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Fire Regimes of Utah: The Past as Prologue

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Abstract: (1) Background: Satellite monitoring of fire effects is widespread, but often satellite-derived values are considered without respect to the characteristic severity of fires in different vegetation types or fire areas. Particularly in regions with discontinuous vegetation or narrowly distributed vegetation types, such as the state of Utah, USA, specific characterization of satellite-derived fire sensitivity by vegetation and fire size may improve both pre-fire and post-fire management activities. (2) Methods: We analyzed the 775 medium-sized (40 ha $\leq$ area < 400 ha) and 697 large ($\geq$400 ha) wildfires that occurred in Utah from 1984 to 2022 and assessed burn severity for all vegetation types using the differenced Normalized Burn Ratio. (3) Results: Between 1984–2021, Utah annually experienced an average of 38 fires $\geq$ 40 ha that burned an annual average of 58,242 ha with a median dNBR of 165. Fire was heavily influenced by sagebrush and shrubland vegetation types, as these constituted 50.2% (17% SD) of area burned, a proportion which was relatively consistent (18% to 79% yr^{-1}). Medium-sized fires had higher mean severity than large fires in non-forested vegetation types, but forested vegetation types showed the reverse. Between 1985 and 2021, the total area burned in fires $\geq$ 40 ha in Utah became more concentrated in a smaller number of large fires. (4) Conclusions: In Utah, characteristic fire severity differs both among vegetation types and fire sizes. Fire activity in the recent past may serve as an informative baseline for future fire, although the long period of fire suppression in the 20th century suggests that future fire may be more active. Fire managers planning prescribed fires < 400 ha in forests may find the data from medium-sized fires more indicative of expected behavior than statewide averages or vegetation type averages, both of which are weighted to large fires.

Keywords: burn severity; dNBR; fire effects; fire size; spruce-fir; aspen; interior Douglas-fir; sagebrush steppe

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1. Introduction

The long period of fire exclusion and anthropogenic changes to forests in the West has resulted in much less annual fire activity in the twentieth century than during the period of pre-Euro-American settlement [1]. Recent years have seen an increase in fire activity as a result of higher fuel loading and permissive climate and fostered the emergence of 'megafires' throughout the West [2], and the prevalence of larger fires is likely to continue [3,4]. Thus, although the recent past may not be an accurate predictor of the full magnitude of future fire activity, particularly because of the compounding effect of decades of fire suppression, it likely forms a baseline which can be useful in projecting a lower bound of future fire activity. Managers are increasingly concerned with understanding the post-fire effects on regeneration in different forest types under changing environmental conditions [5].

Fires and annual fire statistics often focus primarily on the area burned. This characterization is perhaps overly simplistic as it ignores vegetation type, unburned areas within the fire perimeter, and most importantly, the burn severity—the ecological effect of fire and one of the principal determinants of post-fire revegetation. Burn severity, whether measured by satellite or ground data, varies by vegetation type and fire history [6–9]. Burn severity is frequently measured at landscape scales as the delta normalized burn ratio (dNBR), a measure of the change of surface reflectance, largely from vegetation foliage, between the pre-fire and post-fire condition [10]. However, the ecological effect of remotely-sensed burn severity has different meanings in the context of different vegetation types [11,12]. Satellite-derived spectral data often differs from the actual ecological effect on vegetation (e.g., tree death and soil effects; [11,13,14]).

A very high mean burn severity and its concomitant ecological effects could be characteristic for some vegetation types (e.g., chapparal; [11]) but represent a departure from characteristic fire for others (e.g., ponderosa pine). Therefore, analysis of fire severity and fire severity trends should be presaged on delineation of vegetation types [6,9], a consideration that becomes more important in large, diverse landscapes with a variety of vegetation types that may be present within a large management entity, such as the state of Utah [15] or a large National Park (e.g., Yosemite National Park; [7]). Even at very large scales, the number of fires, area of fires and severity of fires will differ because of climate effects and large-scale topography [16,17] and the interannual variability in fire will be large because of the stochasticity of ignitions and fire weather.

The Monitoring Trends in Burn Severity (MTBS) project provides fire perimeter mapping and severity data for fires $\geq$ 400 ha in the western United States [18]. However, in many management areas, fires $\geq$ 400 ha are considered large and potentially unpredictable, with the result that the management decision for fires of this size near values at risk is frequently for full suppression. Medium-sized fires, here defined as those $\geq$40 ha but <400 ha, are more likely to represent fires of similar area to units being considered for prescribed fire activity. Small- and medium-sized fires are more often constrained by topography, ignition sources, seasonal moisture conditions, and fine-scale variation fuels while broad temporal or spatial filters may be responsible for large fires and their behavior [19,20]. Although any fire ignition has the potential to expand to large areas, those above 40 ha (although this is by no means a scientifically delineated size threshold) may have had a sufficient local effect to persist and grow, particularly if the period of fire suppression has led to high fuel loading. Thus, fires that have already reached $\geq$40 ha are sufficiently large to attract management attention lest they could expand to become large fires if weather and fuel are permissive and suppressive activities are ineffective. Trends in the number of medium-sized or large fires that were successfully managed could therefore be an indicator for increased fire activity in the future when climate and fuel loading make potential management activities less likely to succeed.

High severity fire effects are particularly important for managers as they represent the greatest departure from pre-fire conditions and may exceed ecosystem resistance or resilience [21,22]. Post-fire, the distance to surviving adult plants of reproductive stature may govern the rate of revegetation because seeds must be dispersed longer distances into the burned area. High severity fires may leave large patches of completely burned area that require restoration activity (or long periods of time to become revegetated) and they may kill otherwise fire-resistant large-diameter trees that could be the nucleus of forest revegetation and promote greater biodiversity [23,24]. Thus, the distribution and range of the highest severity fire effects may be more relevant for managers and restoration efforts than mean or median severity values.

Our objectives were to:

1. Establish a 30-year baseline of average fire activity for Utah overall and for each principal vegetation type, considering the number, the area, and the severity of fires $\geq$ 40 ha.
2. Identify differences in satellite-derived burn severity between medium-sized (40 ha $\leq$ area < 400 ha) and large (area $\geq$ 400 ha) fires.

2. Materials and Methods

2.1. Study Area

Utah is an arid state containing 212,761 km^2 of land segmented by numerous mountain ranges with topographic relief from 664 m to 4120 m (Figure 1). The discontinuous basin and range landscape of the western half of the state represents the easternmost boundary of the Great Basin [25]. The eastern portion of the state is dominated by the Colorado Plateau and the east-west Uintah Mountains at the northeast boundary of the state. The extreme variety of topography, soils, and local climate results in a wide variety of ecosystems. Northern Utah is characterized as a semi-arid climate zone whereas southern Utah is characterized as a warmer and desert climate. Strong-seasonality and winter-dominated precipitation generally increases with latitude and elevation with shorter fire seasons at high elevations due to a short snow-free season. Much of Utah's population lives along the foothills of the Wasatch Mountains. The resulting wilderness urban interface (WUI; [26]) occupies a pre-settlement vegetation zone characterized by short-statured trees and shrubs (e.g., *Quercus gambelii* and *Acer grandidentatum*) in dissected terrain which has the possibility for extreme fire behavior.

