Assessing the Influence of Insect Outbreaks on the Effectiveness of Fuel Treatments in the Colorado Forest

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Abstract

Background: Wildfires, insect outbreaks, and fuel treatments significantly affect forest structure, fuel loads, and post-disturbance recovery. **Aims:** This study examined the spatio-temporal relationships among factors and assessed their influence on wildfire occurrence and severity across forest types in Colorado. **Methods:** A geospatial framework was used for incorporating four decades of wildfire, insect outbreak, fuel treatment, topographic, and climatic data, and analyzed through machine learning and statistical methods. **Results:** From 1984 to 2024, Colorado's wildfire mean frequency and burned area increased by 0.24 fires and 433 hectares annually. Insect outbreaks peaked during the early to mid-2000s and have since been less extensive. In contrast, fuel treatment activity increased significantly after 2006, averaging approximately 47 new treatments (1,170 hectares) annually. Across all forest types, fire severity was lower in treated areas (coefficient -0.6733 and $p < 0.001$), primarily due to the contribution of low-elevation forests. Fire severity was higher in forests that had experienced insect outbreaks (coefficient 12.8282, $p < 0.001$). While fuel treatments mitigated wildfire severity, their efficacy varied across forest types and declined with treatment age and post-treatment insect outbreaks. **Conclusion:** The results provide critical insights into the longevity of fuel treatments under varying disturbance conditions.

Implications: This study supports evidence-based forest management and allocation of resources to the most vulnerable regions of Colorado.

Keywords: Wildfire, Insect Outbreak, Fuel Treatment.

1. Introduction

Forest disturbances like wildfires and insect outbreaks have long shaped forest structure, fuels, and resilience, but climate change and human activities are making disturbances larger, more frequent, or more severe, sometimes leading to compounded effects that compromise post-disturbance resilience (Kulakowski *et al.* 2020; Guz and Kulakowski 2021). Depending on the exact interactions and climate conditions, forests may recover, change into different types of forests, or transition to non-forest states after disturbance (Clark-Wolf *et al.* 2025). In this context, forest management may modulate extreme disturbances and promote post-disturbance resilience (Clark-Wolf *et al.* 2025; Senf *et al.* 2025).

The frequency and intensity of different kinds of disturbances are rising globally with changes in climate and land use (Calvin *et al.* 2023). Wildfires are strongly influenced by interactions among fuel, weather, ignition source, and topography (Krawchuk *et al.* 2009) and lead to physical, biological, and ecological changes in ecological systems (Jaiswal *et al.* 2002; Bargali *et al.* 2024). In the forests of the western US, wildfires have increased in size and frequency (Singleton *et al.* 2019; Mueller *et al.* 2020; Ostoja *et al.* 2023), primarily due to increasing temperatures and dryness (Littell *et al.* 2009; Abatzoglou & Williams 2016; Wasserman & Mueller 2023).

In addition to wildfires, extensive areas of forests and woodlands in western North America have been affected by outbreaks of bark beetles (Mietkiewicz *et al.* 2019). Generally, insect outbreaks in forests occur when populations of herbivorous insects grow rapidly and reach high densities

within a short period of time, and significantly influence the structure of the forest by increasing tree mortality (Elderd *et al.* 2013; Hart *et al.* 2015; MacLean 2016; Biedermann *et al.* 2019). Climate variability has been detected as the paramount cause of the recent expansion of outbreaks in the USA and Canada (Hicke *et al.* 2006; Thomson 2009; Carroll *et al.* 2006). Further, longer growing seasons and higher winter temperatures are anticipated to become progressively common in the future (IPCC 2014), which sets the stage for additional intensification of forest insect outbreaks. In western North America, mountain pine beetle (MPB) outbreaks are one of the most pivotal disturbances influencing lodgepole pine (*Pinus contorta*) (Mietkiewicz and Kulakowski 2016; Woo *et al.* 2024).

In response to intensifying forest disturbances across the American West, there are expanding efforts to reduce wildfire hazards, most commonly by modifying surface fuels, height of live crowns, canopy bulk density, and stand composition (Agee and Skinner 2005; Fettig *et al.* 2022). Fuel treatments can enhance forest resilience by affecting fire regimes and post-fire environments (Stephens *et al.* 2024). However, the efficacy of fuel treatments varies across forest types, biophysical settings, and with any post-treatment secondary disturbances such as insect outbreaks, which have the potential to affect forest structure, tree mortality, and fuel load, leading to the reduction or enhancement of the mitigation potential of the implemented treatments.

Forests in Colorado have a complex disturbance history that includes wildfires, insect outbreaks, and fuel management (Addington *et al.* 2018; McKinney 2019). Using GIS and remotely sensed data, this research seeks to assess whether insect outbreaks influence longevity and fuel treatments across diverse forest landscapes. We map the spatial and temporal distribution of fuel treatments, insect outbreaks, and wildfires in Colorado between 1984 and 2024 to assess whether fire severity

is affected by fuel treatments and whether this effect is maintained in the presence of subsequent insect outbreaks.

2. Materials and Methods

2.1. Study Area

This study covers the US state of Colorado (Fig. 1) and includes the part of the Rocky Mountains, alpine zones, coniferous forests, and semi-arid plains (Romme *et al.* 2009). Major forest types in Colorado include ponderosa pine, Douglas fir, and Gambel oak at lower elevations, lodgepole pine and quaking aspen at mid elevations, and Engelmann spruce and subalpine fir at upper elevations. Colorado's forests have a long history of wildfires, insect outbreaks, and active forest management, including fuel treatments (Hart *et al.* 2015).

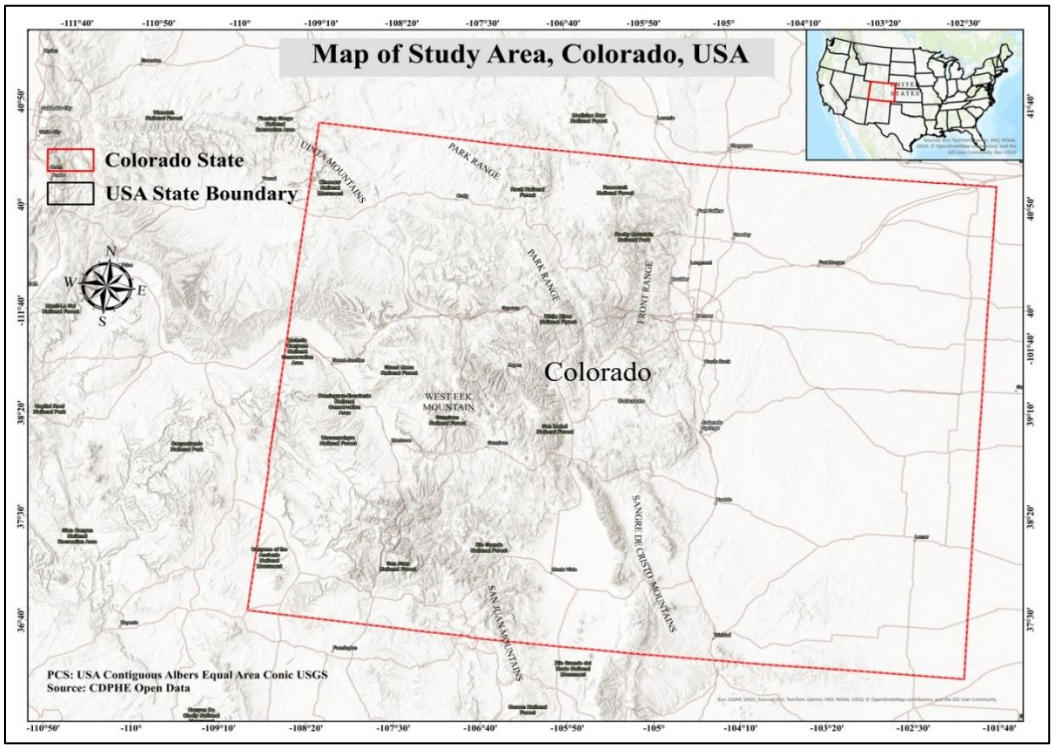


Fig. 1. Location of the study area in Colorado, USA.

2.2. Data Sources

Fuel treatment and insect outbreak data were derived from United States Forest Service data (USFS 2025). Wildfire data were derived from Monitoring Trends in Burn Severity (MTBS)-2025. Digital Elevation Model (DEM) was based on U.S. Geological Survey (USGS)-2022 NASA 30-m Shuttle Radar Topography Mission (SRTM) and processed in Google Earth Engine (GEE), then the aspect was calculated and discretized into eight classes (N, NE, E, SE, S, SW, W, NW) in ArcGIS Pro from DEM (Table 1). Forest types were aggregated into six categories (Ponderosa & Dry Pines, Lodgepole Pine, Spruce–Fir, Douglas-fir, Aspen & Deciduous, and Other). Weather data such as precipitation (pr), wind speed (ws), maximum temperature (tmax), and minimum temperature (tmin) were based on TerraClimate (Abatzoglou *et al.* 2018) through GEE. Vector and raster layers were reprojected to the USA Contiguous Albers Equal Area Conic coordinate system. Data were processed by integrating ArcGIS Pro 3.5, R programming, and GEE (Fig. 2).

Table 1: Source of Data

Dataset	**Type**	**Geometry/ Resolution**	**Source**	**Format**
Fuel Treatments	Vector	Polygon	U.S. Forest Service, 2025	Shapefile
Insect Outbreaks	Vector	Polygon	U.S. Forest Service, 2025	Shapefile
Wildfire Perimeters	Vector	Polygon	Monitoring Trends in Burn Severity (MTBS), 2025	Shapefile
Differenced Normalized Burn Ratio (DNBR)	Raster	30 m	Monitoring Trends in Burn Severity (MTBS), 2025 (Fire Bundles)	GeoTIFF
Burn Severity Class	Raster	30m	Monitoring Trends in Burn Severity (MTBS), 2025 (Burn Severity Mosaics)	GeoTIFF

DEM	Raster	30m	USGS/NASA SRTMGL1 v3 (2022) via Google Earth Engine	GeoTIFF
Aspects	Raster	30m	USGS/NASA SRTMGL1 v3 via Google Earth Engine	GeoTIFF
Colorado State Boundary	Vector	Vector	Colorado Department of Public Health and Environment (CDPHE), CDPHE Open Data, 2018	Shapefile
Colorado, County Subdivision	Vector	Vector	U.S. Census Bureau, Department of Commerce	Shapefile
Weather Data with fire point	Raster	4638.3 m (4 km)	TerraClimate: Monthly Climate and Climatic Water Balance for Global Terrestrial Surfaces, University of Idaho	Table

2.3. Analysis

Wildfire, climatic, and ecological data were compiled for Colorado to examine the relationships among fuel treatments, insect outbreaks, and fire severity (Fig. 2). Wildfire data included burn area, fire severity, incident type, fire year, and ignition year in ArcGIS Pro (Fig. 2). Insect outbreaks were analyzed by insect species. Fuel treatments were analyzed based on year, area, and treatment type.

