MULTIDECADAL CHANGE IN ASPEN EXPERIENCING LONG-UNBURNED, MIXED-SEVERITY WILDFIRE, AND REBURN DISTURBANCE REGIMES

By

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ABSTRACT

MULTIDECADAL CHANGE IN ASPEN EXPERIENCING LONG-UNBURNED, MIXED-SEVERITY WILDFIRE, AND REBURN DISTURBANCE REGIMES

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Quaking aspen (*Populus tremuloides*) is a valued, minor component on western landscapes. It provides a wide range of ecosystem services, and has been in decline for the last century. This decline may be explained partially by the lack of fire on the landscape as aspen benefit from fire that eliminates conifer competition and stimulates reproduction through root suckering. Managers are interested in aspen restoration but have a lack of knowledge about their spatial dynamics in response to fire. Improving our understanding of aspen stand spatial changes over time may be important for maintaining their presence on landscapes where their role is unique from neighboring ecotypes. Our study area in northeastern California on the Lassen, Modoc and Plumas National Forests has experienced recent large mixed-severity wildfires where aspen was present, providing an opportunity to study the re-introduction of fire. We observed two time periods; a 54-year absence of fire from 1941 to 1993 preceding a 24-year period of wildfire activity from 1993 to 2017. We utilized historical (1941, 1993) and current (2017) aerial photos to delineate aspen stand size, location and succession to conifers. We chose aspen stands in areas where wildfires overlapped (twice burned), where only a single wildfire burned, or areas that did not burn within the recent 24-year period. We looked at these same stands within the first period of fire exclusion for comparison (i.e., 1941-1993). In the absence of fire, all aspen stand areas declined and all stands experienced increases in conifer composition. After wildfire, stands that burned experienced a release from conifer competition and increased in stand area. Stands that burned twice or at high severity experienced a larger removal of conifer competition than stands that burned once at low severity, promoting aspen recovery and expansion. Stands with less edge:area ratio also expanded more with fire present. Across both time periods, stand movement, where aspen stand footprints were mostly in new areas compared to footprints of previous years, was highest in smaller stands. In the fire exclusion period, smaller stands exhibited greater changes in area and location (movement), highlighting their vulnerability to loss in the absence of disturbances that provide adequate growing space for aspen over time.

ACKNOWLEDGEMENTS

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INTRODUCTION

From the mid-1800s, changing land-use patterns and active wildfire suppression throughout the western US has altered fire regimes (Sugihara et al. 2006, Stephens et al. 2007, Skinner et al. 2009, Van de Water and Safford 2011). Historically, wildfires maintained more open forest conditions (Agee 1993, Sugihara et al. 2006, Baker 2014). In the absence of wildfire disturbances over much of the 20^{th} Century, stand density has increased steadily (Collins et al. 2011). These conditions have promoted a shift in species composition towards more shade-tolerant species (Parsons and DeBenedetti 1979), and are not favorable for light-demanding pioneer species such as aspen (Perala 1979, DeByle and Winokur 1985, Shepperd et al. 2006). As aspen have declined 50-90% in the western United States (Bartos 2000). Absence of fire may be contributing to aspen decline, as fire is an important disturbance agent promoting persistence of aspen in many stands (Mueggler 1989, Skinner and Stephens 2004).

Quaking aspen (*Populus tremuloides*) is a valuable, although infrequently encountered, component on northeastern California landscapes that may be at risk of loss without disturbance (DeByle and Winokur 1985). Aspen ecosystem services range from biodiversity hotspots of plant and animal species, economic value, cultural significance and aesthetic appeal (Chong et al. 2001, Shinneman et al. 2013). The vegetation composition associated with aspen stands is richer than other ecotypes on a shared landscape (Chong et al. 2001). As this rich vegetation promotes higher volumes of insects, more bird species have been found in aspen stands than in neighboring conifer stands due this greater food source (Richardson and Heath 2004, Winternitz 1980). Bat species have also been found to select aspen cavities over conifer cavities due to cooler temperatures in aspen trees (Kalcounis and Brigham 1998). Additionally, aspen stands have been observed as small mammal hotspots within conifer dominated landscapes (Oaten and Larsen 2008).

