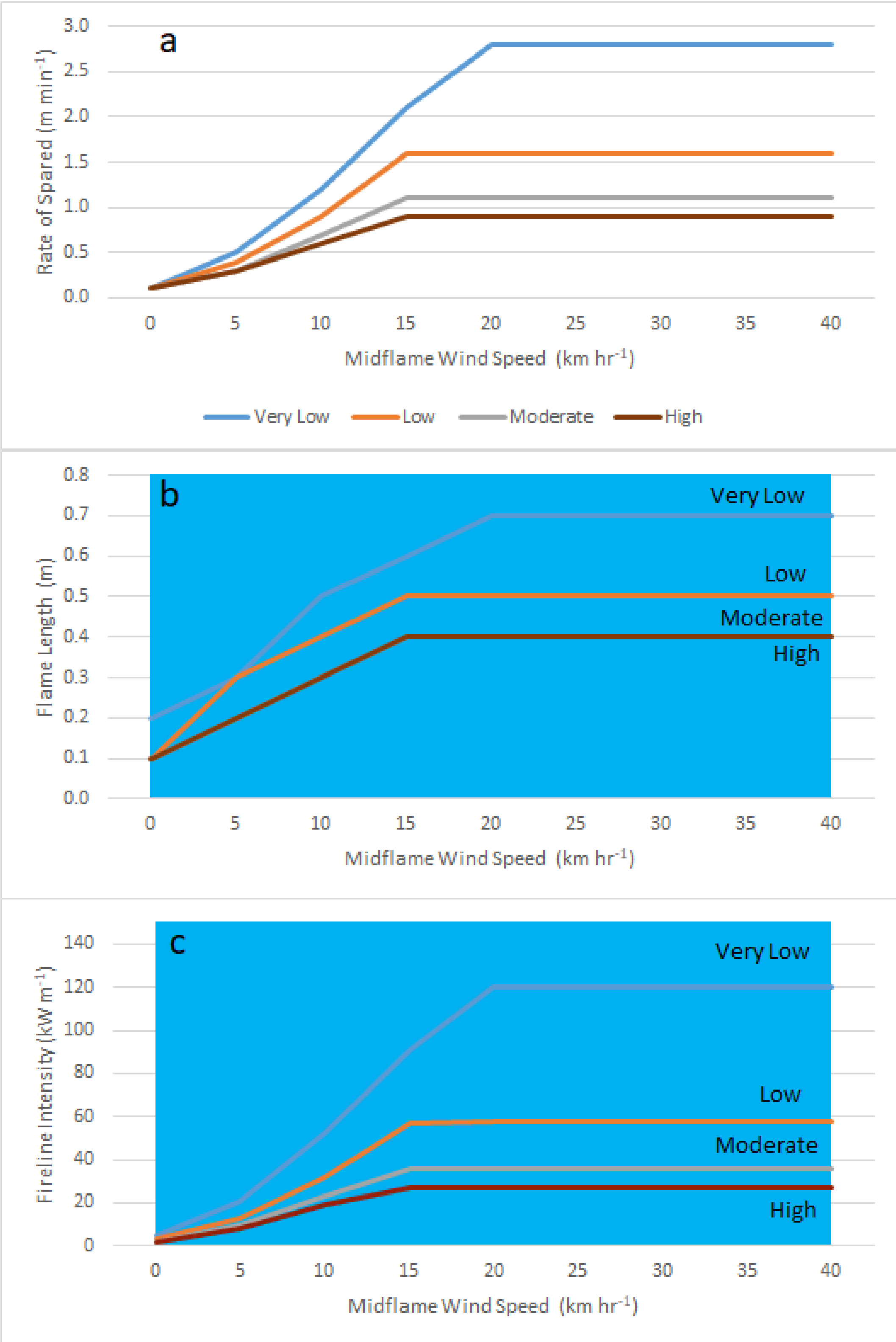

Figure S7. BehavePlus simulation results for 'very low', 'low', 'moderate', and 'high' fuel moisture scenario conditions and wind speed for the Anderson [9] Fire Behavior Fuel Model 8 – Closed timber litter.

