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Woody Cover Fuels Large Wildfire Risk in the Eastern US

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Key Points:

- Woody cover is increasing across the Eastern United States
- Large wildfires are more common in areas with higher woody cover
- The odds of large wildfire occurrence increase with increasing woody cover

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Large wildfires are increasing in the eastern United States; however, what factors are heightening large wildfire risk remains unclear. Increases in fuel loads from woody encroachment and canopy infilling have been associated with increasing wildfire risk in other US regions. Understanding if and where woody cover increases wildfire risk can help direct proactive fuels management. We characterize multi-scale changes in woody cover through time and assess the relationship between woody cover and large wildfire (>200 ha) occurrence in the eastern US between 1990 and 2020. We found a 37% increase in woody cover across the eastern US, with increases occurring in every ecoregion. The odds of large wildfire increased as woody cover increased in most central and southern ecoregions, where large wildfires were typically more likely in areas with high woody cover (70%–100% cover). Our findings suggest fuels management will be an important tool for reducing large wildfire risk.

Plain Language Summary Large wildfires have been increasing across the eastern United States, but what factors heighten large wildfire risk remain unclear. Since large wildfires have been linked to high tree and shrub cover in other parts of the United States, we investigated whether woody cover has been increasing across the eastern US and whether this can be linked to large (>200 ha) wildfire occurrence. We found that woody cover has increased across the entirety of the eastern US. Moreover, large wildfires are more likely to occur in areas with higher woody cover in central and southern ecoregions of the eastern US, suggesting that fuel management techniques can help reduce wildfire risk.

1. Introduction

Large wildfire occurrence has increased across the United States over the past 40 years (Dennison et al., 2014; Donovan et al., 2017; Iglesias et al., 2022). Some of these have been high-impact “Mega fires,” which have been exceedingly large, taken human life, caused extensive property damage, and required large suppression resource expenditures (Williams, 2013). Although western wildfires are often larger and more publicized, the eastern US has also recently experienced increasing large wildfires, with some areas experiencing a tenfold increase over the last four decades (Donovan, Crandall, et al., 2023). With an expansive wildland-urban interface (Radeloff et al., 2018, 2023, p. 20), this shift in wildfire occurrence poses a substantial risk to human populations. For instance, the 2016 Great Smoky Mountains Wildfire Complex destroyed 2400 structures and claimed 14 lives (James et al., 2020; Praskievicz & Sigdel, 2021). To proactively address the growing wildfire problem in the eastern US, it is essential to understand what factors increase large wildfire risk.

Fire regime patterns are constrained by ignitions, climate, and vegetation (Mhaweji et al., 2015; Moritz et al., 2005). In eastern North America, ignition patterns have been largely tied to human activity (Balch et al., 2017; Kay, 2007). Native Americans used fires for hunting, maintaining open game lands, improving forage, and clearing ground for thousands of years before Euro-American settlement (Fowler & Konopik, 2007). Widespread fire suppression driven by colonialism shifted the eastern US from fire regimes largely shaped by cultural burning and lightning-ignited wildfires to fire regimes dominated by accidental and destructive wildfires. Eighty-four percent of contemporary wildfires are human-started (Balch et al., 2017, p. 20). Local weather patterns control the success of fire propagation post-ignition through precipitation, air temperature, wind, and humidity (Archibald et al., 2009; Gedalof, 2011). At larger scales, climate interacts with fire and herbivores to influence vegetation type and density along with fuel accumulation and decay (Onega & Eickmeier, 1991; Staver et al., 2011). Vegetation type and density, in turn, affect fire spread and intensity (Moritz et al., 2005). Among these variables, vegetation type and load are the most readily manipulated by humans and thus hold the greatest potential for proactive management action over the short term (Andreu et al., 2018; Viedma et al., 2020).

Increasing woody cover has been associated with increased large wildfire risk in multiple regions (Andreu et al., 2012; Donovan et al., 2020). Fire suppression over the last century, among other factors including land use change, increasing CO₂ levels, and altered grazer and browser assemblages, has led to woody encroachment in many open ecosystems and increasing density of overstory and understory woody plants within some forested systems (Archer, 1994; Heyward, 1939; Miller et al., 2017; Morford et al., 2022). Woody vegetation can create a heavy fuel load of both standing and downed material that can produce higher flame lengths and greater fire intensities than fine litter and grasses, making fires much more difficult to control and suppress (Andreu et al., 2012; Palmero-Iniesta et al., 2017). Understory woody vegetation can act as “ladder fuel,” carrying fire from the ground to the tree canopies (Forbes et al., 2022; Ritter et al., 2022). High tree density and canopy closure heighten the risk of active crown fire (Stephens et al., 2012). Lofted embers from woody fuels can also support the creation of spot fires at much greater distances than grass embers (Donovan, Fogarty, & Twidwell, 2023; Wadhvani et al., 2022). Lofted embers landing on roofs or in vents are the leading cause of property destruction during wildfire (Manzello et al., 2010, 2011).