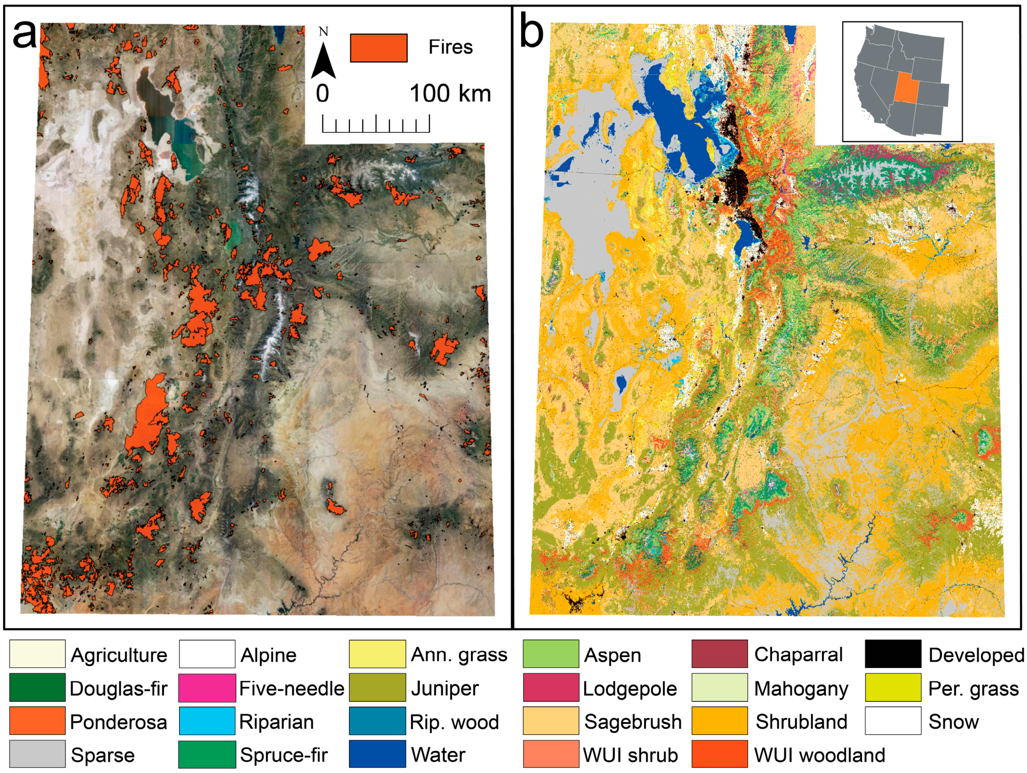

Figure 1. Wildfire boundaries for fires ≥ 40 ha that burned from 1984 to 2021 (**a**) and vegetation categories aggregated from existing vegetation type vegetation classifications [27,28] (**b**) in Utah, USA. Background imagery (**a**) sourced from 0.6 × 0.6 m 2021 NAIP imagery [29].

Vegetation varies with topography, fire, and the history of human influences, and generally transitions from low-productivity grassland and sagebrush steppe to pinon-juniper woodlands at intermediate elevations. In the mountains, pinon-juniper, scrub oak and maple woodlands, and riparian hardwood drainages exist along and in the WUI and transition to closed-canopy mixed-conifer forests with increasing elevation.

Common tree species (from lowest to highest elevation) include *Juniperus osteosperma* (Torrey) Little (Utah juniper), *Juniperus scopulorum* Sargent (Rocky Mountain juniper), *Pinus monophylla* Torrey and Fremont (singleleaf pinon), *Quercus gambelii* Nuttall (Gambel oak), *Acer grandidentatum* Nuttall (bigtooth maple), *Pseudotsuga menziesii* var. *glauca* (Mayr) Franco (interior Douglas-fir), *Populus tremuloides* Michaux (aspen), *Cercocarpus ledifolius* Nuttall (curl-leaf mountain mahogany), *Pinus contorta* Douglas ex Loudon (lodgepole pine), *Pinus flexilis* E. James (limber pine), *Picea pungens* Engelmann (blue spruce), *Picea engelmannii* Engelmann (Engelmann spruce), *Abies concolor* (Gordon and Glendinning) Hildebrand (white fir), *Abies bifolia* A. Murray bis (Rocky Mountain subalpine fir), and *Pinus longaeva* D. K. Bailey (Great Basin bristlecone pine) [30].

Fire behavior in Utah encompasses most of the fire regimes present in the western United States [31–33]. Fire return intervals vary from a low of 10 to 20 years in ponderosa pine and mixed-conifer stands to more than 100 years in higher elevation alpine forest types [34–36]. The basin and range geography tends to limit contiguous areas of similar vegetation and fuel types, potentially contributing to the relative lack of megafires (so far) compared to other western states (>10,000 ha; [2]).

2.2. Classifying Vegetation

We classified vegetation types using the 2018 30 × 30 m LANDFIRE National Vegetation Classification Existing Vegetation Type (EVT) data for Utah, [27,28]. The EVT is a national-level dataset curated by the U.S. Department of Agriculture and the U. S. Department of the Interior that classifies vegetation using a moderated classification and regression tree approach which uses a combination of plot-based data, local climate, topography, LANDSAT imagery, and temporal changes in normalized difference vegetation index (NDVI) to assign classifications to each 30 × 30 m pixel [27]. Multiple levels of classifications and species associations are provided within the EVT with varying levels of details in species associations ranging from the broad physiological categorizations of trees, shrubs, and grasses, to individual species-assemblages on the landscape [27]. We aggregated the 61 EVT 'group' classifications into 23 broader classifications of Utah vegetation that are likely to have similar fire behavior (Tables 1 and S1). We did not analyze areas categorized as "Agriculture", "Developed", "Snow", or "Water". Although there are some uncertainties with LANDFIRE data, particularly with respect to vegetation conversion (particularly in or near the WUI) or forest successional stage (with composition and structure potentially altering fuel loadings and potential fire effects), our aggregation into broad classifications (and the large number of LANDFIRE pixels; 24,703,822) enables us to characterize fire at the landscape scale.

2.3. Identification of Fire Perimeters

We sourced fire perimeter and ignition data from the Wildland Fire Interagency Geospatial Services (WFIGS) which curates wildland fire incident data within the USA [37]. In cases with medium-sized fires, prescribed fires, and fires < 1990, the WFIGS dataset was occasionally incomplete, and we sourced additional perimeters and fire information directly from the managers of the Dixie, Ashley, Uinta-Wasatch-Cache, and Manti-La Sal National Forests as well as the Bureau of Land Management and Utah state land managers. We selected all fire perimeters $\geq$ 40 ha between 1984 and 2022, the Landsat Thematic Mapper (and later) period of record and analyzed each fire individually. For all fires that burned across state boundaries, we analyzed data only for the area burned within Utah but classified the fire size according to its full extent. We identified and removed all fire perimeters from our analyses that were identified or suspected to be prescribed fires. We identified prescribed fires using associated fire metadata, naming conventions (e.g., "BrianHeadFireRehabProject" or "DuckCreekFuels1"), or in rare cases from perimeters with right-angles or unusually linear shapes that did not follow visible landscape features. Escaped prescribed burns were analyzed as wildfires.

Table 1. Vegetation categories aggregated from the Existing Vegetation Type of the LANDFIRE National Vegetation Classification [27]. The number of fires burned refers to those fires that burned at least one LANDFIRE pixel of that vegetation type.

