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Land-Use Type as a Driver of Large Wildfire Occurrence in the U.S. Great Plains

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Abstract: Wildfire activity has surged in North America's temperate grassland biome. Like many biomes, this system has undergone drastic land-use change over the last century; however, how various land-use types contribute to wildfire patterns in grassland systems is unclear. We determine if certain land-use types have a greater propensity for large wildfire in the U.S. Great Plains and how this changes given the percentage of land covered by a given land-use type. Almost 90% of the area burned in the Great Plains occurred in woody and grassland land-use types. Although grassland comprised the greatest area burned by large wildfires, woody vegetation burned disproportionately more than any other land-use type in the Great Plains. Wildfires were more likely to occur when woody vegetation composed greater than 20% of the landscape. Wildfires were unlikely to occur in croplands, pasture/hay fields, and developed areas. Although these patterns varied by region, wildfire was most likely to occur in woody vegetation and/or grassland in 13 of 14 ecoregions we assessed. Because woody vegetation is more conducive to extreme wildfire behaviour than other land-use types in the Great Plains, woody encroachment could pose a large risk for increasing wildfire exposure. Regional planning could leverage differential wildfire activity across land-uses to devise targeted approaches that decrease human exposure in a system prone to fire.

Keywords: ecoregions; exposure; grassland; natural disaster; regional planning; woody encroachment

1. Introduction

Natural disasters result when human populations are unable to cope with biophysical processes that push systems to the extreme ranges of variability in system functioning [1–3]. Increases in natural disasters have been recorded globally [2,4], leading to high economic costs and loss of life. Almost 1 million fatalities worldwide resulted from natural disasters between 2004 and 2013 [5]. The damages resulting from weather and climatic disasters alone in the United States cost over $1.5 trillion between 1980 and 2018 [6]. With increases in the frequency and magnitude of extreme events occurring around the world [7,8], it is a growing priority to identify patterns and processes associated with a heightened propensity for extreme events so that we can better identify and manage current and future risk.

Natural disasters resulting from wildfire are increasing [9], fuelling the need to understand patterns in wildfire in regions experiencing rapid increases in wildfire trends. North America's grassland biome saw a surge of large wildfire activity in recent decades [10]. The average number of large wildfires per year increased from 33 between 1985 and 1994 to 117 between 2005 and 2014 while total hectares burned increased by 400% during this time [10]. Multiple Great Plains states, including Texas, Oklahoma, Montana, and North Dakota, were part of wildfire disaster events that each individually exceeded $1 billion in losses between 2008 and 2018 [6]. The Wildland Fire Executive

Council lists the Great Plains as a region that is mostly at low to moderate risk for large, long duration wildfire (Figure 1). While this may still be true relative to the forested west, more large wildfires have been occurring across this region than in the historical past [10]. Many of these wildfires have similar duration to large wildfires in the west (e.g., the Rhea fire in Oklahoma burned 14 days in 2018; National Wildfire Coordinating Group).

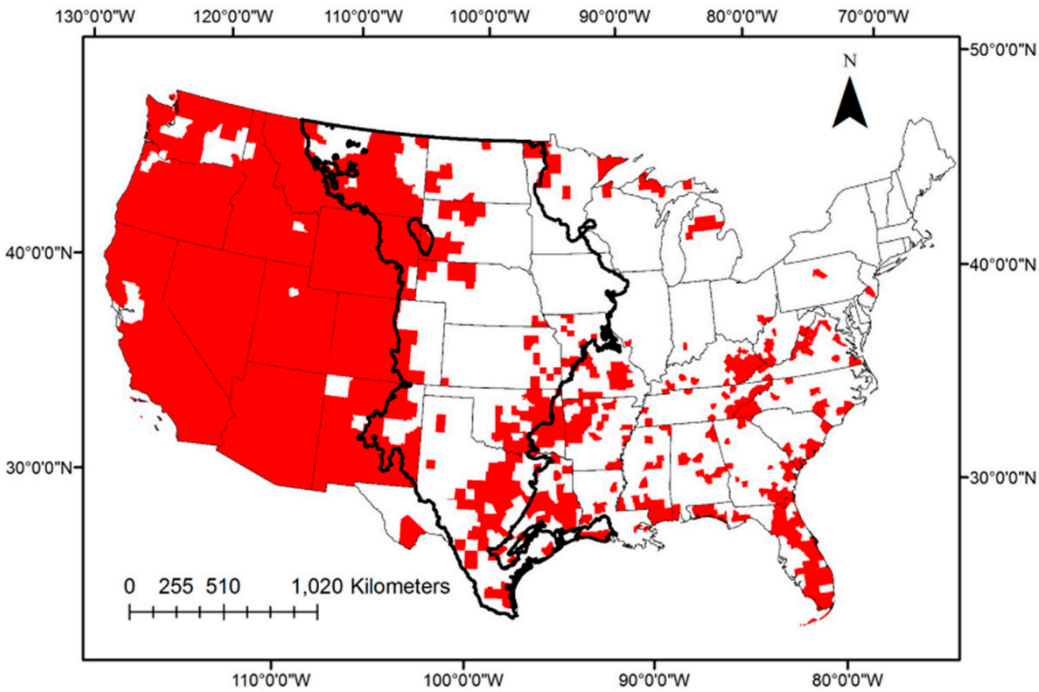

Figure 1. Areas designated as high risk for large, long-duration wildfire (red) by the National Cohesive Wildland Fire Management Strategy [11]. The black outline delineates the Great Plains L1 ecoregion.

Wildfire used to be frequent in the Great Plains, with an average fire return interval between 2 and 14 years [12]. However, a shift in land management practice from the application of fire by Native Americans to post-European land management practices of fire suppression almost eradicated large fire from the Great Plains over the last century [12–15], and it is this characterisation of fire that shapes most assessments of current wildfire risk. However, past trends are incapable of predicting current and future risks in systems that are rapidly transitioning and reorganizing [16,17]. Four of the top 10 largest wildfire complexes since 2010 within the conterminous U.S. occurred in the Great Plains, and the largest wildfire on record in the conterminous U.S. occurred in Texas in 2006 [18]. The western United States experienced abrupt increases in wildfire that contrasted with previously recorded wildfire patterns resulting in an altered and more hazardous wildfire regime [19]. Increases in wildfire across the Great Plains could similarly represent a shift in wildfire regime tied to a rapidly changing environment.