Wildfire perimeters, fuel treatment polygons, and insect outbreak data were combined to a common spatial reference and integrated with stratified randomly distributed points (n = 4,030; 10 points per wildfire polygon) to enable spatially balanced sampling for statistical calculation in ArcGIS Pro (Fig. 2). Spatial joins were performed sequentially to associate each random point with wildfire attributes, fuel treatment data, and insect outbreak records. Nine new variables were created to capture key dimensions of disturbance interactions: fire occurrence (Fire_YN), fire

severity (Fire_Severity), treatment presence (Fuel_YN), treatment age relative to fire or year before fire (Fuel_YBF), outbreak occurrence (Outbreak_YN), outbreak age relative to fire or year before fire (Outbreak_YBF), forest type, elevation, and aspect. Corrected dNBR was calculated from raw dNBR (extracted from fire bundle raster images) and dNBR offset by subtracting (Lutz *et al.* 2009; Parks *et al.* 2016; Picotte *et al.* 2020). Fire severity was classified into three levels (low, medium, high) based on dNBR such as Class 1 (Low Severity- less than 270), Class 2 (Moderate Severity- 270 to 660), and Class 3 (High Severity- more than 660) (Key and Benson 2006) while fire, treatment and outbreak presence were coded as binary indicators 1 and 0. The resultant classification led to the analysis of thirteen variables ("Fire_YN", "Fire_Severity", "Elevation", "Aspect", "Forest_Type", "Fuel_YBF", "Fuel_YN", "Outbreak_YBF", "Outbreak_YN", "ws_overall", "pcp_overall","tmax", and "tmin").

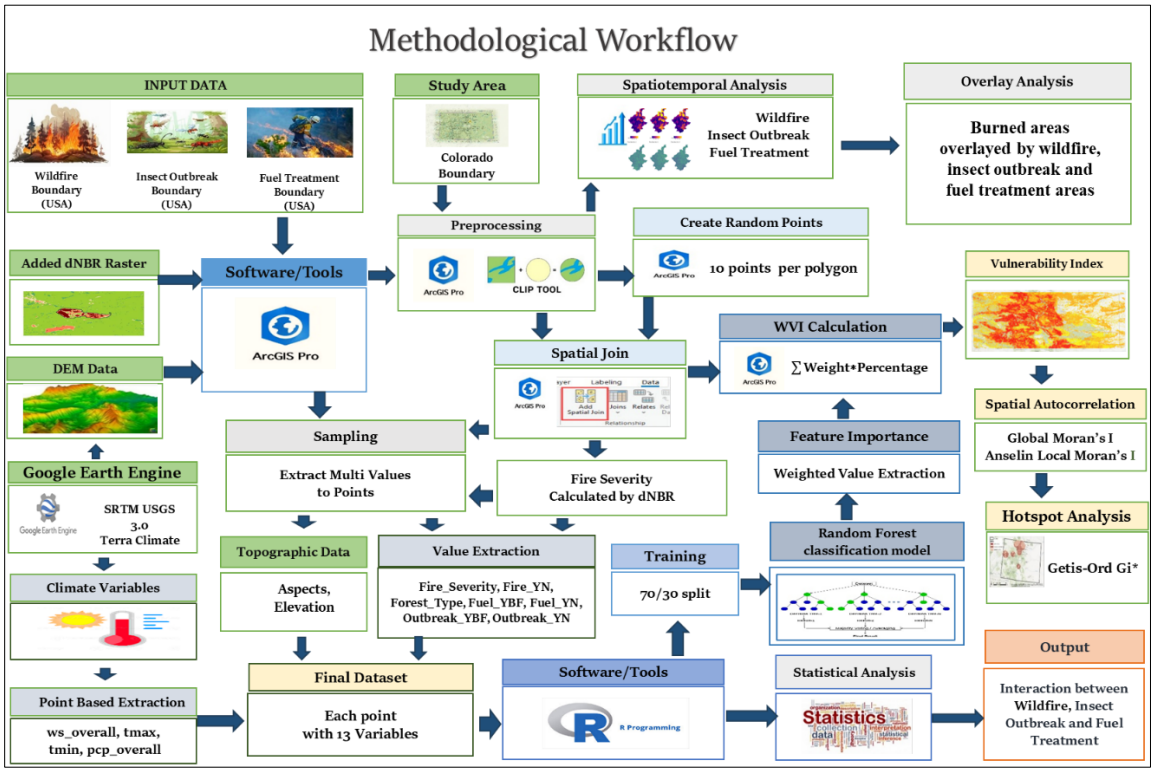


Fig. 2. Working flowchart

After the dataset was compiled, it was used to train a Random Forest (RF) Classification model and analyzed in R (R Core Team 2024) using the packages *sf* (Pebesma 2018) and *tidyverse* (Wickham *et al.* 2019). Geometry columns were removed after extraction to facilitate statistical analyses. A Random Forest (RF) model (Breiman 2001) was developed to predict wildfire severity classes from topographic, climatic, and ecological variables. All data were divided into a training set (70%) and a testing set (30%) for ensuring balance in class representation (Kuhn 2008). Using RF packages, this model was trained with 500 trees and three random predictors per split (Liaw and Wiener 2002)**.** Descriptive and inferential analyses were performed in R using *ggplot2* (Wickham *et al.* 2019) and *vcd* package (Meyer *et al.* 2006). Ordinal Logistic Regression (OLR) was implemented using the *MASS* package (Venables and Ripley 2002) to test the magnitude and direction of treatment and outbreak effects on ordered categories of fire severity.

3. Results

3.1. Wildfire, insect outbreak, and fuel treatments in Colorado (1984-2024)

The majority (87.36%) of all fire events in Colorado during 1984-2024 were wildfires. Prescribed fires accounted for 6.45%, followed by unknown (5.52%) and wildland fire use (1.38%). Relatively few fires (< 15 fires/year) occurred most years between 1984 and 2024 whereas a small number of years had notably higher incidence of fire, such as in 2002 (48 fires), 2018 (35 fires), 2000 (23 fires), and 2020 (21 fires) (Fig. 3). Over the 40-year period examined here, the mean number of fires/year increased by 0.24 fires/year (Sen's slope; Mann–Kendall test $\tau = 0.257$, $p = 0.0265$).

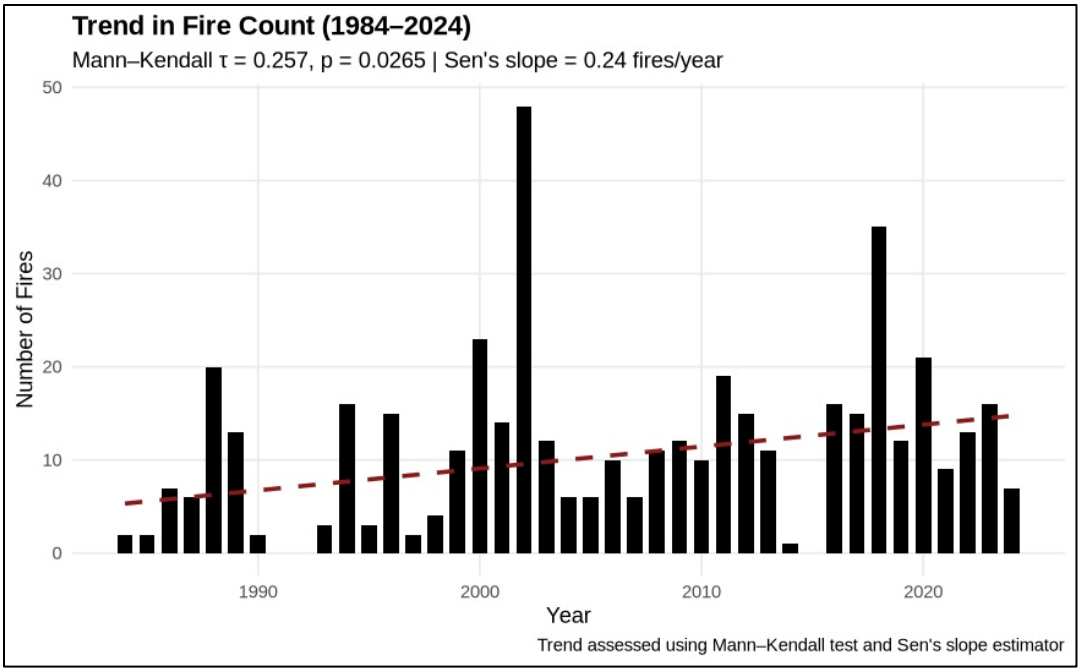


Fig. 3. Wildfire trend as per fire count

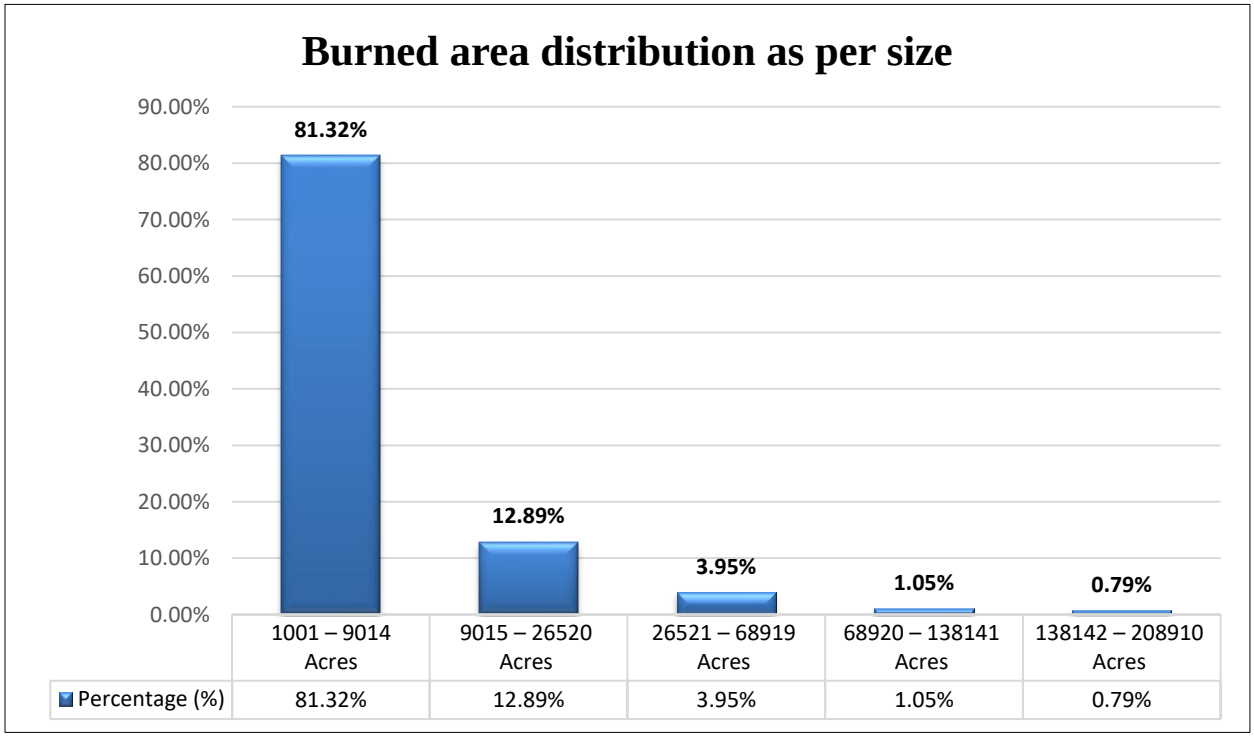


Fig. 4. Burned area percentage as per fire perimeter size

Most of the burned area falls within the 1,001–9,014 acre range, representing 81.32% of the total (Fig. 4 & Fig. 5). The combination of more and larger fires contributed to an increase in total burned area (Mann–Kendall $\tau = 0.306$, $p = 0.007$), with a mean increase of 433 ha per year (Fig. 6).