Recent increases in wildfire risk have been linked in part to woody encroachment and infilling in both the western US (Hessburg et al., 2005) and the Great Plains (Donovan et al., 2020). In the eastern US, however, it is unclear how woody vegetation is changing over large scales and if woody cover contributes to heightened wildfire risk. Understanding if and where woody cover is increasing and whether woody cover influences large wildfire occurrence is paramount to supporting proactive wildfire management. We aimed to (a) identify and characterize changes in woody cover over the last 30 years and (b) determine how the probability of large wildfire (>200 ha) occurrence changes with woody cover across the eastern US.

2. Data

We used the Environmental Protection Agency (EPA) Level I (LI) Eastern Temperate Forests ecoregion to isolate our eastern US study region (EPA, 2023; Omernik & Griffith, 2014). The Eastern Temperate Forests encompass just under half of the conterminous US land area, from the Great Lakes in the north to the Gulf of Mexico in the south (Figure S1 in Supporting Information S1). Thirty-three EPA Level III (L3) ecoregions were used to spatially subdivide the eastern US based on biophysical characteristics (Bryce et al., 1999). EPA ecoregions have been used extensively in the assessment of large wildfire regimes (e.g., Donovan, Crandall, et al., 2023; Iglesias et al., 2022). For wildfire analyses, ecoregions containing less than 10 large wildfires (>200 ha in the eastern US) during the study period (1991–2021) were excluded (Figure 1b) due to insufficient data to assess trends over time (Donovan, Crandall, et al., 2023).

We sourced large (>200 ha) wildfire perimeter data from 1991 to 2021 from the Monitoring Trends in Burn Severity database (MTBS Project, 2023; Van Leeuwen, 2008). MTBS maps large fire perimeters across public and private land using Landsat remotely sensed imagery. These fires are classified by ignition type into categories: “prescribed fires” (fires intentionally ignited for management purposes), “wildfire” (fires resulting from an unplanned and unwanted ignition), “wildland fire use,” (management of a naturally ignited fire to accomplish predetermined objectives) or “unknown” (MTBS Project, 2024). We only selected fire perimeters classified as “wildfire.”

We acquired woody cover data from 1990 to 2020 from the Rangeland Analysis Platform v. 3.0 (Allred et al., 2021; Jones et al., 2018, 2021; RAP, 2023) using Google Earth Engine (Gorelick et al., 2017). Although our fire records started in 1991, we used vegetation records for the year prior to each fire to determine woody cover before the fire occurred. We chose a start date of 1990 for our vegetation assessment because of high inter-year variability in RAP estimates before 1990 (Fogarty et al., 2020; Kleinhesselink et al., 2023; Morford et al., 2022). The RAP uses sub-pixel classification of Landsat cover data to capture yearly percent vegetation cover at the 30m scale for five vegetation functional groups: bare ground, annual and perennial herbaceous vegetation, shrubs, and trees (Jones et al., 2018; Robinson et al., 2019). Because the RAP was originally designed for western rangelands typified by low shrubs (Roberts et al., 2022), we combined shrub cover and tree cover into a single “woody cover” classification to avoid misclassification among shrubs and trees in the east (Scott Morford, University of Montana, personal communication).