Vegetation Category	Typical Species	Area Burned 1984–2022 (ha)	Area Burned 1984–2022 (%)	Total Area (ha)	Total Area (%)	# of Fires Burned
Alpine	Herbs and graminoids	13,779	0.6	72,359	0.3	605 (40%)
Agriculture	Herbs and graminoids	31,957	1.3	927,014	4.2	793 (53%)
Annual grassland	*Bromus tectorum* graminoids	205,165	8.9	389,816	1.8	1254 (84%)
Aspen	*Populus tremuloides* *Abies bifolia*	63,902	2.8	777,045	3.5	475 (32%)
Chaparral	*Arctostaphylos* spp. *Ceanothus* spp.	17,879	0.8	47,969	0.2	577 (39%)
Developed	-	22,355	0.9	410,262	1.9	765 (51%)
Douglas-fir	*Pseudotsuga menziesii* *Acer grandidentatum*	64,029	2.8	445,029	2.0	556 (37%)
Five-needle pine	*Pinus flexilis* *Pinus longaeva*	20,855	0.9	143,649	0.6	353 (23%)
Lodgepole	*Pinus contorta* *Pseudotsuga menziesii*	9791	0.4	126,803	0.6	44 (2%)
Mountain Mahogany	*Cercocarpus ledifolius* *Juniperus* spp.	14,549	0.6	87,451	0.4	498 (33%)
Pinon-Juniper	*Pinus monophyla* *Juniperus osteosperma*	249,141	10.9	3,926,194	18.0	1234 (83%)
Perennial grassland	*Elymus elymoides* *Agropyron cristatum*	125,463	5.4	341,010	1.5	1325 (89%)
Ponderosa Pine	*Pinus ponderosa*	23,197	1.0	214,773	1.0	315 (21%)
Riparian	*Juncus* spp. *Salix* spp.	4938	0.2	95,369	0.4	498 (33%)
Riparian-hardwood	*Populus trichocarpa* *Salix* spp.	7102	0.3	146,511	0.7	681 (46%)
Sagebrush	*Artemisia* spp.	776,510	34.0	4,318,832	19.7	1422 (96%)
Shrubland	*Sarcobatus* spp. *Ericameria nauseosa*	371,556	16.2	4,535,391	20.7	1296 (87%)
Snow	-	-	-	68	0.0	-
Sparse	*Chenopodiaceae* spp.	27,989	1.2	3,020,926	13.8	927 (62%)
Spruce-fir	*Abies bifolia* *Picea engelmannii*	46,055	2.0	438,129	1.9	289 (19%)
Water	-	-	-	635,871	2.9	-
WUI Shrub	*Prunus virginiana*	22,857	1.0	224,830	1.0	857 (58%)
WUI Woodland	*Acer grandidentatum* *Quercus gambelii*	149,082	6.5	599,930	2.7	900 (60%)
Total [1]	-	2,268,151	100	21,925,231	100	1477

[1] Area for each vegetation type was calculated with a Transverse Mercator projection (UTM Zone 12). Total area burned includes agricultural and developed areas which were not analyzed.

2.4. Image Acquisition and Calculation of Remotely Sensed Fire Severity

To assess the accuracy of the fire perimeter delineation and assess fire severity we examined each fire perimeter individually with current and historical National Agriculture Imagery Program (NAIP) imagery to assess the pre-fire vegetation type and continuity [29]. We sourced burn severity for most fires $\geq$ 400 ha from the MTBS database [18] with pre-calculated metric of dNBR following the same equations as Miller and Thode [10]. For all MTBS-derived fire data we adjusted the default dNBR values using the MTBS provided offset, provided in the metadata associated with each fire. The offset adjusts burn severity by subtracting background changes in reflectance due to non-fire related stressors. In some cases, large fires were missing from the MTBS database and we calculated burn severity manually.

For each fire we estimated the percent of forest cover within the fire boundary using pre-fire NAIP imagery. Fires with ≥50% forest cover were analyzed with an extended assessment [38] in which we used post-fire LANDSAT imagery approximately one year after the date of burning. We analyzed fires with <50% forest cover with an initial assessment where post-fire imagery was selected as close to the date of fire extinguishment as possible and within the same year as the pre-fire image [38]. For both initial and extended assessments, we selected LANDSAT scene pairs that minimized smoke, clouds, and particulates around the fire boundary, had similar solar angle, and matched pre-fire and post-fire vegetation phenology [39]. We assessed phenology using non-burned vegetation adjacent to the fire perimeter and high-elevation snowpack extent in the spring and fall. In cases where we could not ascertain the date of fire extinguishment, we used the first post-fire LANDSAT image that did not have signs of fire or smoke within the fire boundary.

After selecting an appropriate pre- and post-fire scene pair, we calculated the normalized burn ratio (NBR), delta NBR (dNBR), and the relative dNBR (RdNBR). We calculated the NBR (Equation (1)) and dNBR (Equation (2)) using the near-infrared (NIR) and shortwave infrared (SWIR) bands [10,38].

$$\mathrm{NBR} = (\mathrm{NIR} - \mathrm{SWIR})/(\mathrm{NIR} + \mathrm{SWIR}) \times 1000 \tag{1}$$

$$\mathrm{dNBR} = \mathrm{NBR}_{(\text{Pre-fire})} - \mathrm{NBR}_{(\text{Post-fire})} \tag{2}$$

Because changes in vegetation reflectance between images may also be due to drought or annual differences in plant phenology, we selected a neighboring ≥ 90 ha unburned region of comparable vegetation with similar aspect and elevation to control for non-fire-induced changes in vegetation reflectance. We calculated the median dNBR offset over the entire non-burned region and used this value to adjust the dNBR of the burned area. We limited our maximum offset to bounds of −50 to +50 dNBR for phenological change and reassessed any offset selection that produced values outside of these limits. The median offset value was 3. All reported values of dNBR within the manuscript are offset-adjusted values. Preliminary analysis showed that RdNBR values were not markedly different from dNBR values, consistent with results reported by others [40,41].

After calculating the offset-adjusted dNBR, we used a combination of pre-and post-fire scenes and dNBR to assess the accuracy of each fire perimeter and make minor adjustments to perimeters. We were conservative with perimeter adjustment and altered fire perimeters only when clearly burned vegetation and elevated dNBR values were visible outside fire perimeters. We avoided reducing fire perimeter size because remotely sensed imagery may fail to capture low-severity, understory burns that were delineated by ground-crews [42]. We recategorized dNBR outliers of <−300 as '−300′ and >1200 as '1200′ for all analyses and graphs. We classified dNBR burn severity using the threshold values defined by Miller and Thode [10] which are: 'Unchanged' < 41 dNBR, 41 < 'Low' ≤ 176, 176 < 'Moderate' ≤ 366, and 'High' > 366.

2.5. Analyses of Differences in Fire Regimes

We conducted analyses in R 4.2.1 [42] using the graphical user interface R Studio 2022.02.3 [43]. We generated maps in ArcMap10.8.1 (ESRI, Redlands, CA, USA) using background data from 2021 0.6 × 0.6 m NAIP imagery [29]. We generated graphs using the ggplot2 3.3.3 and ggpubr 0.4.0 R packages [44,45]. We used the R packages raster 3.6-3 [46], rgdal 1.6-2 [47], and rgeos 0.5-9 [48] to load, analyze, and export raster data. Area calculations were done in ArcMap based on a Transverse Mercator map projection (Zone 12).

We used an analysis of variance (ANOVA) in base R to test significant differences in mean burn severity between medium-sized and large fires, by vegetation type. We analyzed assumptions of normality using Shapiro-Wilk tests, and homoscedasticity using a Bartlett test in base R [42]. To assess differences in severity distributions, we binned dNBR distributions by 10, and used a Kolmogorov-Smirnov (KS) test in base R. To assess variation in burn severity through time we calculated Mahalanobis dissimilarity of the mean of severity quartiles, by year, vegetation type, and between medium-sized and large fires. To test for differences in homogeneity of variance between medium-sized and large fires and between vegetation types we used the 'betadisper' test and a permutational analysis of variance with 999 permutations (random seed = 4711) [49]. To measure if the proportion of area burned by the largest fires varied through time, we calculated the Gini coefficient, a measure of inequality among numeric values that is well represented in the natural and social science literature. The Gini is bounded between 0, representing complete equality among values (e.g., all fires burned the same area in a given year), and 1, complete inequality between values (e.g., one fire burned all area in a given year). We calculated the Gini coefficient using the DescTools 0.99.48 R Package [50]. After visualizing the Gini, we detected non-linear trends with time and used the mgcvv 1.8-40 R package [51] to model the relationship with a nonlinear generalized additive model (GAM) with a 'betar' distribution. Because we had only partial LANDSAT data for 1984 and 2022, we did not include these years in analyses relating to fire area.

