Ratcliff F, Rao D, Barry S, et al. 2022. Cattle grazing reduces fuel and leads to more manageable fire behavior. Calif Agr 76(2):60–69. https://doi.org/10.3733/ca.2022a0011

Supplemental Appendix

This appendix is provided as supplement to the paper ***Cattle grazing reduces fuel and leads to more manageable fire behavior*** to present additional detail on the data sources, estimation methods and results from the study.

Data and Methods:
Six data sources were used to estimate regional fuel reduction rates by cattle. These sources are outlined in Supplemental Table 1.

Supplemental Table 1. Data sources used to estimate fuel reduction rates by cattle.

Dataset	Source	Description	Year(s)
USDA Agricultural Census	United States Department of Agriculture (USDA) Link: https://www.nass.usda.gov/Publications/AgCensus/2017/index.php	Inventory of beef cows and "other cattle" for each California county	2017 (some data from 2012)
Brand Inspection Data	California Department of Food and Agriculture (CDFA)	For every brand inspection, data includes: date, location, and class of cattle (bull, cow, heifer, "mixed", steer). The "mixed" class refers to batch inspections of multiple cattle with differing classes. Cattle are inspected when they are sold, moved out	2017

		of state, or brought to a feed yard or slaughterhouse.	
County Crop Reports	County Agricultural Commissioner's Offices Link: https://www.cdfa.ca.gov/exec/county/documents/CountyCropReportManual.pdf	Includes total "harvested acreage" of rangelands. Methods to determine rangeland acreage vary by county. We supplemented this data through consultation with staff at county agricultural commissioner's offices, and reduced rangeland acreage from Mono and Inyo counties to exclude large swaths of federal lands with very low grazing intensity (UCANR 1982; see supplemental appendix).	2017 (other years to fill information gaps—see Crop Report Data below)
GAP LANDFIRE	US Geological Survey Link: https://www.sciencebase.gov/catalog/item/573cc51be4b0dae0d5e4b0c5	A continuous, remotely-sensed classification of vegetation communities across California. Includes "total rangeland" acres (grazed and ungrazed)	2011

MODIS	National Aeronautics and Space Administration (NASA) Link: https://modis.gsfc.nasa.gov/data/	Satellite imagery used to determine percent canopy cover using methods described in Sexton et al (2013)	2010
County UCCE Offices	Consultation regarding irrigated pasture use and rangeland cattle production regions	Delineations of rangeland cattle production regions and estimates of county irrigated pasture use (percent of cows using irrigated pasture, and months of use). Numbers were based on observations and experience, not survey results.	2020

Data from these sources were used to estimate regional fuel reduction rates using the following equation (an explanation of these variables is in Supplemental Table 2):

$$forage\ consumed = \sum_{region\ k} (\sum_{county\ j} (\sum_{cattle\ class\ i} (head_{ijk} * \ months_{ijk} * AUE_i - IP.adust_{ijk}\ ) * \frac{1000\ pounds}{AUM}))$$

Supplemental Table 2. Variables used to estimate forage reduction per acre per region.

Variable	Description	Dataset	Calculation
Head	Number of head of cattle (per class)	USDA Census[1] and Brand Inspection	Census includes # of beef cows per county. All other classes are combined in "other cattle" with non-cow dairy cattle. We used the ratio of beef:dairy cows in the Census data to estimate the proportion of "other cattle" that were beef cattle. Then we multiplied the proportion of each non-cow cattle class in each county in the brand inspection data by the total number of other beef cattle to determine the number of each class of non-cow cattle in each county. Feedlot inventories were removed from beef cattle estimates for Fresno, Kings, Kern and Imperial counties.
Months	Number of months on rangeland	Brand Inspection Data	We used average brand inspection date to determine total number of months each class was on range in each county. For steers and heifers, we added one month to the calculation to account for cattle coming to range in the fall (before Jan 1). We assumed that cows were on range year-round except for those replaced each year. Thus, we estimated their months on range as: $$months\ on\ range\ (cows) = 12 - (replacement\ rate * avg.number\ of\ months\ until\ brand\ inspection)$$

			Where replacement rate was the ratio of cows in the brand inspection data : cows in the USDA Census for a given county.
AUE	Animal unit equivalent	Bush (2006)	AUEs convert all cattle classes to Animal Units. Animal units are multiplied by number of months to calculate Animal Unit Months (AUMs). AUEs used in this calculation were: bulls: 1.35 AUE, cows: 1 AUE, stockers/heifers: 0.6 AUE, “mixed” 1 AUE.
AUM	Animal Unit Month	Bush (2006)	An animal unit month is the amount of forage consumed by an animal unit (typically described as a 1000-pound [454 kilogram] cow) over one month. We used 1000 pounds (454 kilograms) of forage for 1 AUM (Bush 2006). See “Animal Unit Months and Forage Removal” below for more detail.
IP.adjust	Irrigated Pasture Use Adjustment	UCCE Livestock and Range Advisors	Irrigated pasture use in each county was estimated through discussion with livestock and UC Cooperative Extension livestock and range advisors. Given the season of use of irrigated pasture and the months on range of each class of cattle, irrigated pasture use was only estimated for cows. Irrigated pasture use (as a portion of total grazing use) was then subtracted from total AUMs in each county to get an adjusted estimate of AUMs grazed on rangelands. While representative of general practices in the counties, these estimates are not based on survey or

			census data and may therefore lead to some estimation error, especially in regions with higher irrigated pasture use: San Joaquin-Sierra and Sacramento-Sierra-Cascade.