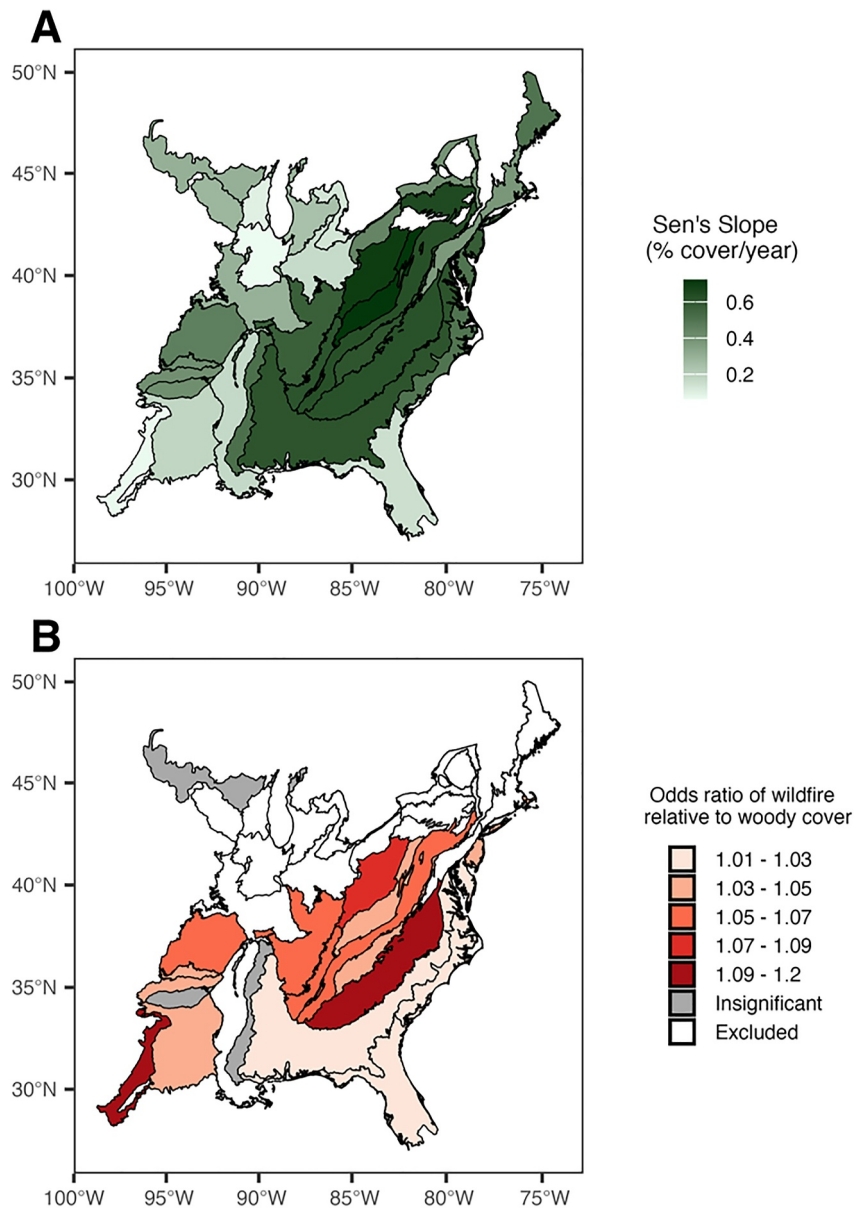


Figure 1. (a) Geographic depiction of woody cover increases (percent of total landcover/year) as measured by Sen's Slope (a nonparametric estimate of the slope of a trend) across ecoregions of the eastern US. A darkening green color represents ecoregions with greater rates of increase in woody cover per year. (b) The change in the odds of large wildfire occurrence relative to woody cover across Level 3 ecoregions in the eastern US between 1991 and 2021. A darkening red color indicates higher odds of wildfire with each 1% increase in woody cover. Regions that showed insignificant results are depicted in gray. Regions excluded due to insufficient fire numbers are depicted in white.

3. Methods

3.1. Trends in Woody Cover Through Time

To determine trends in woody cover across L1 and L3 ecoregions in the eastern US, we extracted annual shrub and tree cover for both ecoregion scales and summed their area for every year between 1990 and 2020. We performed the Modified Mann-Kendall Trend tests to account for temporal autocorrelation (Hamed & Ramachandra Rao, 1998; Patakamuri & O'Brien, 2021), using Tau and Sen's Slope metrics (Pohlert, 2023) to assess how woody cover has changed through time. Tau ranges from -1 to 1 and indicates the directionality and consistency of a trend, with 1 representing a perfect monotonic positive trend and -1 representing a perfect

monotonic negative trend (Kendall, 1955; Mann, 1945). Sen's Slope ranges from positive to negative infinity and indicates the magnitude of a trend (Sen, 1968). All analyses were performed in the R statistical environment (version 4.3.1 R Core Team, 2023) using RStudio (Posit team, Inc. Boston, MA, 2023).

3.2. Relationship Between Woody Cover and Wildfire Propensity

To determine patterns in woody cover within large wildfire perimeters, we first grouped all wildfires by L3 Ecoregion (sf and terra packages in R statistical environment; Hijmans et al., 2024; Pebesma et al., 2024). We then calculated the percentage and total area of woody vegetation cover within every wildfire perimeter using woody cover data from the year immediately prior to a wildfire (e.g., for a 1991 wildfire, 1990's woody cover estimates were extracted). When a wildfire crossed L3 Ecoregion boundaries, its full size and percent woody cover were attributed to both ecoregions equally.