3. Results

3.1. Wildfire Frequency, Area Burned, and Severity

Between 1984–2022, there were 1652 fires $\geq$ 40 ha, comprising 24,703,822 analyzed Landsat pixels. Of those, 180 were prescribed fires and excluded from our analyses. Within the characteristic vegetation types of Utah (Table 1) there were 775 medium-sized (40 ha $\leq$ area < 400 ha) and 697 large ($\geq$400 ha) wildfires 1984–2022 (Figure 1, Table 2). From 1985 to 2021 there were an average of 20 medium-sized fires each year which burned an average of 2901 ha and 18 large fires that burned an average of 55,341 ha (Figure 2). Area burned varied widely among years (Figure 2b), partially driven by the differing consumption of vegetation types (Table 3). Annual variation in area burned was 98% of mean annual area burned. Large fires burned more area (mean percent burned 90 $\pm$ 10% SD) than medium-sized fires (10 $\pm$ 10%), and the inequality in area burned between fires, as measured by the Gini coefficient, increased with time from 1985 to 2021 (R^2 = 0.23; $p < 0.001$; Figure 3), with most of the change occurring from 1985 to 2005 (Figure 3). Large fires burned at least one LANDFIRE pixel of a mean of 13 vegetation types (median = 13) while medium-sized fires burned a mean of 9 of vegetation types (median = 9). However, both large and medium-sized fires had the majority of burn area within a single vegetation type ($\text{proportion}_{large}$ = 53 $\pm$ 17%; $\text{proportion}_{medium}$ = 57 $\pm$ 18%), whose type varied depending on the fire. Fire severity varied widely by year and vegetation type (Figure 4). Median severity ($-300 \leq \text{dNBR} \leq 1200$) for all burned pixels was 157, although this was highly influenced by the results from sagebrush and shrublands, which were 50.2% of area burned, a proportion which was relatively stable (18% to 79% yr^{-1}, 17% SD). All large fires and 97% of medium-sized fires burned at least one pixel classified as either sagebrush or shrublands.

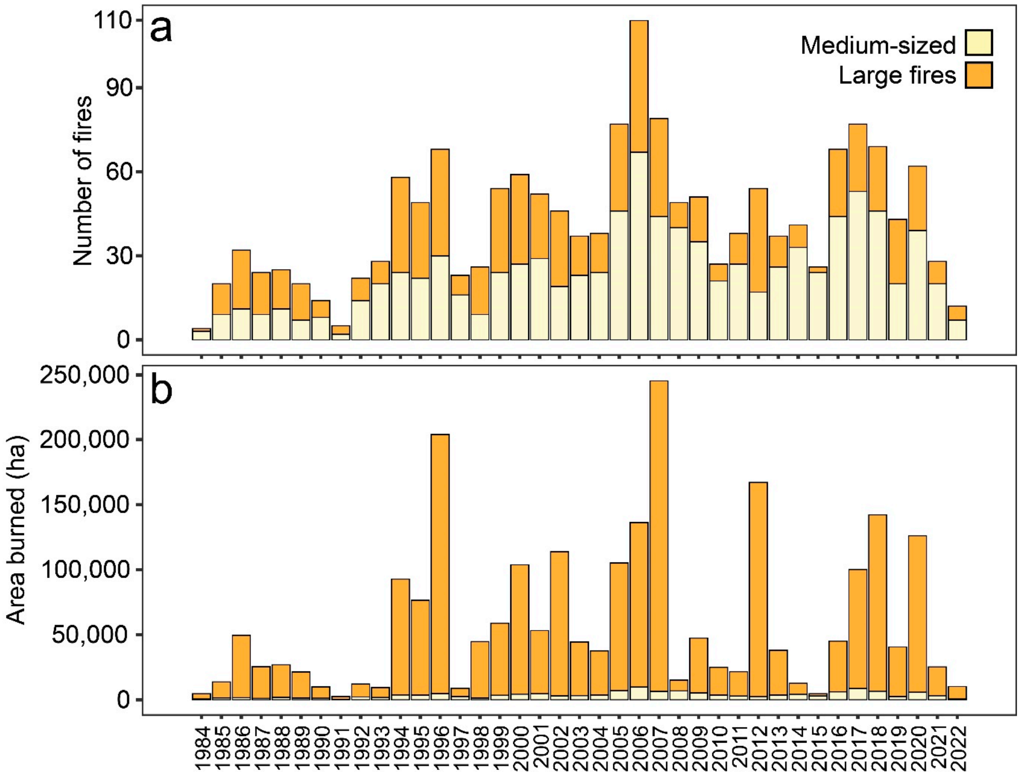

Figure 2. The (**a**) number of large (≥400 ha) and medium-sized (40 ha ≤ area < 400 ha) fires that burned in Utah, USA from 1984 to 2021. (**b**) The total area burned in fires ≥ 40 ha from 1984 to 2022 in Utah, USA.

For forested vegetation types, large fires had a higher top quartile severity than medium-sized fires. In general, medium-sized fires had greater burn severity at lower quartiles while large fires had 7.5% greater 4th quantile burn severity relative to medium-sized fires (Figure 5). Kolmogorov-Smirnov tests indicate that 13 of 19 vegetation types differed in their burn severity distribution (Table S2) with aspen, Douglas-fir, ponderosa pine, riparian-hardwood, spare, and spruce-fir having similar burn severity distributions (Figure 4). Notably, annual and perennial grasslands, chaparral, and sparse vegetation had greater burn severity in medium-sized fires (+7.9% Q4) relative to large fires (Figure 6). Large fires had greater interannual variation in burn severity (Figure S1) than medium-sized fires (F_{1139} = 30.43, p < 0.001) but this differed by vegetation type (Figure S2) with forested vegetation types having greater interannual variation in burn severity than non-forested vegetation types (Figures 6, 7 and S2). Sagebrush, shrubland, and annual grassland had the lowest interannual variation in burn severity (Figure S2) among vegetation categories.

Table 2. The number of wildfires ≥ 40 ha, the area burned of wildfires ≥ 40 ha, and the severity of wildfires ≥ 40 ha from 1984 to 2021 in Utah, USA.

Year	40 ha ≤ Area < 400 ha		Area ≥ 400 ha		Total ≥ 40 ha	
	# of Fires	Area Burned (ha)	# of Fires	Area Burned (ha)	# of Fires	Area Burned (ha)
1984	3	634	1	3956	4	4590
1985	8	1308	11	12,013	19	13,321
1986	11	1588	21	47,044	32	48,632
1987	7	792	14	23,669	21	24,461
1988	9	1182	14	24,398	23	25,580
1989	5	919	13	19,805	18	20,724
1990	7	1148	6	8483	13	9631
1991	2	313	3	2168	5	2481
1992	10	1485	8	9450	18	10,935
1993	18	1415	7	7008	25	8423
1994	24	3504	34	84,934	58	88,438
1995	18	2894	27	71,860	45	74,754
1996	27	4221	38	193,612	65	197,833
1997	13	1982	7	6322	20	8304
1998	7	963	17	42,199	24	43,162
1999	23	3015	30	51,798	53	54,813
2000	27	4336	32	98,364	59	102,700
2001	23	3709	23	46,957	46	50,666
2002	19	2982	27	109,045	46	112,027
2003	22	3152	14	40,412	36	43,564
2004	19	2921	14	33,653	33	36,574
2005	40	6138	31	99,176	71	105,314
2006	62	8906	47	125,040	109	133,946
2007	36	4527	35	234,207	71	238,734
2008	31	5276	7	6623	38	11,899
2009	18	2705	16	41,185	34	43,890
2010	11	1582	6	21,263	17	22,845
2011	24	2663	11	18,179	35	20,842
2012	10	1412	37	163,087	47	164,499
2013	16	2413	11	33,598	27	36,011
2014	17	2334	8	8019	25	10,353
2015	15	1868	2	1680	17	3548
2016	27	3433	24	37,450	51	40,883
2017	46	6676	24	89,946	70	96,622
2018	36	4984	23	132,567	59	137,551
2019	18	2456	23	37,810	41	40,266
2020	39	5642	23	94,326	62	99,968
2021	20	2777	8	21,652	28	24,429
2022	7	638	5 [1]	9493 [1]	12	10,131 [1]
Total	775	110,893	703	2,122,451	1477	2,223,344

[1] Includes wildfires that were not analyzed for extended burn severity.