[1] If inventory data for a county were suppressed in the 2017 census, data from the 2012 census were substituted. If 2012 data were suppressed, data were estimated based on number of operations of different size classes in the county in 2017 (see *2017 USDA Agricultural Census Data* below for details).

2017 USDA Agricultural Census Data

The Agricultural Census is conducted by the US Department of Agriculture every five years. It was last completed in 2017 (USDA 2017). The census includes an inventory of cattle in each county in California as of December 31st 2017. This inventory details the number of beef and dairy cows in each county but does not give information about the number of any other cattle class. Instead, other cattle classes (beef and dairy) are lumped into one number called "other cattle" for the county. To estimate the number of each non-cow beef cattle class in each county, we had to first estimate what proportion of the "other cattle" were beef cattle (not dairy), and then split those beef cattle into their constituent classes. This was done using the 2017 Brand Inspection Data (below).

The Agricultural Census suppresses data if they believe the data could reveal information about individual producers or businesses. This usually happens when there are only a few livestock operators in a given county. When we encountered suppressed data, we estimated the missing data using the following procedure:

1) Replace with the 2012 value if available.
2) For data that don't have a 2012 value:
    a. Calculate the average number of cattle per operation size class, for beef cows and other cattle. (The census tallies # of operations by size class, and unless suppressed, lists number of inventory in each size class)
    b. Replace suppressed values in the census data with estimates for those size classes.
    c. Sum the number of cattle in each size class by adding the total number of animals in each size class for each county. For any suppressed operation size class information: multiply the number of operations in each suppressed size class by the average number of head in that size class and add to the sum of size classes for the county.
3) Add these summed values back into the Census data frame for the total "beef cow" and "other cattle" categories.

Between "Beef Cows" and "Other Cattle", there were 20 suppressed entries, seven of which we replaced with 2012 values, and 13 of which we estimated based on operation size classes.

We removed beef cattle "on feed" from the four counties with major feedlot operations in the state: Fresno, Imperial, Kern, and Kings Counties. For Imperial and Kern Counties, the feedlot reduction number came directly from the Census. For Kings and Fresno Counties, the feedlot cattle numbers were estimated from the brand inspection data, and adjusted by the ratio of total cattle on feed in California (from census) : total cattle in feedlots in brand data.

2017 Brand Inspection Data

Brand inspection data is collected by California Brand Inspectors at the following times:

1. At the time of sale or transfer of ownership
2. Prior to moving out of state

3. Prior to slaughter
4. Upon entry to registered feedyard
5. Prior to release from a saleyard

Inspections occur at approximately 20,000 ranch locations, 30 livestock sale yards, 31 feed yards, and four major meat processing plants. The brand inspection data includes descriptions of breed or color, and class of animal (e.g., cow, bull, heifer, steer, calf). Sometimes class is referred to as "mixed" if there are several classes in a mixed inspection batch. Brand inspectors also record the date of inspection and change in status, location of inspection, the reason for inspection, cattle county of origin, and owner identification. If applicable, inspectors will include information on the cattle buyer and destination, and on the agents, who facilitated the sale.

We categorized cattle as beef or dairy using breed and color information. Cattle of beef breeds were classified as dairy if they originated from a dairy. Dairy cattle in California are primarily raised in confined feeding operations or, if pasture-based, they are raised on improved pastures. Few cattle for dairy production utilize dryland pasture or rangeland. Movements of beef cattle from grazing lands to new pasture, feedyards, saleyards, or meat processing plants were identified based on inspection type, buyer, and destination information.

We used the brand inspection data for three primary purposes. They were:

1) To determine the relative number of beef versus dairy "other" cattle in each county. This ratio was used to break up the number of "other cattle" in the 2017 USDA Agricultural Census into beef and dairy cattle.
2) To determine the number of each non-cow beef cattle class in each county the proportion of each non-cow beef cattle class was multiplied by the total number of "other cattle" that were determined to be beef cattle. This yielded estimates of number of head of each non-cow beef cattle class in each county.
3) To determine length of time on rangeland. We assumed that since most brand inspections occur when the animal is going to a feedyard, leaving the state, being slaughtered, or otherwise transferring ownership, a brand inspection generally coincided with an animal leaving rangeland in the region it was in at the time of inspection. Therefore, the average number of months before the inspection occurred was deemed the average time spent on range by a particular class of cattle in a particular county. For Steers and Heiffers we added one month to this average number assuming that most stocker cattle are brought onto rangelands before January 1st, and therefore we should account for grazing in some portion of the previous year. For cows, we assumed that most cows are on rangeland year-round in California. Thus, it was necessary to estimate the proportion of cattle that are replaced every year (replacement rate) and only apply the average brand inspection date to the portion of cows being replaced. The equation to determine months on range for cows was:

$$months\ on\ range\ (cows) = 12 - \ (replacement\ rate * avg.number\ of\ months\ until\ brand\ inspection)$$