Understanding recent changes in wildfire in the Great Plains needs to begin with investigations of the dominant constraints on wildfire occurrence and distribution: (1) fuel availability, (2) ignition sources, and (3) climatic and weather conditions conducive to combustion [20–22]. Patterns in ignitions have been documented across the conterminous U.S., with 84% of wildfires started by humans, e.g., [23]. Similarly, climate has been tied to wildfire across western forested regions, e.g., [24,25]. It is well-established that fire patterns are also strongly limited by fuel type, abundance, and distribution [21,26,27]. In fuel-limited systems like grasslands, fuel structure and availability have been shown to constrain fire activity to a greater extent than climate [21,27]. Shifts in wildfire occurrence have been linked to unintended shifts in fuel composition and contiguity in a number of grassland regions (e.g., sagebrush to cheatgrass dominance in western North America [28,29], invasion of jaragua grass in Central America [30,31], and gamba grass invasion in Australia [32,33]).

Land-use plays a predominant role in shaping wildfire distributions from global to local scales because of strong ties to fuel patterns [20,34]. In the Great Plains, shifting land management practices over the last century have led to substantial changes in land-use. Historically, the Great Plains was dominated by grassland interspersed with rare patches of woody vegetation that managed to escape frequent grassland fires [15,35]. Like many contemporary biomes, human development has now created a patchwork of intact grassland and forested vegetation interspersed with croplands, pastures, and developed areas. Fire suppression combined with extensive tree planting has allowed for recent regional-scale increases in the distribution and cover of woody vegetation [15,36,37]. Understanding how wildfire is associated with different land-use types across the Great Plains would allow us to better deduce the potential exposure of people to the changes in large wildfires in the Great Plains and how land-use could be utilised to decrease risk of human exposure to wildfire in the future.

This study determines how large wildfire (>400 ha) activity is linked to land-use across North America's temperate grassland biome. We expect that large wildfires will be most frequent in intact grasslands, which are highly pyrogenic and historically hosted a frequent fire cycle in the Great Plains [12,15,38], and less frequent in woody-dominated land-use types, croplands, and pasture lands. Moreover, Donovan et al. [10] found regional differences in large wildfire trends across Great Plains ecoregions. For instance, Cross Timbers and Edwards Plateau ecoregions of the Great Plains experienced some of the greatest increases in large wildfire number between 1985 and 2014 (3900% and 2600%, respectively), while the number of large wildfires in the Nebraska Sandhills remained relatively consistent [10]. We predict that trends in area burned by large wildfires and the degree to which different land-use types are implicated will vary spatially across Great Plains ecoregions tied to differences in climate-vegetation relationships. We quantify the percent of area burned by large wildfires of each dominant land-use type at both the Great Plains and ecoregion scale between 1993 and 2014. We then contrast this with regional abundance and distribution of land-use types to determine on which land-use types large wildfires were more likely to occur over the last two decades.

2. Materials and Methods

2.1. Data

The Environmental Protection Agency (EPA) L1 Great Plains ecoregion was used to designate the boundary of our study area [39]. L3 ecoregions were used to subdivide the Great Plains to assess regional patterns. EPA ecoregion designations are based on similarities in climate, vegetation, land-use, soils, geology, landforms, hydrology, and wildlife [40]. Only ecoregions with 5 or more large wildfires were included in our analysis, consistent with Donovan et al., [10]. Areas with less than 5 fires were considered to have too few wildfires to assess broad-scale wildfire trends. All ecoregions we assessed had greater than 5000 ha burned by large wildfires (Table 1). Palmer Drought Severity Index (PDSI) values, used to assess relative dryness of an area, demonstrate that dryness at wildfire initiation averaged across ecoregions ranged from Near Normal (PDSI of −1.9 to 1.9) to Moderate Drought (PDSI of −2.0 to −2.9) conditions based on U.S. National Oceanic and Atmospheric Administration PDSI categories (Table 1). Mean population density per square kilometre ranged from an average of 1 to 90 across ecoregions (Table 1).

Large wildfire perimeter information (wildfires > 400 ha in size) was collected from 1993 to 2014 from the Monitoring Trends in Burn Severity (MTBS) project [41]. MTBS includes 30 m resolution large wildfire data for the entire conterminous United States. Fire perimeters are delineated using pre- and postfire satellite imagery along with Normalised Burn Ratio (NBR), differenced Normalised Burn Ratio (dNBR), and Relativized differenced Normalised Burn Ratio (RdNBR) images [41]. MTBS covers both private and public lands, ensuring a continuous spatial distribution of large wildfire data. Moreover, burn areas are collected using a standardized methodology, creating consistency in spatial and temporal reporting across the dataset. MTBS wildfire perimeters have been used to assess wildfire trends across a number of studies in the U.S., e.g., [7,10,42], though have been found to overestimate

total area burned by including unburned patches within the fire [43]. Only perimeters classified as "wildfire" by MTBS were included in our analysis. Because MTBS does not map wildfires greater than ~400 ha in size (≥1000 acres) in the western U.S., we restricted our analysis to large wildfires >400 ha.

Table 1. L1 and L3 ecoregion statistics between 1993 and 2014 in the U.S. Great Plains.

Ecoregion	Ecoregion Area (ha)	Number of Wildfires [a]	Total Area Burned (ha)	Average PDSI at wildfire initiation [b]	Average Population Density per km^2 in 2010[c]
Great Plains	2.23×10^8	1870	5.04×10^6	−1.46 ± 2.27 SD	16 ± 133 SD
Central Great Plains	2.75×10^7	180	3.17×10^5	−1.98 ± 2.31 SD	12 ± 104 SD
Central Irregular Plains	1.14×10^7	19	1.31×10^4	−2.35 ± 2.20 SD	30 ± 158 SD
Cross Timbers	8.81×10^6	234	4.39×10^5	−2.78 ± 1.93 SD	35 ± 167 SD
Edwards Plateau	7.49×10^6	102	3.84×10^5	−1.47 ± 2.24 SD	12 ± 90 SD
Flint Hills	2.79×10^6	49	1.13×10^5	−1.65 ± 2.39 SD	9 ± 87 SD
High Plains	2.88×10^7	299	7.92×10^5	−1.60 ± 1.76 SD	15 ± 150 SD
Lake Agassiz Plain	4.51×10^6	60	2.87×10^4	−1.17 ± 2.16 SD	8 ± 87 SD
Nebraska Sandhills	5.91×10^6	41	8.17×10^4	−0.92 ± 2.56 SD	1 ± 11 SD
Northern Glaciated Plains	1.35×10^7	5	5.10+3	−2.01 ± 1.43	4 ± 52 SD
Northwestern Glaciated Plains	1.74×10^7	63	8.62×10^4	−0.32 ± 1.15 SD	2 ± 35 SD
Northwestern Great Plains	3.58×10^7	414	1.39×10^6	−0.78 ± 2.34 SD	2 ± 35 SD
Southern Texas Plains	5.34×10^6	12	3.11×10^4	0.71 ± 2.26 SD	10 ± 111 SD
Southwestern Tablelands	1.99×10^7	350	1.13×10^6	−1.73 ± 1.99 SD	5 ± 72 SD
Western Gulf Coastal Plain	7.54×10^6	163	2.26×10^5	−0.98 ± 2.53 SD	90 ± 146 SD

[a] The number of wildfires across L3 ecoregion does not sum to the number of wildfires that occurred within the Great Plains as some wildfires occurred across multiple L3 ecoregion boundaries and thus were counted multiple times.
[b] Palmer Drought Severity Index (PDSI) data was summarized using Google Earth Engine [44] from Abatzoglou et al., [45].
[c] Population data was summarized from 2010 data sets generated by CIESIN, [46] using Google Earth Engine [44].

