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Research Article

California Agriculture: The Journal of UC Agriculture and Natural Resources

Grassland biomass thresholds critical to fire behavior in California

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Abstract

Anecdotal and fire behavior modeling evidence indicates that livestock grazing can reduce herbaceous fuels and improve ecosystem resilience in an era of expanding and intensifying wildfires. To quantify these effects in California, we established a statewide, multi-year (2020 to 2022) study manipulating herbaceous biomass levels within prescribed fire footprints to examine the relationship between herbaceous biomass levels and key fire behavior metrics. We identified multiple biomass thresholds that may be incorporated into land management and planning documents. Grasslands with fewer than 384 pounds (lb) per acre (43 grams per square meter [g/m²]) biomass had greater than 90% probability of stopping a fire before reaching 33 feet (ft) (10 meters [m]) while grasslands with biomass greater than 1,248 lb/acre (140 g/m²) had a near zero probability of stopping a fire before reaching 33 ft. Biomass values below 2,496 lb/acre (280 g/m²) had only a 3% probability of reaching 4 ft (1.2 m) flame height. These biomass thresholds and associated fire behavior metrics can be strategically employed to manage grasslands to protect California's communities in the context of meeting other goals, including minimum residual dry matter standards.

The intensity, extent and frequency of wildfires have been increasing in California due to multiple factors (Steel et al. 2015; Stephens and Ruth 2005; Stephens et al. 2007). Livestock grazing is commonly used to reduce herbaceous and small diameter woody fuels at the landscape scale (Taylor 2006). Although some land management entities identify grazing as one of their primary landscape-level fire hazard reduction tools, typical grazing plans lack upper biomass thresholds that are related to goals for fire behavior (EBRPD 2013, 42).

Livestock alter fuel loads on rangelands by consuming herbaceous material, reducing the frequency and cover of woody plants, and by compacting and incorporating organic material into the soil (Taylor 2006). The amount of annual herbaceous biomass depends on inherent soil productivity and variable climatic factors within the growing season (Becchetti et al. 2016, 5). One California study used regional datasets to estimate that cattle (*Bos taurus*) grazing removes between 174 and 1,020 pounds per acre (lb/acre; 20 to 114 grams per square meter [g/m^2]) of herbaceous biomass annually (Ratcliff et al. 2022, 64). This reduction in biomass has been directly tied to decreases in annual wildfires (Siegel et al. 2022).

An earlier study (Stechman 1983) assessed the impact of multiple vegetation management approaches, including grazing, on fire behavior, but grazing levels were not quantified beyond "moderate" grazing. Field-based manipulative studies in other regions have successfully demonstrated the effects of cattle grazing on rate of spread and flame length (Bruegger et al. 2016; Davies et al. 2010; 2015; Diamond et al. 2009; Orr et al. 2022; Schmelzer et al. 2014), but these are not directly applicable to the dominant California grassland types. Grasslands in the other studied regions, includ-

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Fig. 1. Locations of nine prescribed burn study sites across California, where blocks of herbaceous biomass were mowed to mimic different grazing levels (2020 to 2022). From north to south, the sites are located in the following counties: Site F, Humboldt; G and E, Sonoma; B, Santa Cruz; A, San Luis Obispo; I and H, Santa Barbara; C and D, Madera County. Data sources: USGS (GAP, 1998; TIGER, 2012).

ing California Floristic Province and Great Basin Province in northeastern California, are more often dominated by native perennial bunchgrasses adapted to colder high-elevation conditions compared to California grasslands, which are dominated by non-native annual and perennial grasses adapted to Mediterranean and coastal climatic conditions. This study aimed to inform land management and livestock grazing policy by identifying critical biomass thresholds that affect relevant fire behavior metrics in California.

Experimental study design

Our study assessed how a spectrum of herbaceous biomass affected fire behavior across 45 randomized blocks located within nine prescribed burn sites in California (fig. 1). Each 33-foot-by-21-foot (10-m-by-6.5-m) block had four treatments clipped with string trimmers and biomass raked off to mimic livestock grazing (fig. 2). Use of livestock to graze these levels was not feasible due to their small size, need for rapid implementation of treatments, and challenges in creating uniform treatment blocks.