Animal Unit Months and Forage Removal

Animal Unit Months (AUMs) are the total number of animal units * total number of months each animal unit grazes. An animal unit is described as a cow and her calf, which usually consume approximately 1000 pounds of rangeland forage per month (Bush 2006). Other cattle classes consume forage at different rates and must first be converted to animal units (using "animal unit equivalents" for their classes). After converting all head to animal units, we multiplied animal units per class by months on range per class to generate total animal unit months per county. Before summing this to calculate total forage removed per county, we subtracted estimated AUM of beef cows using irrigated pasture. There is no comprehensive dataset that can account for the amount of beef cattle grazing occurring on irrigated pasture in counties across the state, so we consulted with UC Cooperative Extension offices to provide estimates of percent, duration, and seasonality of irrigated pasture use by beef cattle. Based on the season of use of irrigated pasture and the months on range of each class of cattle, we decided to only estimate irrigated pasture use for cows. Once we knew the approximate percentage of cows using irrigated pasture in each county, and the approximate number of months they used irrigated pasture in each county, we calculated AUM of beef cows on irrigated pasture and subtracted that from county totals. The estimates from UC Cooperative Extension offices are not from survey data or extensive analysis. They are estimates from people familiar with these regions that were provided to help guide this analysis, but several Extension officials emphasized that land use and grazing practices are dynamic in their counties and vary due to weather, industry consolidation, land use change and annual forage conditions. Therefore, although these estimates constitute the best available information, they may vary from actual irrigated pasture use in any given year. This could lead to error in the estimate of total forage removed from the areas with higher proportions of irrigated pasture use: San Joaquin-Sierra and Sacramento-Sierra-Cascade.

Another important consideration regarding irrigated pasture use is that movements of cattle to and from irrigated pasture often cross county lines. Since the 2017 Agricultural Census is just a snapshot of livestock operations on December 31st 2017, the county inventories do not necessarily reflect the location of animals throughout the year. This is especially true in areas with significant seasonal movement of cattle (as is often the case to and from irrigated pasture). To account for this discrepancy, we created the "regions" used in this study. These regions are based on our conversations with UC Cooperative Extension offices and represent our best information about inter-county beef cattle movements in the state.

Crop Report Data

We used "harvested rangeland" data from county crop reports to provide an estimate of the total grazed rangeland in each county. Crop reports are produced annually by each county's Agricultural Commissioner's office. There is no consistent methodology across counties (and in some cases across years within the same county) for determining rangeland acreage. Counties may base their numbers on surveys with ranchers, restricted materials permits, crop insurance statistics, or other methods. Some counties include portions of federal grazing allotment acreages, others do not. We used crop reports from 2017 whenever possible, however not all counties had 2017 reports available. We also consulted several county agricultural

commissioner's offices to discuss inconsistent or perplexing rangeland acreage numbers (such as precipitous shifts in rangeland acreage between years). In cases where data were not available for 2017 or another year was deemed to better represent grazed rangeland acreage, we used crop report data from other years.

Mono and Inyo County crop reports included large swaths of federal grazing allotment acreage in their crop report. In order to avoid including vast acreages that are only minimally (or not actually) grazed, we reduced these rangeland acreage numbers to exclude federal lands (Supplemental Table 3). We did this by subtracting the acreage of government, farm, irrigated, and water district (Los Angeles Department of Water and Power) from the total acreage of the county (UCANR 1982). This provided an upper cap to the number of private grazed lands in the county, and we reduced the counties' grazed acreage to this number.

After removing federal grazing lands from Mono and Inyo Counties, the total Crop Report acreage across California sums to 19.4 million acres. This is close to the 17 million acres of private grazing land estimated to be in the state (FRAP 2017). Although it probably includes some federal acreage and some local public lands (e.g., county parks and regional park districts), it is a fair approximation of privately-owned grazed rangelands. In general, we believed it was necessary to minimize federal grazing allotments in our estimate of grazed rangelands because they constitute large acreages, with relatively few livestock, and thus would skew the grazing intensity numbers to be much lower than they are on the non-federal rangelands where the great majority of cattle grazing occurs. US Forest Service (USFS) has seven million acres in grazing allotments in the state (FRAP 2017), with only 71,481 cattle authorized to graze 321,602 authorized AUMs in 2016 (USFS 2017). This means that only approximately 4% of the California herd is grazing USFS lands at some point in the year, for an equivalent of only 2.8% of the total rangeland AUMs in the state in 2017. BLM grazing allotments cover about 7.1 million acres in the state (FRAP 2017), with approximately 472,000 authorized AUMs annually. This is equivalent to 4% of the total AUMs in the state. So, while USFS and BLM lands collectively account for 45% of total land authorized for grazing in the state, grazing on these public lands only account for about 7% of the total forage consumed. One caveat is that the Sacramento – Sierra – Cascade region has more public lands grazing than other regions, and therefore, the estimate of pounds per acre of fuel reduction on grazed rangelands for this region may be somewhat higher than it would be if all public lands were included. An important note however, we did not remove acreage from any crop reports in the Sacramento-Sierra-Cascade region, and some of the crop reports for those counties do likely include some federal acreage.