We used 30 m resolution National Land Cover Database (NLCD) land cover classifications for 1992, 2001, 2006, and 2011 (all years available at the time this study was conducted) to identify land-use types across the Great Plains (https://www.mrlc.gov/). NLCD is the most temporally extensive fine-resolution land-use classification currently publicly available for the United States. Unlike when merging data sets from multiple sources, NLCD data has relatively consistent thematic land-use classes and classification criteria across land cover years, making this the most comprehensive and temporally extensive data set available to assess land-use and large wildfire patterns for this biome.

2.2. Analysis

We created five dominant land-use types across the Great Plains using NLCD information: grassland, woody vegetation, crop, pasture and hay fields, and developed areas (Table S1). Woody vegetation represented a consolidation of evergreen, deciduous, and mixed forest types along with shrublands (Table S1). NLCD does not distinguish between shrubs, young trees, and trees stunted from environmental conditions (Table S1). Developed areas included regions with constructed materials including parks, single-family homes, and apartment complexes (Table S1). To determine land-use type abundance across regions, we calculated the average percent cover of each land-use type in the Great Plains and each L3 ecoregion across the 1992, 2001, 2006, and 2011 NLCD land cover classifications, separated by year.

We overlay large wildfire perimeter information from 1993 to 2014 with our land-use information to calculate the percent of the total area that burned that was composed of different land-use types (Figure 2). In order to sample the most accurate representation of land-use types that burned each year, we extracted land-use information from the 1992 NLCD land cover classification with large wildfires from 1993 to 2001, from the 2001 NLCD land cover classification with large wildfires from 2002 to 2006, from the 2006 NLCD land cover classification with large wildfires from 2007 to 2011, and from the 2011 NLCD land cover classification with large wildfires from 2012 to 2014.

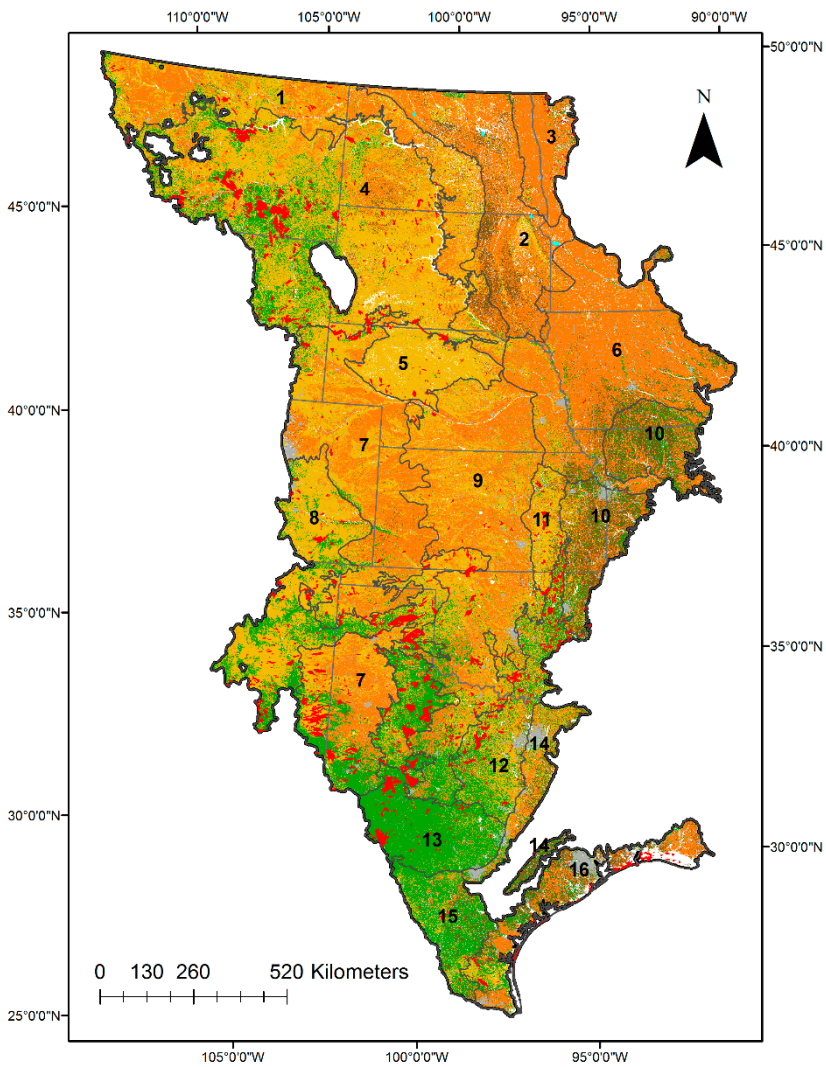

Figure 2. The distribution of large wildfire (>400 ha) perimeters (red) across land-use types (grassland in yellow, woody vegetation in green, crops in orange, pasture/hay fields in brown, and developed areas in grey) in the U.S. Great Plains and level 3 ecoregions designated by the EPA (1 = Northwestern Glaciated Plains, 2 = Northern Glaciated Plains, 3 = Lake Agassiz Plain, 4 = Northwestern Great Plains, 5 = Nebraska Sandhills, 6 = Western Corn Belt Plains, 7 = High Plains, 8 = Southwestern Tablelands, 9 = Central Great Plains, 10 = Central Irregular Plains, 11 = Flint Hills, 12 = Cross Timbers, 13 = Edwards Plateau, 14 = Texas Blackland Prairies, 15 = Southern Texas Plains, 16 = Western Gulf Coastal Plain).

To determine land-use types that have the greatest propensity for large wildfire, we measured which land-use types disproportionately appeared in large wildfire perimeters. We took the difference between the percent of the total area burned of each land-use type and the average percent cover of each land-use type within the Great Plains and each L3 ecoregion. Values near zero indicate that large wildfire occurrence is not influenced by a given land-use type. Positive values indicate land-use types where large wildfires are more likely to occur, and thus that have a higher propensity for large wildfire. Negative values indicate where large wildfires are less likely to occur, and thus that have a lower propensity for large wildfire.