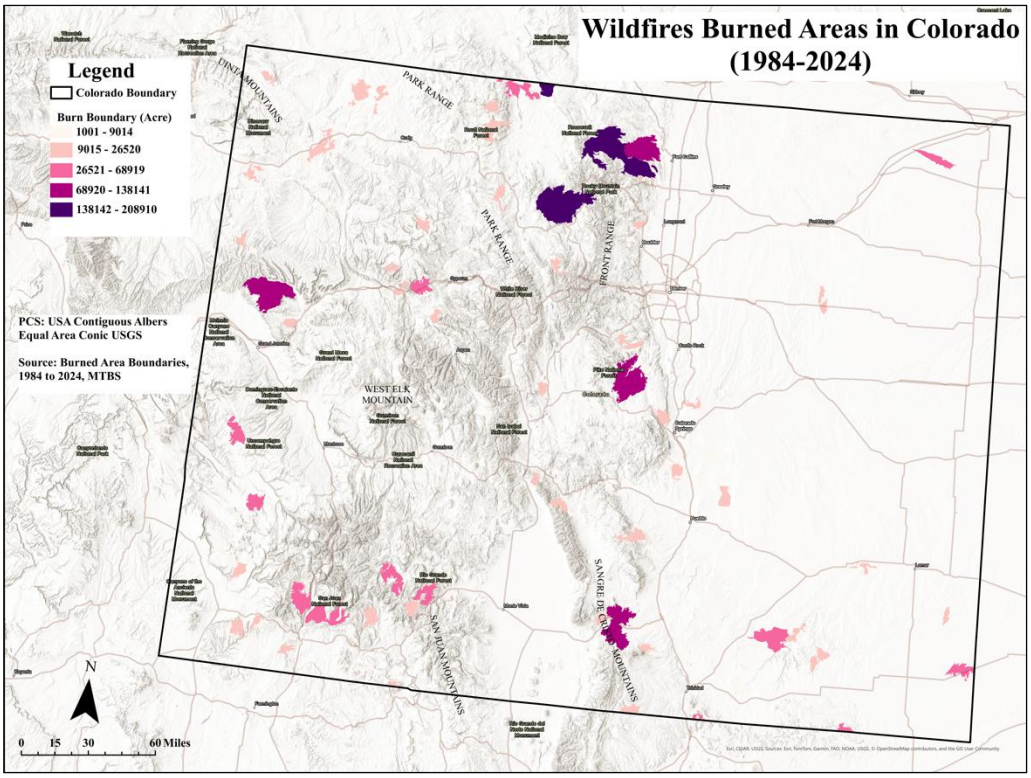


Fig. 5. Location of fires

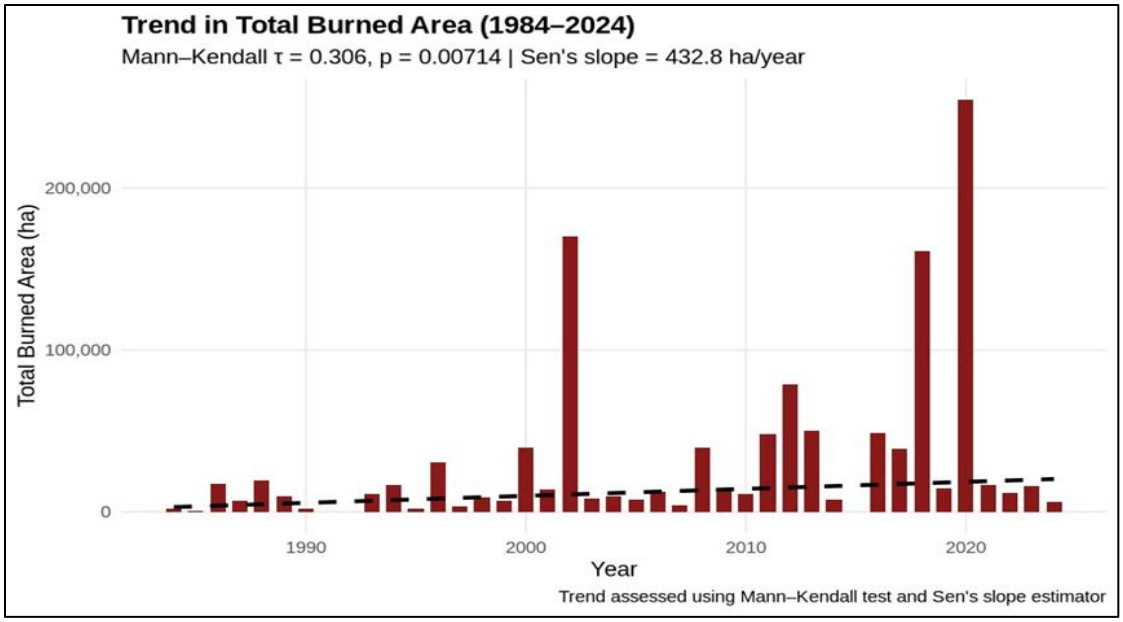


Fig. 6. Burn severity pattern

3.2. Insect outbreak patterns

Insect outbreaks in Colorado were most widespread during the early to mid-2000s (Fig. 7 & Fig. 8), and the number of incidences did not exhibit a significant long-term trend (Mann–Kendall τ = 0.037, p = 0.797), though the area affected decreased over the period (τ = −0.365, p = 0.0068) (Fig.9).

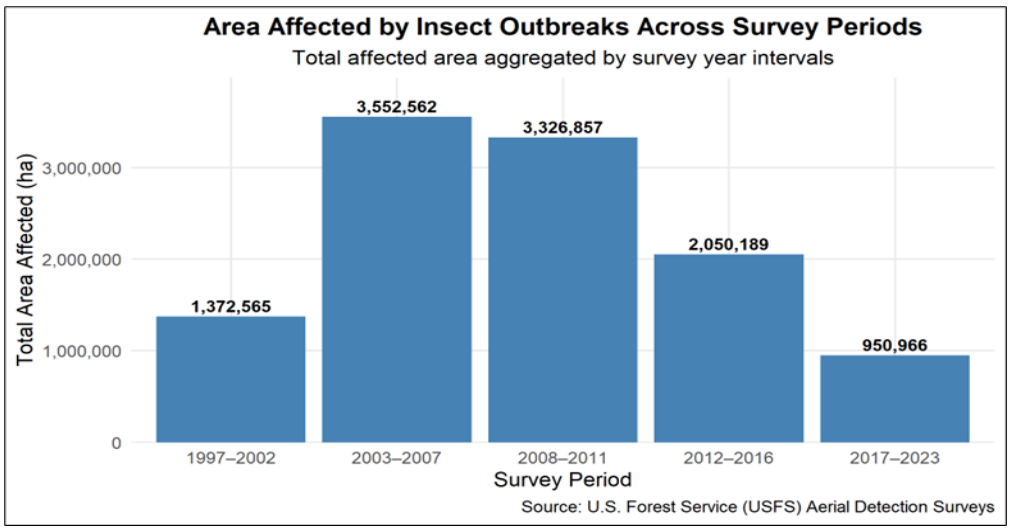


Fig. 7. Decadal distribution of insect outbreak areas

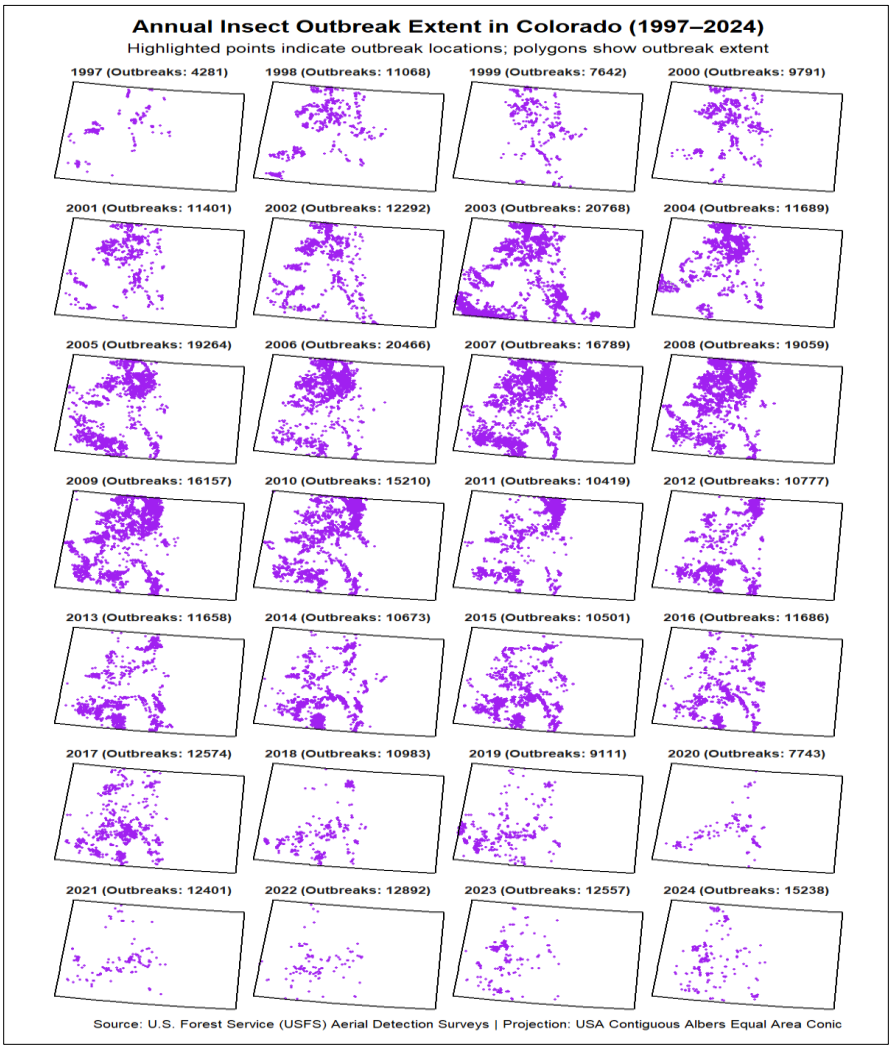


Fig. 8. Annual Distribution of Insect Outbreak

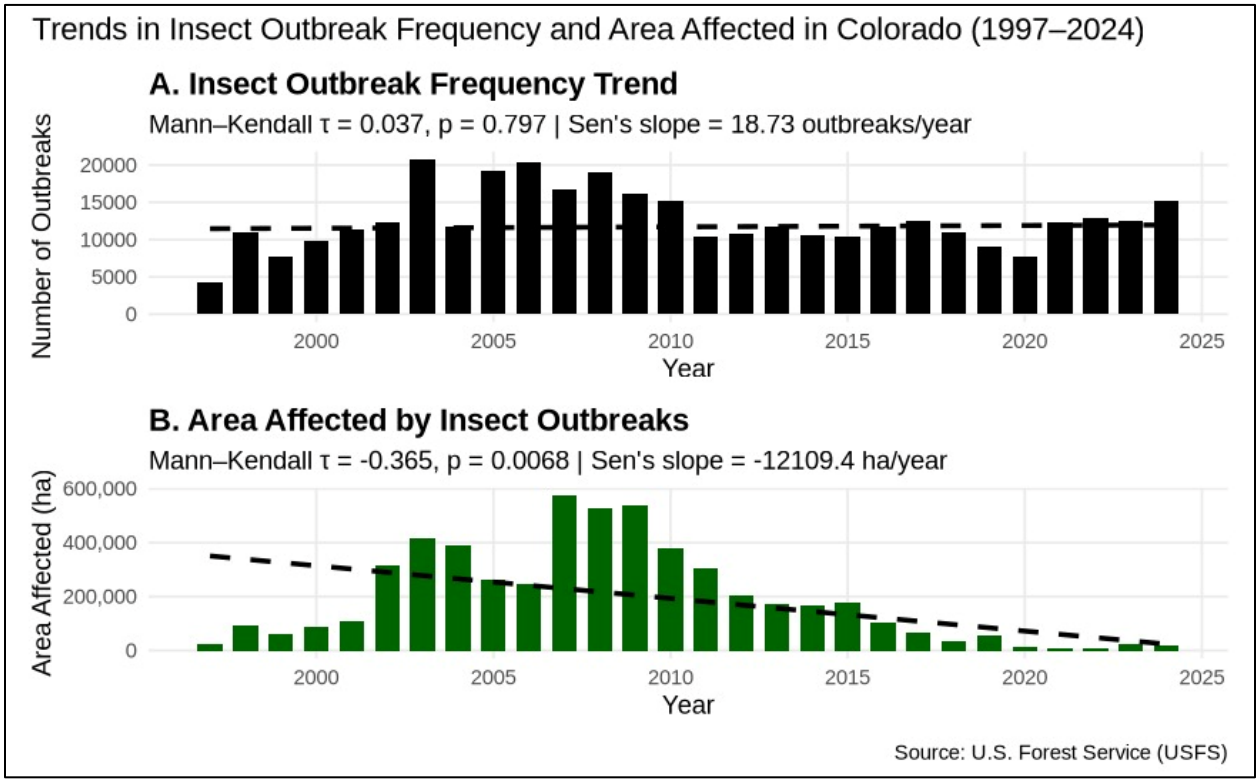


Fig. 9. Annual insect outbreak

Outbreaks differentially affected host tree species over this period. Lodgepole pine had the highest proportion of affected forest area at approximately 24.6%, followed by subalpine fir at 20.5%, Engelmann spruce at 14.4%, Douglas-fir at 10.7%, and quaking aspen at 10.6%. Ponderosa pine and common or two-needle pinyon were affected across approximately 6.8% and 6.6% of their forest areas, respectively, while most remaining species experienced impacts across less than 2% of their total forest extent (Fig. 10).