To determine how the propensity for large wildfire changes relative to woody cover, we compared the woody cover of known wildfires to that of a null distribution of fires created by randomly assigning wildfire-sized points across the landscape following the approach of Donovan et al. (2020). We distributed 10,000 random points within the L1 ecoregion and one thousand random points throughout each L3 ecoregion ($n = 19,000$), with a buffer area equivalent to that of the average wildfire within a given ecoregion. For each buffer zone, we extracted woody cover in Google Earth Engine following the same procedure used for wildfire perimeters. We randomly assigned a year to each random point from a list of all years associated with a verified wildfire in each ecoregion. Verified wildfire years were used to account for other drivers of large wildfires, such as climate or ignitions, which may not have been conducive to wildfire during non-verified wildfire years; however, there was no substantial difference between null distributions generated by this approach compared to sampling all wildfire years (Figure S2 in Supporting Information S1). As with verified fires, woody cover in the random buffer zones was only sampled for the year prior to the assigned year. We subsampled random points in numbers equivalent to the total number of large wildfires within each ecoregion (L1 $n = 2,184$; L3 n varied by ecoregion). This generated a balanced sample of woody cover within wildfires relative to woody cover within null points distributed at random across the landscape. At both scales, the random points were re-sampled 999 times to generate 1,000 null frequency distributions. We averaged these frequency distributions across percent woody cover bins ranging from 0% to 100% to create single null distributions for the L1 and L3 ecoregions. We then visually compared the null and verified wildfire frequency distributions.

We used Generalized Linear Models with a binomial family (i.e., logistic regression) to determine how the probability of large wildfire changes as woody cover increases:

$$\log\left(\frac{\mu}{1-\mu}\right) = \alpha + \beta X$$

Where μ represents the probability of large wildfire and X represents woody cover. Our dependent variable, large wildfire occurrence, was binary, with 1's for verified wildfires and zeros for null points randomly selected in equal numbers to the number of verified wildfires within each ecoregion.

4. Results

4.1. Trends in Woody Cover Through Time

Across the Eastern United States, woody cover consistently increased over the 30-year study period at both the L1 and L3 ecoregion scale (Figure S3 in Supporting Information S1, Table 1). At the L1 scale, woody cover increased by 12.3%, with 33.5% woody cover in 1990 and 45.8% woody cover in 2020. These values equate to a 36.7% relative increase over the 30-year study period (Table 1). At the L3 scale, woody cover increases per year were greatest in the Western Allegheny Plateau, Central Appalachians, and Northern Allegheny Plateau (>0.65% per year). The Southern Coastal Plain had lower rates of increases in woody cover than the ecoregions adjacent to it in the southeast (Southeastern Plains and Middle Atlantic Coastal Plain) (Figure 1a, Table 1). Woody cover increases in ecoregions in the western half of the Eastern US were lower than most ecoregions in the eastern half. Ecoregions excluded from our wildfire analyses due to a low number of wildfires (mostly in the north) had a wide range of woody increases per year, between 0.03% and 0.7% (Figure 1a, Table 1).

Table 1

For L1 and L3 Ecoregions of the Eastern US, Total Area of an Ecoregion (Hectares), Percent Woody Cover in 1990 and 2020, the Relative Percent Change of Percent Woody Cover From 1990 to 2020, Mann Kendall's Modified Tau, the Variance-Corrected P Value of Tau, the Sen's Slope (Percent Cover Increase/Year) and the Sen's Slope P Value