GAP Classification and MODIS Canopy Cover

We used remotely-sensed vegetation classifications from the California Gap Analysis Project and canopy cover estimates from MODIS imagery (Sexton et al 2013) to classify rangeland vegetation across the state. In our classification: grasslands, shrublands, and woodland/savannahs (<30% canopy cover) were considered rangeland.

Supplemental Table 3. Crop Report rangeland acreage data.

County	Year	Rangeland Acres	Notes
ALAMEDA	2017	175360	
ALPINE	2017	133000	
AMADOR	2017	156801	
BUTTE	2017	195000	
CALAVERAS	2017	197805	
COLUSA	2017	180000	
CONTRA COSTA	2017	169000	
DEL NORTE	2015	15500	
EL DORADO	2017	233000	
FRESNO	2017	840000	
GLENN	2017	224325	
HUMBOLDT	2009	470000	Rangeland acreage not included in 2017. Included in reports before 2010. It is consistently 470K acres for several years.
IMPERIAL	NA	0	Ag Commissioner's Office and UCCE told us that there is really no rangeland grazing in Imperial County
INYO	2017	600000	This figure was reduced to eliminate vast federal lands acreage. Previous number was: 1,187,859 acres
KERN	2017	1446000	
KINGS	2016	338243	2016 was the most recent year
LAKE	2017	90000	
LASSEN	2017	1291253	
LOS ANGELES	2017	4595	
MADERA	2017	387000	
MARIN	2017	154000	
MARIPOSA	2015	416000	
MENDOCINO	2017	718000	
MERCED	2017	552632	
MODOC	2018	456600	
MONO	2017	210000	This figure was reduced to remove vast federal lands with low grazing use. Previous acreage was: 1059838
MONTEREY	2017	1062686	
NAPA	2017	95000	
NEVADA	2017	95000	
ORANGE	2017	16187	
PLACER	2017	130000	

PLUMAS	2018	94795	
RIVERSIDE	2017	15000	
SACRAMENTO	2017	57860	
SAN BENITO	2017	504600	
SAN BERNARDINO	2017	1407720	
SAN DIEGO	2017	190778	
SAN FRANCISCO	2016	0	
SAN JOAQUIN	2017	120000	
SAN LUIS OBISPO	2017	1012000	
SAN MATEO	2017	24107	
SANTA BARBARA	2017	574326	
SANTA CLARA	2017	263375	
SANTA CRUZ	2017	0	Rangeland acreage not included in report
SHASTA	2017	293000	
SIERRA	2018	46844	
SISKIYOU	2017	445000	
SOLANO	2017	187000	
SONOMA	2017	315412	
STANISLAUS	2017	421949	
SUTTER	2017	63000	
TEHAMA	2017	917700	
TRINITY	2016	125802	
TULARE	2017	615000	
TUOLUMNE	2017	200000	
VENTURA	2017	197699	
YOLO	2013	116200	Used 2013 acreage number. All years before 2013 have >100K acres. In 2014, it changed to 15,446 acres. Something changed in how they accounted for this.
YUBA	2017	187110	

Production and RDM Data:

Four forage production and Residual Dry Matter (RDM) datasets were used to characterize variability in production and RDM within and between regions. These four datasets represent 52 sites in the Central Coast, North Coast, and Sacramento-Sierra-Cascade regions, where production data was collected between 2000 and 2019; and 105 sites in these regions where RDM data was collected between 1987 and 2019 (Supplemental Table 4).

Supplemental Table 4. Production and RDM datasets used in the analysis.

Region	Data Source	Years	Number of Sites
Central Coast	Larsen et al. (2020)	RDM and Production sampled 2001-2020 (sites phased in over time)	**Production**: 43 **RDM**: 43
Northern California	Bartolome et al. (2015) and Point Reyes National Seashore (unpublished data)	Production: 2018-2019 RDM: 18 years between 1987-2014	**Production**: 6 sites **RDM**: 3-50 sites (average 32 sites per year)
Central Coast	NRCS unpublished data (2010)	Production and RDM: 2007-2010	**Production**: 2 ungrazed sites **RDM**: 11 grazed sites
Sacramento-Sierra-Cascade	UCANR (unpublished data)	Production: 1979-2019 RDM: Estimated	**Production:** 1 site (with extensive subsampling) **RDM**: Estimated

Results:
Supplemental Table 5 shows the average number of months on range for each cattle class. Note: there are cattle in each class that graze rangelands year-round (especially cows). An average below 12 months does not mean that all cattle of that class use rangeland for less than 12 months. Rather, the numbers in Table 2 represent the number of months on range averaged across cattle of each class in each county, including those that leave range early in the year.

Supplemental Table 5. Average, minimum and maximum number of months on range by class. Minimum and maximum refer to the county with the lowest and highest average number of months on range for that class.