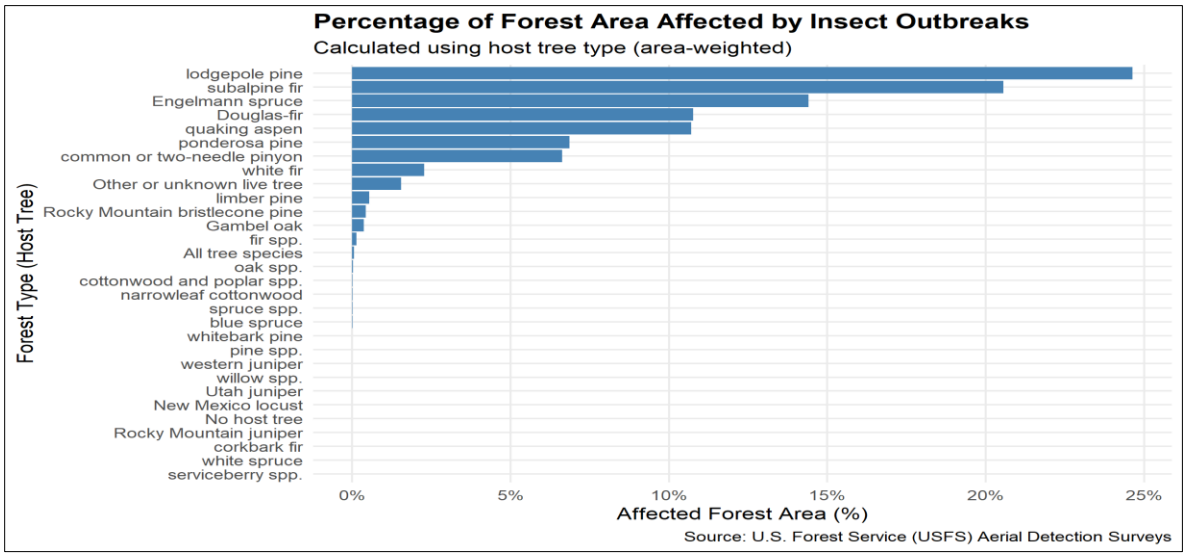


Fig. 10. Forest types affected by outbreaks

Forest insect outbreaks were dominated by a small number of key insect agents (Fig. 11). Mountain pine beetle was the most extensive, accounting for 23% of all recorded outbreaks, followed by the subalpine fir mortality complex at 17%, western spruce budworm at 14%, spruce beetle at 11%, Douglas-fir beetle at 10%, and western balsam bark beetle at 7%. The remaining insect agents each accounted for less than 5% of the total outbreak area.

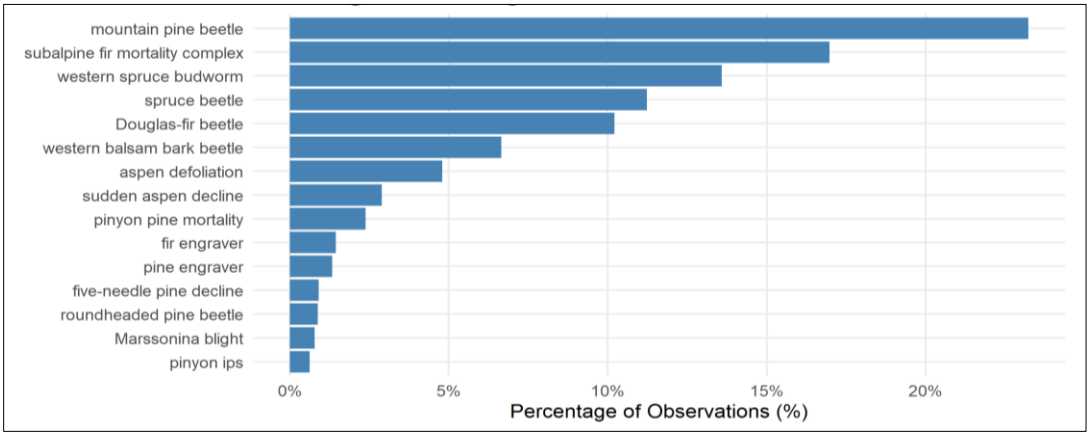


Fig. 11. Dominant biotic disturbance agents.

3.3. Fuel treatment (1997-2025)

A total of 500,900 hectares of forest were treated between 1997 and 2025, with higher rates of treatment in recent years (Fig. 12 and Fig. 13) and a significant increase in fuel treatment activity over this period (Fig. 14), with a mean increase of about 47 treatments (Mann–Kendall $\tau = 0.70$, $p < 0.001$) and 1,171 ha per year ($\tau = 0.494$, $p = 0.001$). (Fig. 15)

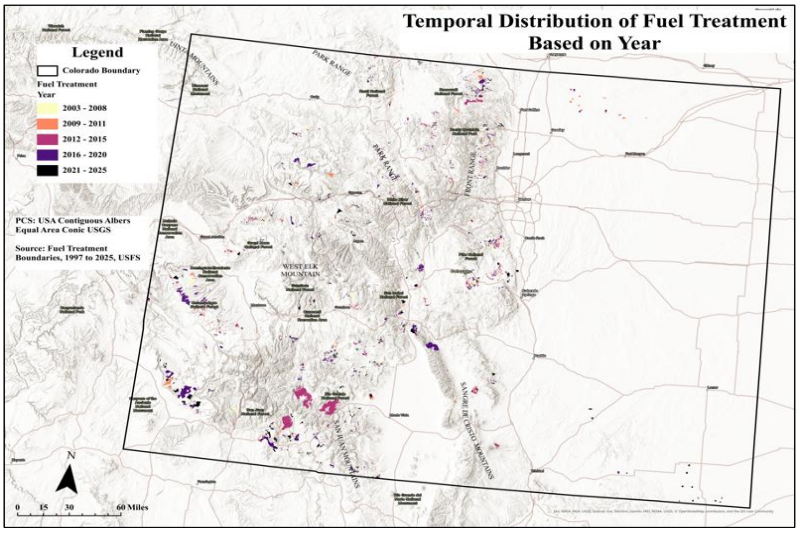


Fig. 12. Distribution of Fuel Treatment as per decade

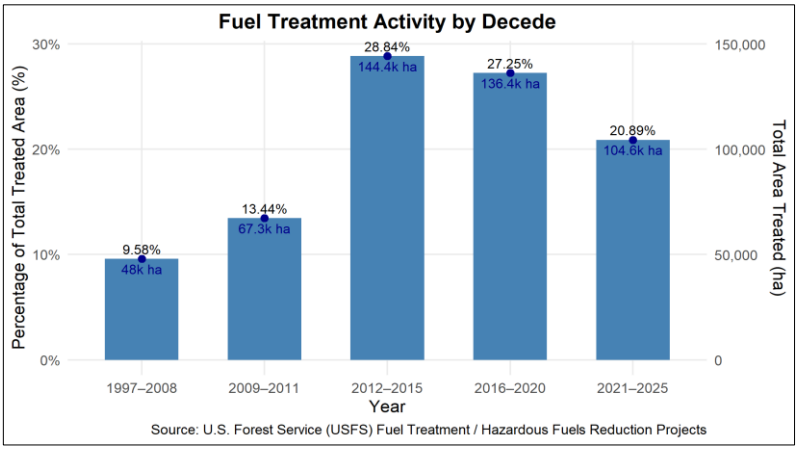


Fig. 13. Fuel Treatment with Area coverage as per decade

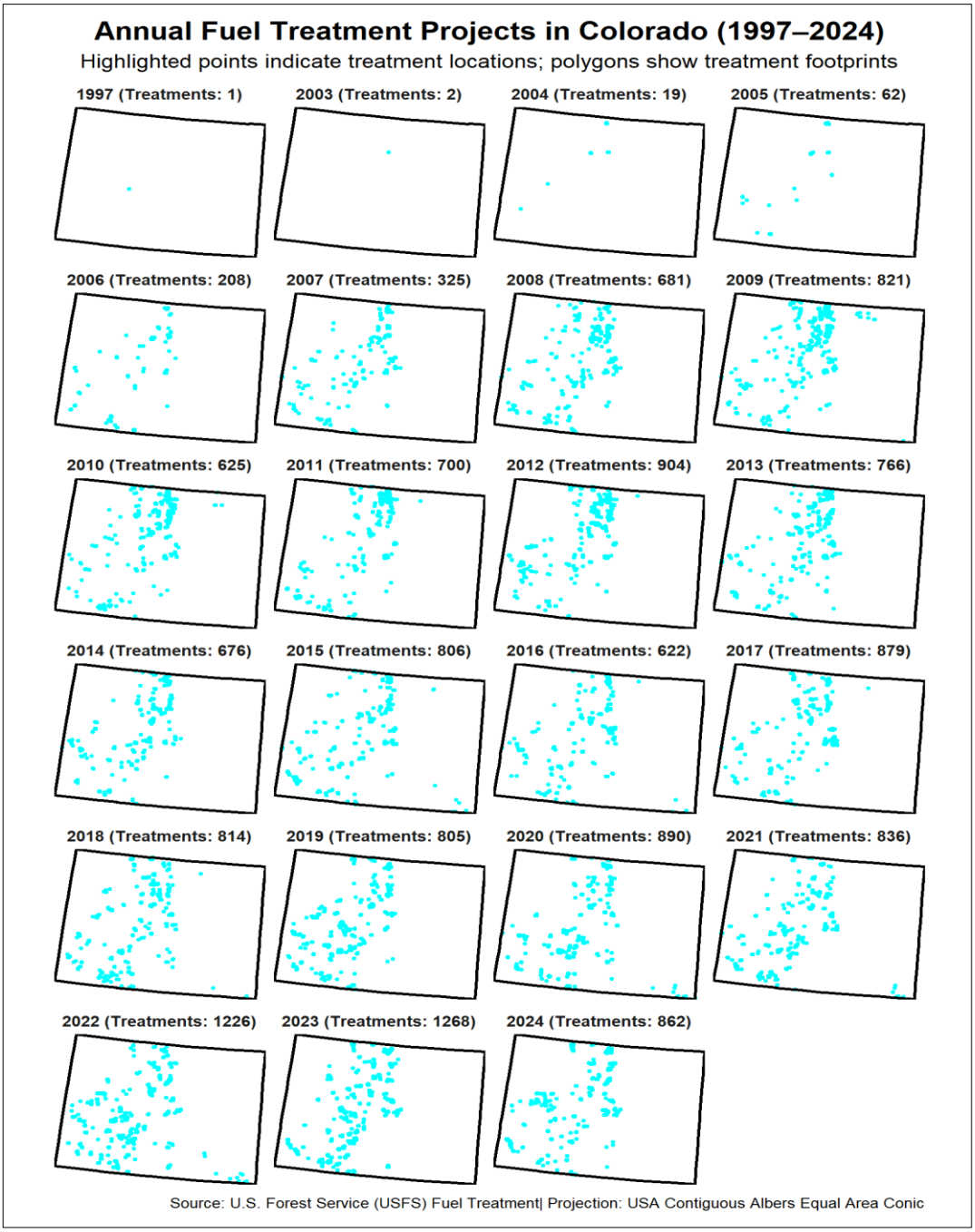


Fig. 14. Fuel treatment by year.

