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Tracking decadal changes in frequent fire activity across the southeastern U.S. (2000–2019): insights from Southeast FireMap

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Abstract

Background The dominant natural habitats in the southeastern US depend on frequent fire ignited by humans or lightning. However, fire activity has sharply declined in the region since the early 1900s, and reduced fire activity has degraded natural habitats and increased wildfire risk. Identifying changes in fire use during recent decades is necessary to guide the conservation of fire-dependent wildlife, management of hazardous fuels, and identify areas where increased fire use could improve ecosystem resilience. To address this need, we created the Southeast FireMap dataset by fine-tuning the US Geological Survey's Landsat Burned Area product to track burned area and provide a fire history across the southeastern US. We used the Southeast FireMap data to quantify changes in areas frequently burned, as measured by areas with multiple burns within a decade. We compared the periods 2000–2009 and 2010–2019 to identify where frequently burned area is increasing or declining. We examined patterns of change across ownership, land cover, and soil orders to provide geographic context, and we considered future implications of these changes for land use categories of ecological interest.

Results Frequently burned area increased between decades across the region. This increase occurred on both private and public lands, in upland vegetation types, and on upland soils, though these increases were moderately offset by decreased wetland burning and its associated soil orders. However, changes varied among states, with burned area decreasing in some states.

Conclusions The overall increase in frequently burned area across the region reflects a summation of positive and negative shifts associated with specific combinations of physiography, ownership class, and government jurisdiction. SE FireMap marks a significant advancement in our ability to identify changes in prescribed burning within the geographic and cultural contexts that will likely influence the complex future of fire in the region.

Keywords Burned area, Landsat, Prescribed fire, Remote sensing, Satellite, Wildfire, Wildland fire

Resumen

Antecedentes Los hábitats naturales dominantes en el sudeste de los EEUU dependen de fuegos frecuentes iniciados tanto por humanos como por rayos. Sin embargo, la actividad de los incendios ha declinado abruptamente en la región desde los inicios del 1900, y esta actividad de reducción de incendios ha degradado hábitats naturales e incrementado el riesgo de incendios. La identificación de los cambios en el uso del fuego en décadas recientes

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es necesaria para guiar la conservación de especies fauna que dependen de los fuegos, el manejo de combustibles vegetales peligrosos, e identificar áreas en las cuales un incremento en el uso del fuego puede mejorar la resiliencia del ecosistema. Para abordar esta necesidad, creamos el conjunto de datos *Southeast FireMap* mediante un ajuste más fino del producto del Servicio Geológico de los EEUU llamado *Landsat Burned Area* (área quemada estimada mediante imágenes Landsat) para trazar el área quemada, y presentar así la historia de los incendios a través del sudeste de los EEUU. Usamos luego los datos del *Southeast FireMap* para cuantificar los cambios en áreas frecuentemente quemadas, medidas como aquellas que presentaron quemas múltiples dentro de una década. Comparamos los períodos 2000–2009 y 2010–2019 para identificar donde áreas frecuentemente quemadas se están incrementando o reduciendo. Examinamos los patrones de cambio debidos a la propiedad de la tierra, la cobertura, y el orden del tipo de suelo para proveer de categorías de uso de interés ecológico.

Resultados El área frecuentemente quemada se incrementó entre las dos décadas analizadas en toda la región. Este incremento ocurrió tanto en tierras privadas como en públicas, y en tipos de vegetación altos y suelos de altura, aunque estos incrementos fueron moderadamente compensados por un decremento en las áreas quemadas en humedales y sus órdenes de suelos asociados. Sin embargo, los cambios variaron entre los distintos estados, con áreas que registraron disminuciones del área quemada en algunos de ellos.

Conclusiones El generalizado incremento en el área frecuentemente quemada en la región refleja la suma de cambios positivos y negativos asociados con combinaciones específicas de fisiografía, tenencia de la tierra y jurisdicciones gubernamentales. El *Southeast FireMap* marca un avance significativo en nuestra habilidad para identificar cambios en las quemas prescriptas dentro de contextos culturales y geográficos que podrían probablemente influenciar el futuro complejo del fuego en la región.

Background

The prevalence of fire in the southeastern U.S. has varied substantially during the past few hundred years and continues to change. Such changes have important implications for the future health and resilience of the regional landscape. Fire is an important natural process for maintaining the native, fire-dependent ecosystems in the region (Duncan et al. 2011; Ryan et al. 2013; Noss et al. 2015; Lake et al. 2017). Fire regimes prior to European colonization for the most dominant ecosystems across the southeastern US were characterized by frequent, low-intensity fires initiated by lightning or purposefully set by Indigenous people to manage the land for agriculture, navigability, visibility, hunting, and promoting native plant food sources (Frost 1998; Snitker et al. 2022; Magerl et al. 2023). After colonization, European settlers burned, often annually, the pine-dominated plant communities covering most of the landscape to enhance cattle range (Grelen 1978; Fowler and Konopik 2007). Beginning in the early twentieth century, intentional burning steadily declined following the nearly complete logging of longleaf pine (*Pinus palustris*) and other fire-tolerant trees, widespread planting of fire-sensitive pines to replace them, banning open range herding of livestock, expansion of industrial agriculture, and spread of urban areas (Landers et al. 1995; Van Lear et al. 2005). As a result, the remaining natural areas shifted from mostly open canopy habitats with grassy and shrubby understories to closed canopy forests, with significant implications for many fire-adapted wildlife species (Ryan et al. 2013).

At the same time that pressure against intentional burning mounted during the twentieth century, it was increasingly recognized that fire was a necessary component of most natural ecosystems in the southeastern US (Chapman 1932; Green 1935), and in some areas frequent burning was never discontinued (Rother et al. 2020). Currently, prescribed fire is actively practiced in the southeastern US to improve habitat for multiple imperiled animal and plant species (Cox and Slater 2007; Wood et al. 2008; Palmer and Sisson 2017) and to protect timber resources (Ferguson 1998), though not nearly as extensively as in the past when robust populations of these species and their associated native plant communities were common (Frost 1998; Leenhouts 1998; Houghton et al. 2000; Lorimer 2001; Ryan et al. 2013; Vanderhoof et al. 2022). Thus, there is widespread interest in maintaining or restoring these fire-adapted landscapes and their associated ecosystem services, including timber resources resilient to regional stressors (Matthews et al. 2020; Randall and Brewitt 2023), plant and animal biodiversity (Breininger and Carter 2003; Quintana-Ascencio et al. 2003; Means 2006), wildfire resilience and mitigation (Outcalt and Wade 2004; Martinson and Omi 2008; Addington et al. 2015; Nowell et al. 2018), water conservation (McLaughlin et al. 2013; Qi et al. 2022), and carbon sequestration (Hurteau et al. 2008; Godwin et al. 2017; Dixon et al. 2022). Given the strong associations between prescribed burning and ecosystem services, trends in prescribed burning are an indicator of the sustainability of multiple resources in the

face of various stressors (Prestemon et al. 2016; Carter et al. 2018). Accurate monitoring of prescribed fire area, along with estimates of fuel loading and emissions of the burned species, is essential for informing emission inventories and guiding emission reductions and offsets. Prescribed burning also contributes to restoration goals supported by federal, state, and private investments, such as the Natural Resources Conservation Service cost-share agreements and initiatives like the Longleaf Alliance.

Efforts to track prescribed fire burned area across the southeastern U.S. have relied on both ground-based and satellite data, each with their unique limitations. The Fire Program Analysis Fire Occurrence Database (FOD; Short 2014) compiles wildfire reports, and the Southeastern US Prescribed Fire Permit Database (SE Rx Database; Cummins et al. 2023) collects prescribed fire reports across agencies and states, but both vary in completeness and spatial accuracy. Satellite detection helps fill gaps in agency reporting, but the fires in the southeastern US are often small, short duration, and low-intensity with detections further limited by cloud cover, rapid vegetation regrowth, and tree canopies obscuring burned areas (Picotte and Robertson 2011; Hawbaker et al. 2017; Nowell et al. 2018; Vanderhoof et al. 2021). For example, Nowell et al. (2018) found common satellite products (e.g., Global Fire Emissions Database, Landsat Burned Area Essential Climate Variable, Monitoring Trends in Burn Severity, and Hazard Mapping System) detected only ~25% of burned area compared to ground-based reports. Since then, the Landsat Burned Area (Landsat BA) product improved detection of burned area across the continental US by 29% compared to its predecessor, the Landsat Burned Area Essential Climate Variable product (Hawbaker et al. 2020a).