Cattle Class	Average Months on Range	Minimum Months on Range	Maximum Months on Range
Bull	6.6	4.8	8.8
Cow	10.7	7.3	11.8
Heifer	7.7	6.4	9.4
Mixed	6.6	3.2	10.9
Steer	7.6	6.8	9.3

Fire Behavior Models

The fire behavior models evaluated flame height along a range of wind speeds, terrain slopes, dead fuel moistures, and for the spring model, live fuel moistures. Specific model parameters are in Supplemental Table 6. Supplemental Figures 1-9 show how varying these model parameters affected wildfire flame length across a range of fine fuel loads.

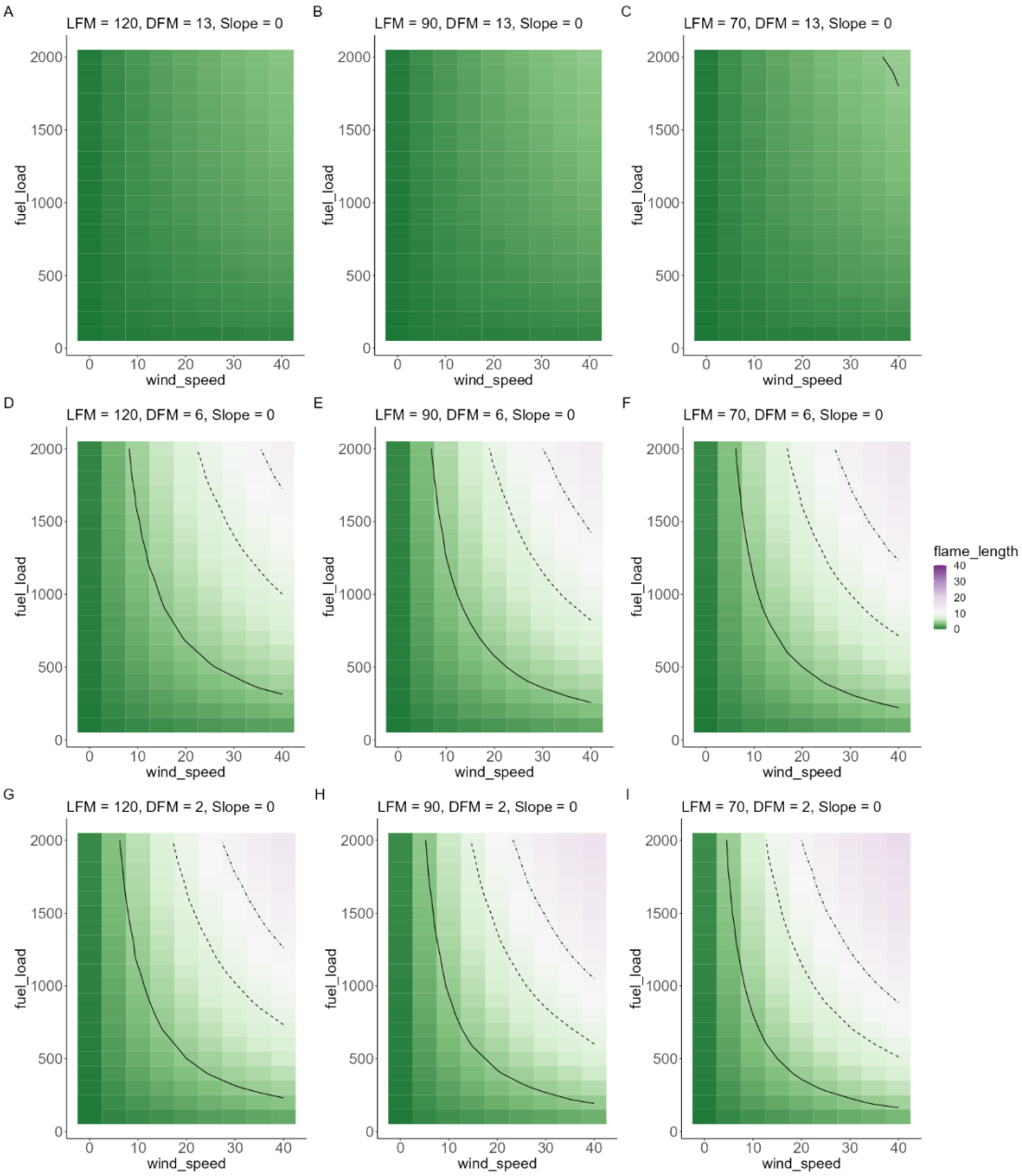
Models used the GR2 model and both of the grass models from the original 13 fuel models as the input and altered fuel loads in 100lb/acre increments. The spring scenario has half of the fuel in the dead 1-hr fuel load class, half as live herbaceous fuel, dead fuel moisture (percent of biomass made up of water) set to either 13%, 6%, or 2%, and live fuel moisture (LFM) set to either 120%, 90%, or 70%. The summer scenario has all fuel in the dead 1-hr fuel load class and dead fuel moisture (DFM) set to either 13%, 6%, or 2%. For both scenarios, moisture of extinction (fuel moisture at which the fuel no longer carries a fire) was set to 15%, so, our DFM values are to show how critical fuel load changes as DFM approaches moisture of extinction. LFM values were chosen to represent the progression of senescence as live herbaceous fuels progress from alive to fully cured.