The propensity for large wildfire in a given land-use type may be dependent upon its relative cover within an area. We measured the percent cover of each land-use type within each large wildfire perimeter that burned between 1993 and 2014 (n = 1870) in the Great Plains. We used this information to generate frequency distributions of large wildfire occurrence relative to the percent cover for each land-use type using 10 bins of land-use type cover ranging from <0 to 100%. This was repeated for

each L3 ecoregion (wildfire numbers per ecoregion are summarised in Table 1). To determine how the propensity for large wildfire changes relative to a land-use type's cover on the landscape, we compared these measured fire frequency distributions to null distributions, created by randomly distributing large wildfire across land-use types. In the Great Plains, our null distribution was generated by distributing 5000 random points across the Great Plains and creating buffer zones around each point that matched the average large wildfire size in the Great Plains (2698 ha). In each L3 ecoregion, we distributed 500 random points across the ecoregion and created buffer zones around each point matching the average large wildfire size within that ecoregion (Table S2). Within each buffer zone, we measured the percent cover of each land-use type for each NLCD land cover classification for each year (1992, 2001, 2006, and 2011). The number of buffer zones sampled was equal to the number of large wildfires that occurred within the Great Plains and each L3 ecoregion. For instance, in the Great Plains, we sampled 490 buffer zones (the number of large wildfires that burned in the Great Plains between 1993 and 2001) from the 1992 NLCD land cover classification, 505 (the number of large wildfires that burned in the Great Plains between 2002 and 2006) from the 2001 NLCD land cover classification, 688 (the number of large wildfires that burned in the Great Plains between 2007 and 2011) from the 2006 NLCD land cover classification, and 187 (the number of large wildfires that burned in the Great Plains between 2012 and 2014) from the 2011 NLCD land cover classification. This totalled to 1870 sampled buffer zones (the total number of large wildfires in the Great Plains over our study period). We repeated random sampling an additional 999 times within the Great Plains and each L3 ecoregion. Data were used to generate 1000 null frequency distributions. We averaged these frequency distributions to create a single null distribution for each land-use type in the Great Plains and each L3 ecoregion. We then subtracted the values of our generated null frequency distribution from the measured large wildfire frequency distribution for each land-use type to determine how the relative cover of each land-use type altered the propensity for large wildfire. A value near zero indicates that large wildfires are not influenced by the relative abundance of a given land-use type on a landscape. A positive value indicates that large wildfires are more likely to occur, and thus there is a higher propensity for large wildfire, given the relative abundance of a land-use type. A negative value indicates that large wildfires are less likely to occur, and thus there is a lower propensity for large wildfire, given the abundance of a land-use type.

This comparison was further supplemented with nonparametric Fisher Exact Tests with R statistical software (version 3.5.2) to determine if there was a significant difference between the measured wildfire frequency distribution and our generated null distribution. P-values were simulated using Monte Carlo tests with 10,000 replicates.

Assumptions associated with our approach need to be articulated. Our assessment is limited by the assumptions that were used to develop NLCD and MTBS geospatial data sets. It is important to note that NLCD is unable to provide associated fuel flammability (including fuel availability, condition, and connectivity) or ignition probability. Differences in land-use management (e.g., haying, grazing) exist within and across land-use types in the Great Plains, however, there is no data available across this biome that allow us to determine how these patterns influence intrinsic and extrinsic fuel properties among land-use types. Moreover, our assessment does not directly incorporate patterns in other factors that can influence wildfire distribution, like ignitions, weather, and climate, e.g., [23,24]. Thus, our assessment should represent a starting point for more in-depth mechanistic assessments of ties between fuel pattern and large wildfire in the Great Plains.

3. Results:

3.1. Wildfire and Land-Use in the Great Plains

Woody vegetation and grasslands had the greatest propensity for large wildfire in the Great Plains (Figure 3C). Woody vegetation burned disproportionately more than any other land-use type in the Great Plains, composing over two times the percent land area in large wildfire perimeters than it did in the Great Plains as a whole (Figure 3). Large wildfires were more likely to occur in woody vegetation

and grassland as woody and grassland cover increased on the landscape (Figure 4F,G; $p < 0.01$, $p < 0.01$ respectively). Large wildfires occurred more frequently when woody cover exceeded 20% (Figure 4G) and when grassland cover exceeded 60% of the landscape (Figure 4F).

Croplands had the lowest propensity for large wildfire. While crops were abundant across the Great Plains, they burned over 15 times less than their proportional land coverage (Figure 3). The propensity for large wildfire was lower when crop cover was higher. Large wildfires were more likely when crop cover made up between >0 to 10% of the landscape (Figure 4H; $p < 0.01$) but were unlikely to burn when crop cover exceeded 10% of the landscape. Only five large wildfires occurred in regions where crop made up >90% to 100% of the landscape (Figure 4C).

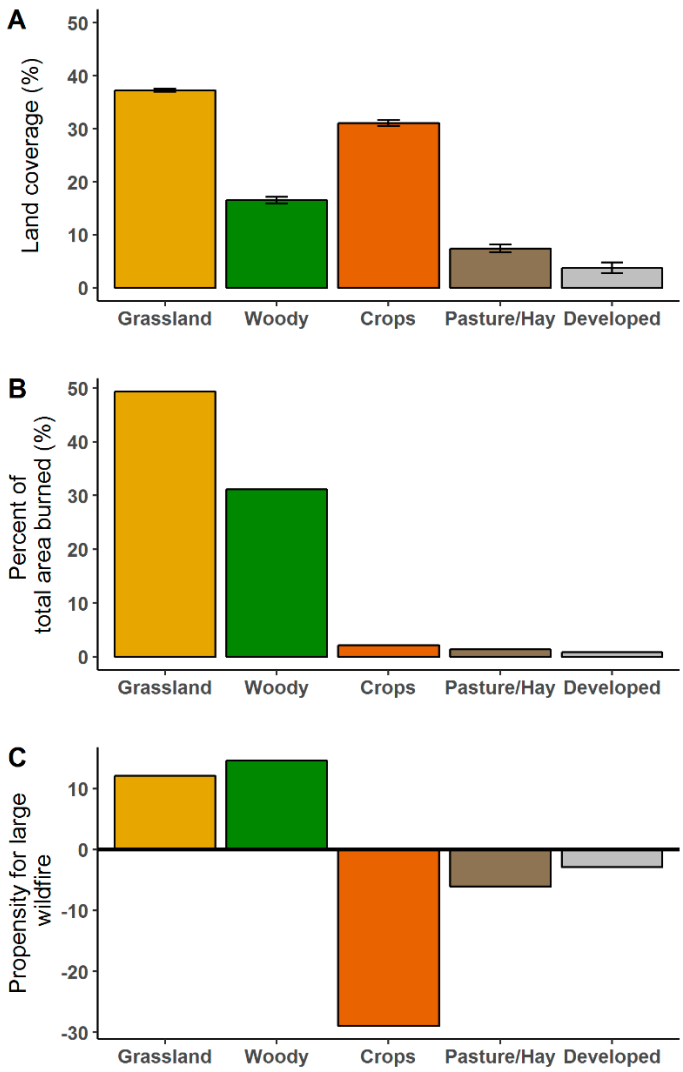

Figure 3. (**A**) The average percent of the U.S. Great Plains coved by grassland vegetation, woody vegetation, crops, pasture and hay fields, and developed areas based on 1992, 2001, 2006, and 2012 National Land Cover Database land cover classifications. (**B**) The percent of the total area burned in the Great Plains between 1993 and 2014 that occurred within grassland vegetation, woody vegetation, crops, pasture and hay fields, and developed areas. (**C**) The propensity for large wildfire, calculated from taking the difference between the percent total area burned and the percent cover of each land-use type, where a positive value indicates land-use types where wildfires were more likely to occur.