Ecoregion	Area (ha)	1990	2020	30 year mean	Relative increase	Tau	Tau P value	Sen's slope	Sen's slope P value
L1 Eastern Temperate Forests	252,118,221	33.4	45.7	40.6	36.7	0.847	3.3e-06	0.403	1.1e-11
Acadian Plains and Hills	4,524,817	60.5	71.1	66.1	17.5	0.609	1.3e-04	0.501	1.1e-06
Arkansas Valley	2,842,153	31.9	44.7	39.9	39.9	0.746	2.2e-05	0.404	2.2e-09
Atlantic Coastal Pine Barrens	1,430,693	25.7	38.4	31.7	49.3	0.742	1.2e-06	0.581	2.7e-09
Blue Ridge	4,659,532	62.4	80.2	72.0	28.4	0.823	2.4e-06	0.608	4.1e-11
Boston Mountains	1,417,758	60.9	74.3	70.0	22.0	0.690	5.7e-18	0.409	3.2e-08
Central Appalachians	6,205,036	48.6	78.8	68.7	62.0	0.831	1.2e-06	0.723	2.6e-11
Central Corn Belt Plains	7,650,965	3.8	5.5	4.9	42.8	0.472	8.9e-03	0.062	1.6e-04
Driftless Area	4,738,624	24.4	29.8	26.1	22.0	0.617	5.7e-04	0.280	7.6e-07
East Central Texas Plains	5,575,260	23.8	30.3	29.4	27.2	0.258	3.9e-02	0.067	3.9e-02
Eastern Corn Belt Plains	8,685,741	7.6	11.9	10.1	58.0	0.778	6.6e-06	0.163	4.3e-10
Eastern Great Lakes Lowlands	4,030,180	30.1	40.2	34.9	33.6	0.790	2.3e-10	0.398	2.3e-10
Erie Drift Plain	3,095,964	24.5	39.0	32.8	59.6	0.714	1.1e-07	0.442	1.0e-08
Huron/Erie Lake Plains	3,159,468	8.9	13.7	12.0	53.6	0.629	7.9e-11	0.130	4.6e-07
Interior Plateau	12,352,702	28.3	43.9	36.8	55.1	0.786	6.5e-06	0.569	2.8e-10
Interior River Valleys and Hills	12,044,749	13.9	22.2	19.3	59.4	0.766	3.3e-05	0.296	7.9e-10
Middle Atlantic Coastal Plain	7,842,106	37.3	50.7	45.6	35.8	0.794	5.8e-05	0.501	1.9e-10
Mississippi Alluvial Plain	11,592,916	16.3	20.3	18.9	25.0	0.790	3.8e-06	0.171	2.3e-10
Mississippi Valley Loess Plains	5,180,989	34.0	48.8	41.6	43.4	0.794	1.8e-09	0.514	1.9e-10
North Central Hardwood Forests	8,890,941	21.9	30.0	25.0	36.5	0.673	6.1e-05	0.298	6.7e-08
Northeastern Coastal Zone	4,205,087	41.2	48.1	46.8	16.8	0.581	1.5e-03	0.380	3.3e-06
Northern Allegheny Plateau	4,651,021	42.6	58.8	50.9	37.9	0.827	9.4e-08	0.650	3.3e-11
Northern Piedmont	3,134,629	22.8	30.1	27.3	32.2	0.742	2.6e-05	0.375	2.7e-09
Ouachita Mountains	2,689,544	57.6	70.4	65.4	22.1	0.653	3.9e-05	0.409	1.6e-07
Ozark Highlands	10,639,087	38.7	51.8	47.1	33.9	0.766	9.8e-06	0.457	7.9e-10
Piedmont	16,611,725	41.6	59.3	50.6	42.8	0.859	2.1e-06	0.621	5.5e-12
Ridge and Valley	11,671,572	39.1	55.3	47.7	41.5	0.843	4.9e-07	0.626	1.4e-11
South Central Plains	15,213,175	52.3	59.3	57.3	13.5	0.512	5.1e-03	0.180	4.1e-05
Southeastern Plains	32,880,347	39.7	56.8	49.7	43.4	0.806	1.6e-05	0.611	9.8e-11
Southeastern Wisconsin Till Plains	3,135,031	9.6	12.7	11.4	32.7	0.359	2.6e-02	0.096	4.1e-03
Southern Coastal Plain	14,119,438	38.2	45.1	42.8	18.0	0.524	1.2e-02	0.146	2.7e-05
Southern Michigan/Northern Indiana Drift Plains	5,303,510	15.5	24.3	21.3	57.2	0.649	1.1e-04	0.245	1.9e-07
Southwestern Appalachians	3,799,459	51.1	68.3	60.2	33.6	0.762	2.3e-05	0.612	9.7e-10
Western Allegheny Plateau	8,144,005	38.3	64.9	54.5	69.4	0.847	3.6e-07	0.698	1.1e-11

4.2. Relationship Between Woody Cover and Wildfire Propensity

At the L1 ecoregion scale, the odds of wildfire occurrence increased by 3.9% with each 1% increase in woody cover (Table S1 in Supporting Information S1). Woody cover had a significant impact on the odds of large wildfire occurrence across 84% (16 of 19) of ecoregions assessed (Figure 1b, Table S1 in Supporting Information S1). The Piedmont (Odds Ratio [OR] = 1.118, $p = 2.6e-07$), the Western Allegheny Plateau (OR = 1.077, $p = 2.3e-03$), and the Ridge and Valley (OR = 1.067, $p = 1.1e-09$) in the central part of the region, along with the East Central Texas Plains (OR = 1.114, $p = 7.0e-03$) and Ozark Highlands (OR = 1.069, $p = 3.6e-18$) in the west,

