Supplementary Information: Hakkenberg et.al. (2024). *Ladder fuels rather than canopy volumes consistently predict wildfire severity even in extreme topographic-weather conditions.*

Supplement S1: Wildfires description

Table S1.1. Description of 42 large (>2000 ha) wildfires in California's North Coast, Central Coast, and Sierras regions between 2019-2021.

Name	Abbv.	Year	Region	Start date	End date	Size (ha)
AUGUST COMPLEX	AC	2020	North Coast	8/16/24	11/11/24	417919
BRICEBURG	BG	2019	Sierras	10/6/24	10/20/24	2229
CALDOR	CR	2021	Sierras	8/15/24	11/18/24	89754
CARMEL	CL	2020	Central Coast	8/18/24	9/6/24	2832
CASTLE	CE	2020	Sierras	8/19/24	1/4/24	69059
CREEK	CK	2020	Sierras	9/4/24	12/24/24	153717
CREWS	CS	2020	Central Coast	7/5/24	7/15/24	2231
CZU LIGHTNING COMPLEX	CZU	2020	Central Coast	8/16/24	9/24/24	35027
DEVIL	DL	2020	North Coast	9/9/24	11/16/24	3590
DIXIE	DE	2021	Sierras	7/14/24	10/25/24	389877
DOLAN	DN	2020	Central Coast	8/18/24	12/31/24	50394
FAWN	FN	2021	Sierras	9/22/24	9/29/24	3471
FRENCH	FH	2021	Sierras	8/18/24	10/19/24	10738
GLASS	GS	2020	Central Coast	9/27/24	10/20/24	27310
HENNESSEY	HY	2020	Central Coast	8/17/24	9/16/24	123572
HOG	HG	2020	Sierras	7/18/24	8/28/24	3871
KINCADE	KE	2019	Central Coast	10/23/24	11/10/24	31469
KNP Complex	KNP	2021	Sierras	9/10/24	12/16/24	35716
LOYALTON	LN	2020	Sierras	8/14/24	8/27/24	18907
MCCASH	MH	2021	North Coast	8/1/24	10/27/24	38433
MCFARLAND	MD	2021	North Coast	7/30/24	10/26/24	49553
MINERAL	ML	2020	Central Coast	7/13/24	7/26/24	12006
MONUMENT	MT	2021	North Coast	7/31/24	11/3/24	90289
NORTH COMPLEX	NC	2020	Sierras	8/17/24	12/3/24	129013
RATTLESNAKE	RS	2020	Sierras	8/16/24	12/28/24	3409
RED SALMON COMPLEX	RN	2020	North Coast	7/27/24	11/19/24	58208
RIVER	RR	2020	Central Coast	8/16/24	9/4/24	20321
RIVER COMPLEX	RC	2021	North Coast	7/31/24	10/25/24	80676
SALT	ST	2021	North Coast	6/30/24	10/26/24	5099
SCU COMPLEX	SCU	2020	Central Coast	8/16/24	9/11/24	160589

SHEEP	SP	2020	Sierras	8/17/24	9/7/24	11955
SLATER	SR	2020	North Coast	9/8/24	12/12/24	63710
SLINK	SK	2020	Sierras	8/29/24	11/13/24	10826
SOUTH	SH	2019	North Coast	9/5/24	12/2/24	2159
STAGECOACH	SC	2020	Sierras	8/3/24	8/3/24	3137
SUGAR	SGR	2021	Sierras	7/2/24	10/28/24	42494
TABOOSE	TE	2019	Sierras	9/4/24	11/23/24	4155
WALKER	WR	2019	Sierras	9/4/24	1/15/24	22102
WALKERS	WS	2021	Sierras	8/15/24	12/8/24	3553
WALLBRIDGE	WB	2020	Central Coast	8/17/24	9/2/24	22342
WINDY	WY	2021	Sierras	9/10/24	11/11/24	39468
ZOGG	ZG	2020	North Coast	9/27/24	10/13/24	22799

Supplementary Information: Hakkenberg et.al. (2024). *Ladder fuels rather than canopy volumes consistently predict wildfire severity even in extreme topographic-weather conditions.*

Supplement S2: spGLMM beta coefficients

Table S2.1. Standardized slope estimates spatial GLMM (spGLMMs) quadratic regressions between standardized (std) fuel structure metrics and wildfire severity based on dNBR. Low and high credible intervals (CI), as well as mean estimates. spGLMM beta coefficients correspond to Fig. 3b.