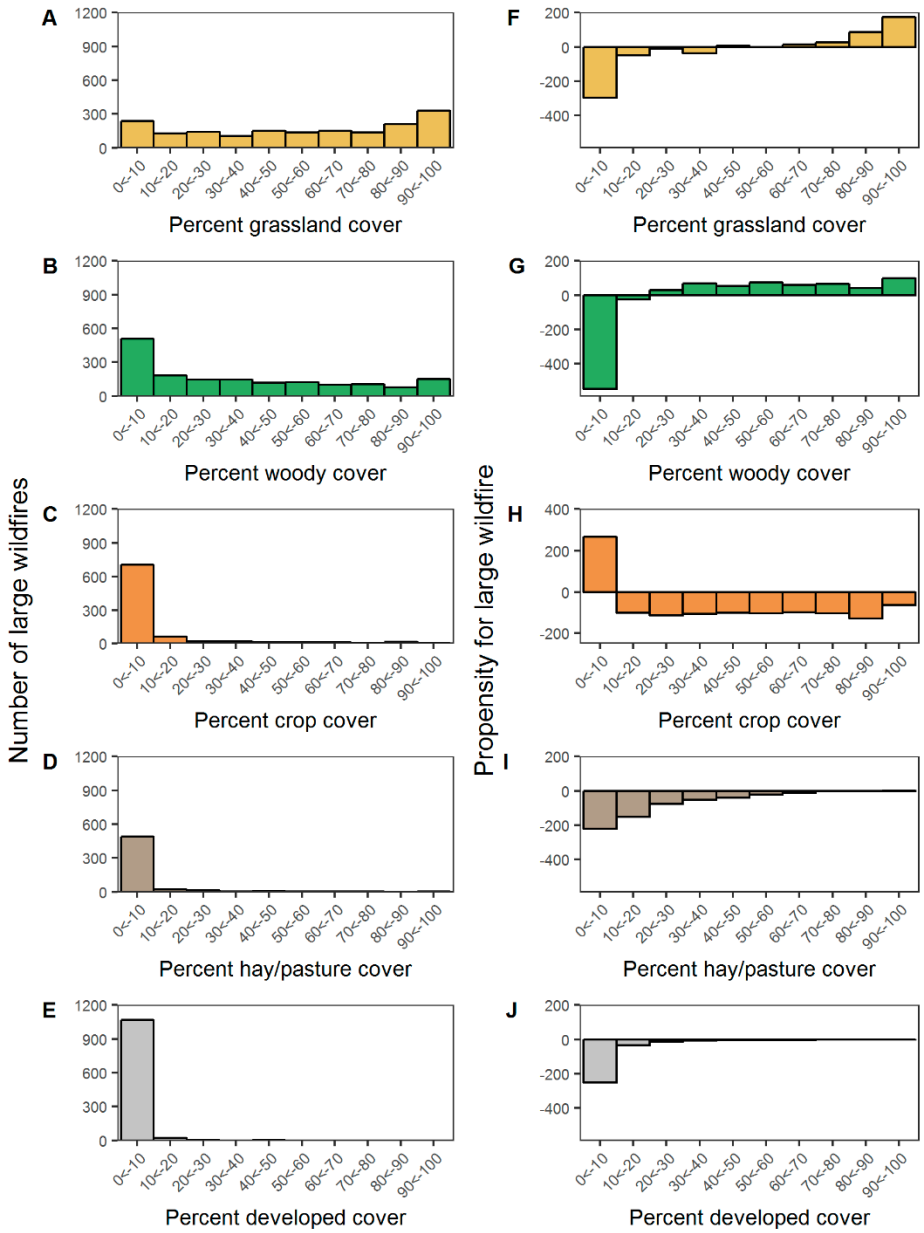

Figure 4. The number of wildfire perimeters between 1993 to 2014 that contained varying percent cover of (**A**) grassland, (**B**) woody vegetation, (**C**) crops, (**D**) hay and pasture, and (**E**) developed areas, as well as the relative propensity for large wildfire of varying land-use type cover (**F**–**J**), calculated by subtracting the null wildfire frequency distribution (random distribution) from the recorded wildfire frequency distribution (**A**–**E**), where positive values indicate land-use types where large wildfires were more likely to occur.

Large wildfires were similarly unlikely to burn in pasture/hay fields and developed areas. Pasture/hay fields burned eight times less than their proportional land coverage in the Great Plains (Figure 3). Developed areas burned in large wildfires four times less than their proportional representation in the biome (Figure 3). Almost no large wildfires occurred in locations with high coverage of pasture/hay fields or developed areas (Figure 4D,E). Four hundred eighty-eight large wildfires occurred in areas where pasture/hay fields covered less than 10% of the landscape, while large wildfire numbers ranged from 0 to 22 when landscape coverage of pasture/hay fields exceeded 10% (Figure 4D). Similarly, over 1000 large wildfires occurred where developed areas covered >0 to 10% of

the landscape (Figure 4E); however, almost no large wildfires occurred in locations where developed regions covered greater than 10% of the landscape (numbers ranging from 0 to 20 wildfires; Figure 4E). Regardless of their abundance on the landscape, large wildfires were unlikely to occur in pasture/hay fields or developed areas (Figure 4I,J; $p < 0.01$; $p < 0.01$).

3.2. Ecoregional Differences

In the majority of ecoregions (11 of 14), areas burned by large wildfire were primarily composed of woody vegetation and grassland (Figure 5B). For instance, 96% of the total area burned by large wildfires in the Edwards Plateau was composed of woody vegetation, while 97% of the total area burned by large wildfires in the Nebraska Sandhills was composed of grassland. Exceptions to this included the Lake Agassiz Plain, where crops dominated the total area burned by large wildfires (Figure 5B). Of the land-use types assessed in our study, crop and pasture/hay fields were the most common within large wildfire perimeters in the Northern Glaciated Plains, though they only represented a small portion of the total area burned by large wildfires (Figure 5B).