Treatments reflected typical grazing intensities: ungrazed or very lightly grazed (>1,500 lb/acre [168 g/m^2]), light (1,000 to 1,500 lb/acre [112 to 168 g/m^2]), moderate (500 to 1,000 lb/acre [56 to 112 g/m^2]), and heavy (0 to 500 lb/acre [0 to 56 g/m^2]). We clipped biomass from one representative sample of each treatment level of each block using standardized quadrats and weighed the sample in the field. We then dried these samples in a controlled environment and reweighed them to assess minimum dry weight, which was used in the analysis.

Our randomized complete block design included three block replicates within each available slope class: 0% to 10%, 10% to 20%, and 20% to 40% slopes (see table 1). The nine sites were categorized as coastal prairie (CP) or annual grassland-hardwood (AGH) grassland types (Barbour et al. 2007; Bartolome et al. 2006). AGH sites were dominated by wild oats (*Avena* spp.) and bromes (*Bromus* spp.) while CP sites had higher perennial grass cover (e.g., *Elymus glaucus*, *Agrostis* sp.).

Three aluminum metal tags painted with temperature-sensitive paints (Tempilaq) were placed within each treatment to estimate maximum soil surface temperature during the burn; paint thresholds ranged from 225°F to 650°F (107°C to 343°C) (Iverson et al. 2004). Before and after each burn, we conducted 33-ft (10-m) point intercept transects, recording cover type every 4 inches (10 centimeters [cm]) along the midline of each treatment to assess cover classes: grass, forb, thatch, bare ground, rock, and ash (Caratti et al. 2006).

Blocks were ignited along the lowest elevation of the block and/or downwind to mimic natural fire movement up hills and with the wind. During the burn, we recorded wind speed and direction, relative humidity, and ambient temperature at regular intervals. We recorded time for the fire line to move from 0 to 16 ft (0 to 5 m) and from 16 to 33 ft (5 to 10 m), and approxi-

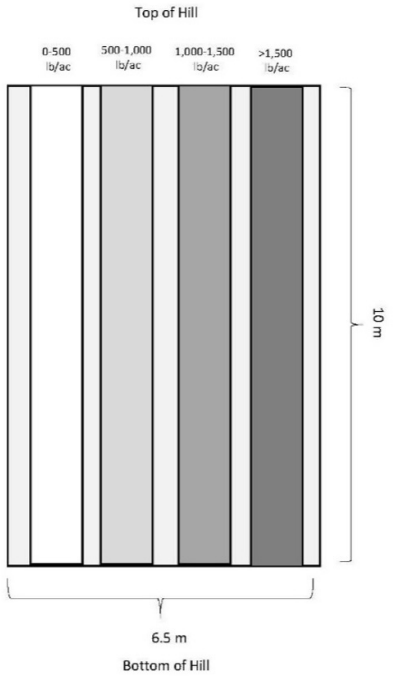


Fig. 2. Example block of biomass manipulation treatment strips replicated within prescribed burn study sites across California (2020 to 2022). The ">1,500 /acre" strip was untreated (up to 60,300 lb/acre).

Table 1. California vegetation (CALVEG) zone (USDA 2011), season, year, slope classes (1 = 0%–10%; 2 = 10%–20%; 3 = 20%–40%), grassland type (Bartolome et al. 2006), ambient temperature (°C), relative humidity (%), and notes for each prescribed burn study site. Grassland types include the following: AGH = annual grassland-hardwood; CP = coastal prairie. Ambient temperature and relative humidity data reported were documented on the burn day.

CALVEG mapping zone	Site	Season of burn	Year	Slope class(es)	Grassland type	Ambient temperature (°C)	Relative humidity (%)	Notes
Central Coast and Montane	A	Spring	2022	1; 3	AGH	32	24	—
	B	Summer	2021	1; 2	AGH	18	71	—
Central Valley	C	Spring	2021	1	AGH	27	13	—
	D	Spring	2022	1; 2	AGH	27	29	—
North Coast	E	Spring	2020	1	AGH	19	32	Tempilaq strips excluded; no flame height taken
	F	Summer	2021	1	CP	23	56	—
	G	Summer	2021	2; 3	CP	21	55	—
South Coast and Montane	H	Fall	2020	1; 3	AGH	28	40	No flame height taken
	I	Spring	2022	1	AGH	28	45	—

mate flame height (measured in feet) at 0, 16, and 33 ft (0, 5, and 10 m, respectively) along the linear treatments. We took photographs and videos at critical intervals to document fire characteristics at the 0-, 16-, and 33-ft (0-, 5-, and 10-m) points (Stephens et al. 2008, 77–78).