Variable	**Abbr.**	**β_1 coefficients (linear term)**			**β_1 coefficients (quadratic term)**		
		low CI	mean	high CI	low CI	mean	high CI
Biomass	AGBD	0.0138	0.0619	0.1099	-0.0398	-0.0341	-0.0284
Canopy height	RH98	0.0094	0.0579	0.1064	-0.022	-0.0164	-0.0109
Layering	nmode	0.055	0.0959	0.1367	-0.0175	-0.0109	-0.0042
Ladder fuels	$mPAI_{10m}$	0.0615	0.0878	0.1141	-0.0387	-0.0321	-0.0256

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Supplement S3: Region, forest type and year

Among all wildfires assessed, 7 occurred in the Central Coast, 16 were in the North Coast, and 19 were located in the Sierras region. Among the >803K GEDI samples, 67% occurred in conifer forests, 16% occurred in hardwoods, and 16% were in mixed forests. 5 wildfires occurred in 2019, while 24 were in 2020 and 13 in 2021 (Fig. S2.1).

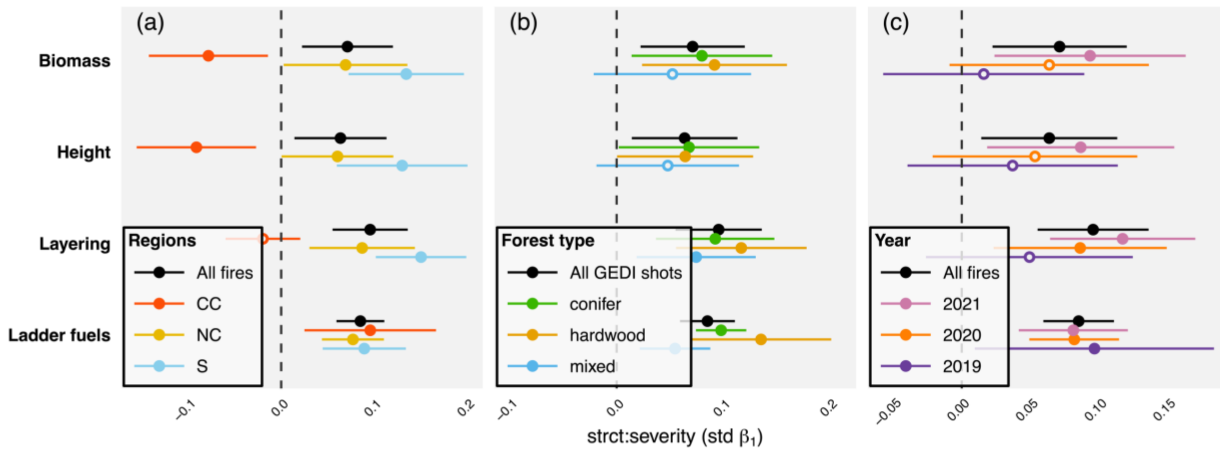

Figure S3.1. Fuel structure - fire severity relationships subset by region, forest type and year. Data were subset into (a) wildfires occurring in the Central Coast (CC), North Coast (NC) and Sierras (S) regions; (b) conifer, hardwoods and mixed forest types; (c) and fire year. Standardized slope estimates (std. β_1) represent linear effects from a series of spatial GLMMs. Terms not significant (open symbol) when the credible interval includes zero (dashed vertical line). In each case the "all" category represents all data, without subsetting (equivalent to Fig. 4) for comparison.