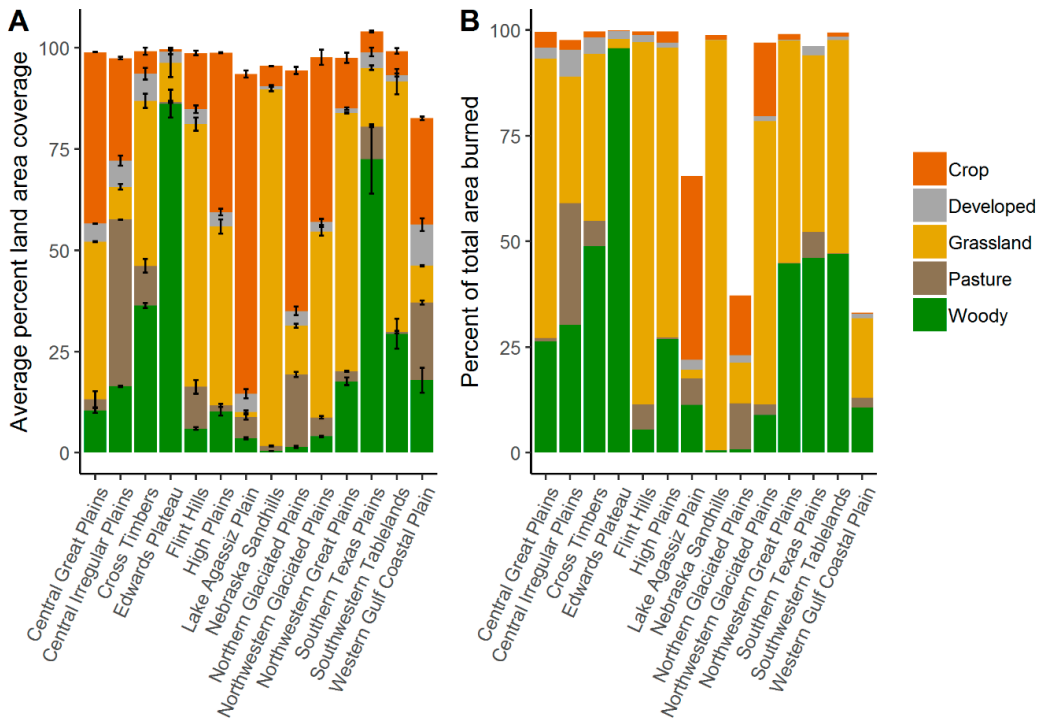

Figure 5. (**A**) The average percent land coverage of each land-use type assessed in this study and (**B**) the percentage of each land-use type that composed the total area burned within L3 ecoregions that contained ≥5 large wildfires in the U.S. Great Plains between 1993 and 2014. Error bars represent standard error. The percentage of land-use did not always add up to 100% because we only included predominant land-use types of the Great Plains in our analysis. Percentages could also slightly exceed 100% (i.e., Southern Texas Plains) when there was a higher amount of variation in values averaged to calculate percent land coverage.

Grassland or woody vegetation had the highest propensity for large wildfire in almost every ecoregion (13 of 14; Figure 6). There was a high propensity for large wildfire in grassland vegetation in eight ecoregions, while in four ecoregions (Edwards Plateau, Northwestern Great Plains, Southwestern Tablelands, and Northern Glaciated Plains), wildfire was unlikely to burn in grasslands (Figure 6). In 6 of the 14 ecoregions assessed, large wildfires were more likely to occur with greater levels of grassland cover on the landscape (Figures S1-S14; Table S3). This relationship was bimodal in both Cross Timbers and the Northwestern Great Plains, where large wildfires were more likely to burn in an area when

grassland cover was either of low or high dominance (Figures S2, S11). Woody vegetation had a high propensity for large wildfire across nine ecoregions, however, in the southern most ecoregions (Southern Texas Plains and Western Gulf Coastal Plain), wildfire was unlikely to occur in woody vegetation (Figure 6). In 8 of the 14 ecoregions assessed, large wildfires were more likely to occur with greater levels of woody vegetation cover on the landscape (Figures S1-S14; Table S3). In contrast, in the Edwards Plateau and the Southern Texas Plains, large wildfires were more likely to occur within a landscape when woody cover was at low or high dominance.

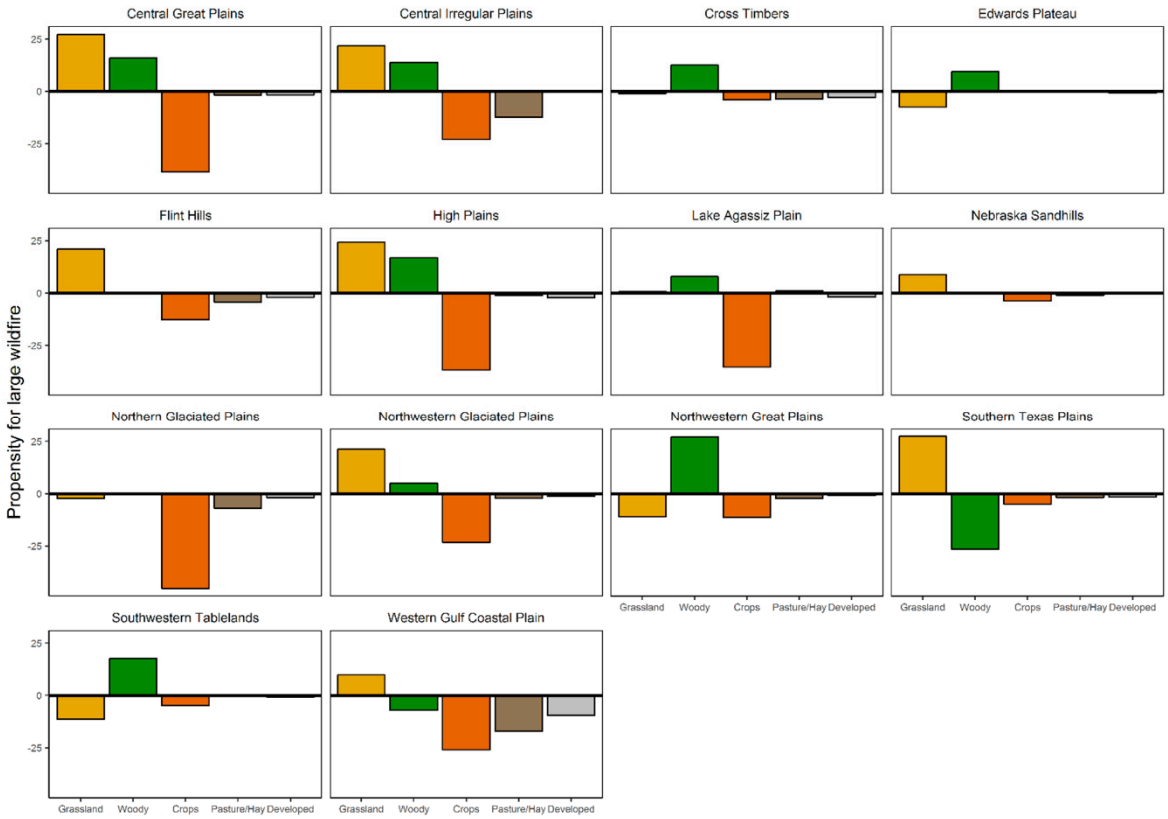

Figure 6. The relative propensity for large wildfire of grasslands, woody vegetation, crops, pasture/hay fields, and developed areas in U.S. Great Plains L3 ecoregions, calculated by taking the difference between the percent total area burned within each L3 ecoregion between 1993 and 2014 and the average percent cover of each land-use type in each L3 ecoregion. Positive values indicate land-use types where wildfires were more likely to occur.