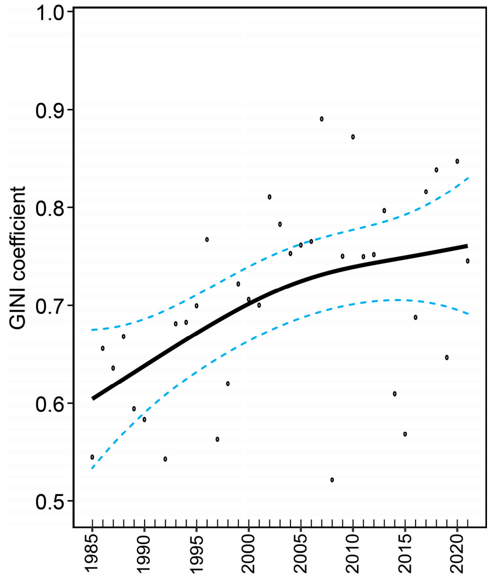

Figure 3. The trend in the Gini coefficient for the area burned in fires ≥ 40 ha from 1985 to 2021 in Utah, USA. An increasing Gini coefficient shows that the annual area burned in Utah is becoming more concentrated in fewer, larger fires. Dashed lines mark the 95th percentile confidence interval.

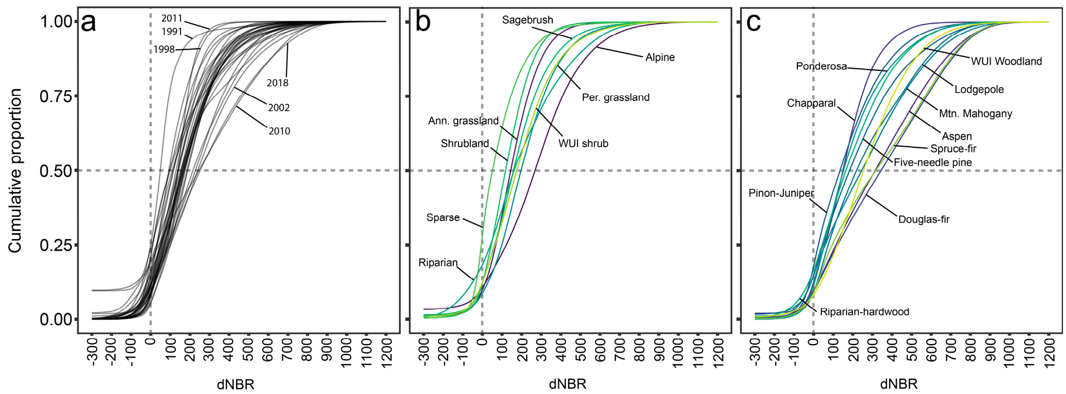

Figure 4. Cumulative severity distribution for fires ≥ 40 ha in Utah for (**a**) all fires, (**b**) by non-forested vegetation, and (**c**) forested vegetation types. Curves further to the right (left) represent more (less) sever fire years and vegetation types.

3.2. Fire Severity and Area Burned by Vegetation Type

Burn severity varied substantially among vegetation types, and between medium-sized and large fires (Figure 5). Medium-sized fires generally had significantly lower Q4 severity than large fires, except for annual grassland, perennial grasslands, sparse, and chaparral which had higher Q4 severity ($p < 0.05$). Medium-sized and large fires had similar ($p > 0.05$) Q4 severity in the WUI woodland. The annual area burned varied widely by vegetation type (Tables 3, S5, S6 and S7) with consistently high burn areas in non-forested vegetation of annual grassland, perennial grassland, shrubland, and sagebrush steppe which cumulatively burned an average of 72% of the total area (annual range 26–98%). In contrast, Douglas-fir, aspen, and spruce-fir (Tables 4, S4, S6 and S8) were the forested vegetation types which contributed the greatest proportions to the annual area burned (mean: 8%, annual range 0–39%) and burned at the highest severities (Figure 6). The WUI woodland had an average of 4 fewer fires per year than WUI shrubland, but burned 6.5 times more area (Table 3).