Still, trends in burned area remain mixed. Some satellite datasets (MODIS Burned Area and Monitoring Trends in Burn Severity) show increasing burned area nationally (Morton et al. 2013; Jones et al. 2022), but miss much of the burned area in the southeastern US. Survey-based studies also diverge. A 2020 state forestry agency survey found a regional decline in the southeastern US in prescribed fire area compared to the 2011–2019 average (Melvin 2020). In contrast, Kobziar et al. (2015) reported that perceptions of prescribed fire trends over the previous decade in the South were mixed on private lands, but predominately increased on public lands, followed by leveling off, according to its Southern Fire Exchange list-serve member respondents. Together, these inconsistencies underscore the challenge of accurately quantifying regional trends in prescribed fire burned area.

While prior studies have documented long-term trends in burning, our analysis compares frequently burned areas between two decades (2000–2009 and 2010–2019)

using Southeast FireMap (SE FireMap). We assess broad-scale changes in burn patterns across land cover, ownership, and soil order. Our analysis considered differences among areas characterized by tree cover (forested), grass/shrub, and wetland land cover types, where prescribed fire provides the most ecological benefit and among which prescribed fire may have different motivations and challenges. Ownership is important to consider since treatment policies differ for private and public lands, as private land policies typically rely on incentives, while public land treatments depend on mandates and public funding. Soil orders often correspond to historical and current land uses associated with vegetation type and productivity, which in turn influence motivations for and benefits from prescribed burning. As most natural ecosystems in the region benefit most from frequent fire (multiple fires per decade), we concentrated on changes in areas that burned repeatedly. Accordingly, we addressed three primary research questions:

1. How has the extent of frequently burned areas changed at regional and state levels over the last two decades?
2. How do these changes vary by land cover, ownership, and soil order?
3. Where frequent fire detection has changed, are there patterns across land cover, ownership, and soil order that could guide future decisions and priorities?

Our findings provide the first region-wide analysis of changes in frequent fire activity within one of the most frequently burned regions of the U.S.

Methods

SE FireMap

The SE FireMap product uses the Landsat BA product as a backbone (Hawbaker et al. 2020b). As fires in the southeastern US are difficult to detect (Nowell et al. 2018; Teske et al. 2021), we adjusted the Landsat BA algorithm to better suit the environmental conditions of the region. Specifically, any fire detection with a 90% or greater burn probability was marked as burned, compared to the original Landsat BA product which required a burn probability of 96% or more. Pixels within this 90 to 100% threshold were smoothed using a 3×3 majority filter, with missing-data pixels classified as unburned. Meetings with prescribed fire experts and land managers indicated that this lower threshold more accurately reflected verified, prescribed fire events while minimizing increases in false positives. Additionally, only fires with 10 or more congruous pixels (i.e., 0.9 ha or 2.2 acres [ac]) were kept as a burned area, and areas smaller than this were removed to denoise the final product. While

these filtering thresholds may lead to a more conservative estimate of burned area by omitting very small or highly fragmented burns, they ensure observations reflect actual identifiable fires rather than detection artifacts. For our analysis, we used the 2023 SE FireMap product release covering 1994–2022. While more recent annual releases are available, the underlying historical data for our study period (2000–2019) remains identical across versions. In addition to mapped burned area, SE FireMap has several fire history metrics and tools to help support end user decisions (Hawbaker et al. 2026; Tall Timbers 2026).

The SE FireMap extent covers the historical range of longleaf pine, which spans portions of nine states: Texas, Louisiana, Mississippi, Alabama, Florida, Georgia, South Carolina, North Carolina, and Virginia (states are listed

in geographical order from west to east; Fig. 1). This region lies within the Southeast Plains and Coastal Plains Level II ecoregions (Omernik and Griffith 2014), with an average annual precipitation of 1324 mm, and average maximum and minimum temperatures of 24.4 °C and 12.0 °C, respectively (1990–2020; Abatzoglou 2013; Vanderhoof et al. 2025). Across the study area, annual precipitation increased by approximately 5% (~70 mm/year; Table S1) between the 2000s and 2010s according to the Gridded Surface Meteorological dataset (gridMET) (Abatzoglou 2013), with monthly averages indicating this increase primarily occurred from January through May. Maximum and minimum average temperatures remained fairly stable, varying by 0.3 °C (Table S1). Looking into moisture deficits, the Standardized