Data analysis

First, to examine the specific relationship (both shape and significance), between biomass and fire behavior, we ran generalized linear models, accounting for the non-normal data distribution, using R Statistical Software (R Development Core Team 2008). We fit univariate (biomass) generalized linear models with appropriate error distributions (gamma or binomial) and link functions for each measured fire behavior metric (table 2). Then, to identify specific biomass thresholds and evaluate the role of the other measured independent variables, we generated decision trees using the ctree function in the partykit package.

These decision trees included all independent variables (i.e., season, CALVEG zone, slope class, biomass, burn direction, average relative humidity during the burn, and average wind speed during the burn) as inputs the model could choose from to best partition the data. Importantly, variables included as an input in the model may not show up in the final decision tree. Only variables that significantly partition the dependent variable are included in the final tree. We ran two decision trees with management focused outcomes (did flame lengths reach 10 ft and did fire stop by 33 ft) to make the identified thresholds most applicable.

Biomass relationships with fire metrics

Generalized linear models with biomass as a continuous variable

Generalized linear models (glms) showed significant relationships existed between biomass as a continuous variable (fig. 3) and multiple fire behavior metrics (table 2): maximum flame height (fig. 3A), stopping by 33 ft (10 m) (fig. 3C), proportion burned vegetation (fig. 3D), surface temperature (fig. 3E), and white ash cover (fig. 3F). We did not observe a significant relationship between biomass and rate of spread (fig. 3B). Furthermore, these models revealed two potential biomass thresholds: fuel loads above 586 lb/acre (66 g/m^2) have a greater than 50% probability of spreading past 33 ft (10 m) and fuel loads above 3,556 lb/acre (399 g/m^2) have 99% of their biomass consumed by fire.

Decision tree analysis identifying biomass thresholds

In the decision tree analyses, biomass was the only independent variable included in both developed trees. This means that (1) biomass has the strongest association with the dependent variables, and (2) none of the

Table 2. Range of observed values, statistical family, intercept, coefficient estimate, significance, and variance explained (%) for dependent fire behavior variables with biomass manipulation as the independent variable in a generalized linear model for grassland burns across California (2020 to 2022). Rate of spread had one outlier excluded.

Dependent variable	Range of values	Statistical family	Intercept / coefficient estimate	Significance (*P*-value)	Variance explained (%)
Maximum flame height	0.08 to 9.00 ft	Gamma	0.645 / −0.008	≤ 0.001	16
Rate of spread	0.01 to 1.56 m/s	Gamma	8.284 / 0.003	Not significant	0
Stopped by 10 m	0 or 1	Binomial	2.070 / −0.339	≤ 0.001	39
Total burned	0 to 1 (proportion)	Binomial	−0.829 / 0.146	≤ 0.001	39
Surface temperature	225°F to 650°F (107°C to 343°C)	Gamma	2.304e-03 / −1.233e-05	≤ 0.001	10
White ash	0 to 0.56 (proportion)	Binomial	−3.285 / 0.024	≤ 0.001	8

other included variables meaningfully explain the remaining variance/uncertainty in the data. For the decision tree determining whether a fire had 4-ft (1.2-m) flame heights, there was one node with a split threshold of 2,496 lb/acre (280 g/m^2). Flame lengths almost never reached 4 ft (3%) under that threshold (fig. 4A). For the probability of stopping fire, the first node split at 384 lb/acre (43 g/m^2); 93% of fires stopped by 33 ft under that biomass threshold. A second node split at 1,248 lb/acre (140 g/m^2), with only 34% of fires stopping by 33 ft in the 1,248 to 2,496 lb/acre biomass range. Above 2,496 lb/acre, no fires stopped by 33 ft (fig. 4B).