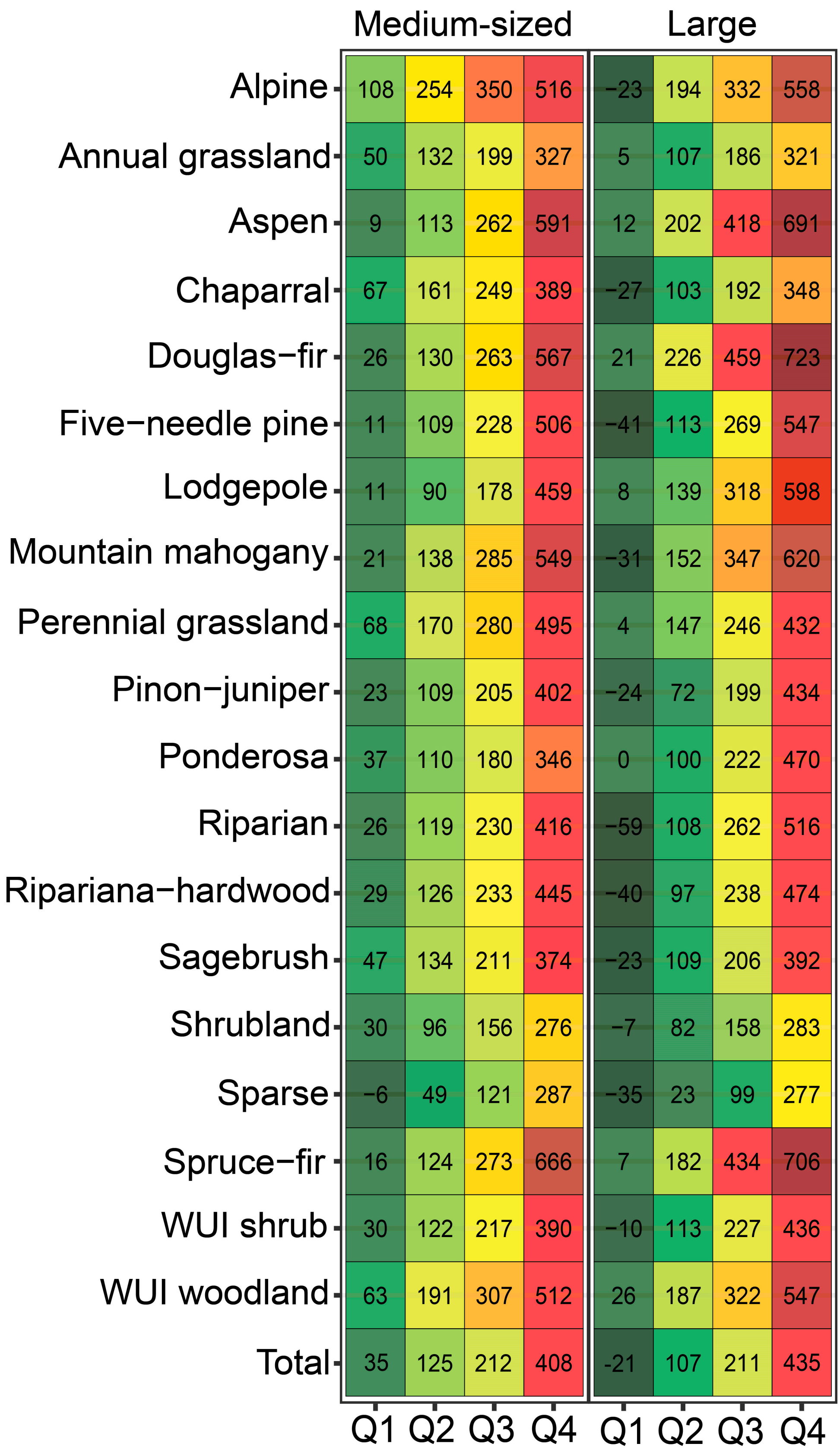

Figure 5. Delta normalized burn ratio (dNBR) averaged across quartiles, by vegetation type, for medium-sized (40 ≤ area < 400 ha) and large (≥400 ha) fires in Utah, USA between 1984 and 2021.

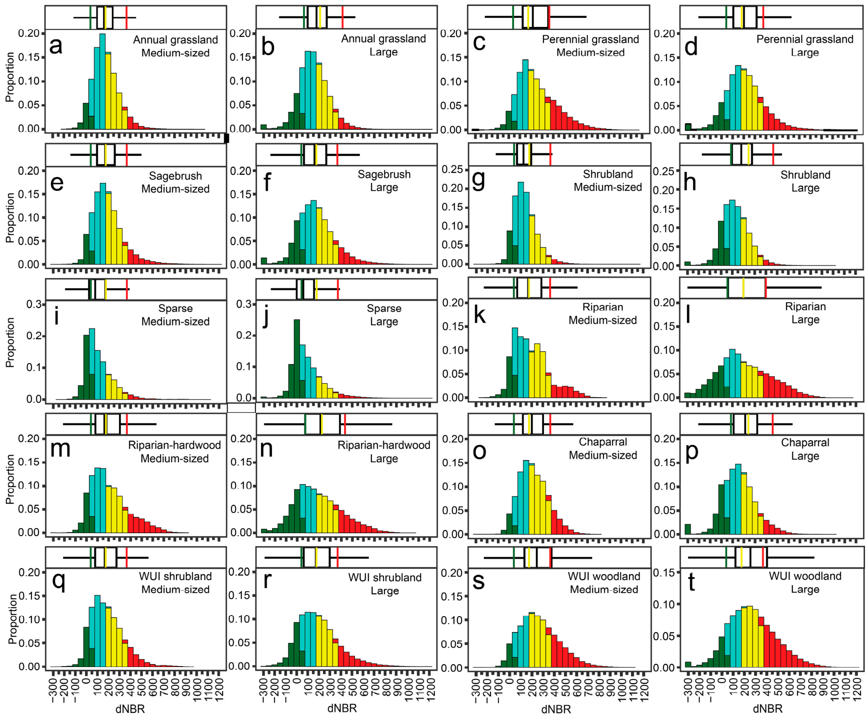

Figure 6. The distribution of satellite-derived fire severity (dNBR) for medium-sized (40 ≤ area < 400 ha; **a**,**c**,**e**,**g**,**i**,**k**,**m**,**o**,**q**,**s**) and large (≥400 ha; **b**,**d**,**f**,**h**,**j**,**l**,**n**,**p**,**r**,**t**) fires across primarily unforested vegetation types in Utah, USA from 1984 to 2021. Colors indicate classified fire severities using delineations from Miller and Thode 2007 (red—high severity, yellow—moderate severity, cyan—low severity, and dark green—no change detected by satellite).

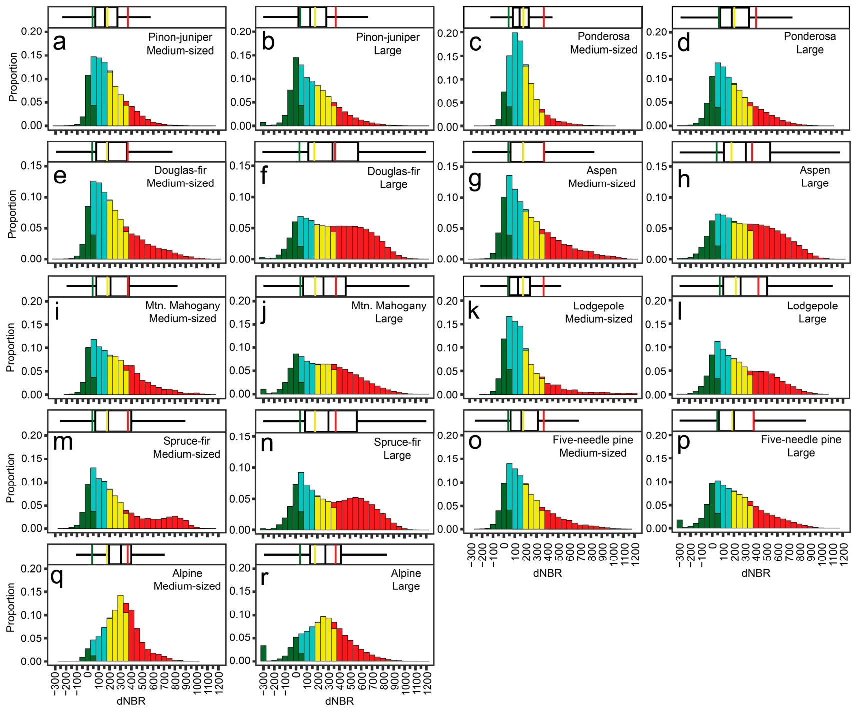

Figure 7. The distribution of satellite-derived fire severity (dNBR) for medium-sized (40 ≤ area < 400 ha; **a**,**c**,**e**,**g**,**i**,**k**,**m**,**o**,**q**) and large (≥400 ha; **b**,**d**,**f**,**h**,**j**,**l**,**n**,**p**,**r**) fires across primarily forested vegetation types in Utah, USA from 1984 to 2021. Colors indicate classified fire severities using delineations from Miller and Thode 2007 (red—high severity, yellow—moderate severity, cyan—low severity, and dark green—no change detected by satellite).

Table 3. The area burned (ha) in wildfires ≥ 40 ha, by year and non-forested vegetation type, in Utah from 1984 to 2022.