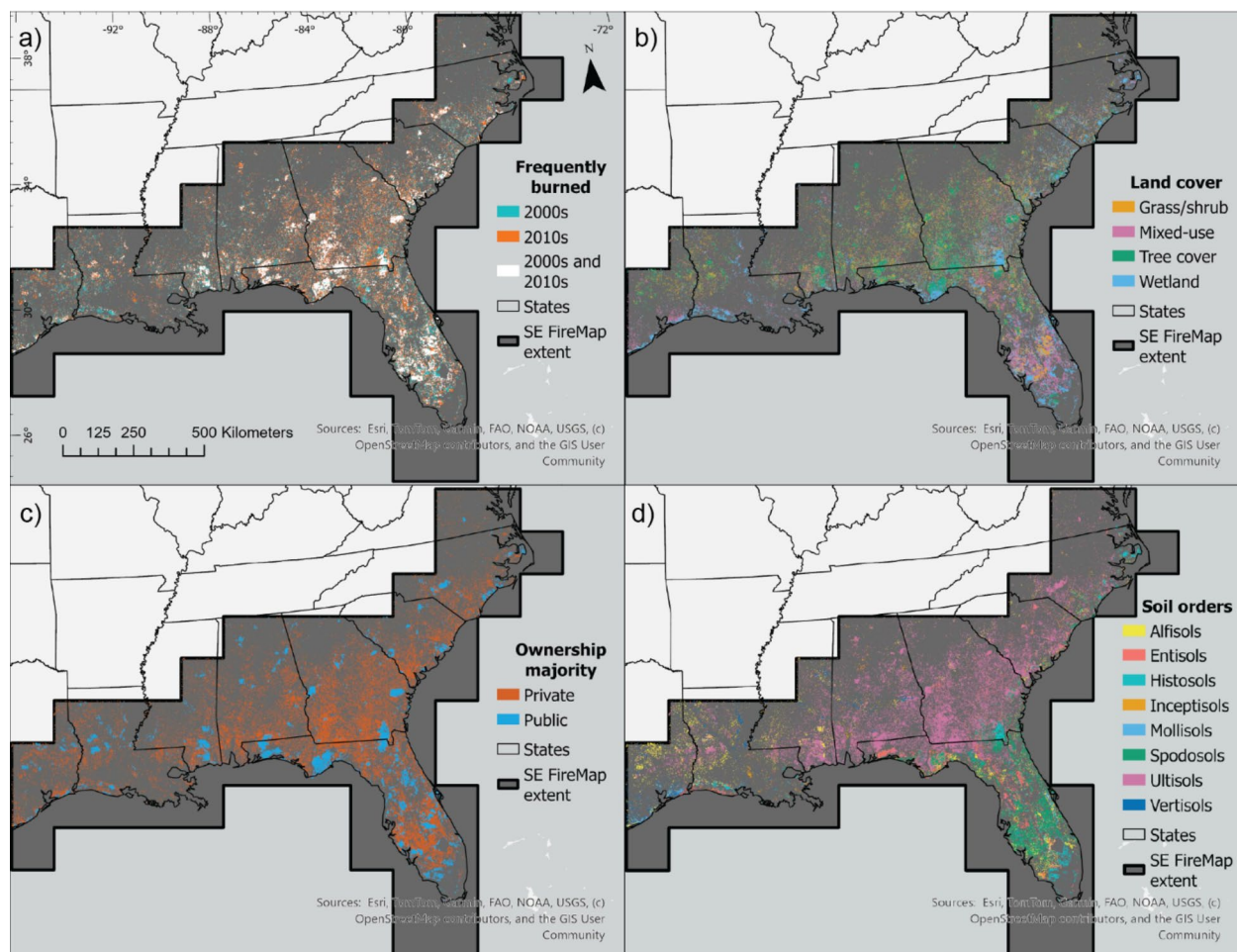


Fig. 1 Spatial distribution of frequently burned areas (areas burned two or more times per decade) within the Southeast FireMap (SE FireMap) extent (Hawbaker et al. 2026; Tall Timbers 2026). Each panel displays frequently burned area according to a different classification scheme: **a** frequently burned areas by decade (2000s and 2010s), including if they were frequently burned in both decades; **b** land cover type from the US Geological Survey (USGS) Land Change, Monitoring, Assessment, and Projection product (LCMAP) (USGS 2021); **c** ownership type (public or private) indicated by the USGS Protected Area Database (PAD) (USGS Gap Analysis Project (GAP) 2022); and **d** soil orders from the Soil Survey Geographic Database (SSURGO) (Esri and USDA NRCS 2023)

Precipitation-Evapotranspiration Index (SPEI) indicated that the 2010s had near normal conditions during the typical prescribed burning window of late winter/early spring, while the 2000s were slightly drier (negative SPEI) during this same time period (Table S1). As these baseline climatic variables remained fairly stable between the decades of our analysis, we focused on changes in frequently burned area in relation to ownership, land cover, and soil orders.

Although SE FireMap presumably missed some burned areas, the adjusted algorithm was applied consistently across the region and all years. Detection can also be affected by systematic variability in data acquisition, such as overlapping versus non-overlapping path-rows. Across the eastern US, the Landsat BA product has a reported omission and commission accuracy of 45% and 37%, respectively (Hawbaker et al. 2020a). In contrast, state permitting systems exhibit distinct biases related to their individual data entry and reporting protocols (Cummins et al. 2023).

Preliminary analyses showed that in states where prescribed burn permits are required and tracked, SE FireMap shows similar spatial patterns and temporal changes across land cover, ownership, and soil order for annual burned area, providing confidence in SE FireMap's representation of temporal trends (Appendix A). While the direction and magnitude of changes between decades are generally consistent across the datasets, summed burned areas differ. These discrepancies arise for several reasons: burn permits were requested for more area than actually burned, the requested burn was not conducted, or the burn was not detected by our algorithm (Nowell et al. 2018). Additionally, our preliminary analyses suggest that in states with robust ground-based records, SE FireMap captured 18–65% of reported burned area (Appendix A). Independent validation indicated that the Landsat BA products underestimated burned area by 12% in the eastern U.S. (Hawbaker et al. 2020a).

Identifying SE FireMap polygons with frequent burning

The dominant natural community types in the region include upland pine (including longleaf pine), sandhill pine, flatwoods pine, and open grasslands (Florida Natural Areas Inventory (FNAI) 2010; Schafale 2024). These community types typically require 1- to 3-year fire return intervals for most ecological, game management, and fuel reduction goals (Waldrop et al. 1992; Cox and Jones 2009; Robertson et al. 2021; Weber et al. 2022). With the omission error rates of the parent Landsat BA product of 45% in this region (Hawbaker et al. 2020a), a polygon burned every 2 years would expect to have about five burns per decade. Statistically, there is a likely probability of SE FireMap detecting at least two of these five

events per decade given the omission error. Therefore, we considered all burned area polygons with at least two burn detections per decade (2000–2009 or 2010–2019) as indicative of a 1- to 3-year fire return interval under the assumption that more area burned than was detected (Fig. 1a).

To validate our threshold of two fires per decade, we conducted a preliminary comparison of frequently burned area between SE FireMap and the US Forest Service Forest Service Activity Tracking System (FACTS) (U.S. Department of Agriculture, Forest Service 2026) database at Camp Shelby in Mississippi, and three National Forests in Florida (Apalachicola, Ocala, and Osceola; Appendix A). This validation revealed a systematic bias: FACTS reports entire burn unit boundaries rather than truly burned area and appears to be influenced by shifting reporting protocols. In contrast, while SE FireMap more conservatively estimates burned area, it provides a temporally consistent measure of actual burned area independent of agency reporting changes (Appendix A).

In order to obtain the fire history metrics, yearly raster layers of burned area across the region were converted to polygons and combined into a single layer in Python (Python Software Foundation, Wilmington, DE, USA) using the glob, NumPy (Harris et al. 2020), GDAL/OGR (Open Source Geospatial Foundation, Beaverton, OR, USA), GeoPandas (Jordahl et al. 2020), and Shapely (Gillies et al. 2007) packages. Each polygon contained binary attributes for whether it burned in each year, along with additional metrics. Polygons with two or more burn detections in one decade were identified in R (R Foundation for Statistical Computing, Vienna, Austria) and RStudio (Posit Software PBC, Boston, MA, USA), where subsequent statistical analyses were conducted using the dplyr (Wickham et al. 2022), tidyr (Wickham et al. 2014), and tidyverse (Wickham et al. 2019) packages. Results were plotted using ggplot2 (Wickham 2016) and ArcPro (Esri Inc. 2024).

While our dataset does not distinguish between prescribed fire and wildfire, we labeled areas that experienced at least two burn detections per decade as landscapes with frequent fire. Therefore, wildfires that occurred in frequently burned areas were retained, as their ecological effects may be similar to those produced by repeated prescribed fire (Martinson and Omi 2008). Overall, wildfire accounts for a relatively small portion of total burned area in the study region, e.g., <10%, in most states where prescribed fire is routinely tracked (Nowell et al. 2018) (Table 1). To focus on the amount of land that is receiving frequent fire, we analyzed the total hectares of land impacted by multiple burns rather than the cumulative amount of burned area (e.g., a 100-ha parcel

Table 1 Wildfire area (FOD^a, Short 2022), proportion (SE Rx Database^b, Cummins et al. 2023), and changes (ha) by state as compared to SE FireMap^c (Hawbaker et al. 2026). Wildfire proportion is only given for the 2010s due to the temporal span of SE Rx Database^b. Wildfire trends are calculated only for wildfire reports 2.2 acres or larger to correspond to the SE FireMap^c fire size threshold. States are listed west to east across the study region

State	All fire sizes (2010s)		WF ^d Prop. ^f (%)	SE FireMap ^c detectable area (≥ 2.2 ac)			SE FireMap ^c change (%)	Permit ^e status
	WF ^d area (ha)	Permit ^e area (ha)		WF ^d area 2000s (ha)	WF ^d area 2010s (ha)	WF ^d change (%)		
TX	131,168	362,766	26.6	106,885	128,707	20.4	-7.8	Voluntary
LA	89,696	380,696	19.1	129,258	88,415	-31.6	-36.1	Voluntary
MS	85,118	1,176,184	6.7	149,187	82,484	-44.7	-25.6	Required
AL	135,393	3,306,726	3.9	179,831	132,597	-26.3	18.9	Required
FL	726,096	9,083,664	7.4	895,370	720,749	-19.5	-3.8	Required
GA	254,924	6,086,241	4	290,426	247,458	-14.8	53.5	Required
SC	50,798	1,774,743	2.8	84,970	47,176	-44.5	13	Notification
NC	92,401	202,138	31.4	88,901	88,615	-0.3	14.9	Required
VA	9070	19,491	31.8	14,642	8429	-42.4	19.5	Voluntary

^a FOD = Fire Program Analysis—Fire Occurrence Database

^b SE Rx Database = Southeast Prescribed Fire Database

^c SE FireMap = Southeast FireMap

^d WF = wildfire

^e Permit = permit area from Southeast Prescribed Fire Database

^f Prop. = proportion

burned three times per decade is counted as 100 ha of frequently burned area).