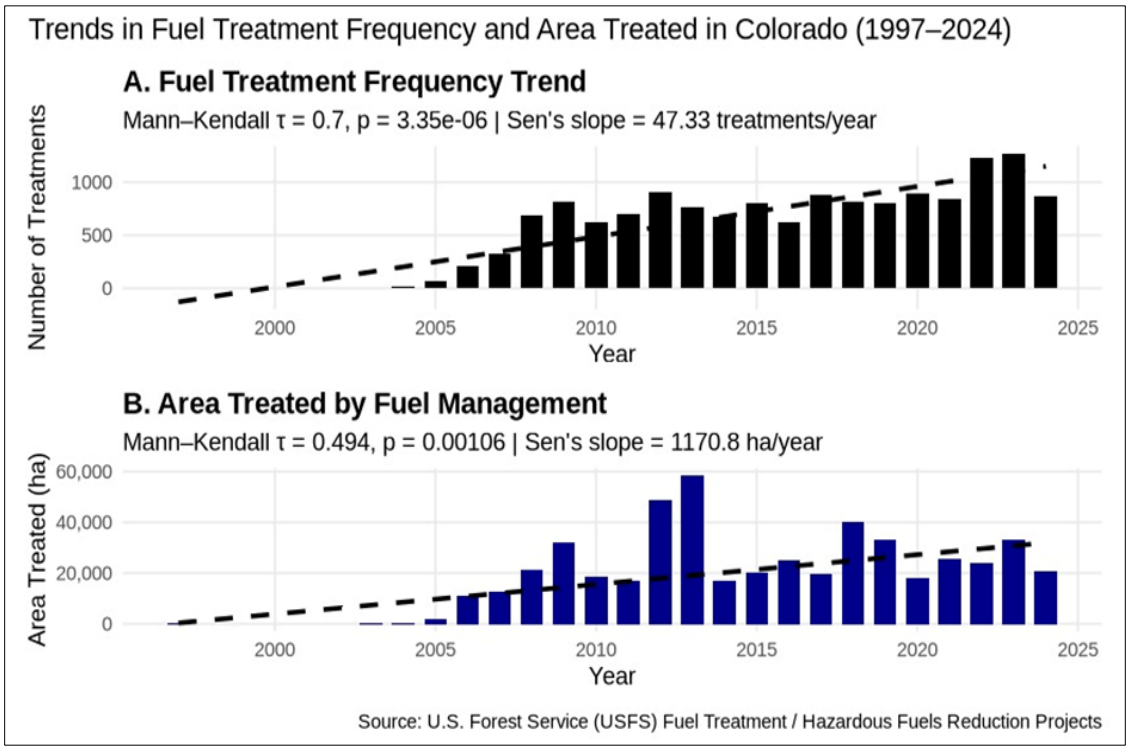


Fig. 15. Fuel Treatment trend as per count and area treated

Fuel treatments involved various approaches, the most common of which were tractor logging, mechanical, and manual methods, with treated areas of about 87.1 thousand ha, 84.9 thousand ha, and 75.1 thousand ha, respectively (Fig. 16).

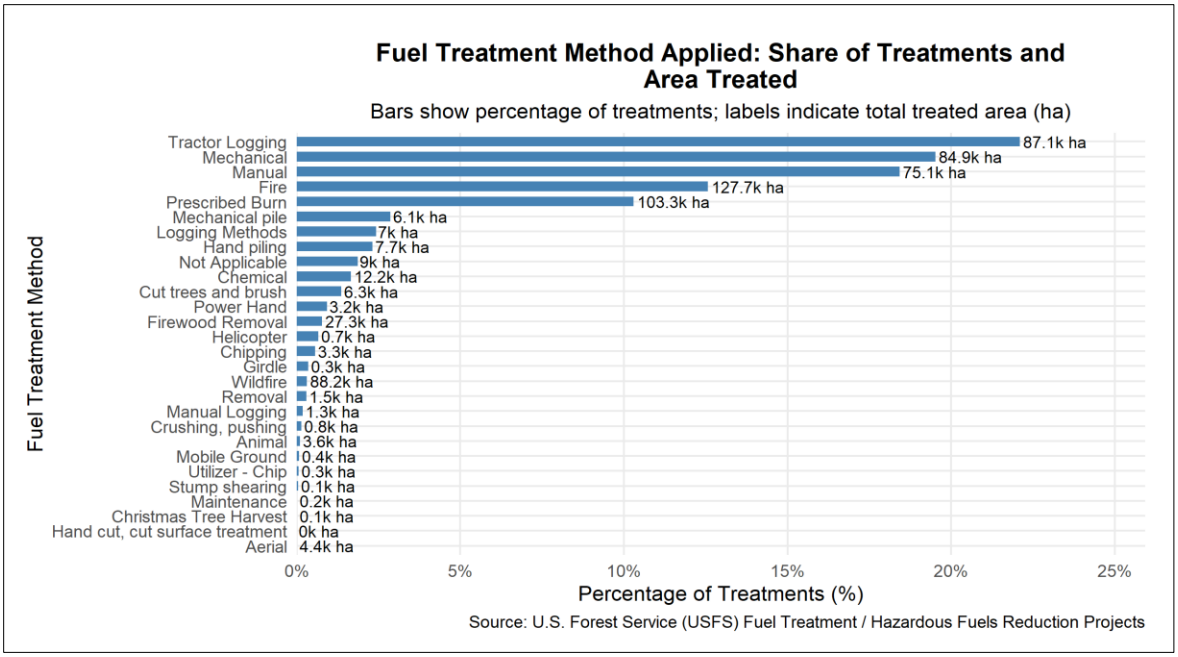


Fig. 16. Fuel treatment approach

3.4. Determinants of fire severity

The RF model used for wildfire ensured an overall accuracy of 71.7%, which is higher than the no-information rate (69.9%), indicating moderate model reliability. Model performance varies by class. Class 1 (low severity fire) dominates the dataset (prevalence = 69.9%) and is predicted well, with high sensitivity (0.88) and a rate of 0.62, Class 2 (moderate severity) displays moderate performance, while Class 3(high severity) is poorly detected, with very low sensitivity of 0.13 and a rate near to 0.005, signifying difficulty in detecting rare or extreme environments. Topographic and climatic variables are the main drivers of fire severity. Elevation is the most prominent predictor, contributing about 24% of total importance, followed by minimum temperature (13.8%), maximum temperature (13.5%), wind speed (13.5%), and precipitation (12.1%) (Fig. 17). Collectively, these climate and terrain variables explain the majority of variance, emphasizing the robust control of environmental gradients on wildfire severity. In contrast, pre-fire disturbance and

management variables, including fuel treatment and insect outbreaks, contribute comparatively little (generally <5% each), suggesting that their effects are either secondary or spatially heterogeneous at this spatial scale.

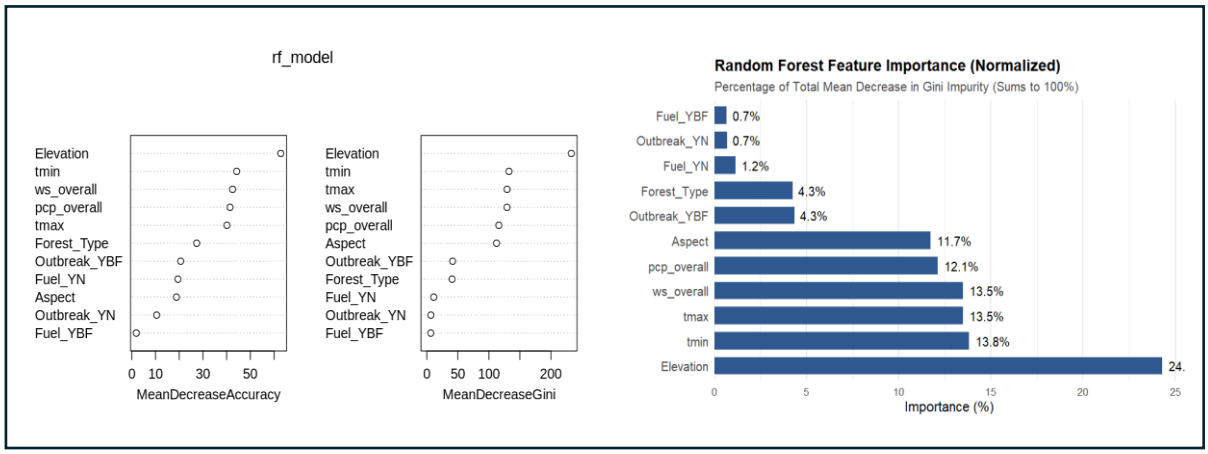


Fig. 17. Feature Importance of RF modeling

3.5. Effects of fuel treatments

Areas in which fuels were treated displayed a slightly lower mean fire severity compared to untreated areas, indicating that treatments are effective in reducing overall fire severity (Fig. 18). On the contrary, areas experiencing outbreaks are characterized by a higher mean fire severity compared to non-outbreak areas. Together, these results support that fuel treatments lessen fire severity, whereas insect outbreaks increase fire severity, highlighting their contrasting roles in shaping wildfire outcomes.

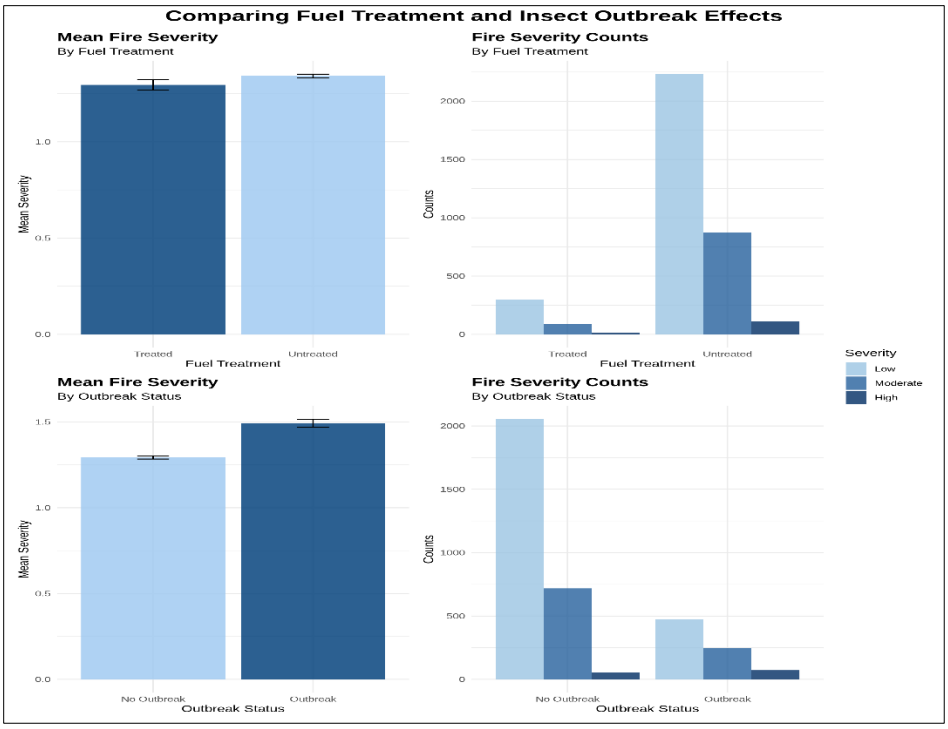


Fig. 18. Fuel treatment and insect outbreaks on fire severity assessment

To examine whether the overall effects are confounded by forest type composition, the analysis was stratified across the three dominant forest types: Ponderosa & Dry Pines, Spruce-Fir (Subalpine), and Lodgepole Pine (Fig. 19). For fuel treatments, the results suggest partial confounding; treated points are disproportionately concentrated in Ponderosa & Dry Pines, which naturally burn at lower severity. However, within Lodgepole Pine, the treated areas still show less severe damage on average than the untreated areas. Lodgepole Pine, the species most vulnerable to bark beetle infestations, consistently exhibits the most severe impacts during insect outbreaks. Specifically, fuel treatments reduce fire severity, while insect outbreaks increase it.