Subsetting wildfires by region reveals that unlike main effects from all data, biomass and height are negatively related to severity in the Central Coast while ladder fuels are significantly, positively related to severity across all regions (Fig. S3.1a). Among the 42 wildfires in the study domain, 7 occurred in the Central Coast (CC), 16 in the North Coast (NC) and 19 in the Sierras (S). When split by forest type, the significant positive structure-severity relationships found in the full dataset ("all GEDI shots") are likewise observed in conifer and hardwood forests, and in mixed forests for canopy layering and ladder fuel metrics (Fig. S3.1b). Unlike the per-wildfire split across regions, forest type is unique to all 830K GEDI samples and splits approximately as 67%, 16% and 16% for conifer, hardwoods and mixed forests, respectively. Finally, subsetting by year reveals that all structure-severity relationships from 2021 wildfires are significant and positive, with a minority of relationships from 2019 and 2020 being so (Fig. S3.1c). Only in the case of ladder fuels is the structure-severity relationship significant in all years. Fire year is closely related to data volumes. With GEDI data coming online in 2019, a far smaller proportion of GEDI shots were available corresponding to time before the fire compared with 2021. Thus while 5, 24, 13 wildfires occurred in 2019-2021, respectively, the total footprint sample sizes increases consistently with year: comprising 0.4%, 41.6%, and 58% of the total dataset for the three years 2019-2021.

Supplementary Information: Hakkenberg et.al. (2024). *Ladder fuels rather than canopy volumes consistently predict wildfire severity even in extreme topographic-weather conditions.*

<u>Supplement S4: Spearman correlation matrices</u>

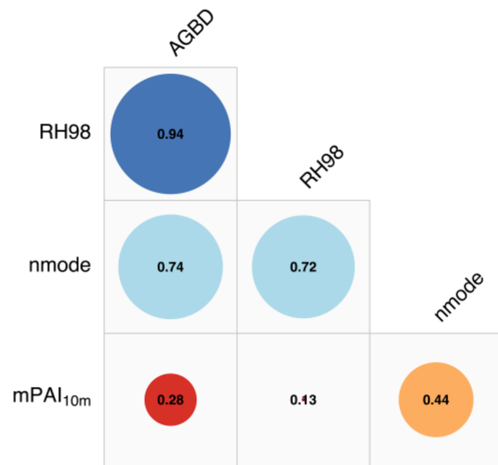

Figure S4.1. Spearman correlation matrix among GEDI structural metrics. Biomass from GEDI's L4 aboveground biomass density (AGBD) product; Canopy height, or the 98 percentile of relative heights (RH98); Canopy layering based on the number of modes in the raw GEDI waveform profile (nmode); and Ladder fuels, which we characterize using the mean PAI below 10 m, for all canopies with RH98 >10 m ($mPAI_{10m}$). Boxes empty when terms not significant (p<.05). See Table 1.

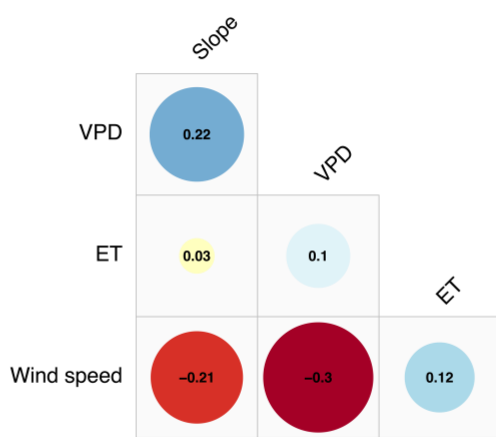

Figure S4.2. Spearman correlation matrix among topo-weather metrics. 10-m resolution topographic slope (°), 4-km resolution vapor pressure deficit (VPD) in kPa, evapotranspiration (ET) as mm/8days, 4-km resolution wind speed (m/s). Boxes empty when terms not significant (p<.05). See Table 1.