Subsetting data to ecologically significant fires

Our analysis focused on fire in natural or semi-natural ecosystems and excluded fires related to agriculture, land clearing, or potential classification errors (e.g., burned areas detected in open water). To assign a land cover type to each observed burned area polygon, we used the US Geological Survey (USGS) Land Change Monitoring, Assessment, and Projection (LCMAP) product Collection 1.3 (Zhu and Woodcock 2014; Brown et al. 2020; USGS 2021; USGS Eros 2022). Specifically, we overlaid the polygons with LCMAP data and assigned each polygon the land cover class that occupied the largest area within a given polygon.

LCMAP categorizes land cover into eight classes: developed, cropland, grass/shrub, tree cover, water, wetland, ice/snow, and barren (Pengra et al. 2020). In the LCMAP classification system, areas with both grass/shrub and tree cover are assigned based on canopy density: locations with less than 10% tree cover are classified as grass/shrub, while areas with more than 10% are classified as tree cover. Forested areas that are used for tree harvesting are also classified as tree cover, while cropland includes cultivated crops, hay fields, orchards, vineyards, and livestock operations. Wetlands may include woody or herbaceous vegetation, but they are classified based on

hydrologic influence. As a result, the tree cover category in LCMAP effectively represents upland, non-wetland forested areas. A full description of land cover categories can be found in the LCMAP Collection 1.3 Science Product Guide (U.S. Geological Survey 2024).

As LCMAP is an annual product, we determined the land cover type for each year using the corresponding LCMAP year. To assess the accuracy of the LCMAP product within our study region, we compared the primary land cover type identified by the LCMAP algorithm to the LCMAP Reference data at locations that fell within the SE FireMap extent between 1994 and 2018 (Appendix B). The LCMAP Reference data is a product of over 25,000 reference plots randomly distributed around the continental US that have undergone additional quality assurance and control measures using various additional datasets to get a more accurate classification of land cover type at these locations (Horton et al. 2020; Pengra et al. 2022).

For polygons classified as majority cropland by LCMAP, we attributed the polygons a second time using the National Land Cover Database (NLCD) product (Dewitz 2023) to reduce the number of commission errors for cropland that occurred when using LCMAP alone (Appendix B). Polygons that were classified as majority cropland by LCMAP and cultivated crop by NLCD retained the classification of cropland, while all other LCMAP cropland polygons with NLCD

classifications other than cultivated crop were assigned a new mixed-use category. In order to focus our analysis on ecologically significant fires, only polygons classified by our analysis as a majority of grass/shrub, tree cover, mixed-use, or wetland were retained (Fig. 1b). The introduction of the new mixed-use category mitigates the high commission error (51%) of the standard LCMAP cropland class (Appendix B; Tables B2–B4). Specifically, by using NLCD, we recovered nearly 33% of the study's true grass/shrub reference points that were erroneously classified as cropland by the LCMAP algorithm. Ultimately, this hybrid approach retained approximately 90% of ecologically significant grass/shrub habitat while minimizing cropland misclassification, though the mixed-use category includes some agricultural burning (see Appendix B for details).

Attribution of ownership and soil order to SE FireMap polygons

In addition to land cover classification, all SE FireMap polygons were attributed with land ownership (public/private) types (Fig. 1c) and majority soil orders (Fig. 1d). Each fire polygon was designated as public or private using a majority rule and data from the USGS Protected Areas Database (PAD) dataset (USGS Gap Analysis Project (GAP) 2022). Building on the methodology employed by Healey et al. (2023), we utilized the “PAD US 3.0 Combined Proclamation, Marine, Fee, Designation, Easement” feature for our classification. PAD “Designation” types classified as proclamation or tribal, and “Ownership” types classified as private, non-governmental organization, or tribal were classified as “Private” ownership, with all remaining areas in the PAD dataset classified as public.

For attribution by soil order, we used soil orders as defined by the U.S. Department of Agriculture Natural Resources Conservation Service (USDA–NRCS) Soil Survey Geographic Database (SSURGO) data product (USDA NRCS 2025). These soil orders approximately align with the major natural vegetation types in the region. For example, Ultisols mostly correspond to the historical distribution of upland pine communities with high herbaceous plant cover dominated by grasses; Entisols in uplands tend to correspond to sandhill pine communities with less herbaceous vegetation and more exposed, sandy soils; Spodosols generally correspond to low-lying flatwoods pine communities with flammable evergreen vegetation; and Histosols correspond to swamps and wetlands with organic soil subject to smoldering and high severity fires (Table S2; Florida Natural Areas Inventory (FNAI) 2010; Schafale 2024). The remaining soil orders and their associated plant communities are described in Table S2. The SSURGO

dataset was downloaded from ArcGIS Online (Esri and USDA NRCS 2023), and areas were joined together following previously published methodology (Price 2020).

Analysis of decadal changes in burning

After attributing each polygon with land cover, ownership, and soil order, we used this dataset to calculate the area burned during each decade (2000–2009, 2010–2019) across the different categories. These calculations were done for the entirety of SE FireMap, and at the state level for each portion of the state that is included within the SE FireMap extent (Fig. 1). To obtain a decadal difference in frequently burned area, decadal totals from 2000–2009 were subtracted from the 2010–2019 decadal totals; thus, any positive decadal difference indicated an increase in burned area between the decades, while a negative difference indicated decreased burned area. Although previous work found stable error rates in the Landsat Burned Area Essential Climate Variable product (Vanderhoof et al. 2017), temporal variability in the frequency of clear-sky Landsat imagery could still introduce uncertainty or bias in estimates of total burned area. These effects are most pronounced prior to 2000, when only Landsat-5 was operational (Hawbaker et al. 2020a). Therefore, we assumed that variability in image frequency had a minor influence compared to the overall observed changes, especially the relative changes among geographic regions, land cover types, and land ownership categories.

Wildfire change analysis

To identify the mechanisms behind shifts in the observed decadal frequently burned area, we analyzed wildfire variability to understand if wildfires could potentially be driving any observed changes rather than prescribed fire using wildfire records from FOD (Short 2014, 2022). First, we took all wildfire reports from the 2010s across the SE FireMap extent and coupled them with burn permits from the SE Rx Database (Cummins et al. 2023) at the state level to determine the proportion wildfire activity contributing to the total fire area. This analysis was only done in the 2010s because no data were available in the SE Rx Database prior to 2010 (Cummins et al. 2023). We also examined the change in wildfire by state as compared to changes observed by SE FireMap. To ensure a consistent comparison with SE FireMap, we filtered wildfire events in the decadal change analysis to 0.9 ha (2.2 ac) or larger to match the minimum fire size in SE FireMap. These analyses allowed us to determine if observed increases in frequently burned area were driven by wildfires or prescribed fire.

Statistical analysis

To determine if the observed changes in frequently burned area between decades were meaningful, we applied three formal statistical tests. First, we used the Wilcoxon signed-rank test on the frequently burned decadal area aggregated in 20 km×20 km grid cells ($n=2302$) to evaluate spatial significance in decadal changes while minimizing spatial autocorrelation. The Wilcoxon signed-rank test evaluates the median difference across the grid cells, making the results less skewed to a few outliers. Second, we used Poisson rate tests to compare total decadal frequently burned areas across states and the SE FireMap extent between decades. This allows us to test whether frequently burned area seen in the 2010s is a statistically significant departure from the 2000s. Lastly, chi-squared tests of independence were conducted to see if shifts in the distribution of frequently burned area across ownership, land cover, and soil orders were significant across both state and SE FireMap levels.

Results

Decadal changes in burned area

Frequently burned area detected by SE FireMap over its entire extent increased from the first decade (2000–2009; 1,041,000 ha) to the second decade (2010–2019; 1,106,000 ha) resulting in a 6.2% increase (Table S3; Figs. 1a, 2a, c, 3a, c, 4a, c). The Wilcoxon signed-rank test across the 2302 grid cells confirmed that the increase in frequently burned area was statistically significant ($p<0.001$, see Table S4 for complete test statistics) with a median increase of 2.7 ha per grid cell signaling that the increase in frequently burned area is broadly distributed across the region rather than being driven by local anomalies.