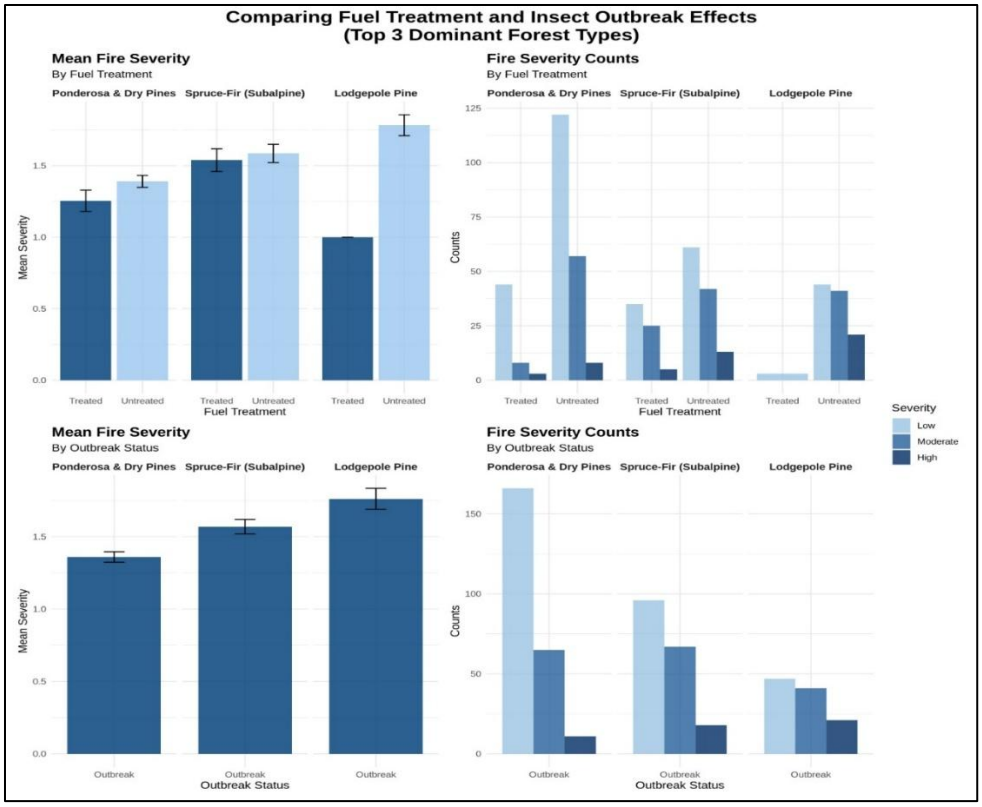


Fig. 19. Comparing fuel treatment and insect outbreak effect among dominant forest types

The ordinal regression model revealed fuel treatments and insect outbreaks have a significant interaction with fire severity, but in opposite directions (Fig. 20). Fuel treatment has a negative effect on fire severity with a coefficient of -0.6733 and $p < 0.001$, indicating fire severity is reduced with treatment. Insect outbreaks have a strong positive effect on severity (outbreak coefficient: 12.8282, $p < 0.001$), indicating increased severity with outbreak occurrence. Fuel × Outbreak interaction is positive and significant (coefficient = 0.2434, $p = 1\times10^{-4}$), indicating that the severity-reducing effect of fuel treatment is partially weakened in outbreak-affected areas. Interaction plots demonstrated that untreated areas with outbreaks had substantially higher mean severity than treated areas with outbreaks, and the severity difference between outbreak and no-outbreak conditions was greater in untreated forests compared to treated forests.

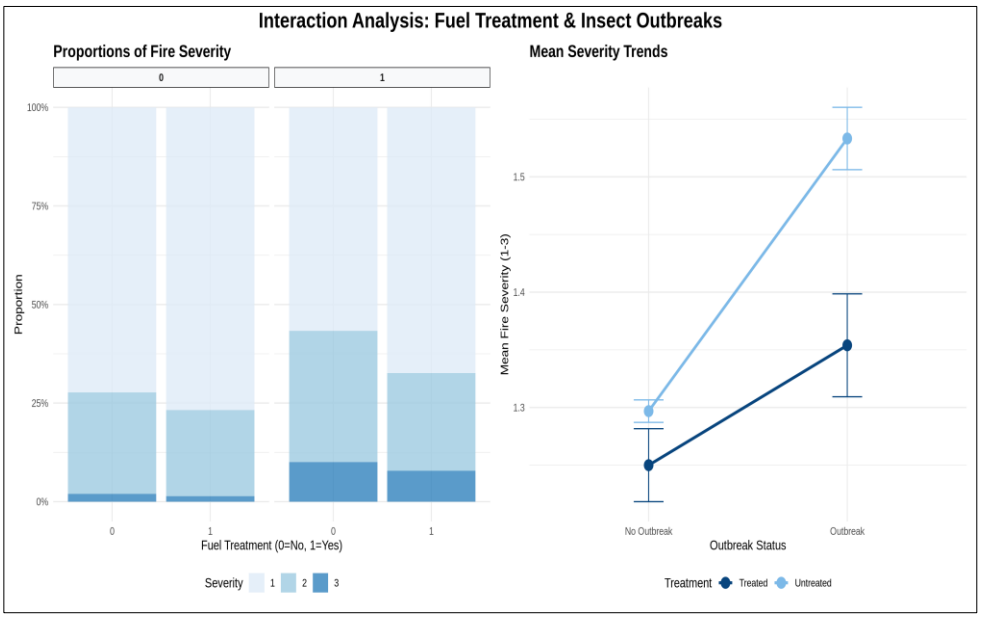


Fig. 20. Interaction between fuel, fire, and insects

3.5.1. Mean fire severity in different forest types

Fire severity distribution varied noticeably by forest type (Fig. 21). Lodgepole Pine showed the highest proportion of high severity fires (356,777 ha), representing approximately 40% of the total Lodgepole pine area, with 491,202 ha classified as low severity and 179,778 ha as moderate severity. Aspen & deciduous forests mainly burned at low severity (91,716 ha low, 30,663 ha moderate, 7,575 ha high). Ponderosa & dry pines burned with mixed severities with 693,437 ha low severity, 204,523 ha moderate, and 127,582 ha high. Douglas-fir also burned at low severities with 210,146 ha low, 163,978 ha moderate, and 108,575 ha high severity. Spruce-Fir recorded 345,144 ha low, 418,284 ha moderate, and 84,344 ha high severity.

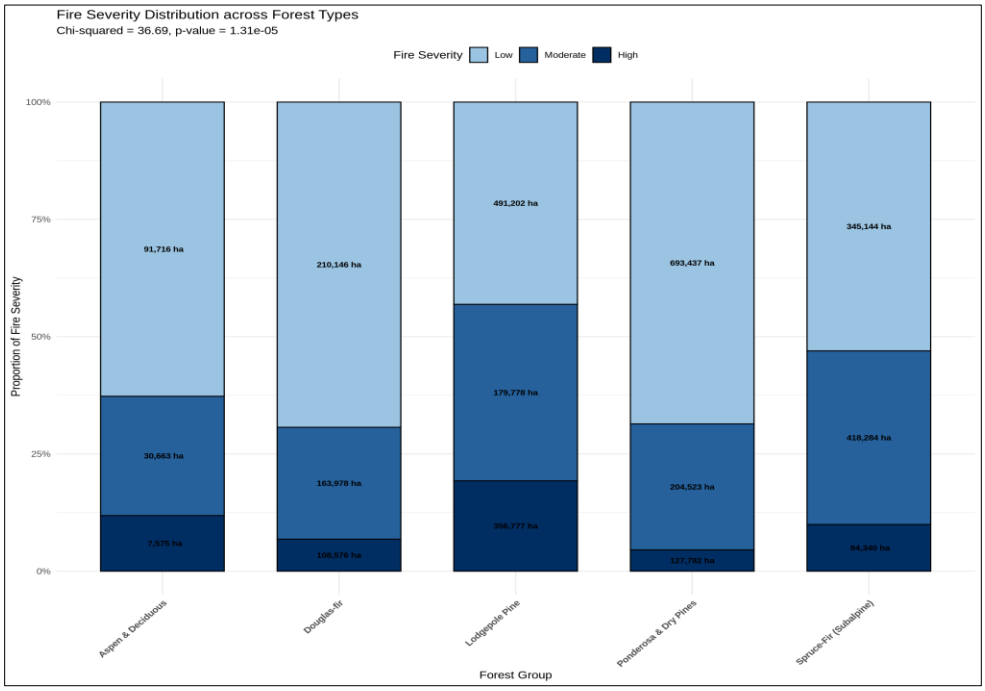


Fig. 21. Interaction between fuel, fire, and insect

3.5.2. Treatment effectiveness across outbreak scenarios

Forest types are grouped into five types for further analysis. The three-way interaction between forest groups, fuel treatment, and insect outbreak status is significant (global $p < 2.2e\text{-}16$) and controls fire severity patterns (Fig. 22). Forest types treated areas consistently showed lower fire severity proportions than untreated areas within the same outbreak type. Following outbreaks (0–10 years), Lodgepole Pine and spruce–fir recorded the highest proportions of moderate and high severity fires (Fig. 23). Treatment effectiveness in reducing outbreak severity was maintained across outbreak scenarios, though outbreak presence elevated fire severity in both treated and untreated sites relative to no-outbreak conditions.

In the absence of recent outbreaks, treated forests were dominated by low-severity fire (≈75–90%), with high-severity fire generally below 5–10% across most forest groups. Untreated forests show

a reduced proportion of low severity (≈60–75%) and a higher proportion of moderate to high severity fire (≈20–35%), particularly in lodgepole pine and spruce–fir forests (Fig. 22).

In outbreak-affected, untreated areas, the proportion of high-severity fire increases to roughly 20–30%, with low-severity fire reducing to about 40–55%, especially in Douglas-fir, lodgepole pine, and spruce–fir forests. Fuel-treated areas with outbreak conditions still maintain a higher portion of low-severity fire (≈55–70%), but high-severity fire remains elevated (≈10–20%), indicating reduced treatment effectiveness (Fig. 23).