Supplemental Table 6. Variables and values used in the fire behavior models.

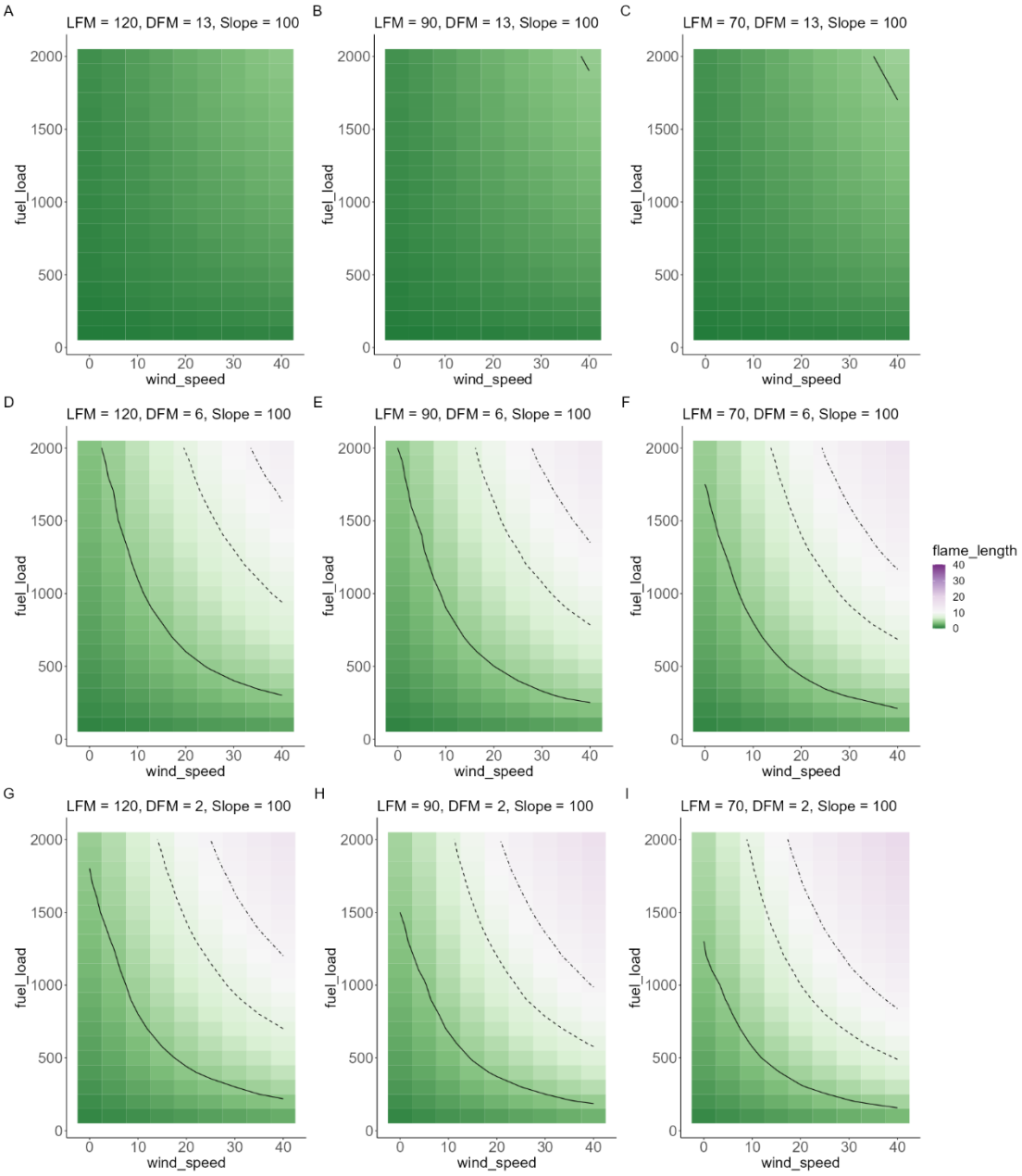
Variable	Value(s)
Fuel Load	100-2000 pounds per acre (112-2242 kilograms per hectare), by increments of 100 pounds

Dead Fuel Moisture	Summer model: 13%, 6%, 2% Spring model: 13%, 6%, 2%
Live Fuel Moisture	Spring model: 120%, 90% 70%
Dead : Live Fuel Ratio	Summer model: 1:0 Spring model: 1:1
Fuel Bed Depth	GR2: 1.00 ft Short grass: 1.00 ft Tall grass: 2.5 ft
Terrain Slope	Low slope: 0% High slope: 100%
Wind Speed	Variation: 0 – 40 miles per hour (0-64 kilometers per hour), by increments of 5mph
Surface Area : Volume	GR2: Dead fuel: 2000 Live fuel: 1800 Short Grass: Dead fuel: 3500 Live fuel: 1500