At the state level, the direction of change varied. Frequently burned area increased in Alabama, Georgia, South Carolina, North Carolina, and Virginia, while it decreased in Texas, Louisiana, Mississippi, and Florida (Table S5; Figs. 2b, d, 3b, d, 4b, d). For example, Georgia saw an almost 95,000-ha increase (54%), while Florida

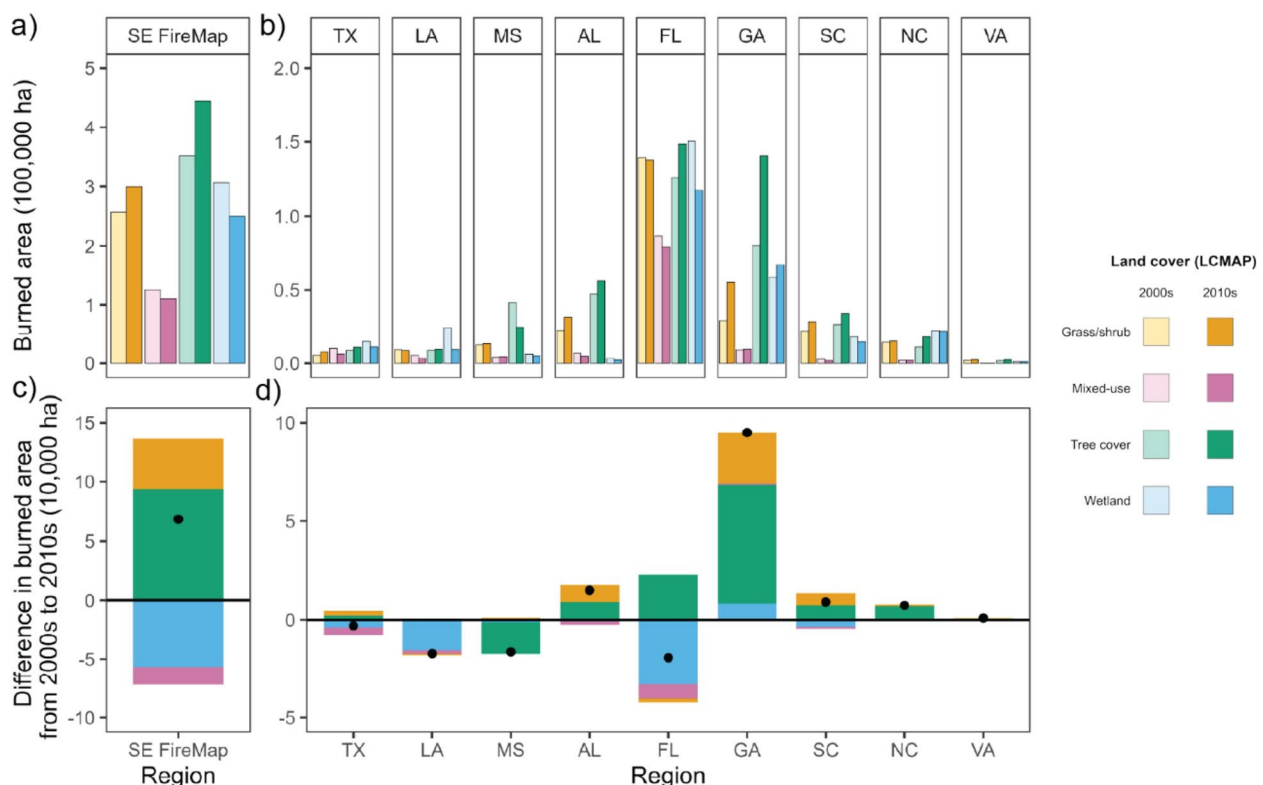


Fig. 2 Distribution and change in satellite-detected frequently burned areas (i.e., areas burned two or more times per decade) by majority land cover (LCMAP) (USGS 2021). **a** Full SE FireMap extent and **b** individual states, categorized by majority land cover type. Each bar represents a decade, with the left, lighter shaded bar corresponding to 2000–2009 (2000s), and the darker shaded right bar to 2010–2019 (2010s). **c** Decadal difference in frequently burned areas (2010s burned area minus 2000s burned area) across the entire SE FireMap extent. **d** Same decadal difference as **c** but analyzed separately for each state. Values above the zero line indicate an increase in burned area from the 2000s to the 2010s, while values below indicate a decrease. The black dot represents the total decadal difference in burned area, combining grass/shrub, mixed-use, tree cover, and wetland land cover types

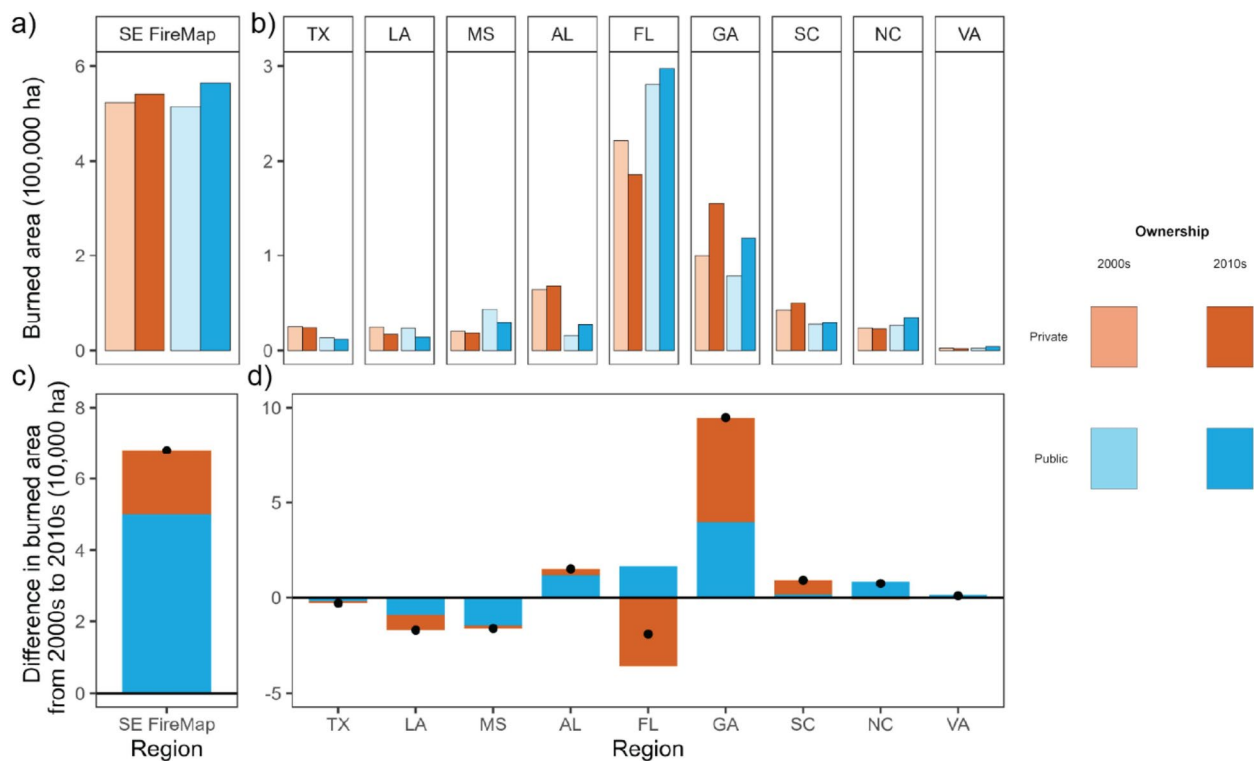


Fig. 3 Distribution and change in satellite-detected frequently burned areas (i.e., areas burned two or more times per decade) by ownership (PAD) (USGS Gap Analysis Project (GAP) 2022). **a** Full SE FireMap extent and **b** individual states, categorized by majority ownership. Each bar represents a decade, with the left, lighter shaded bar corresponding to 2000–2009 (2000s), and the darker shaded right bar to 2010–2019 (2010s). **c** Decadal difference in frequently burned areas (2010s burned area minus 2000s burned area) across the entire SE FireMap extent. **d** Same decadal difference as **c**, but analyzed separately for each state. Values above the zero line indicate an increase in burned area from the 2000s to the 2010s, while values below indicate a decrease. The black dot represents the total decadal difference in burned area, combining public and private lands

saw a decrease of 19,300 ha (−4%) between the decades (Table S5). Louisiana had the largest percent decrease of frequently burned area at 36.1% (−17,200 ha). Unclassified burned area in the PAD and SSURGO categories accounted for less than 1% per decade, primarily reflecting differences in water masks, boundary edges, and minor spatial mismatches between datasets. As the unclassified amount accounted for so little of the burned area, it was excluded from analyses described below. However, the unclassified values were included in the supplement tables (Tables S3 and S5). All Poisson rate tests indicated that these changes were statistically significant across the decades ($p < 0.001$; Table S4).