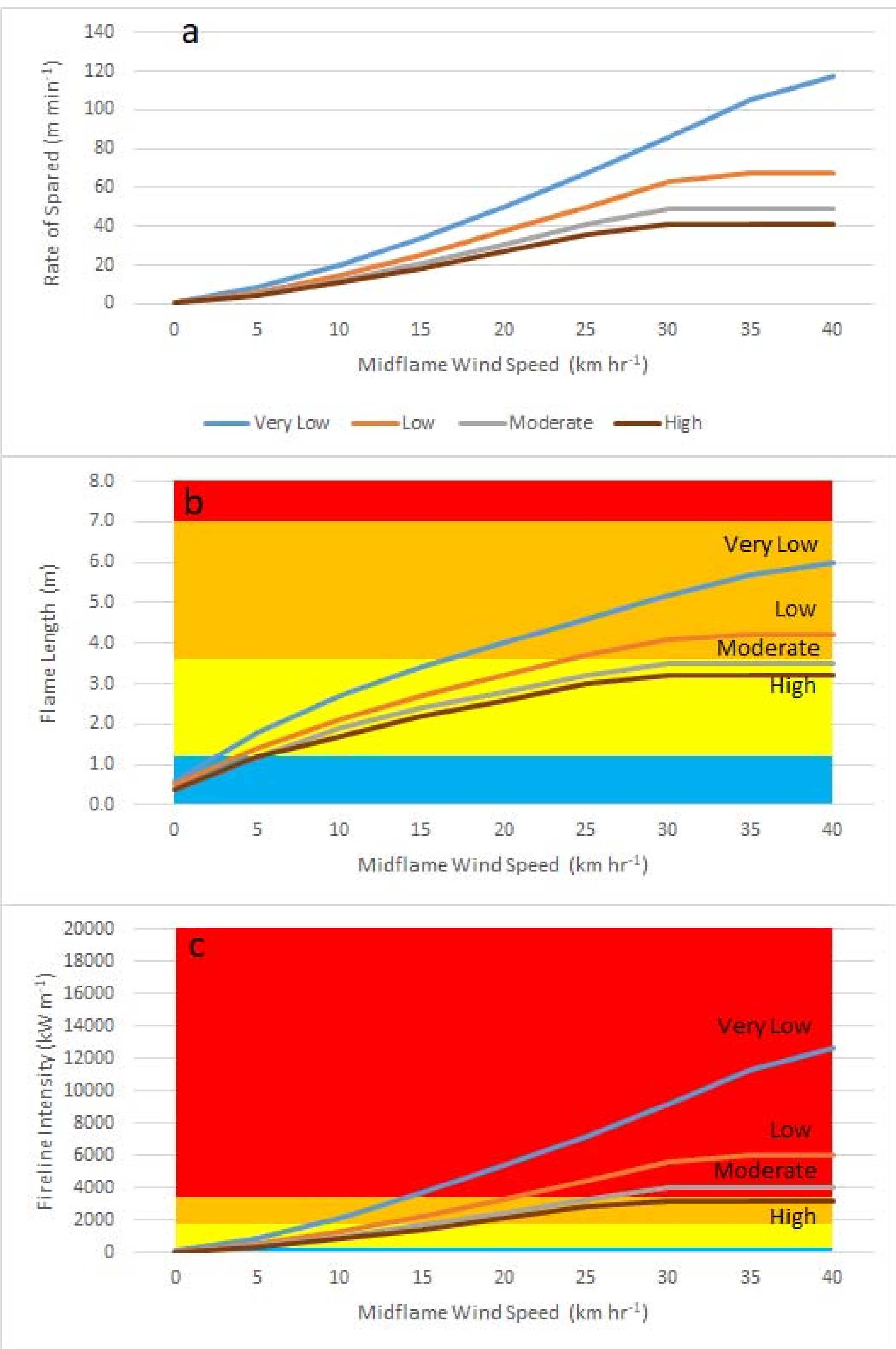

Figure S8. BehavePlus simulation results for 'very low', 'low', 'moderate', and 'high' fuel moisture scenario conditions and wind speed for the Anderson [9] Fire Behavior Fuel Model 6 – Dormant brush.

Table S5. Area of juniper cover at Army Garrison Camp Williams, UT, and the proportion of total area by canopy cover class.