While crops did make up a predominant portion of the total area burned by large wildfires in some ecoregions (for instance, the Lake Agassiz Plain where crop made up 43% of the total area burned; Figure 5), crops consistently had a low propensity for large wildfire across all ecoregions (Figure 6). In the majority of ecoregions, large wildfires were more likely to occur when crops covered between >0 to 10% or >10 to 20% of the landscape. Large wildfire was less likely when crop cover was greater (Figures S1–S14; Table S3). However, in the Lake Agassiz Plain, large wildfires were more likely to occur when crop cover made up less than 50% of the landscape.

Pasture/hay fields comprised a large portion of land-use in a number of ecoregions and was the dominant land-use type within the Central Irregular Plains (Figure 5A). Despite this, pasture/hay fields generally had a low propensity for large wildfire (Figure 6). Large wildfires were more likely to occur when pasture/hay fields made up between >0 to 10% of the landscape in three ecoregions: the Central Great Plains, Flint Hills, and Northern Glaciated Plains (Figures S1, S5, S9). The propensity for

large wildfires was lower when pasture/hay cover was greater in all ecoregions except the Northern Glaciated Plains and the Southern Texas Plains (Figure S9, S12).

Developed areas consistently made up less than 7% of the land-use across ecoregions, with the exception of the Western Gulf Coastal Plain (Figure 5A). They also consistently made up less than 7% of the total area burned (Figure 6). When wildfires occurred in developed areas, they were largely concentrated in landscapes that were composed of >0 to 10% developed area (Figure S1–S14; Table S3). However, in all other ecoregions, developed areas had a low propensity for large wildfire, regardless of landscape coverage (Figure 6; Figures S1–S14).

4. Discussion

Propensity of large wildfire was highest in grasslands and woody vegetation in the Great Plains, while developed areas, croplands, and pastures were less likely to burn in large wildfires. We expected intact grasslands to host the highest number of large wildfires. Grasses in the Great Plains are the most flammable fuel type that host important feedbacks with fire [15,38,47]. However, although grasslands comprised the greatest area burned by large wildfires, woody vegetation burned disproportionately more than any other land-use type in the Great Plains. In ecoregions that were found to have the greatest increases in wildfire number and total hectares burned by Donovan et al., [10], wildfires were most likely to occur in woody vegetation (e.g., Cross Timbers, Southwestern Tablelands, Edwards Plateau, Northwestern Great Plains) or in woody and grassland vegetation combined (High Plains and Central Great Plains). This pattern occurred across ecoregions with largely different woody vegetation types, including ponderosa pine (*Pinus ponderosa*) which dominates the Northwestern Great Plains and oak (*Quercus*) species which dominate the Cross Timbers [48]. Patches of shrubs or trees generally have a lower probability of burning in a fire compared to grassland [49]. One potential explanation could be that human driven fire suppression is a more dominant driver of large wildfire pattern than differences in ignition potential and fire spread between woody and grassland vegetation types in the Great Plains. Wildfire suppression capabilities can be greatly reduced or ineffective entirely when crown fire is initiated in woody-dominated fuel types [50,51]. Fire suppression becomes ineffective when flame lengths exceed 3.35 m [50]. Woody vegetation has the potential for flame lengths over 90 m, well above this threshold, when crown fires ignite [51]. Grassland fires do not produce such flame lengths, though can still exhibit flame lengths well above the 3.35 m threshold [52]. Despite greater ignition and fire spread potential in grasslands, greater ease of suppression could result in proportionally fewer large wildfires in grass- versus woody-dominated land-use types. Other factors like fragmentation by roads and highways could also play a role by impeding grassland fire spread to a greater extent than woody fires [53].

Woody encroachment in the Great Plains is a biome-wide phenomenon tied to fire suppression and active tree planting [15,54,55]. An ecological regime shift (a persistent shift in system structure, function, and feedbacks [16]) from grassland to woody vegetation may pose a greater risk of wildfire exposure for people in the Great Plains. Human populations and infrastructure are embedded within both land-use types within the biome. Because woody fuels are conducive to much more extreme fire behaviour than grasses, when woody fuels ignite, they are more difficult to control and suppress [15]. An increasing number of wildfires have been recorded along the wildland urban interface (WUI) in the United States, where development and wildland vegetation intermingle [56]. Some states in the Great Plains, like Montana, Wyoming, and New Mexico, have 50 to 100% of their population residing in the wildland urban interface [56]. Areas with higher levels of fragmentation have been shown to maintain higher woody cover in the southern Great Plains [57]. Urban and exurban sprawl have been suggested to provide refuges for woody vegetation, allowing it to spread in the absence of controlling processes near developed areas [57,58]. We found that large wildfires were more likely to occur when woody vegetation comprised greater than 20% of the landscape, suggesting that relatively low levels of woody encroachment (~20% of the landscape) could be sufficient to increase large wildfire risk.

Further region-specific investigations tied to wildfire and land-use relationships will allow for a more nuanced understanding of where woody encroachment can increase large wildfire exposure.

Unlike in a number of forested regions, agriculture and pastureland were not tied with higher wildfire risk in the Great Plains. This finding differs from regions like central Africa, south-east Asia, and regions of South America [59–61]. Tropical forests, like those in Indonesia and Brazil, have experienced surges in large wildfires associated with slash-and-burn agricultural practices [59,61]. In South America, burned area increases when pasture cover exceeds 31% in comparison with the surrounding rainforest where wildfire frequency tends to be low [62]. We found that large wildfires burned disproportionately less in pastures, regardless of how much of the landscape they composed, while treed areas burned disproportionately more when they composed greater than 20% of the landscape. Croplands had a low propensity for wildfire; however, we found that croplands burned more than expected when they composed >0 to 10% of the landscape. This could be linked to fires burning along crop edges. Croplands can act as barriers to fire spread [63]. Low occurrence of wildfire in croplands, pasture/hay field, and developed areas in the Great Plains is likely linked in part to fuel properties that promote lower ignition probabilities and spread rates than native grassland vegetation in the Great Plains [52]. For instance, high-moisture exotic grasses used in pastures have been shown to require four times the wind speed to produce the same rate of fire spread as in native grasses [64]. Similarly, irrigation in croplands and pastures decreases fuel aridity because of increases in fuel moisture and effects of local climate [65], making fuels less conducive to wildfire [52]. However, irrigation is primarily concentrated in two ecoregions (Figure S15), while crops and pastures consistently had a lower propensity for large wildfire across ecoregions (with the exception of pastures in the Lake Agassiz Plain). There is also higher incentive to extinguish fires in croplands, pastures, and developed areas which could influence the occurrence of wildfire. These findings are consistent with Andela et al. [66], who found that agricultural conversion and intensification in grassland and savannah areas has led to declining fire activity globally.