Decadal changes by land cover (LCMAP)

In the 2000s, tree cover was the most frequently burned land cover across the SE FireMap extent, accounting for 351,500 ha (33.8%) of frequently burned area, followed by wetlands (306,700 ha; 29.5%), grass/shrub (257,000 ha; 24.7%), and mixed-use (125,700 ha; 12.1%; Fig. 2a; Table S3). Tree cover was the dominant burned land cover type in four states (Mississippi, Alabama, Georgia,

and South Carolina), while wetlands were the most frequently burned cover type in the coastal states of Texas, Louisiana, Florida, and North Carolina. Virginia was the only state where grass/shrub was the primary burned type (Fig. 2b; Table S5).

In the 2010s, tree cover remained the most frequently burned land cover region-wide (Fig. 2a; Table S3). This pattern also persisted in Mississippi, Alabama, Georgia, and South Carolina, and emerged in Louisiana and Florida, where it had not been the most burned land cover in the previous decade (Fig. 2b; Table S5). Wetlands remained the most burned in Texas and North Carolina, while Virginia continued to burn grass/shrub land most commonly. Despite tree cover burning becoming more common in Florida, there was a near-even distribution in burning across grass/shrub, tree cover, and wetlands in both decades with each land cover accounting for 25 to 30% of total frequently burned area (Fig. 2b; Table S5).

Regionally, grass/shrub and tree cover saw increases in frequently burned area (42,900 ha, 16.7%; 93,700 ha, 26.6%, respectively), while wetlands and mixed-use declined (−56,800 ha, −18.5%; −15,100 ha, −12.0%,

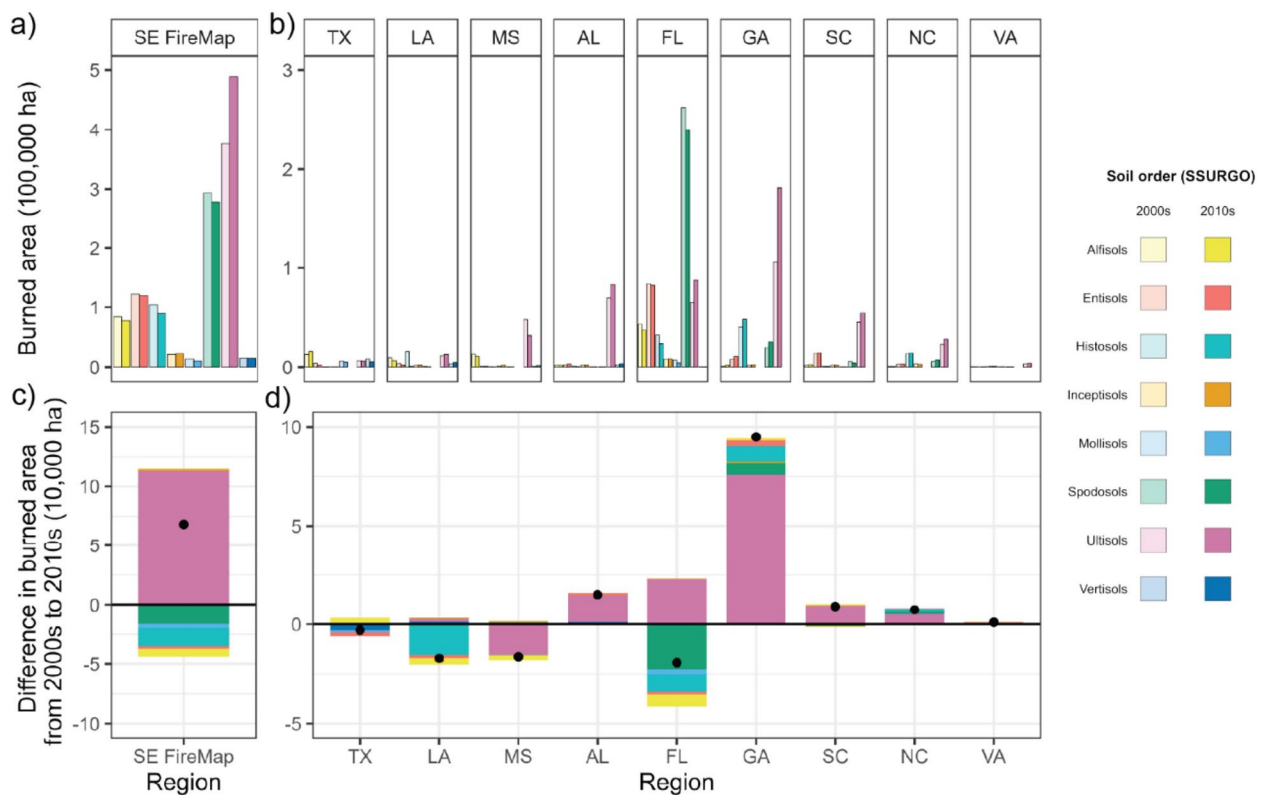


Fig. 4 Distribution and change in satellite-detected frequently burned areas (i.e., areas burned two or more times per decade) by majority soil order (SSURGO) (Esri and USDA NRCS 2023). **a** Full SE FireMap extent and **b** individual states, categorized by majority soil order from the SSURGO dataset. Each bar represents a decade, with the left, lighter shaded bar corresponding to 2000–2009 (2000s), and the darker shaded right bar to 2010–2019 (2010s). **c** Decadal difference in frequently burned areas (2010s burned area minus 2000s burned area) across the entire SE FireMap extent. **d** Same decadal difference as **c** but analyzed separately for each state. Values above the 0 line indicate an increase in burned area from the 2000s to the 2010s, while values below indicate a decrease. The black dot represents the total decadal difference in burned area, combining all soil orders

respectively; Fig. 2c; Table S3). At the state level, Mississippi was the only state where tree cover burning declined. Large declines in wetland burning occurred in Texas, Louisiana, and Florida, with Louisiana showing a particularly steep 62.7% drop (−15,500 ha). Smaller decreases were also observed in Mississippi, Alabama, North Carolina, and Virginia. South Carolina showed a decrease in burning across wetland and mixed-use land cover (−4500 ha combined), but overall frequently burned area still rose due to increases in tree cover and grass/shrub burning (13,600 ha combined). Increases in tree cover and grass/shrub burning drove overall burned area increases in Alabama, Georgia, South Carolina, North Carolina, and Virginia (Fig. 2d; Table S5). Chi-squared tests confirmed that these shifts were significant across the land cover classes ($p < 0.001$; Table S4).

Decadal changes by ownership (PAD)

Frequently burned area was nearly evenly split between public and private lands in both decades, with private lands accounting for 50.2% and 48.9% of the frequently

burned area in the 2000s and 2010s, respectively, even though private lands account for nearly 89% of ownership in the SE FireMap extent (Fig. 3a; Tables S3 and S6). In the 2000s, burning was more extensive on private than public lands for the majority of states (Texas, Louisiana, Alabama, Georgia, South Carolina, and Virginia), whereas three states had more public than private land burning (Mississippi, Florida, and North Carolina; Fig. 3b; Table S5) despite most of the states being privately owned lands (Table S6). These patterns of land ownership for frequently burned areas remained consistent in the 2010s, with the exception of Virginia which changed to more public than private land burning (Fig. 3c; Table S5).