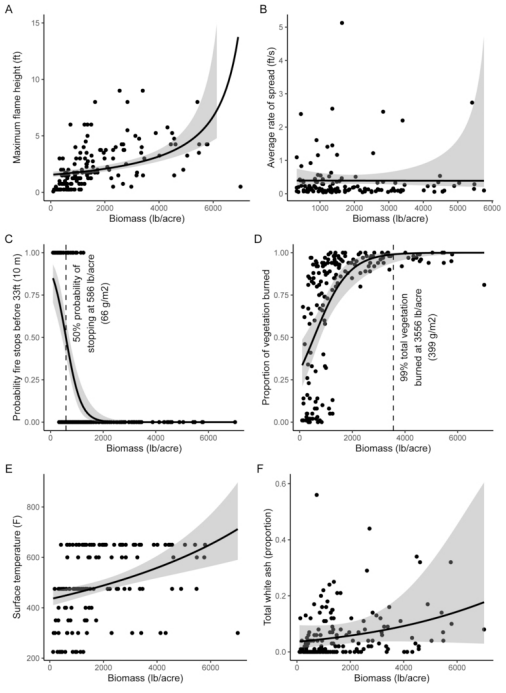


Fig. 3. Predicted relationships (generalized linear model) between herbaceous biomass (lb/acre) and fire behavior metrics from prescribed burn study sites across California (2020 to 2022). Fire behavior metrics include flame height (A), average rate of spread (B), probability fire stops before 33 ft (10 m) (C), proportion of vegetation burned (D), surface temperature (E), and total white ash (F). All models except (B) (not significant) were significant at $P < 0.001$. Relationships are depicted with 95% confidence level intervals for predicted relationships.

Discussion

Thresholds in the context of other goals

Nearly one-fifth of California's land mass is currently grazed (Ratcliff et al. 2022, 64). Livestock and livestock producers represent a critical resource to help address landscape-level wildfire hazards in the state. Until now, it was not well understood how specific grazing intensities affect fire behavior metrics. The thresholds described in table 3 and placed in a regional biomass

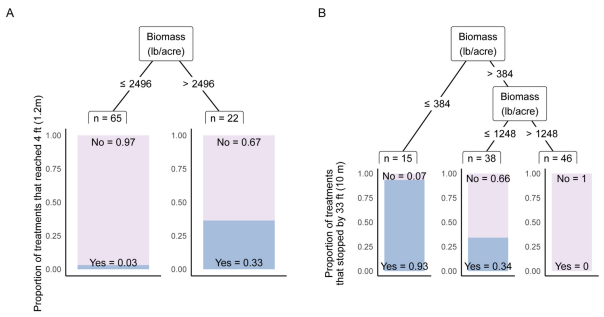


Fig. 4. Conditional inference trees for fire behavior metrics from herbaceous biomass treatments within prescribed burn study sites across California (2020 to 2022). Fire behavior metrics include proportion of treatments where flame height reached 4 ft (1.2 m) (A) and proportion of treatments where fire stopped by 33 ft (10 m) (B).

Table 3. Interpretation and implication of grassland biomass thresholds related to fire behavior metrics derived from decision trees for prescribed burns across California (2020 to 2022). Values are rounded to the nearest whole number for lb/acre and g/m^2.

Threshold (lb/acre [g/m^2])	Interpretation	Implications for management
2,496 lb/acre (280 g/m^2)	Only 3% of treatments with fewer than 2,496 lb/acre of herbaceous biomass had flame heights exceeding 4 ft (1.2 m).	This level of biomass allows hand crews to fight fire and coincides with light to no grazing levels, depending on the region. This level is above all California minimum fall biomass standards outlined for ecological benefits by Bartolome et al. (2006). This value is above the ungrazed and grazed biomass values in the Central Valley as well as the average grazed fall biomass value in the North Coast and Montane region (Ratcliff et al. 2022).
1,248 lb/acre (140 g/m^2)	None of the treatments with greater than 1,248 lb/acre of herbaceous biomass stopped a fire prior to reaching 33 ft (10 m).	There is a 34% probability that a fire will stop spreading with biomass levels at or below this threshold but 0% probability a fire will be stopped above the threshold. This value is above the minimum fall biomass standard values for all annual grassland and annual grassland-hardwood types, which range from 300 to 800 lb/acre (Bartolome et al. 2006, 2). This value is also above the average grazed fall biomass value for the Central Valley (Ratcliff et al. 2022).
384 lb/acre (43 g/m^2)	93% of treatments with herbaceous biomass below 384 lb/acre stopped a fire before reaching 33 ft (10 m).	Fire will not carry below this threshold during most prescribed fire weather conditions. This level is below most recommended fall biomass values for ecological maintenance. Obtaining this biomass level likely compromises other management goals for both land and livestock.