Year	Annual Grassland	Perennial Grassland	Sagebrush	Shrubland	Sparse	Riparian	Riparian Hardwood	Chaparral	WUI Shrub	WUI Woodland
1984	1384	383	1109	1593	6	0	1	1	3	5
1985	3356	645	3374	5143	29	25	48	25	38	74
1986	10,412	2226	16,999	13,263	826	44	67	25	173	933
1987	7818	1862	5938	6355	67	5	11	13	61	1575
1988	3216	1309	10,758	2632	105	35	301	5	529	3120
1989	698	591	4061	699	1554	33	44	26	507	1850
1990	119	229	3331	127	389	3	40	14	166	2327
1991	53	185	1460	351	9	0	0	11	98	116
1992	438	729	4997	1431	47	6	25	121	109	1379
1993	412	242	3716	2467	86	0	0	129	21	54
1994	15,143	7310	36,360	15,537	475	116	157	182	1579	3628
1995	9545	5839	30,624	21,558	440	13	62	709	262	1872
1996	16,436	12,630	10,4226	21,209	1172	115	253	685	1560	12,477
1997	304	210	2445	1175	119	10	266	112	61	1062
1998	14,979	876	10,760	14,096	139	50	72	641	112	80
1999	3538	2593	31,631	6901	170	35	177	305	401	2728
2000	8914	6576	53,564	13,001	986	49	177	450	794	6135
2001	4957	5967	16,557	6765	368	55	166	120	439	5216
2002	1575	3262	26,828	2979	3514	385	792	108	2755	12,462
2003	1017	1668	9500	9947	701	336	134	1747	515	8429
2004	1218	696	5884	3882	146	428	426	1789	310	9423
2005	10,744	2689	24,729	47,609	356	133	124	3045	395	1244
2006	9608	3700	40,593	39,694	1852	113	287	3749	1385	6006
2007	28,943	11,111	99,928	54,655	2942	167	695	457	2385	12,512
2008	168	355	2800	841	150	77	129	26	238	1278
2009	1713	1878	16,771	4790	198	22	90	151	508	4347
2010	255	954	4834	423	215	8	35	22	239	2321
2011	3116	1591	10,262	4481	79	3	17	80	116	108
2012	9646	10,674	75,095	20,605	1535	95	270	1653	2996	12,886
2013	1330	3664	20,267	1594	168	35	55	228	892	1216
2014	977	876	4640	1468	61	75	31	51	68	1023
2015	115	766	538	38	39	1	5	1	60	467
2016	5458	15,594	6644	2015	299	104	54	70	317	1493
2017	12,735	4672	27,014	15,959	504	681	564	141	376	1313
2018	2042	5826	18,784	3181	2140	171	637	405	1270	21,860
2019	2570	1513	16,441	3901	306	472	252	184	256	1938
2020	9134	2943	16,752	17,377	5223	575	482	515	321	2567
2021	1050	613	6067	1688	538	450	149	58	533	1511
2022	30	16	229	127	39	14	8	21	7	43
Total	205,166	125,463	776,510	371,557	27,992	4939	7103	18,075	22,855	149,078

Table 4. The area burned (ha) in wildfires ≥ 40 ha, by year and forested vegetation type, in Utah from 1984 to 2022.

Year	Pinon-Juniper	Ponderosa	Douglas-Fir	Aspen	Mountain Mahogany	Lodgepole	Spruce-Fir	Five-Needle Pine	Alpine
1984	0	30	0	0	0	0	0	0	0
1985	4	11	40	10	41	0	1	4	30
1986	38	101	39	9	175	1	2	38	39
1987	25	20	28	54	24	0	1	25	24
1988	174	196	262	455	114	20	98	174	99
1989	304	734	1450	802	126	224	896	304	180
1990	38	17	625	187	62	0	22	38	90
1991	5	20	5	1	3	0	0	5	1
1992	295	1	67	248	159	0	8	295	228
1993	36	73	139	224	16	0	126	36	25
1994	506	928	712	1091	737	69	108	506	416
1995	61	13	15	45	26	0	7	61	21
1996	358	705	923	1268	1059	0	282	358	336
1997	18	344	163	23	80	1	2	18	21
1998	0	1	0	0	7	0	0	0	76
1999	189	458	225	231	74	41	17	189	127
2000	180	39	859	574	944	20	70	180	402
2001	304	583	1084	945	401	28	104	304	104
2002	4622	2609	9030	5832	1102	696	3378	4622	2089
2003	475	635	921	743	120	70	212	475	200
2004	53	260	730	613	118	0	78	53	166
2005	253	317	299	601	131	626	301	253	71
2006	151	565	656	254	377	12	78	151	181
2007	622	1474	1332	2482	1028	750	1031	622	1153
2008	136	1668	1383	405	93	0	72	136	89
2009	317	2004	1767	874	584	0	217	317	346
2010	1712	647	3896	1536	950	0	851	1712	367
2011	0	44	5	0	62	0	0	0	11
2012	1344	802	3999	5151	1803	13	1210	1344	1621
2013	447	258	583	208	475	5	51	447	1753
2014	31	2	41	39	11	0	12	31	189
2015	16	753	139	58	52	0	8	16	87
2016	383	169	929	1999	172	242	1381	383	1509
2017	1773	2234	7597	10,211	797	1	4282	1773	240
2018	3064	1640	17,598	18,257	2053	878	8421	3064	762
2019	542	1779	2405	2081	205	96	1606	542	73
2020	2255	442	2458	4301	218	5998	19,889	2255	601
2021	121	624	1610	2090	148	0	1232	121	54
2022	2	0	0	0	1	0	0	2	0
Total	20,854	23,200	64,014	63,902	14,548	9791	46,054	20,854	13,781

4. Discussion

The discontinuous, variable landscape of Utah has experienced a tremendous range of wildfire behavior over the past 38 years (Figures 2 and 4). This behavior has varied with fire size, vegetation type, and the legacy of decades of fire suppression. Medium-sized fires, often overlooked, comprised 5% of all burned land and had greater mean severity and lower interannual variance across most vegetation types. However, medium-sized fires had a lower severity for the highest severity quartile, relative to large fires. For vegetation types that burned at overall higher severity (i.e., predominantly forested vegetation types; Figures 4 and 5) medium-sized fires burned at lower severity than large fires.

Although remote sensing of fire is the only practical method to analyze landscapes, the variation in landforms, vegetation, and fuel loading will always introduce considerable uncertainty. In particular, Landsat-based analyses of fire severity have high uncertainties at moderate levels of severity—tree death is often poorly correlated with changes in reflectance [13] and actual surface fuel combustion can also likewise be poorly correlated with satellite-derived severity [52]. The correlation between satellite-derived fire severity and ground-based surveys tends to increase at very high or very low levels of severity [13]. However, the delineation between truly unburned and very lightly burned remains unclear [41,52,53] and our severity assessments likely encompass small- and large-scale unburned refugia located in the interior of fire perimeters. Development of new remote-sensing technologies such as hyper-spectral imaging and post-fire LiDAR as well as building region-specific relationships between burn severity and ecological effects [54] may improve our ability to delineate fire perimeters, changes in fuels, and burn severity [55].

Our results (Figures 6 and 7) demonstrate the differing effects of fire on diverse vegetation types (see also Thode et al. [6]). Although dNBR, RdNBR, and other satellite-derived metrics of fire severity may be broadly comparable when vegetation and fuel loading are similar (e.g., between Douglas-fir and spruce-fir forests), comparisons will be less meaningful when vegetation and surface fuel loading differ (especially if a defined vegetation type has experienced a long period of fire suppression). The issue of differential fuel loading is perhaps more important in Utah spruce-fir forests because of the large quantity of heavy fuels created by the *Dendroctonus rufipennis* outbreak in the 1990s and the consequent effects on surface fuel evolution [35] as well as the effects of fuel evolution after fires burn in forests where fire has been long excluded [35,56]. Importantly, dNBR and RdNBR can struggle to adequately characterize the ecological effects of fire in non-forest systems [56,57] owing to the potentially rapid sprouting after fire, or inherent differences in fire effects between ecosystems dominated by annual or perennial life. Furthermore, the effects of fire are not limited to mortality and consumption of vegetation. The differential effects of fire on soil between different landcover types makes direct comparison difficult [11].

Although LANDFIRE classification has known accuracy issues with narrow classifications of vegetation [58,59], we aggregated categories of similar vegetation (Table S1) which are more likely to agree with reference plots [26]. However, no single remote sensing classification of vegetation will be completely accurate and will include misclassification errors due to changes in vegetation and land use through time. The summary statistics presented here represent the average of 19 vegetation categories split unevenly across 24,703,822 analyzed pixels, and may not adequately represent fire effects in fringe-case communities and those with underrepresented successional stages or with uncharacteristic fuel loadings.