The increase in frequently burned area across ownership types detected by SE FireMap resulted from an 18,200-ha increase (3.5%) on private lands and a 50,000-ha increase (9.7%) on public lands across the region (Fig. 3c; Table S3). Frequently burned area changes varied by land ownership across states. Florida showed contrasting patterns, with a 35,700-ha decrease (−16.1%) on

private lands, but a 16,400-ha increase (5.9%) on public lands. In several states, changes of either direction were concentrated on public lands: Mississippi's burned area declined primarily on public lands, while increases in Alabama, North Carolina, and Virginia also occurred mainly on public lands. In contrast, South Carolina's increase was driven largely by private lands. Both public and private lands contributed to Louisiana's overall decrease and Georgia's increase. Meanwhile, Texas experienced a near equal decrease in frequently burned area across both land ownerships. The decadal changes across all ownership types were statistically significant (chi-square test, $p < 0.001$; Table S4).

Decadal changes by soil order (SSURGO)

Across the study area, the most frequently burned areas occurred on Ultisols, the dominant soil order covering over 50% of the region (Table S6), expanding from 376,000 ha (36%) in the 2000s to 489,100 ha (44%) in the 2010s. Spodosols accounted for the second largest burned area (2000s: 293,500 ha; 2010s: 277,500 ha), despite being the dominant soil order in just over 5% of the region but the majority soil order in Florida (Fig. 4a; Tables S3 and S6). At the state level, Ultisols were the majority soil order in most states (Mississippi, Alabama, Georgia, South Carolina, North Carolina, and Virginia), and these states also had the greatest burned area occurring on Ultisol soils in both decades (Fig. 4b; Tables S5 and S6). In Texas, Alfisols were the majority soil order, and frequently burned area on Alfisols increased from 12,800 ha (33.5%) in the 2000s to 15,900 ha (45.0%) in the 2010s. In Louisiana, the distribution of frequently burned area shifted away from Histosols, which experienced a 95% decline between decades (dropping from 33.4% of state frequently burned area [15,800 ha] in the 2000s to approximately 3% [900 ha] in the 2010s), shifting instead to Ultisols in the 2010s (42.6%; 12,900 ha). Florida had most of the frequently burned area on Spodosols in each decade, where about half of the state's burned area occurred (Table S5).

Region-wide, burning on Ultisols increased by 113,200 ha (30.1%), while Inceptisols saw a smaller increase of 1700 ha (8.0%; Fig. 4c; Table S3). Burning declined on most of the other soil orders, including Spodosols (−16,000 ha [−5.5%]) and Histosols (−15,000 ha [−14.4%]). State-level gains in burning on Ultisols drove increases in Alabama, Georgia, North and South Carolina, and Virginia, ranging from approximately 20 to over 70%. In contrast, Texas and Mississippi saw declines in burning on Ultisols, with Mississippi experiencing the steepest percentage drop of −32.8% (−15,500 ha). In Florida, both Histosol and Spodosol frequently burned area declined substantially, with decreases of 8400 ha

(−26.2%) and 22,600 ha (−8.6%), respectively (Fig. 4d; Table S5). According to chi-square tests, all decadal differences were statistically significant ($p < 0.001$; Table S4).

Decadal changes in wildfire burned area

To assess whether changes in wildfire activity could explain the observed increases in frequently burned area, we examined wildfire changes using FOD data (Short 2014) across the study area (Table 1). State-level changes in wildfire burned area differed greatly from the changes we documented with SE FireMap data, with eight of the nine states experiencing declines in SE FireMap detectable wildfire area (i.e., sizes greater than or equal to 2.2 ac). For example, FOD data suggests large declines in wildfire burned area in the states of Alabama (−26.3%), Georgia (−14.8%), South Carolina (−44.5%), and Virginia (−42.4%). These steep wildfire declines occurred simultaneously with significant increases in frequently burned areas from SE FireMap data within those same states (18.9%, 53.5%, 13%, 19.5%, for Alabama, Georgia, South Carolina, and Virginia, respectively; Table 1).

Discussion

Decadal analysis

Our analysis shows that there was a statistically significant increase in the extent of frequently burned area across our study region between the 2000s and the 2010s. This change, revealed through SE FireMap data, suggests widespread and sustained prescribed fire activity in land cover types important for ecological integrity and landscape resilience. While shifting weather patterns, population growth, and regulatory pressures were predicted by some to reduce prescribed fire activity (Mitchell et al. 2014; Kupfer et al. 2020), our findings point to an alternative trajectory shaped by active engagement from landowners, agencies, and prescribed fire managers who appear to be overcoming many of the barriers to prescribed fire (Cary et al. 2004; Diaz et al. 2021; Natural Resources Conservation Service 2025).

While there was an overall increase in frequently burned areas, our analysis revealed nuanced changes across individual states, land cover types, land ownership (public vs. private), and physiographic units highlighting the influence of both natural and cultural factors. For example, we found that increases in upland burning were offset to varying degrees by declines in wetland burning. The wetland results should be interpreted with caution given the omission (51–78%) and commission (31%) errors associated with these land cover classes (see Limitations and uncertainties section). However, a decline in wetland burning is concerning given that prescribed fire in wetlands is an important management tool to reduce non-native species, encourage nutrient cycling, and

improve habitat condition (Williams-Jara et al. 2022). This change was particularly evident in states with a high cover of Histosol soils, which support wetlands such as marshes, swamps, and wet prairies, and Spodosols, which are also associated with wetlands, especially flatwoods, and open grasslands. In Louisiana, the large 95% decline in Histosols burning is similar in area to declines in overall burning and wetland burning, suggesting that these changes reflect the same areas and point to decreased frequent burning in wetlands, presumably marshes. In Florida, reductions in wetland burning and on Spodosols and Histosols probably reflect declines in burning flatwoods pine and open grassland communities, as well as embedded peat-based wetlands such as cypress domes, stringers, and bay swamps, in the state (Florida Natural Areas Inventory (FNAI) 2010).

Although identifying the reasons for the observed reductions in wetland burning is beyond the scope of this study, some causes can be speculated. In the southeastern US, development and fragmentation threaten wetlands, particularly in coastal areas including peninsular Florida where development pressure overlaps with wetland landscapes (Volk et al. 2017). In Louisiana, marsh loss from fragmentation, saltwater intrusion, and marsh subsidence may have also reduced burnable habitat (Potter 2021; Twumasi et al. 2026). However, according to LCMAP, wetland extent remained fairly stable from 2000 to 2019 across SE FireMap and in both states, suggesting habitat loss alone does not explain the decline (Table S7). Reluctance to burn on Histosols and Spodosols might also play a role. Their organic soils are prone to smoldering, which has very high emission factors for PM_{2.5} and can create superfog, along with other safety and health risks (Adetona et al. 2011; Robertson et al. 2014; Hsieh et al. 2018). These soils also support flammable vegetation that becomes riskier to burn with increasing time since fire (Sackett 1975; Hough and Albini 1978; McNab et al. 1978).

Despite an overall increase in the amount of frequently burned areas across the study extent, burning generally decreased in the western part of the SE FireMap extent (Texas, Louisiana, and Mississippi) on both public and private lands. On public lands, the lack of resources (e.g., money and staffing) and limits on burning (e.g., close proximity to smoke-sensitive areas, environmental/smoke regulation, and internal regulations/prescriptions) are often the cited causes of decreased burning (Haines et al. 2001; Quinn-Davidson and Varner 2012; Kobziar et al. 2015). The increase in public land burning in Florida occurred despite increased development of surrounding land, where fragmentation typically increases air quality concerns for people residing within these areas (Waldrop and Goodrick 2012), placing downward

pressure on prescribed burning (Radeloff et al. 2005; Gude et al. 2008). This trend of urbanization not only increases smoke impacts on the growing population, but also brings in new residents to the area whose perceptions of prescribed fire may differ significantly from those held historically (Kobziar et al. 2015). The reasons for overall increases in burning in Georgia, South Carolina, and North Carolina are also not clear, but they align well with the regional strategic land management goals and initiatives encouraging prescribed burning (Georgia Department of Natural Resources 2015), and the restoration of longleaf pine (McIntyre et al. 2018).