Aspen regenerates primarily through root suckers and rarely through seed (Perala 1979). Because of this, once aspen is lost in an area, it is difficult for the species to become re-established. Other tree species that can grow in association with aspen, such as pines and firs that are long-lived and reproduce by seed more reliably than aspen, will most likely replace aspen (Bartos and Campbell 1998). In the Sierra Nevada mountains of California and Nevada, aspen functional types include either pure aspen stands that appear stable or seral aspen coexisting in mixture with conifers; these are vulnerable to replacement by conifers in the absence of disturbance (Rogers et al. 2013b). Disturbances such as timber harvesting and fire promote aspen regeneration (Krasnow et al. 2012). After introduced fire, aspen were observed to almost double their sucker counts from preburn conditions (Bartos and Mueggler 1981). After mixed-severity wildfires, aspen patches that burned at high severity exhibited the greatest density of aspen root suckering (Fraser and Leiffers 2004, Keyser et al. 2005, Wan et al. 2014). High densities of young aspen may be necessary to support herbivory when present, preventing potential loss of aspen from overgrazing new cohorts that are needed to eventually replace the older trees. High severity wildfire is also important for relieving pressures of competition. After trees are killed by high severity fire, aspen root suckers quickly re-occupy growing space liberated by the disturbance. In the absence of disturbance, increasing stand density and competition impact growth and vigor of aspen trees (Berrill and Dagley 2012). Under these conditions, aspen continue to produce root suckers, but rarely reach sapling sizes and are therefore unlikely to recruit to the overstory (Berrill and Dagley 2014).

Aspen responds well to compound disturbances, specifically when another disturbance precedes fire (Kulakowski et al. 2013). After fire, aspen regenerate rapidly, but other fire-adapted tree species, such as lodgepole pine (*Pinus contorta*), may also regenerate well. When disturbance events (e.g., insect outbreaks, disease and wind storms) precede wildfire activity, aspen produce even higher sprout counts than with fire alone, while lodgepole pine seed source declines and is not able to regenerate successfully (Kulakowski et al. 2013). While non-sprouting species may be killed and lose their seed source by multiple disturbances, we expect aspen to regenerate by root suckering in response to each disturbance and improve occupancy relative to competing conifers.

Positive regeneration responses to wildfire and to compound disturbances suggests aspen may benefit from frequent wildfire or managed fire events. Wildland fire use is a management tool where naturally ignited fires are allowed to burn in areas based on cultural or natural resource objectives. When wildland fire use was initiated in the Illilouette Creek Basin in Yosemite National Park in 1990, there were many areas that reburned, showing that overlap of managed fire is possible (Van Wagtendonk 2007). It was also shown that wildland fire use can result in burning that is very similar to historical fires (in terms of severity), even after a history of fire exclusion (Collins and

Stephens 2007). Managing wildfires may be the most effective method of promoting regeneration and vigor of declining, fire-adapted species such as aspen.

The Sierra Nevada mountain range and adjacent areas of northern California have experienced different extents, severities and overlapping of naturally occurring fires (Collins et al. 2009). However, within the same region, aspen has also experienced up to 24% loss in the South Warner Mountains within 50 years (Di Orio et al. 2005). Aspen are threatened by drought (Anderegg et al. 2013), climate change (Iverson and Prasad 1998), and succession to conifer (Berrill et al. 2017). There is a need for understanding how aspen populations have changed throughout time, especially their response to disturbance or lack thereof (Rogers et al. 2013a).There is a further gap in understanding the patterns of movement of aspen stand footprints on a landscape. As conifers proceed to replace aspen throughout the west (Bartos 2000), aspen may be forced to migrate to less favorable sites. Conversely, disturbances may let aspen re-occupy lost territory of favorable site quality.

To study long-term change within aspen stands, observations of historical conditions are required. A combination of current satellite imagery and historic aerial photos provided a time series of imagery that allowed us to observe change in tree species composition and extent of aspen stands. Landsat spatial data is a preferred satellite imagery source as it was designed to detect long-term patterns of change on Earth's landscapes (Goward et al. 2001). Landsat digital imagery can be used for tree species detection to an accuracy of 88.8% consistency of ground truth data (Walsh 1980). NAIP and Quickbird imagery can be used to delineate common forest cover types, such as aspen and juniper, but with a lower accuracy of 48% - 63% (Frescino and Moisen 2005). Landsat has been used for measuring temporal change in species composition and stand extent by using imagery from multiple dates with an accuracy of up to 87% (Helmer et al. 2000). Google Earth is a source of Landsat imagery that provides recent and past imagery over 25 years in some areas (Moore and Hansen 2011). When images that predate satellite imagery technology are needed, aerial photography may be available. Determination of species composition and single tree analysis has been accomplished through the use of aerial photos with an accuracy of 70-80% (Leckie 2003). Studies featuring long-term observations of aspen stand spatial dynamics are few and none have looked at the effect of overlapping wildfire. Our goal was to compare aspen stand area change, movement and succession to conifers among stands that have experienced different fire regimes and severities. Our 76-year study period started with a 52-year absence of fire to observe stand conditions without disturbance, followed by a 24-year period where wildfire activity was present with stands experiencing three different fire regimes:

A. frequent fire (2 overlapping fire footprints within the last 24 years),

B. infrequent fire (1 fire within the last 24 years) and

C. fire exclusion (absence of fire within the last 76 years).

We hypothesized that spatial dynamics (expansion/contraction of stand area and movement of stand boundaries) were driven by wildfire activity. Specifically, we expected: 1) stand area to recede and move in the absence of fire, 2) associated increases in conifer dominance in the absence of fire, and 3) greater stand expansion in the presence of frequent wildfires than a single wildfire event. The objective of our study was to gain knowledge of potential causes of aspen decline and expansion to inform land managers who want to increase aspen area on the landscape. We explored these questions by modeling the relationships between:

1. Proportional area change and fire frequency, fire severity, site type, National Forest, stand area, stand edge:area ratio and conifer composition.
2. Stand movement and fire frequency, fire severity, site type, National Forest, stand area, stand edge:area ratio and conifer composition.
3. Conifer composition change and fire frequency, site type, National Forest, stand area and stand edge:area ratio.

METHODS

Project Area

The study sites are located on US Forest Service lands in northeastern California on the Lassen, Modoc and Plumas National Forests (Figure 1). Aspen stands were selected for analysis within large fire footprints on each forest: the 2000 Storrie fire (Lassen NF), the 2001 Blue complex (Modoc NF) and the 2007 Moonlight fire and Antelope complex (Plumas NF). Within each main fire footprint were areas where other fires had burned within the 24-year study period and aspen was present. The 2012 Chips fire reburned areas within the Storrie fire footprint, the 1994 Corporation fire footprint was partly reburned by the Blue complex footprint, and the 2001 Stream fire footprint was partly reburned by the Moonlight fire and the Antelope complex.

Aspen stands within the overlapping fire footprints represent the ‘frequent fire’ condition where two fire disturbances were experienced within 24 years. Stands representing only one instance of ‘infrequent fire’ were selected within the main fire footprint only. A similar number of unburned stands were chosen from outside fire footprints but as close as possible to burned stands in an attempt to minimize site differences among burned and unburned aspen stands.

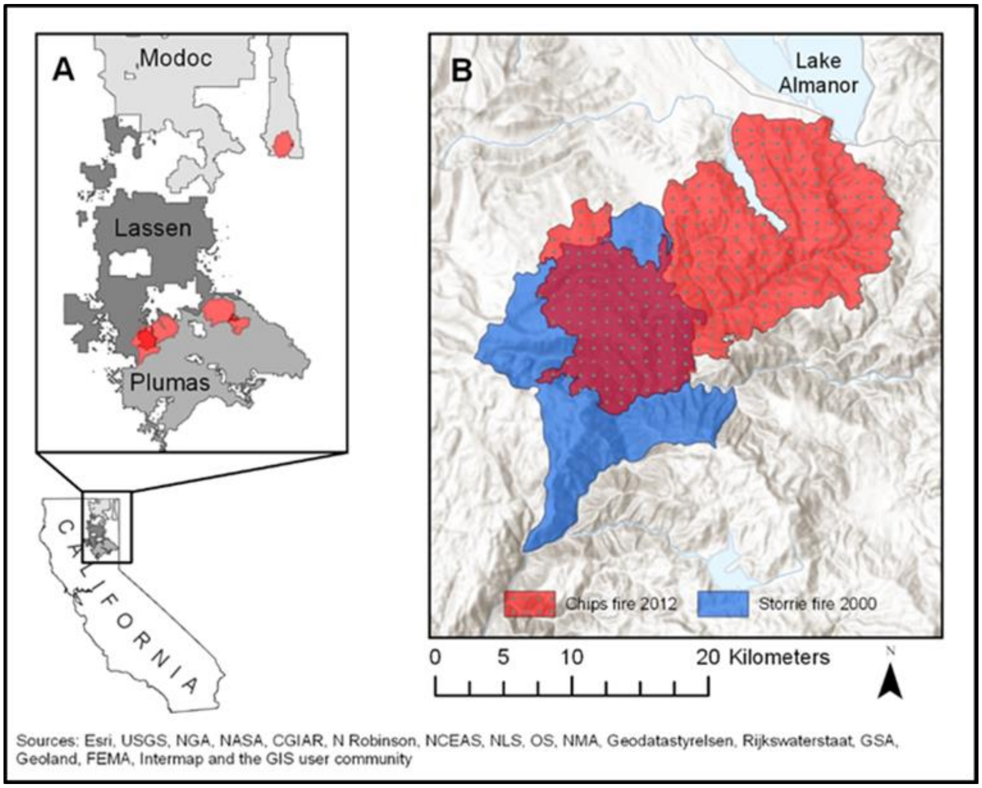

Figure 1. A) Location of study wildfires on three National Forests in northeastern California, and B) example area of wildfire overlap on the Lassen National Forest.