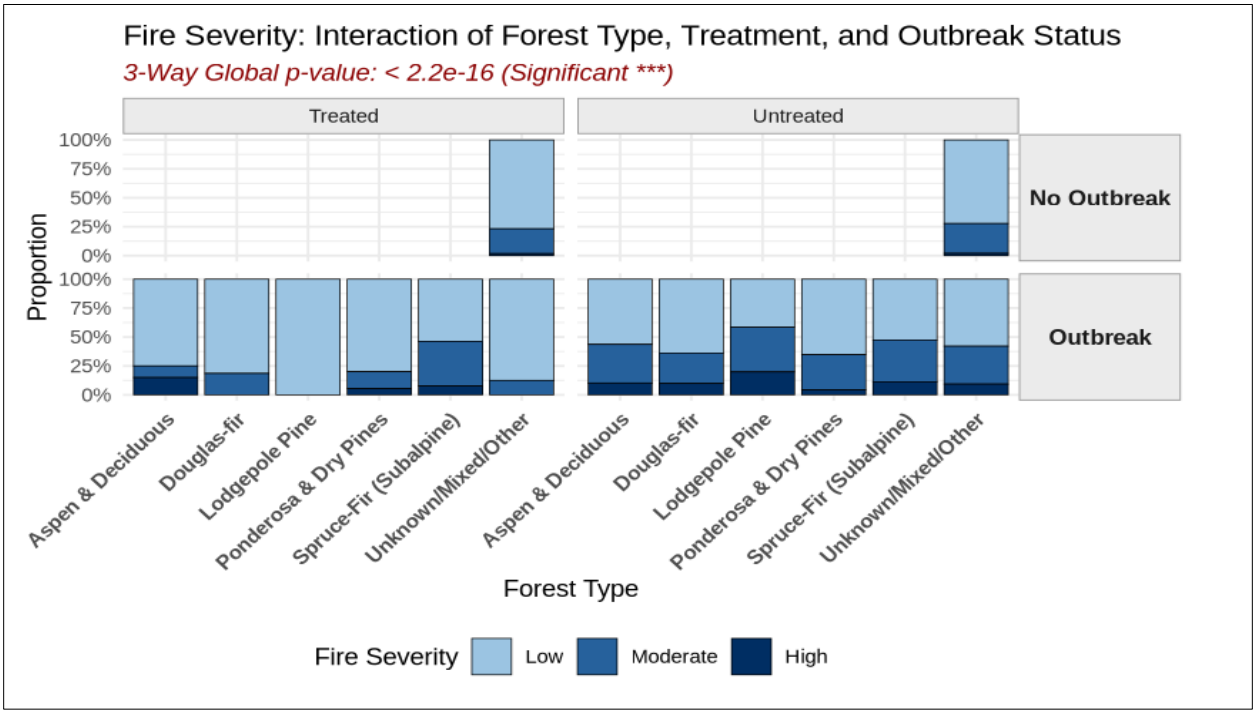


Fig. 22. Assessing of fuel treatment effectiveness

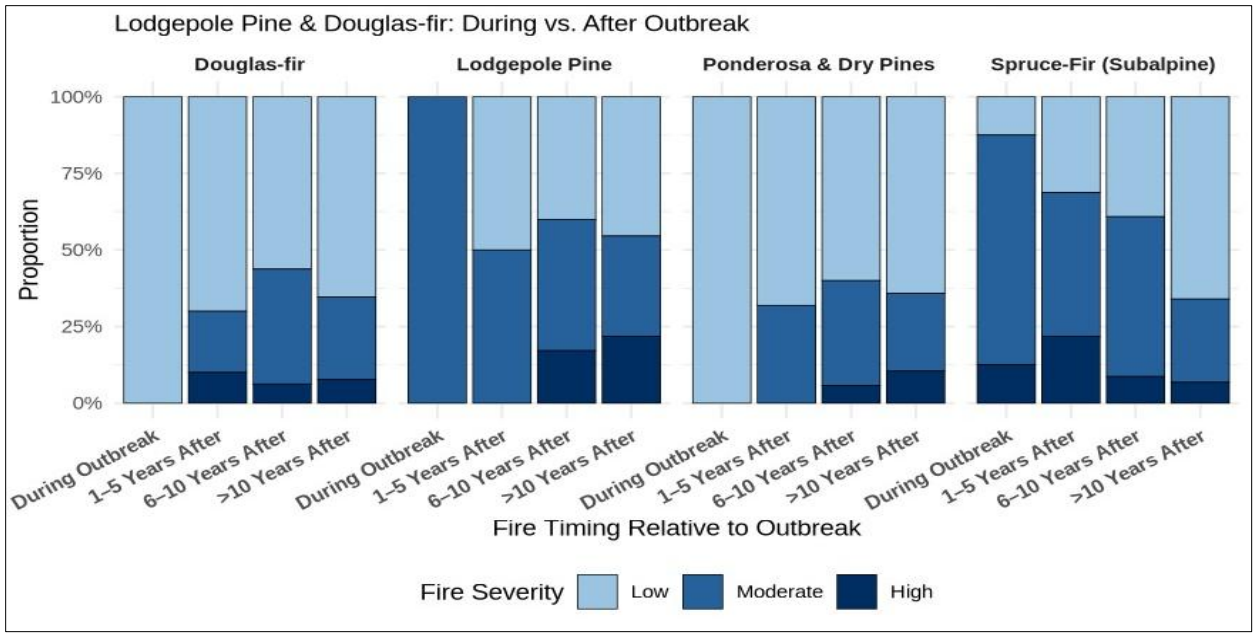


Fig. 23. Fire timing relative to outbreak

3.6. Temporal Analysis: Treatment Age Effect on Fire Severity

3.6.1. Mean fire severity analysis in treated forest under insect outbreak status

Within outbreak-affected forests, previously treated areas exhibited a lower mean fire severity (1.35; n = 8) compared to untreated areas (1.55; n = 497). This analysis was based on the locations where insect outbreaks occurred before fire (Outbreak_YBF ≥ 0) and where fuel treatments were implemented earlier than the outbreak (Fuel_YBF ≥ Outbreak_YBF), ensuring the temporal sequence of fuel treatment → insect outbreak → wildfire. Because the variables represent "years before fire," larger values indicate events further back in time. Although the treated sample size is small, the observed difference indicates lower mean fire severity in treated locations under outbreak conditions (Fig. 24).

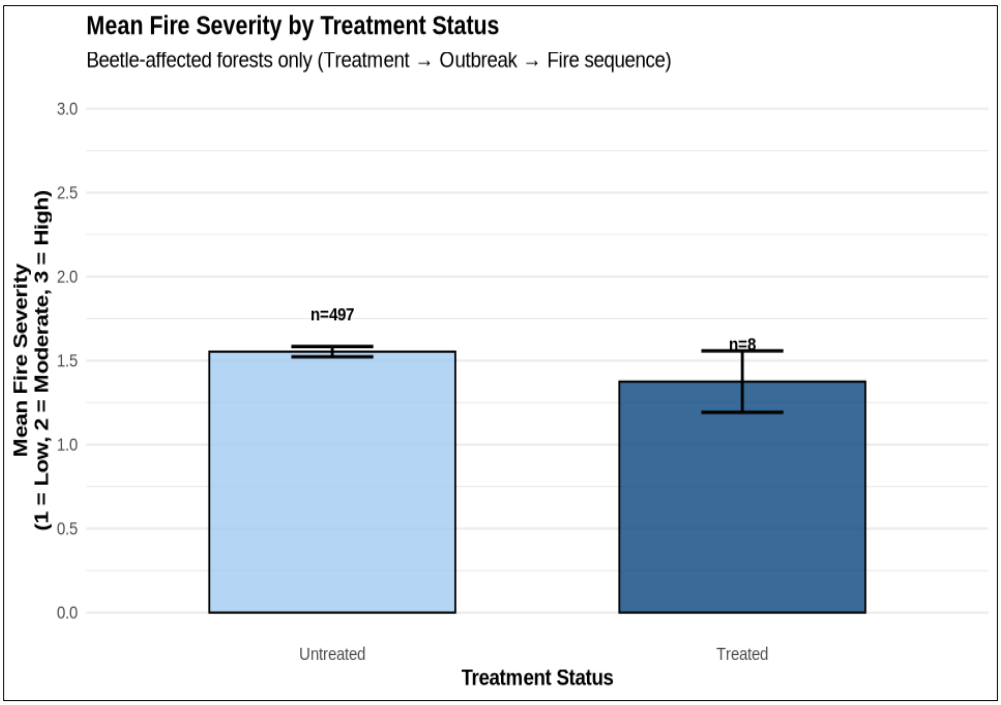


Fig. 24. Mean fire severity in the insect-affected treated forest

3.6.2. Treatment effectiveness with age

Fuel treatments reduce fire severity in the years immediately following treatment (filters for all treated areas where treatment occurred before fire, regardless of outbreak status), with mean fire severity remaining low to moderate (≈1.3–1.4) during the first 0–3 years post-treatment was supported by a large sample size, n = 261. Fire severity reaches the lowest levels around 4–9 years after treatment, with a mean ≈1.0, signifying a period of maximum treatment effectiveness, although estimates are based on very small sample sizes, which is $n \leq 4$. Beyond 10 years, mean fire severity rises (≈2.0 at 10–12 years; n = 1), directing a decline in treatment effectiveness over time, followed by partial reduction at 13+ years (≈1.1; n = 9) (Fig. 25).

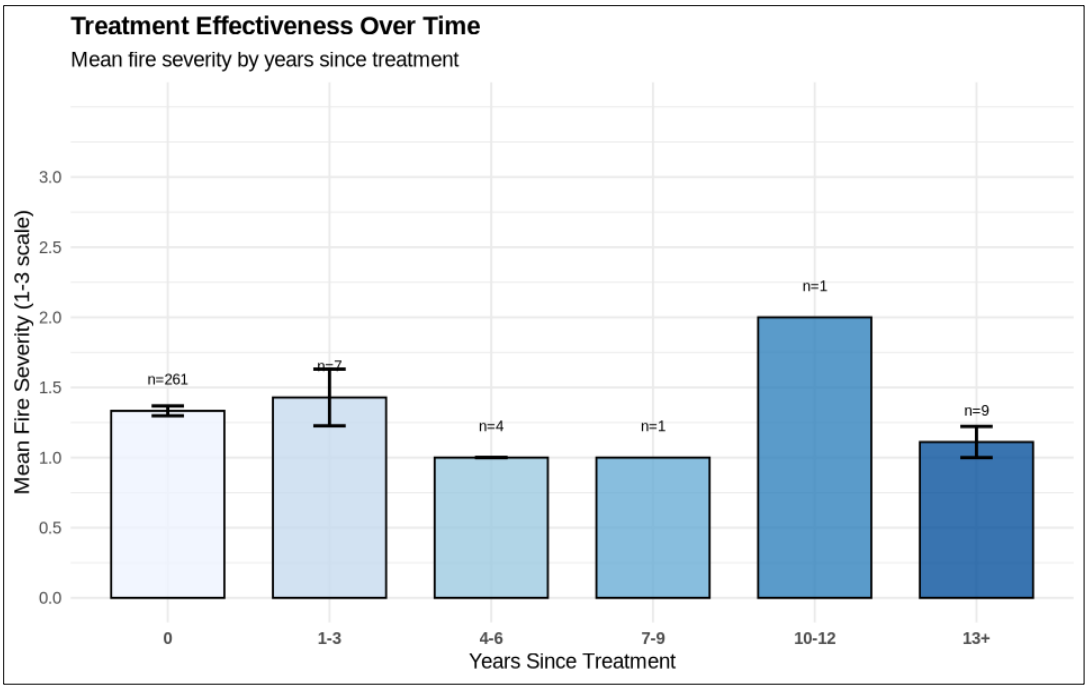


Fig. 25. Treatment effectiveness over time

3.6.3. Treatment effectiveness with age and outbreak

Fuel treatment effectiveness changes over time and is influenced by insect outbreaks (Fig. 26). Datasets were filtered for all treated areas where treatment occurred before fire (treated areas, Fuel_YBF ≥ 0) additionally splits each treatment age bin by outbreak presence (Outbreak_YN == 1 vs. 0). In the absence of outbreaks, mean fire severity remains relatively low within 1.2–1.4 during the first 0–3 years after treatment, but increases in older treatment ages, peaking around 10–12 years (≈2.0), indicating dropping effectiveness over time. When insect outbreaks are present, fire severity is generally higher in the early post-treatment period (1–3 years), indicating that outbreaks reduce the short-term benefits of treatment. Severity converges at lower levels around 4–9 years, before increasing again in older treatments (13+ years). Overall, the fuel

treatments are most effective within the first decade, but their severity-reducing benefits are weakened and shortened when insect outbreaks occur.