Comparison with other data sources

Our findings broadly align with other studies examining trends in burned area during the early twenty-first century. Some other large-scale studies using datasets show an increasing trend in burned area for North America (Jones et al. 2022), including areas within the southeastern US (Otón et al. 2021). Similarly, certain surveys on prescribed fire application in the southeastern US indicate steady or increasing usage in certain types of burning and land ownership categories (Haines et al. 2001; Kobziar et al. 2015). For instance, Kobziar et al. (2015) reported that most respondents believed prescribed fire use had increased compared to the previous decade. On the other hand, the 2020 National Prescribed Fire Use Report stated that in 2019 prescribed fire (excluding agricultural fires) showed a 10% or greater decrease in Louisiana, Georgia, South Carolina, North Carolina, and Virginia compared to the average across previous survey years (2011, 2014, 2017, and 2019), while Texas, Alabama, and Florida showed increases (Melvin 2020). Since the report relies on data collected by state forestry agencies, discrepancies may arise due to variations in state prescribed fire regulations, which are avoided using SE FireMap. Because of its uniform coverage over the region, spatially explicit data that can be analyzed in the context of multiple geographic variables, and multi-decade temporal tracking of fire activity, the SE FireMap product can provide a tool for monitoring and interpreting regional changes in wildland fire response to cultural, economic, and environmental changes going forward.

Wildfire as a driver of observed changes

The divergence between decadal wildfire and SE FireMap burned area activity suggests that the regional increase in frequently burned area is driven by differences in cultural and management practices rather than a changing wildfire regime. The states experiencing some of the largest increases in frequently burned area, such as Alabama, Georgia, South Carolina, and Virginia, also exhibited sharp declines in wildfire activity between decades

(Table 1). Furthermore, across states where both wildfire and frequently burned area decreased, the reduction in frequently burned area was generally less than the steep declines observed in wildfire, as seen in Mississippi. This divergent relationship indicates that wildfire activity does not sufficiently account for the observed patterns, suggesting that prescribed fire is the dominant force shaping the fire regime in our study area.

Limitations and uncertainties

As SE FireMap is a remotely sensed dataset, there are a few limitations to its use that should be considered when interpreting results. First, the precipitation that is common over the region and the corresponding cloud cover can obscure some fires. As the post-fire recovery time is often rapid (e.g., weeks to months) (Picotte and Robertson 2011; Vanderhoof et al. 2021), a burn signal can dissipate before the occurrence of a clear-sky image and therefore miss a burn. Consequently, more frequent images could increase the number of burn detections simply by allowing for more clear-sky images. However, the number of Landsat observations in our analysis can be assumed to be largely similar between our two study periods with Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) available for the 2000–2009 decade, and ETM+ and Operational Land Imager (OLI) available for the 2010–2019 period, with TM only available for a minority of the second decade (2010–2012).

The detection accuracy of SE FireMap is linked to the performance of its parent product, Landsat BA. Regional validation of Landsat BA in the southeastern US indicates that omission error (OE, 45%) generally exceeds commission error (CE, 37%), resulting in a conservative bias of –12% (Hawbaker et al. 2020a). While these error rates vary across the landscape, they are most pronounced in anthropogenic classes such as cultivated crops (CE: 88%; OE: 73%) and pasture/hay (CE 80%; OE: 54%), which were excluded from our study analysis. For the land cover categories in our study, CE ranged from 17% in mixed forests to 44% in grassland/herbaceous, while OE errors remained relatively low in shrub/scrub (21%) and deciduous forest (35%). In wetland vegetation land cover classes, CE was 31% in both emergent and woody wetlands, and OE was 51% in woody wetlands and 78% in emergent wetlands (Hawbaker et al. 2020a). However, because these error rates are relatively stable over time (Vanderhoof et al. 2017), SE FireMap is a useful information source for evaluating broad-scale temporal changes in burning patterns.

Additionally, analyses associated with the mixed-use category should be interpreted with caution. To mitigate a common misclassification in LCMAP of grass/shrub as cropland, we used a LCMAP/NLCD hybrid

classification approach. While this method resolved the grass/shrub classification error, it introduced some true cropland, which accounts for 40% of the final mixed-use category, into the analysis. Therefore, decadal shifts in this category partially capture changes in agricultural fire regimes, which are dictated by a different set of drivers than those outlined in this research. However, because the mixed-use category represents a relatively minor proportion of overall regional fire in our study, this overlap does not alter the primary changes observed across the dominant land cover types.

While the omission errors are a known constraint for satellite-based datasets, our sensitivity analysis (Appendix A) suggests that SE FireMap provides a more temporally consistent baseline than administrative records. At the sites where the two sources diverged, the administrative records showed a substantial increase in reported area while satellite detections decreased between the decades. This discrepancy highlights a known bias: administrative datasets (i.e., FACTS, SE Rx Database) typically record entire burn unit boundaries or reflect changes in documentation protocols across different states and agencies, whereas SE FireMap more precisely captures actual burned area. The same caveats have been noted in other studies concerning permit data (Nowell et al. 2018; Cummins et al. 2023). Consequently, although SE FireMap may underestimate total acreage due to omission errors, it offers a more reliable and uniform representation of actual fire occurrences and regional shifts over time.

Conclusions

The overall increase in frequently burned area in the southeastern U.S. identified by SE FireMap in the face of many challenges is tentatively encouraging for gaining the many ecological and societal benefits of prescribed burning. However, the results are complex and reflect varying forces of change among states, land use, land ownership, and physiographic features on the southeastern US landscape. Declines in burning, particularly at the state level, could be of interest to government agencies and private land conservation efforts as an indicator of where resources might best be directed to maintain or restore habitats. The SE FireMap provides new, geographically, and temporally detailed insight into changes in prescribed burning that will have important implications for land use policy and education.

Abbreviations

ac	Acres
CE	Commission error
ETM+	Enhanced Thematic Mapper Plus
FACTS	Forest Service Activity Tracking System
FOD	Fire Program Analysis—Fire Occurrence Database
gridMET	Gridded Surface Meteorological dataset

ha	Hectares
Landsat BA	Landsat Burned Area product
LCMAP	United States Geological Survey's Land Change, Monitoring, Assessment, and Projection product
NLCD	National Land Cover Database
OE	Omission error
OLI	Operational Land Imager
PAD	Protected Area Database
PM _{2.5}	Particulate matter 2.5 microns or less in diameter
Prop.	Proportion
SE FireMap	Southeast FireMap
SE Rx Database	Southeastern US Prescribed Fire Permit Database
SPEI	Standardized Precipitation-Evapotranspiration Index
SSURGO	Soil Survey Geographic Database
TM	Thematic Mapper
USDA–NRCS	United States Department of Agriculture—Natural Resources Conservation Service
USGS	United States Geological Survey
WF	Wildfire

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42408-026-00561-w>.

Supplementary Material 1.

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Authors' contributions

HKN led the study design, data analysis, figure creation, and manuscript writing. KMR contributed to study design, soil analyses, and manuscript revision. TJH, CVM, CEM, JJP, and MKV provided foundational data, data processing, guidance, and manuscript feedback through regular meetings. KC supplied SE Rx Database and expert advice. JN contributed initial guidance. All authors (HKN, KMR, TJH, CVM, CEM, JJP, MKV, KC, and JN) participated in manuscript editing. TJH, MKV, JJP, KMR, and JN contributed to the original conceptualization, funding acquisition, and project management of the SE FireMap data product used in this analysis.

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Data availability

Data used in this study available from the following sources: SE FireMap (Hawbaker et al. 2026), PAD (USGS Gap Analysis Project (GAP) 2022), LCMAP Collection 1.3 (USGS 2021), and NLCD (Dewitz 2023), are all available from the USGS. SSURGO data are produced by the USDA NRCS and were accessed via ArcGIS online (Esri and USDA NRCS 2023). The SE Rx Database is available upon reasonable request from the dataset creator (Cummins et al. 2023).

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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