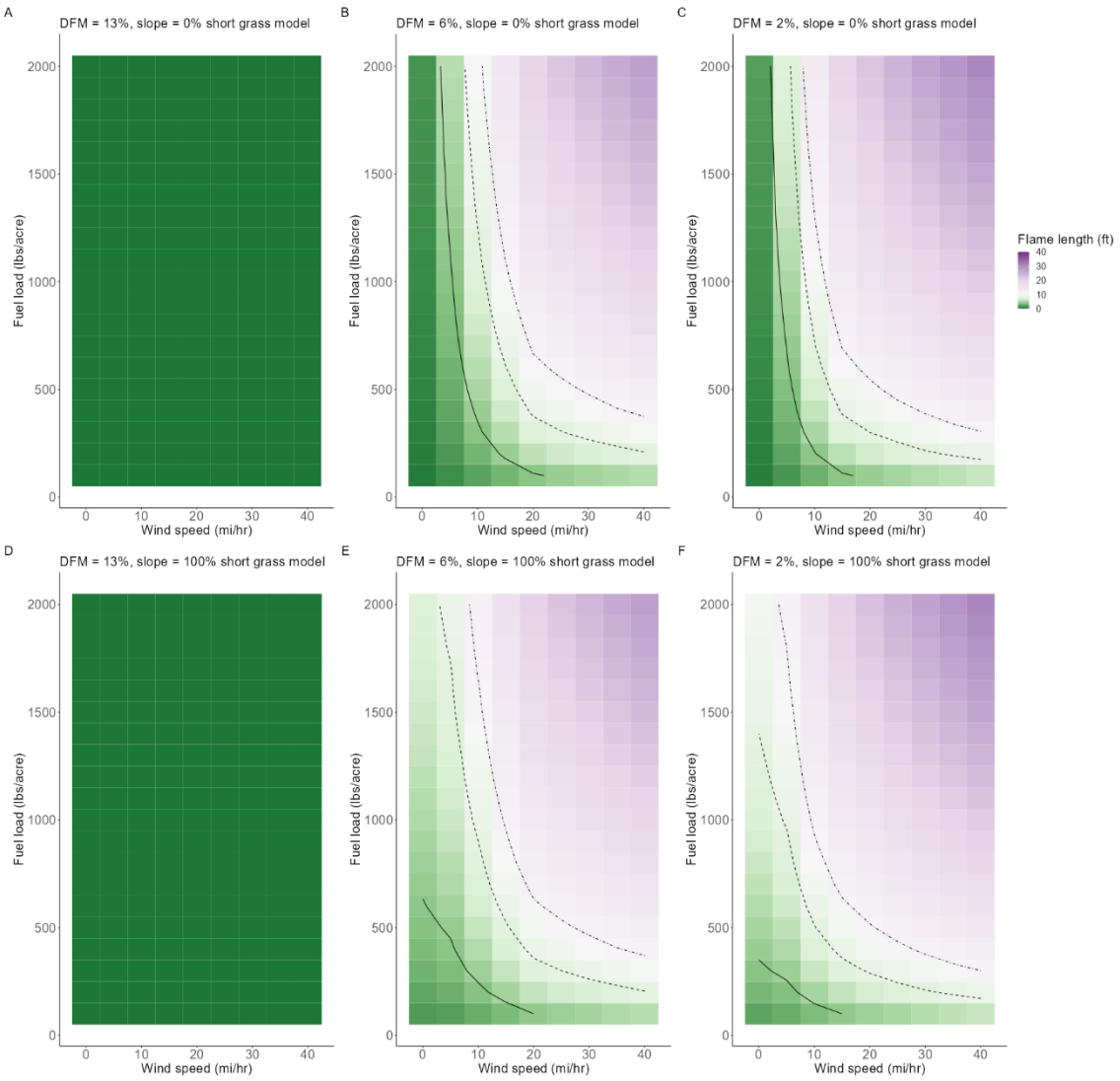
	Tall Grass: Dead fuel: 1500 Live fuel: 1500