4.1. Large Fires Have More Variable Burn Severities Than Medium-Sized Fires

Larger fires exhibited lower mean severity, but this was due to a relatively high area in low and unchanged severities. This satellite interpretation of lower severity could in turn be due to large patches of truly unburned vegetation [60] or to fast regrowth of herbaceous vegetation [41,61]. For some vegetation types, the area of the fire had little impact on either mean severity or the form of the cumulative distribution of severity. For example, sparse and riparian vegetation had the lowest mean quartile of burn severity, suggesting that underlying fuel structure and conditioning may not promote flame propagation and results in unburned refugia inside of fire perimeters.

Importantly, those ecosystems with the greatest Q4 severity, such as spruce-fir or Douglas-fir, also had the greatest interannual variation, highlighting difficulty in generalizing fire effects across time. Other systems, such as sagebrush or shrubland, had low interannual variation in burn severity, indicating that if conditions are suitable for burning (e.g., sufficiently low fuel moisture and suitable weather) that these ecosystems may generally have similar fire effects, regardless of the year. Though, the confluence of fire and encroachment or invasion of species that alter fuel structure, such as *Bromus tectorum* (cheatgrass), may see altered fire behavior and regimes that exceed the resilience of even fire-adapted systems [62,63].

Although medium-sized fires had higher mean severity, large fires may have more negative ecosystem impacts, depending on the vegetation [64], because large fires include larger patches that burn at high severity which may cause delayed vegetation recovery. As well, dispersal and germination of seeds may be hampered over large distances, such as those present in large fire scars [65,66]. Notably, we detected large proportions of 'unchanged' severity in large fires, potentially indicating the presence of unburned refugia in the interior of many of fires. These unburned refugia may act as important sources for the dispersal of seeds into the interior of large, high-severity fire footprints on the landscape [60].

Large fires dominated the area burned in Utah and, have greater upper limits of burn severity that may surpass the natural range of variability, enable establishment by problematic species, and exceed ecosystem resilience [63,67]. Additionally, because large fires are often controlled by top-down climatic influences, the confluence of drought and large fires may contribute to long-term mortality of surviving woody vegetation [68] and more high-severity fires [69].

Predicting the post-fire effects of large fires may be more difficult than medium-sized fires due to the higher interannual variability of burn severity and more extreme values of the least severely burned quartile (of area) and the most severely burned quartile. Importantly, local controls on fire behavior from topography, fuel conditioning, and loadings will act as proximate controls on fire effects [40,70] and average burn severities and area may not be applicable for fringe-case fire weather, communities and landscape positions.

4.2. Variation in Area Burned and Severity across Vegetation Types

Forested vegetation types and large fires had high interannual variation in burn area and severity, likely due to the regional climatic influences on fuel accumulation and drying over multi-year and seasonal scales [70,71]. As well, much of the area burned in Douglas-fir, aspen, and spruce-fir has been within the last decade (Table 4), and may represent abnormally high burn area or severity owing to fuel buildups as a result of fire suppression policies and criminalization of cultural burning over the preceding century [72,73]. While herbaceous fuels can also exhibit multi-year responses to climate [74], it is possible that other confounding factors, such as less topographic variation, fewer physical barriers to fire spread, lower variability in fuel sizes, or uniformly low fire season fuel moistures [75] in non-forested systems may be responsible for the lower interannual variation in burn area and severity. Brown et al. [31] found that regional fire years in Utah occurred approximately every 8-yrs from 1630 to 1900, and were associated with drought and La Niña conditions during the year of fire, though this pattern varied with latitude in Utah, with northern sites having less forcing from the El Niño Southern Oscillation. Altered climates have already shifted western North American fire seasons [76] and further warming and more variable climates may see greater shifts in the timing, frequency, and size of Utah's fires.

Most of the area burned in Utah is driven by fires in lower-elevation, arid vegetation types such as annual and perennial grasslands and the widespread sagebrush steppe and shrublands. However, the more productive vegetation types of Douglas-fir, aspen, and spruce-fir were those with the greatest burn severities and likely those with the most extreme fire intensities owing to their perennial lifecycles, greater fuel loadings, and upper slope positions likely to burn under intense heading fire [40]. Most fires were not confined to a single vegetation type or land cover.

4.3. Wildfires in the WUI

Large fires pose considerable risks to people, developed infrastructure, and ecosystems, although they can lead to some desirable post-fire conditions [77,78]. From 1990 to 2010 the US has seen a 33% increase in the area, and a 44% increase in the number homes within the WUI [79], which poses considerable fire dangers and complications in successfully managing fire on the landscape. Nationally, 32% of all wildfires originate in the WUI and are overwhelmingly human ignitions which are responsible for the majority of threatened and damaged structures [80]. Forested WUI in Utah burned 6.5-fold more area than herbaceous and shrub-dominated WUI, and at higher severity. This suggests that the WUI most at-risk are those occupying the productive and upper-elevation vegetation types in Utah which are capable of supporting trees.

5. Conclusions

Continued monitoring of fires in Utah will further refine the variability in fire regimes and better delineate the scope and severity of wildfire within Utah. Examining the relationships between vegetation and fires in the recent past, we may be able to better predict and mange future fire under increasingly variable climates and the continued expansion of the WUI into wildland systems. Fires of any size can have considerable ecosystem benefits including reducing the fuel loads that can lead to extreme fire behavior and reducing forest density—both of which may become even more important in droughtier conditions. Prescribed fires that are as large as practically manageable can also provide these benefits, and we suggest that a tractable size for prescribed burns- and the characteristic results—may be exemplified by the data on medium-sized fires in each vegetation type.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire6110423/s1, Figure S1: Distance to centroid for dNBR quartile values for medium-sized and large fires from 1991 to 2020, Utah, USA; Figure S2: Distance to centroid for dNBR quartile values for medium-sized and large fires, by vegetation type, from 1991 to 2020, Utah, USA. Table S1: Vegetation categories aggregated from LANDIFRE Existing Vegetation Type categories (LANDFIRE 2022); Table S2: Kolmogorov-Smirnov tests on the distribution of burn severity between medium-sized (40 ha $\leq$ area < 400 ha) and large ($\geq$400 ha) wildfires in Utah, USA from 1984 to 2022; Table S3: The number of medium-sized (40 ha $\leq$ area < 400 ha) and large ($\geq$400 ha) wildfires in predominantly non-forested vegetation types in Utah, USA from 1984 to 2022; Table S4: The number of medium-sized (40 ha $\leq$ area < 400 ha) and large ($\geq$400 ha) wildfires in predominantly forested vegetation types in Utah, USA from 1984 to 2022; Table S5: The area burned in medium-sized (40 ha $\leq$ area < 400 ha) and large ($\geq$400 ha) wildfires in predominantly non-forested vegetation types in Utah, USA from 1984 to 2022; Table S6: The area burned in medium-sized (40 ha $\leq$ area < 400 ha) and large ($\geq$400 ha) wildfires in predominantly forested vegetation types in Utah, USA from 1984 to 2022; Table S7: The median differenced Normalized Burn Ratio (dNBR) in medium-sized (40 ha $\leq$ area < 400 ha) and large ($\geq$400 ha) wildfires in predominantly non-forested vegetation types in Utah, USA from 1984 to 2022; Table S8: The median differenced Normalized Burn Ratio (dNBR) in medium-sized (40 ha $\leq$ area < 400 ha) and large ($\geq$400 ha) wildfires in predominantly forested vegetation types in Utah, USA from 1984 to 2022.

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