Juniper Canoy Cover Class (%)	Area (ha)	Proportion of Total Area (%)
0-20	0	0
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
Totals	475	100

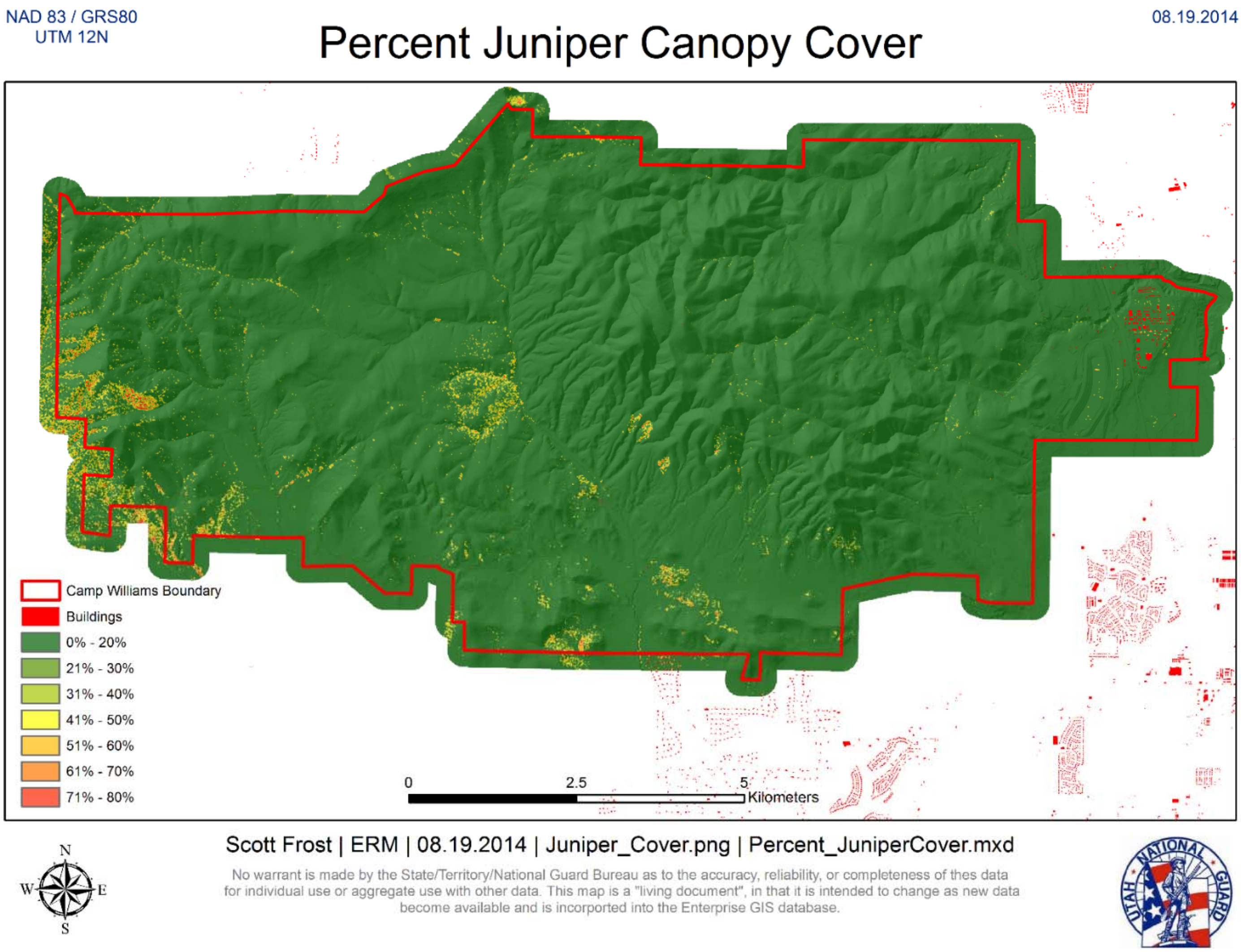

Figure S9. Map of percent juniper canopy cover at Army Garrison Camp Williams, UT, updated to reflect the post-burn vegetation coverage of juniper following the 2012 Pinyon Fire.

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