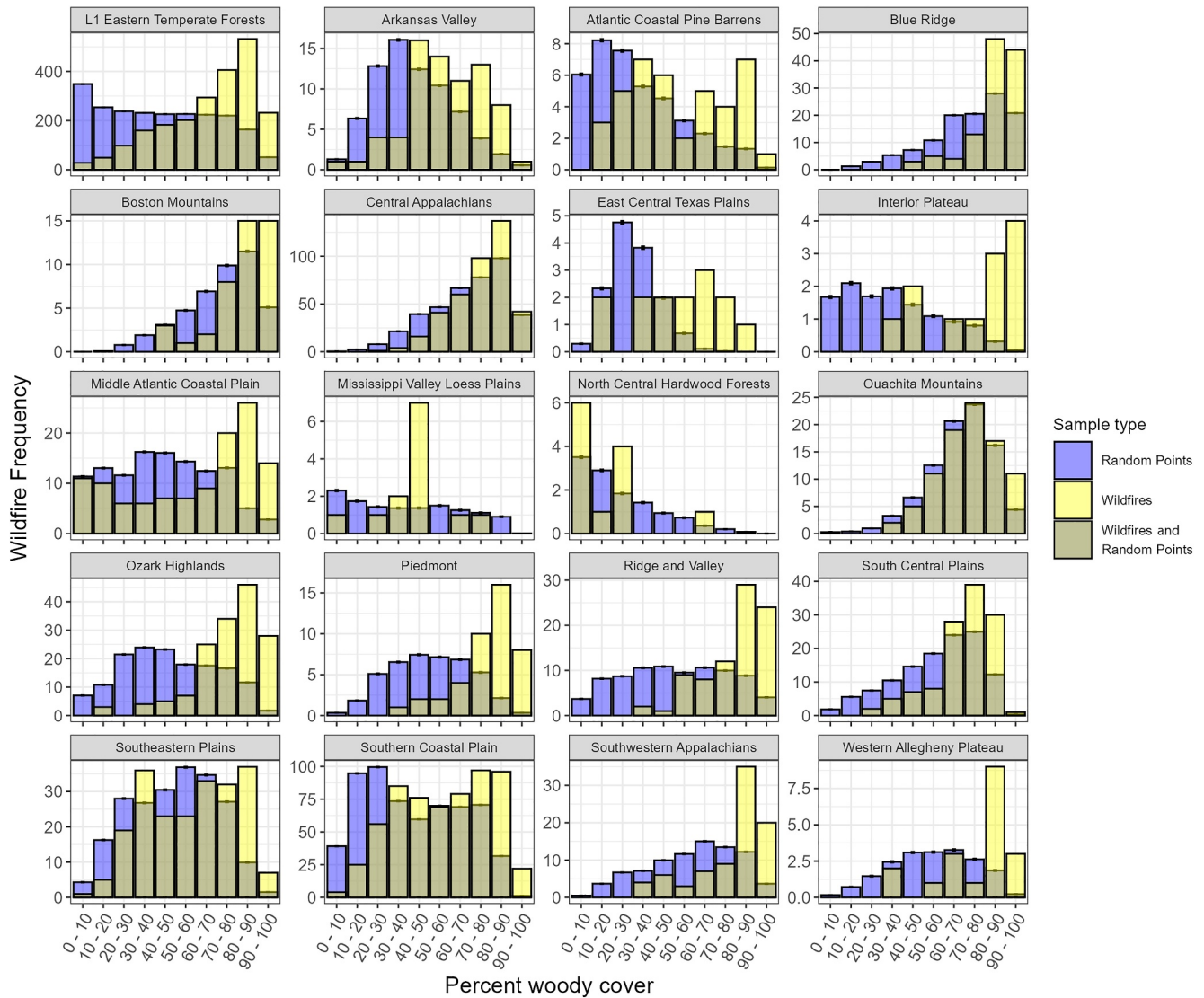


Figure 2. The distribution of woody cover within verified wildfires (yellow) compared to a bootstrapped sample of random points used to represent the distribution of woody cover across the general landscape (blue) within the Level 1 and Level 3 ecoregions of the Eastern US between 1991 and 2021. Random points were sub-sampled in numbers equivalent to the total number of large wildfires within each ecoregion 999 times to generate 1,000 null frequency distributions and then averaged to create a single null distribution for each ecoregion (blue). Error bars represent standard error of the averaged values within each bin of the null distribution.

had the greatest increases in the odds of large wildfire occurrence relative to increases in woody cover (Figure 1b). While the southeastern ecoregions largely experienced significant increases in the odds of large wildfire occurrence with increases in woody cover, the strength of the relationship was lower than in some western and central ecoregions (Figure 1b). The North Central Hardwoods ($OR = 0.983, p = 0.43$) in the far north, Mississippi Valley Loess Plains ($OR = 1.014, p = 0.50$) in the south, and the Ouachita Mountains ($OR = 1.002, p = 0.87$) in the west, showed no relationship between woody cover and wildfire, despite experiencing increases in woody cover.