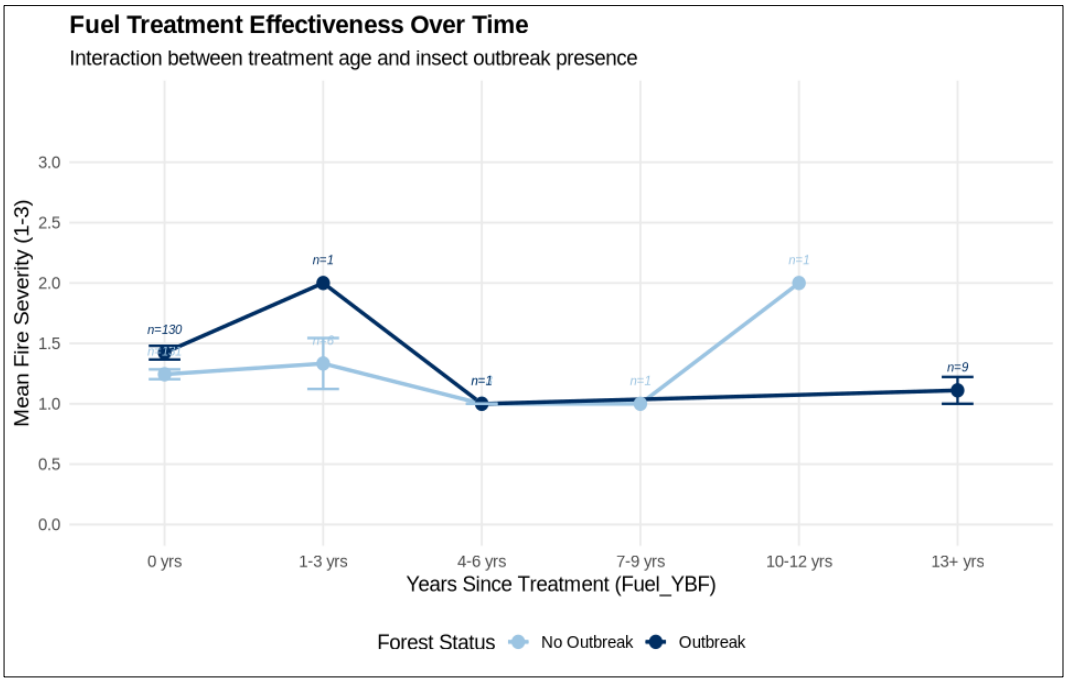


Fig. 26. Treatment effectiveness over time with subsequent outbreaks

4. Discussion

4.1. Wildfire Trends in Colorado

Large wildfires and annual area burnt by wildfires in Colorado have increased since 2000, with fires burning at higher elevations and at higher intensity (Bolinger *et al.* 2023). This is part of a larger trend as over the past decades, wildfires in the western United States have increased in annual area burned, the number of extremely large fires (over 10,000 acres), the extent of the fire season, and the percentage of high-severity burned land (Dennison *et al.* 2014; Parks *et al.* 2023). Between the 1984 - 2000 and 2001 - 2017, the annual wildfire-burned area in forested regions of Colorado and neighboring parts of New Mexico and Wyoming increased by over 300% (Bolinger

et al. 2023). This study found that most fires burned areas smaller than 3,648 hectares. Historically, in Colorado, higher-severity fire patches were more extensive, with a geometric mean of 170.9 hectares and a maximum patch size of 8,331 hectares (Williams and Baker 2012)**.** In recent years, the behavior of wildfires in the western U.S. were mainly influenced by weather and climate, such as drought, low precipitation, high temperatures and several non-climatic factors, like the legacies of historical forest and land management, changes in fuel loads and increasing human activity and development infrastructures within fire-dependent forest, shrublands, and grasslands leads to more ignitions year-round (Littell *et al.* 2009; Bolinger *et al.* 2023).

4.2. Insect Outbreak Dynamics

Insect outbreaks are a key driver that shapes forest landscapes worldwide, including the diverse forest types of the western United States (Canelles *et al.* 2021). Colorado's forests are significantly affected by MPB, spruce beetles, Douglas-fir beetles, etc. (Romme *et al.* 2009), including extensive outbreaks between 2003 and 2009, dominated by MPB but involving multi-agent outbreaks, large high-mortality patches were found in northern, central, and southwestern high-elevation forests. In north-central Colorado, MPB caused nearly 22% cumulative tree mortality (almost 228 million lodgepole pines) from 1996 to 2011, with rapid spread and stand-scale mortality averaging 60% where attacked (Audley *et al.* 2020). Across the subalpine forests of the Southern Rockies, 39.5% of forest area was affected by bark beetles between 1997 and 2019; low–moderate mortality was widespread, while the highest mortality was concentrated in northern and southwestern Colorado and southern Wyoming, with spruce beetles affecting largely the spruce–fir forests of southern and southwestern Colorado (Rodman *et al.* 2021).

4.3. Distribution of Fuel Treatment

Most fuel treatments in Colorado are clustered in central and southern forested areas (Colorado State Forest Service 2020; Mueller and Caggiano 2022) and have expanded over the course of this study, in response to policies and strategies to mitigate wildfire risk. Fuel treatments can be categorized into two groups: canopy treatments (patch, mechanical thin, broadcast burn, hand thin, etc.) and surface treatments (machine pile, biomass removal, pile burn, mastication, etc.) (Mueller and Caggiano 2022; Brodie *et al.* 2024). In Colorado's Front Range, fuel reduction typically combines mechanical thinning and prescribed fire to reduce surface fuels, raise crown base height, and lower crown density, and prescribed fires reduce litter, duff, and rotten coarse woody debris (Ritter *et al.* 2023; Agee and Skinner 2005). Contributing to the increase between 2000 and 2020, the most common treatments were surface only, mechanical thin, canopy only, broadcast burn, and pile burn (Mueller and Caggiano 2022). This study detected untreated areas having a higher mean severity than treated areas. Similarly, another study showed that forest fuel treatments reduced surface fuels and decreased subsequent wildfire severity between 62% and 72% compared to untreated areas (Davis *et al.* 2024).

4.4. Interactions among Wildfire, Insect Outbreak, and Fuel Treatment

Insect outbreaks substantially change fuel load or modify forest conditions, affecting subsequent fire regimes (Crotteau *et al.* 2018). Conversely, fire may dampen bark beetle outbreaks through the reduction of host trees and alteration of stand structures, although it may sometimes create short-term susceptibility in fire-injured trees (Six *et al.* 2014). However, fuel treatment such as prescribed fire can lower overstory mortality during outbreak (Birch *et al.* 2023). The efficacy of treatments decreases with time, with more than a twofold drop in the average reduction in wildfire severity across various treatment types while a wildfire occurred more than 10 years post-initial treatment (Davis *et al.* 2024). However, fuel treatments can increase forests' resistance to insect

outbreaks, for instance, thinning enhances resistance to the mountain pine beetle during outbreaks, while reintroducing fire enhances longer-term resilience (Hood *et al.* 2016). Fire severity after an outbreak may depend on time, outbreak phases, and extreme fire weather conditions (Hicke *et al.* 2006). Higher fire severity is often associated with the red phase when dead needles are still in the canopy, while the gray phase can show mixed effects as canopy fuels fall off and often increase the surface fire potential (Sieg *et al.* 2017). Moreover, controlled or prescribed fire can lower the mortality rate caused by insects while rendering the stand more resilient to fire incidents (Birch *et al.* 2023). The effectiveness of fuel treatment can be shown even during extreme fire events, particularly if treatments are recent, though their benefits tend to decrease (Lydersen *et al.* 2017; Collins *et al.* 2023). Insect outbreaks after fuel treatment may influence treatment performance, but do not diminish its overall effectiveness (Hood *et al.* 2016; Crotteau *et al.* 2018). In recent scenarios, extensive demise of older trees due to factors like wildfire, bark beetles, and drought has sparked the substantial importance of restoration and forest management for minimizing imminent fire risk (Addington *et al.* 2018; McKinney 2019). Instead of intending to eliminate fires or insect outbreaks, effective reforestation and fuel management should be incorporated to maintain landscape diversity and limit large-scale salvage activities (Kulakowski *et al.* 2020).

5. Limitations

First, 10 random points per fire polygon can enhance spatial balance, but there may be an underrepresented area for a large fire incident. Secondly, climate variables were at 4km resolution while MTBS and SRTM were assessed at 30 m resolution. This mismatch in scale can hinder the ability to detect fine-scale relationships. The data set for wildfire is from 1984, while the insect outbreak and fuel treatment are from 1997, which can limit the temporal comparison among variables. In addition, fuel treatment polygons were smaller compared to those for wildfire and

insect outbreaks, which led to bias in the statistical analysis and model development (Random Forest) by underrepresenting treatment effects and increasing uncertainty in treated classes. For model development, some of the key drivers for ignition sources, canopy status, drought indices, road proximity, and human interference are not incorporated, which may be taken into consideration in further studies. The outbreak polygons derived from aerial surveys could represent damage that was seen, rather than actual changes in mortality or biomass. There is a limitation to generalization and reproducibility because this study focused solely on Colorado's climatic gradients, forest types, and management patterns; so, this conclusion may not apply to other areas with different fuel conditions, management styles, or even insect-fire interactions.

6. Conclusion

Wildfires and insect outbreaks are natural processes that shape forest dynamics; however, when compounded with anthropogenic factors and climate change, they can escalate into large-scale, high-severity disturbances. Between 1984 and 2024, both wildfire frequency and burned areas showed an overall increase, whereas insect outbreaks were most widespread in the early to mid-2000s, and fuel treatment efforts increased markedly after 2006. The machine learning model highlighted elevation and temperature as important features associated with wildfire severity. Fuel treatments reduced wildfire severity across Colorado forests, although their effectiveness varied according to forest type, treatment age, and insect outbreak conditions. Insect outbreaks worsened wildfire severity and partially reduced the benefits of fuel treatments across the period. The most significant effects were seen in lodgepole pine and spruce-fir forests, both during and after the outbreaks. Overall, fuel treatments remained beneficial across conditions, but their greatest effectiveness occurred within the first decade after treatment and declined over time, especially where subsequent insect outbreaks occurred. Although these results are limited by data and

sampling constraints, and compound disturbances are inherently difficult to fully capture with statistical modeling, this study nevertheless provides important evidence of the relationships among fuel treatments, insect outbreaks, and wildfire severity. This outcome underscores the need for adaptive fuel management in vulnerable forests to enhance forest resilience to diverse disturbances. However, an integrated strategy needs combining outbreak dynamics, forest composition, and the use of effective and timely fuel treatments for wildfire mitigation. This study highlights that fuel treatments in Colorado will be most effective when they are applied in a timely manner, adapted to changing disturbance conditions, and designed flexibly to maintain their effectiveness in the face of future wildfires and insect outbreaks.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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