Supplementary Information: Hakkenberg et.al. (2024). *Ladder fuels rather than canopy volumes consistently predict wildfire severity even in extreme topographic-weather conditions.*

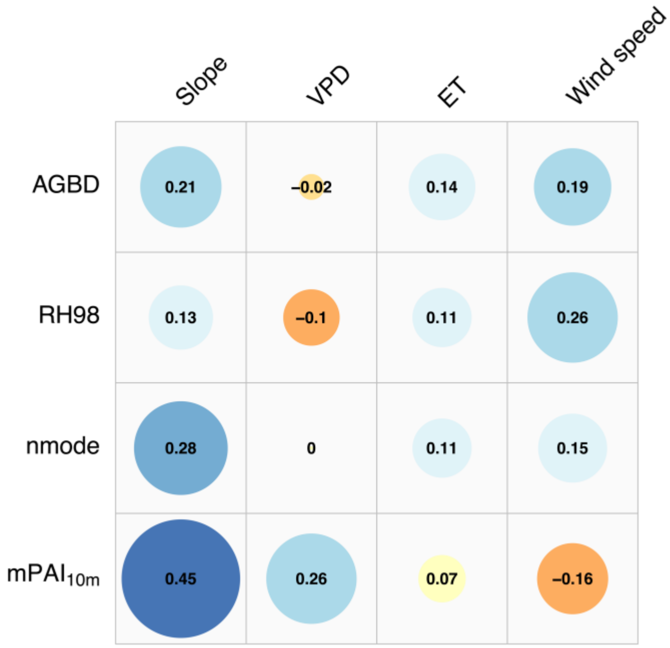

Figure S4.3. Spearman correlation matrix between GEDI structural metrics and topo-weather variables. GEDI structure: Biomass from GEDI's L4 aboveground biomass density (AGBD) product; Canopy height, or the 98 percentile of relative heights (RH98); Canopy layering based on the number of modes in the raw GEDI waveform profile (nmode); and Ladder fuels, which we characterize using the mean PAI below 10 m, for all canopies with RH98 >10 m ($mPAI_{10m}$). Topo-weather: 10-m resolution topographic slope (°), 4-km resolution vapor pressure deficit (VPD) in kPa, evapotranspiration (ET) as mm/8days, 4-km resolution wind speed (m/s). Boxes empty when terms not significant (p<.05). See Table 1.

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Supplement S5: Supplementary results for figures 3-5 for forests >10m only.

Supplementary results for Figures 3-5, based on forests >10m only. This criterion, set to ensure sample size and sample set compatibility between ladder fuels which have a >10m criteria and other metrics (e.g. biomass, height and layering). This reduced the sample size from 830,709 to 734,592 samples, or an 11.6% reduction.

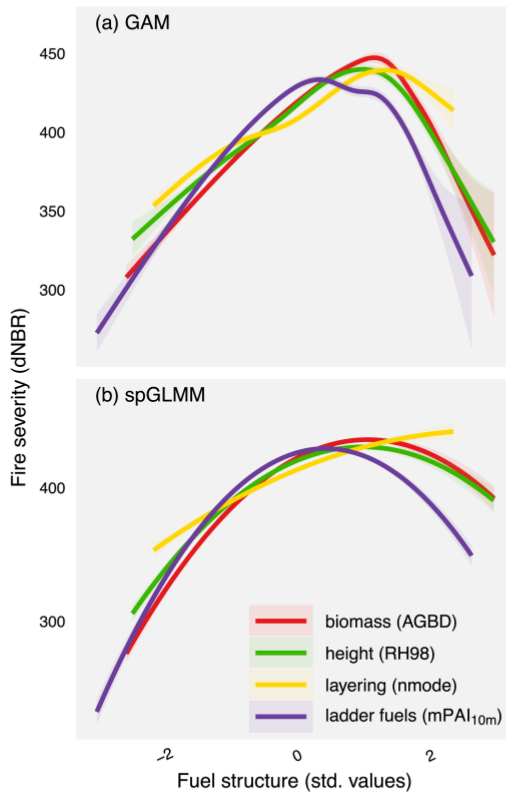

Figure S5.1. Generalized relationships between fuel structure and wildfire severity for forests >10m. (a) Generalized Additive Models (GAMs) and (b) spatial GLMM (spGLMMs) quadratic regressions between standardized (std) fuel structure metrics and wildfire severity based on dNBR. Linear and quadratic coefficients in the four spGLMMs were positive and negative, respectively, and significant at $p<0.05$ (S2.1).