The propensity for large wildfires increases with greater levels of woody cover in the eastern US (Figure 1b). At the L1 scale, wildfires were disproportionately more likely to occur when woody cover was between 60% and 100% of the landscape (Figure 2). In the majority of L3 ecoregions, the propensity for wildfires was highest at the greatest levels of woody cover within an ecoregion, although the distribution of woody cover differed among regions (Figure 2). Multiple ecoregions that showed the highest wildfire propensity at the greatest levels of woody cover also showed a propensity for large wildfires (wildfires occurred more than expected a random) in areas with

low to moderate woody cover (10%–50%; Figure 2). In contrast, the highest propensity for large wildfires was between (0%–10%) woody cover in the North Central Hardwoods; however, there was also a higher propensity for large wildfires at 20%–30%, and at the top end of the ecoregion's spectrum of woody cover (60%–70%; Figure 2). The Mississippi Valley Loess Plains was also a unique exception to broader trends where there was a stark increase in the propensity for large wildfires between 40% and 50% woody cover (Figure 2).

5. Discussion

Woody cover increased across all ecoregions in the Eastern US. In the central and southern regions, we found higher levels of woody cover heighten large wildfire risk. The odds of large wildfire occurrence increased with increasing woody cover across most ecoregions we assessed in the Eastern United States, where the propensity for large wildfires was highest in areas with the highest levels of woody cover. These results align with patterns observed in other regions of the US. Woody cover is also increasing in many regions of the central and western US (Fogarty et al., 2020; Morford et al., 2022), where it has been associated with higher wildfire risk (Donovan et al., 2020; Hanberry, 2020). High flame lengths and the potential for long-range spotting in woody vegetation greatly reduce fire suppression potential (Andrews & Rothermel, 1982; Donovan, Fogarty, & Twidwell, 2023; Rothermel, 1991). In regions like the eastern US, where historical fire frequency has been altered by fire prevention and suppression (Guyette et al., 2012), it is likely that declining suppression potential in woody vegetation helps support the higher propensity for large wildfire in areas with high levels of woody cover.

Managing woody cover could decrease large wildfire risk in many eastern US ecoregions. Much of the eastern US has been in a fire deficit for over a century (Guyette et al., 2012) associated with increasing levels of woody cover and the degradation of fire-dependent ecosystems such as oak savannas and prairies (Abrams, 2003; Hanberry et al., 2020; Heyward, 1939). Reintroducing prescribed fire can halt woody encroachment, reduce stand basal area, and lower the density of understory shrubs (Miller et al., 2017; Waldrop et al., 1992), helping to reduce wildfire risk while also helping to restore historically fire-frequent ecosystems. In the Great Plains, a targeted and aggressive campaign of prescribed fire applied by private landowners was able to halt woody encroachment and restore grassland ecosystems (Bielski et al., 2021; Fogarty et al., 2020). Similarly, in the western US, prescribed fire and understory thinning have increased large tree survival, reduced crown fire risk, and reduced the patch size of high severity fire (Fulé et al., 2012; Prichard et al., 2010; Ritchie et al., 2007; Stephens et al., 2012). Multiple states in the southeastern US are known for their commitment to encouraging prescribed fire through ease of permitting and heightened legal and civil protections for burn teams (Wonkka et al., 2015), and we found the magnitude of increases in woody cover was generally smaller in ecoregions where prescribed fires are more commonly applied, like the Southern Coastal Plain (Cummins et al., 2023). That said, woody cover still increased in these regions, potentially because much of the prescribed fire in the southeast occurs in hotspots on public lands (Cummins et al., 2023). This geographically variable implementation may leave critical areas of the landscape without fuels management (Addington et al., 2015; Brenner & Wade, 2003), driving the lower rates of woody cover increase we observed.

Temporal patterns we observed in woody cover are also likely linked to climatic and land-use factors. For instance, precipitation is an overriding factor constraining woody cover (Good & Caylor, 2011; Scholtz, Fuhendorff, & Archer, 2018). In our assessment, increases in woody cover were more predominant in the eastern half of our study area, which may be due to the strengthening continental east (wet) to west (dry) aridity gradient (Bishop et al., 2021). Variability in increases in woody cover may also be due to differences in land use and fragmentation across regions (e.g., Riitters et al., 2012), which can structure patterns of woody encroachment (Donovan et al., 2018; Scholtz, Polo, et al., 2018). Future research should investigate potential drivers and controls of woody cover across different regions of the eastern US.