context within figure 5 provide land managers and livestock operators with multiple biomass targets that can be utilized in planning for fire protection balanced with ecological concerns. These fire-related thresholds can be compared to regional herbaceous biomass production and minimum residual dry matter (RDM) standards (fig. 5) (Bartolome et al. 2006, 2; Ratcliff et al. 2022, 65). In the highly productive coastal rangelands, higher levels of biomass are produced and maintained for optimum ecological health while interior regions of California produce lower amounts of biomass and may be grazed to lower levels. The minimum RDM standards vary by grassland type, slope, and woody cover, where lower productivity grassland types have a lower minimum RDM standard and vice versa. Meeting the minimum RDM standard improves soil health and germination of desirable species (Bartolome et al. 2006, 1).

Critical upper biomass thresholds

By grazing herbaceous biomass levels below 2,496 lb/acre (280 g/m^2), the likelihood of flames exceeding 4 ft (1.2 m) is greatly diminished. Figures 6 and 7 show grasslands with biomass above and below this threshold. This biomass level generally coincides with modest grazing levels on coastal prairie and Coast Range grasslands, and a single-year rested pasture in the Central Valley (Bartolome 1987, 122; Becchetti et al. 2016; Larsen et al. 2020). These data suggest that even light levels of grazing can provide safer conditions for firefighters. On rural rangelands, the ability of local personnel to conduct initial fire containment rapidly diminishes when flame heights exceed 4 ft because hand crews can no longer directly attack the fire (Andrews et al. 2011, 1).

Reducing biomass below 1,248 lb/acre (140 g/m^2) represents an important reduction in fire movement across a grassland: there is a chance that fire may not carry below this biomass level. Figure 8 shows a grassland with biomass below this threshold.

The lowest of the thresholds, approximately 384 lb/acre (43 g/m^2), represents the most extreme of the mimicked grazing ranges. Figure 9 shows a grassland with biomass below this level. This value may be used for contract grazing where the primary goal is maintaining fire lines adjacent to physical assets or residences, or for fire protection along potential ignition sources (e.g., roads, utilities). However, managing vegetation to this threshold may increase impacts to soil and vegetation health and structure in nearly all grassland types (Bartolome et al. 2006, 1), reduce animal health and performance, and impact visual aesthetics.