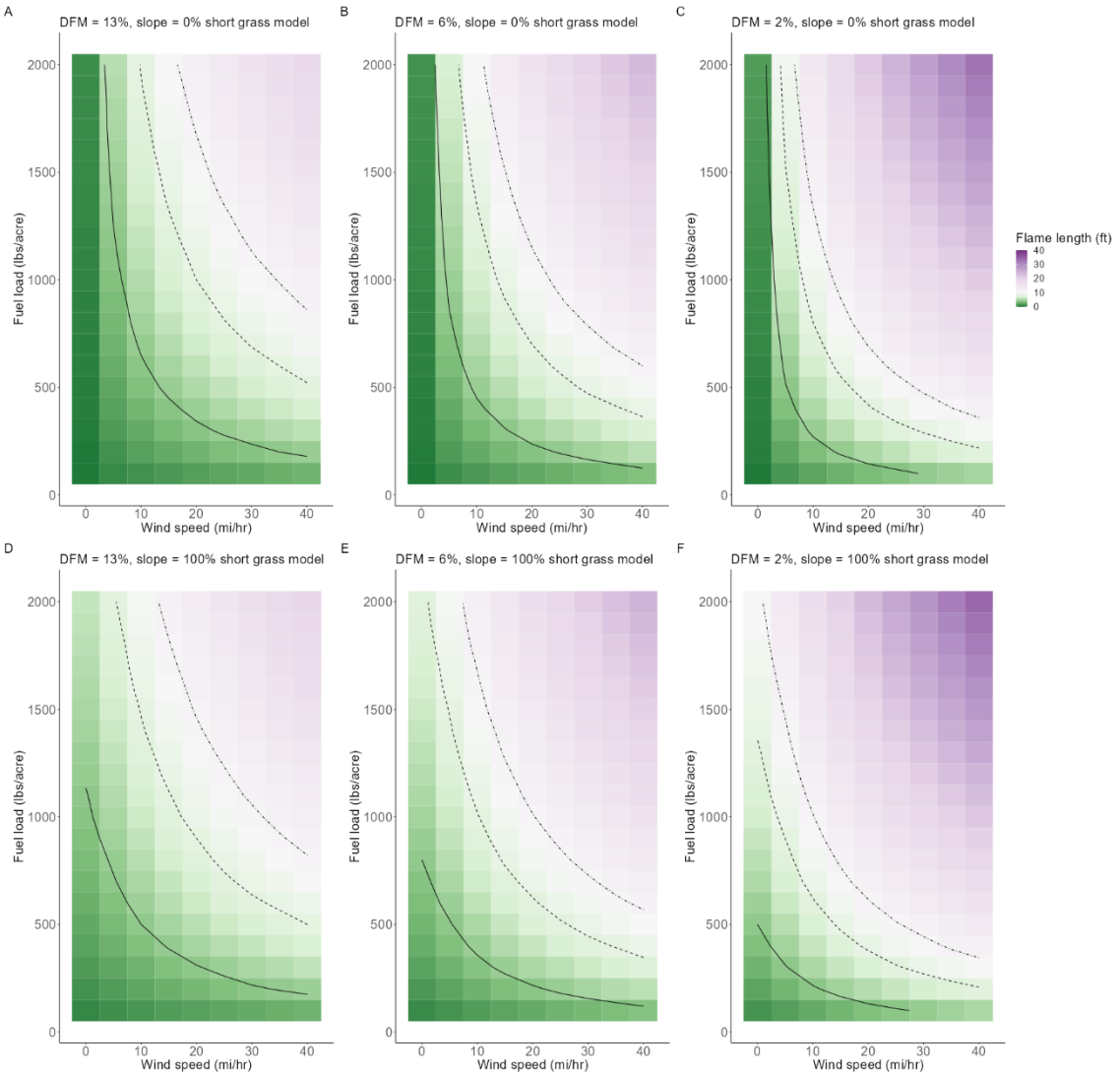
Supplemental figure 1: Fire behavior model results from GR2 model under spring and low slope (0%) scenario. Fire behavior was modeled under three live fuel moisture scenarios of 120% (A,D, and G), 90% (B,E,and H) and 70% (C,F, and I) and three dead fuel moisture scenarios of 13% (A, B, and C), 6% (D, E, and F) and 2% (G,H, and I). Contour lines show when threshold flame lengths of 4ft (solid line), 8ft (dashed line) and 11ft (dotdashed line) are surpassed. Panels A and B lack graphed lines because none of the fuel load or wind speed values in our model resulted in flame lengths greater than four feet.



Supplemental figure 2: Fire behavior model results from GR2 model under spring and high slope (100%) scenario. Fire behavior was modeled under three live fuel moisture scenarios of 120% (A,D, and G), 90% (B,E,and H) and 70% (C,F, and I) and three dead fuel moisture scenarios of 13% (A, B, and C), 6% (D, E, and F) and 2% (G,H, and I). Contour lines show when threshold flame lengths of 4ft (solid line), 8ft (dashed line) and 11ft (dotdashed line) are surpassed. Panel A lacks graphed lines because none of the fuel load or wind speed values in our model resulted in flame lengths greater than four feet.



Supplemental figure 3: Fire behavior model results from the short grass model under summer scenario. Fire behavior was modeled under three dead fuel moisture scenarios of 13% (A and D), 6% (B and E) and 2% (C and F) and two slope scenarios of 0% (A, B and C) and 100% (D, E and F). Contour lines show when threshold flame lengths of 4ft (solid line), 8ft (dashed line) and 11ft (dotdashed line) are surpassed. Note that panels A and D are a uniform shade of green, as those conditions are modeled to not carry fire under any fuel load, so all flame lengths are modeled at zero.



Supplemental figure 4: Fire behavior model results from the tall grass model under summer scenario. Fire behavior was modeled under three dead fuel moisture scenarios of 13% (A and D), 6% (B and E) and 2% (C and F) and two slope scenarios of 0% (A, B and C) and 100% (D, E and F). Contour lines show when threshold flame lengths of 4ft (solid line), 8ft (dashed line) and 11ft (dotdashed line) are surpassed.

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