In addition to an increased propensity for large wildfires within areas of high woody cover, multiple ecoregions also had a higher propensity for large wildfires in areas of low to moderate woody cover. Since agricultural fields and developed areas typically have low wildfire risk and tend to make up a very small proportion of wildfire perimeters, areas of low woody cover within wildfire perimeters may represent open grassland or savanna systems, which are highly predisposed to and dependent on frequent, low-intensity burning (Donovan et al., 2020; Hanberry, 2020) that prevents high levels of woody plant establishment (Bond & Keeley, 2005; Higgins et al., 2000). Fires that burn in these systems have much higher suppression potential than dense woody vegetation due to shorter spot fire distances, intensities, and flame lengths (Donovan, Fogarty, & Twidwell, 2023). However,

areas of low tree cover could also represent recently harvested areas with high levels of woody debris, which tend to have higher wildfire risk (Stone et al., 2004). Disturbed areas with low canopy cover are also susceptible to invasion from species like cogon grass (*Imperata cylindrica*), which is a predominant invasive in southeastern ecoregions and can promote more intense fires (Tomat-Kelly et al., 2021). The WUI, where wildland vegetation and human development intermingle, also likely contributes to wildfire risk by increasing accidental human ignitions, thereby allowing wildfires to burn in areas of low to moderate woody cover (Radeloff et al., 2018, 2023). Further targeted investigations into ecoregion-specific patterns are needed to determine appropriate management strategies for reducing wildfire risk.

Despite increases in woody cover across multiple northern ecoregions of the Eastern US, there were few large wildfires in these regions. There has been a change in precipitation corresponding to a latitudinal gradient, with the Northeast and Upper Midwest increasing in precipitation over the past several decades (Easterling et al., 2017). Dense, closed canopy systems with consistently high precipitation can become less likely to burn due to mesophication, which is a feedback between dense woody vegetation, understory infilling, and fuel moisture (Alexander et al., 2021; Nowacki & Abrams, 2008). While mesophication can reduce wildfire occurrence during periods of average and above-average precipitation, vegetation will become available as fuel during extended drought, with dense understories increasing potential crown fire risk (e.g., Wang et al., 2016). Assessing how climate influences wildfire-woody cover interactions across ecoregions, particularly as this relates to future climate projections, will be paramount for managing wildfire risk in the eastern US now and into the future. Low large wildfire numbers in northern ecoregions could also be due to high agricultural land use driving a highly fragmented landscape (Donovan et al., 2020; Hanberry, 2020) that can lead to smaller wildfire sizes. Donovan, Crandall, et al. (2023) found that wildfires are becoming smaller in some L3 ecoregions, which may be due to increasing levels of fragmentation due to development and agricultural intensifications. Our study only looked at wildfires >200 ha, which limits our ability to determine patterns in small but potentially impactful wildfires.

Our findings identify woody cover as one contributor to large wildfire risk in the central and southern portions of the eastern US, highlighting the importance of fuels management initiatives for reducing large wildfire risk. Fuels management could be particularly impactful in regions with rapidly increasing woody cover, though a time-series analysis of woody cover and wildfire could further support this approach. Additionally, more research is needed that examines which ecosystem types are experiencing the greatest increases in woody cover within ecoregions, and how these align with human development, to best strategize fuel reduction approaches. Research understanding how each of the predominant drivers of wildfire regimes (fuels, climate, and ignitions; Moritz et al., 2005) interact with one another to impact wildfire risk will be needed to fully understand and manage for large wildfires in the eastern US. For instance, central and southern portions of the Eastern US are projected to transition to a warmer and dryer growing season, consisting of droughty weather punctuated by precipitation occurring in sporadic heavy events (Bedel et al., 2013; Fill et al., 2019; Heilman, 2015). In addition to reducing the number of days suitable for prescribed burns that support fuel reduction (Jonko et al., 2024; Kupfer et al., 2020), these warmer and drier conditions are more conducive to larger, more intense wildfires, which could exacerbate wildfire risk in areas with high woody cover. Similarly, there are likely links between the distribution of human ignitions, increasing woody cover, and wildfire risk, which need to be investigated. For instance, the WUI is a major source of human-started wildfires in the US (Mietkiewicz et al., 2020) tied to the high potential for human ignitions close to fuels that can support wildfire spread. Our findings should be used to direct more targeted assessments of how changes in fuels, climate, and ignitions are shaping wildfire risk across the eastern US.

Data Availability Statement

The EPA L1 and L3 ecoregion boundaries used to delineate the study area are available to download as shapefiles via <https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states>. The Monitoring Trends in Burn Severity fire perimeters are available to download via <https://www.mtbs.gov/direct-download>. The Rangeland Analysis Platform vegetation cover data used in the study are available through Google Earth Engine via the repository directory 'projects/rap-data-365417/assets/vegetation-cover-v3,' or through the Rangeland Analysis Platform website <https://rangelands.app/products/#cover>. All code used for analysis and figure creation is available at https://github.com/chaellabird/GRL-Manuscript_Ivey-et-al.-.

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