Supplementary Information: Hakkenberg et.al. (2024). *Ladder fuels rather than canopy volumes consistently predict wildfire severity even in extreme topographic-weather conditions.*

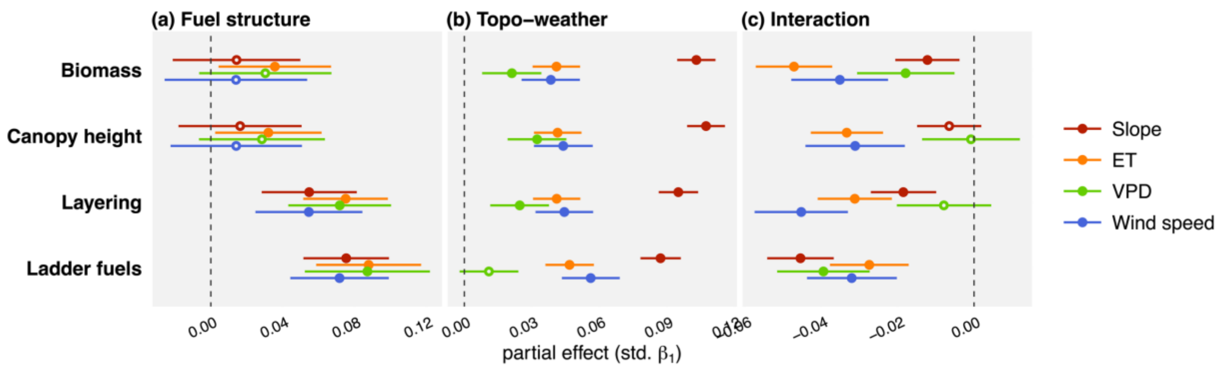

Figure S5.2. Partial and interactive effects of fuel structure and topo-weather on fire severity for forests >10m. Standardized slope estimates (std. β_1) represent the partial linear effects of (a) fuel structure, (b) topographic and weather variables, or "topo-weather", and (c) their interaction on wildfire severity from a series of spGLMMs. Across all combinations of fuel structure and topo-weather, partial effects correspond to the linear effect of a given predictor on dNBR-based severity (response) after accounting for the effect of the other predictor, plus its interaction. Median posterior estimate (points) and associated 95% credible interval (error bars); terms not significant (open symbol) when the credible interval includes zero (dashed vertical line).

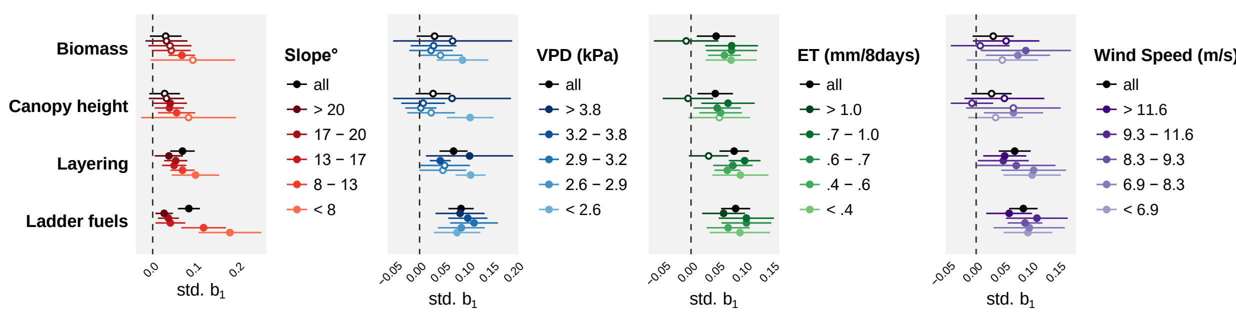

Figure S5.3. Effects of fuel structure on fire severity across five levels of topo-weather for forests >10m. Standardized slope estimates (std. β_1) represent the univariate, linear effects of GEDI-derived fuel structural variables on dNBR wildfire severity from a series of spGLMMs. Model results were obtained from all data samples ("all") in addition to subsets defined as five equal-sized classes stratified by their corresponding topography and fire weather variables. Median posterior estimate (points) and associated 95% credible interval (error bars); terms not significant (open symbol) when the credible interval includes zero (dashed vertical line).