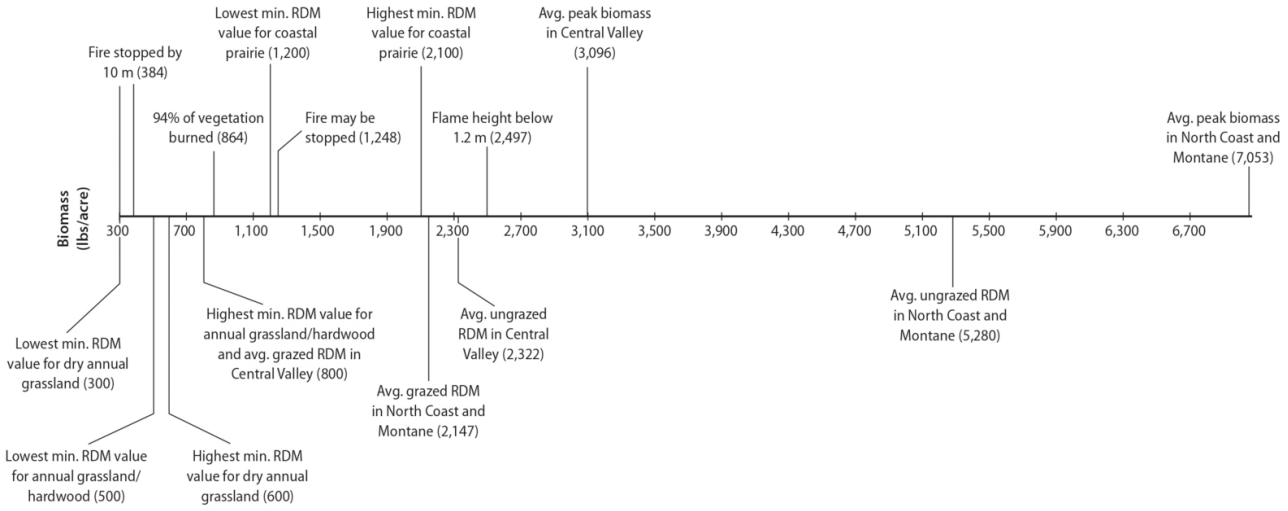


Fig. 5. Average herbaceous biomass production and recommended fall biomass or residual dry matter (RDM) amounts (lb/acre) for grazed and ungrazed California vegetation zones as well as herbaceous biomass (lb/acre) thresholds related to fire behavior metrics observed at prescribed burn study sites across California (2020 to 2022). Minimum RDM values are from Bartolome et al. 2006. Average peak biomass and grazed and ungrazed RDM are from Ratcliff et al. 2022. North Coast is from Northern California Coastal (Point Reyes) data cited in Ratcliff et al. 2022.

Managing for biomass below 1,248 lb/acre and above 384 lb/acre (as shown in figure 8) aligns with achieving some fire hazard reduction while meeting most of the minimum RDM standards and biological goals in the AGH (Bartolome and Betts 2005). However, this range may compromise sensitive ecological resources in coastal prairie, which has higher minimum RDM standards.

Implications for management

It is important to note that our study was conducted during prescribed burns, which are typically limited to milder weather conditions. It is expected that flame heights, rate of spread, and other parameters would intensify in more extreme weather conditions. With this consideration, managers may desire lower herbaceous biomass targets for grasslands with higher wildfire hazard concerns. Future research is needed in a wildfire setting to better understand the nuances of wildfire interactions with biomass, but these data offer initial insight into the relationship between grazing levels and fire behavior.

Significant relationships between herbaceous biomass and multiple key fire behavior metrics indicate that grassland management, which often consists of grazing, alters on-the-ground fire behavior. Grassland fire metrics that were significantly altered by mimicking grazing levels included flame height, fire stopping within 33 ft (10 m), total area burned, surface temper-



Fig. 6. Example field in Santa Barbara County (California) with 3,140 lb/acre of herbaceous biomass (over 2,496 lb/acre threshold) representing ungrazed or very lightly grazed biomass where flame heights can exceed 4 ft. *Photo*: M. Shapero.



Fig. 7. Example field in Contra Costa County (California) with 1,918 lb/acre of herbaceous biomass (within 1,250 and 2,496 lb/acre range), representing light to moderately grazed biomass where flame heights are below 4 ft and fire will not be stopped. *Photo*: R. Foss.



Fig. 8. Example field in Ventura County (California) with 1,160 lb/acre of herbaceous biomass (within 1,250 and 384 lb/acre range), representing moderate to heavily grazed biomass where flame heights are below 4 ft and fire may be stopped. *Photo*: M. Shapero.



Fig. 9. Example field in San Joaquin County (California) with 315 lb/acre of herbaceous biomass (below 384 lb/acre threshold), representing very heavily grazed biomass where fire will be stopped. *Photo*: R. Foss.

ature, and white ash cover. Specific thresholds at 384, 1,248, and 2,496 lb/acre were identified through the decision tree approach and may be used by land managers to achieve site goals.

The lowest of the biomass thresholds may apply to fire lines or "fire fields" adjacent to critical infrastructure, or along potential ignition sources, while other areas may be managed to the intermediate thresholds where fire risk is lower. Rangelands may also be managed to create a strategic patchwork effect where more heavily grazed pastures are distributed throughout a larger operation to create fire-safe islands where livestock or crews may reside during wildfires. Managers may utilize these thresholds to increase ecosystem fire resiliency by working with natural landscape heterogeneity to increase the patchiness of fire intensity and reduce the total area burned. The thresholds reported from these results are intended to help inform a more comprehensive planning process that weighs the specific goals for different areas.

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Supplementary Materials

Technical appendix

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