Coexisting with wildfire requires strategic regional planning. Knowledge of the differences in wildfire occurrence across alternative land-use types holds promise for developing targeted management actions that lower the exposure of people and infrastructure to wildfire when it occurs. Large wildfires are an inevitable natural process that need to be reconciled with management and policy goals, particularly as society attempts to balance priorities of protecting human safety and economic interests with the conservation of intact ecosystems and their services. With increasing wildfires across the Great Plains [10], shifting focus from reducing fire to designing a less vulnerable wildland urban interface will allow for a more sustainable coexistence with fire by allowing fires to burn where ecologically appropriate and avoiding fires in human environments [26,67]. WUI growth rates in the Great Plains are equivalent to the western U.S. [56] and yet there has been relatively little focus on wildland urban interface in the Great Plains, where national policy perceives wildfire risk to be relatively low [11]. New housing was the cause of >80% of wildland urban interface growth in the Great Plains [56]. Strategic placement of new development near land-use types that infrequently burn (e.g., agricultural lands in the Great Plains) and avoidance of land-use types that burn with higher probability (e.g., woody vegetation in the Great Plains) could assist in decreasing wildfire risk in the face of rapid increases in large wildfire activity. The spatial arrangement of fuel types across a landscape can alter the proportion of area burned by fire [68]. Strategic organisation of fuels less conducive to fire spread are twice as effective at reducing fire growth compared to random distributions of wildland fuel management [69]. Targeted fuels management (e.g., mechanical tree removal, prescribed fire, etc.) in developed areas embedded within land-use types with the highest propensity for fire will also help decrease exposure of developed areas to wildfire in a system with a long history and dependence on frequent fire occurrence.

Our study represents a necessary first step toward developing ecosystem-specific solutions to wildfire in the Great Plains [26,70]. Future assessments should investigate the roles of flammability, ignition probability, weather, and climate in order to better isolate drivers behind region-specific

patterns in wildfire across land-use types. Fuel load and fuel connectivity can play a large role in the spread of fire across a landscape, where patchy distributions of fuels can alter fire spread [68]. How the spatial arrangement of fuels within and among land-use types alter wildfire occurrence and spread will be an important line of investigation for future studies. Similarly, fuel moisture is critical to fire potential, largely dictating the amount of fuel available for combustion [52]. Fine fuel moisture responds quickly to weather changes [71]. Similarly, climatic patterns across the Great Plains could cause differing fuel moisture in the same land-use types among regions, altering the probability of wildfire initiation and spread, e.g., [24]. Wind can alter the propagation of fire [72,73]. The distribution and sources of ignitions can similarly differ by location [23] and land-use type which will likely influence wildfire distribution across the Great Plains. Our findings provide the baseline determination necessary for targeting more spatially explicit and mechanistic analyses to isolate the impacts of such factors.

While we found that land-use may in part drive large wildfire occurrence in the Great Plains, we did not evaluate climate and ignitions, which are also strong drivers. An increasing number of human ignitions have been recorded across the Great Plains [23]. Changes in climate have been tied to changing wildfires patterns in neighbouring forested systems, e.g., [24,25,74]. However, the relative influence of climate, land-use, and ignitions has yet to be compared. Determining the interdependence of these factors in shaping large wildfire distribution in the Great Plains will help society prevent wildfire driven natural disasters under future global change. In complex social-ecological systems like the Great Plains, changes in human patterns and behaviours can have large impacts on ecosystem processes [20]. Continued changes in the number and distribution of ignitions may increase wildfire number or alter how wildfires are distributed across different land-use types. Drought patterns are predicted to change in the Great Plains under future climate change scenarios [75,76]. Changing precipitation patterns could shift vegetation distribution [77], creating fuels more conducive to ignition and fire spread or in extreme cases could lead to desertification (i.e., absence of fuels [78]). Thus, wildfire risk will likely be altered by changing social and ecological responses to drought. Future analyses could target areas and land-use types determined by our study to be highly impacted by wildfires with more nuanced assessments of the three major drivers of wildfire occurrence—fuels, climate, and ignitions—so we can better prepare for future change.

5. Conclusions

Woody vegetation and grassland have the highest propensity for large wildfire in the Great Plains, while croplands, pastures, and developed areas are less likely to burn in large wildfire. Woody vegetation burned disproportionately more than any other land-use type, suggesting that it has the highest propensity for large wildfire in the Great Plains. Our results can be used to assist strategic regional planning with decreasing wildfire risk near human development. While our study represents a necessary first step in understanding changing wildfire patterns in the Great Plains, assessments tied to weather, climate, and ignitions, along with more detailed assessments of fuel patterns and characteristics will be necessary to understand and better prepare for shifting wildfire patterns in the Great Plains.

Supplementary Materials: The following are available online at http://www.mdpi.com/2072-4292/12/11/1869/s1. Figure S1. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Central Great Plains. Figure S2. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Central Irregular Plains. Figure S3. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Cross Timbers. Figure S4. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Edwards Plateau. Figure S5. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Flint Hills. Figure S6. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the High Plains. Figure S7. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Lake Agassiz Plain. Figure S8. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Nebraska Sandhills.

Figure S9. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Northern Glaciated Plains. Figure S10. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Northwestern Glaciated Plains. Figure S11. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Northwestern Great Plains. Figure S12. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Southern Texas Plains. Figure S13. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Southwestern Tablelands. Figure S14. The number of wildfire perimeters and propensity for large wildfire relative to varying percent cover of land-use types in the Western Gulf Coastal Plain. Figure S15. Irrigated Lands in the U.S. Great Plains. Table S1. A summary of National Land Cover Database (NLCD) land cover classes consolidated into the five dominant land-use types analysed in our study, along with NLCD land cover classification descriptions. Table S2. Buffer zone areas, based on the average large wildfire size (>400 ha), used to calculate the percent cover of each dominant land-use type assuming a random distribution of wildfire across each Level 3 ecoregion in the U.S. Great Plains. Table S3. Simulated p-values comparing true count of wildfires across varying percent cover categories relative to the null distribution.

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