Aspen Stand Measurements

Aspen stand assessments from years 2014-2018 provided a field-derived GPS polygon of the stand and site description for the 33 sampled stands (Table 1). Mapped polygons of aspen from the stand assessments were overlaid on aerial images from past years as a guide to help identify and delineate aspen in each historical image. New polygons were created around aspen visible in each image. Polygons in recent years (1993-2017) were digitized on aerial images in Google Earth. Historic (1941) extent of aspen visible from aerial images was digitized on georeferenced aerial photos from that year. Aerial photos from 1941 on the Lassen and Plumas national forests were previously georeferenced by US Forest Service employees. Photos of the Modoc National Forest were scanned at 600dpi and georeferenced in ArcMap (ESRI 2011).

All polygons from each year were brought together on one map file in ArcMap for each of the three forests. Within the attribute table of each year, all polygons were assigned a stand number based on site type and proximity to other polygons (Figure 2).

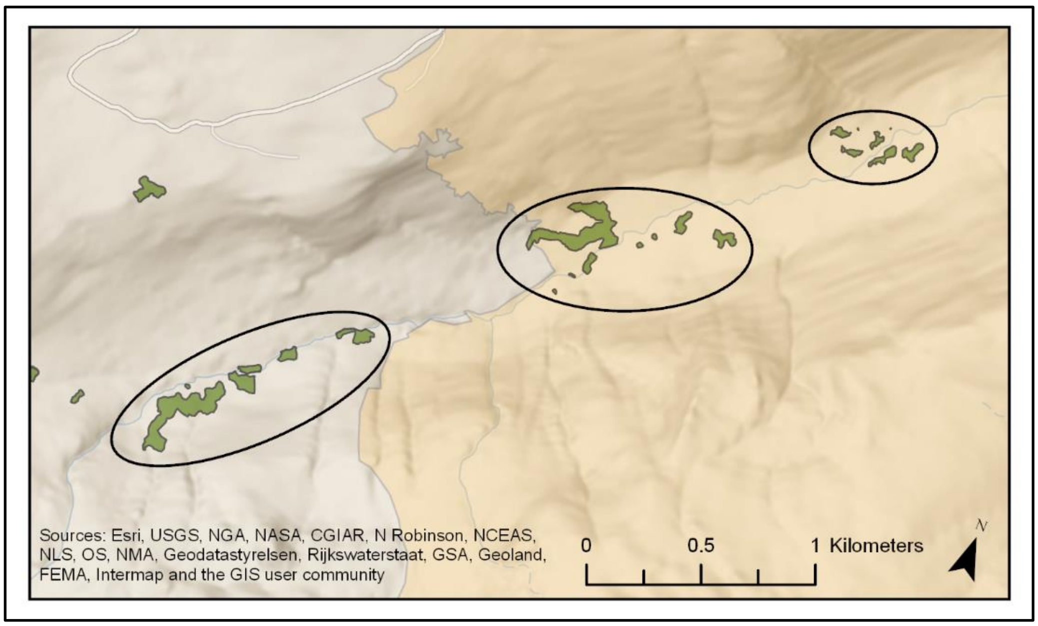

Figure 2. Example of aspen polygon grouping procedure where all polygons in close proximity (shown here within an ellipse) were grouped together as a single stand.

Table 1. Number of aspen stands by disturbance type, and range of stand areas.

Forest	n	Unburned	1 Burn	2 Burns	Min (ha)	Max (ha)	Mean (ha)
Lassen	10	4	3	3	0.02	1.08	0.29
Modoc	9	2	5	2	0.02	5.21	1.63
Plumas	14	3	6	5	0.09	8.84	1.45

Variable Calculations

To describe change in aspen over time, three metrics were calculated: proportional area change (A_1/A_0) as a ratio; movement of stand boundaries; change in conifer cover percent. In addition, predictor variables were calculated: edge:area ratio, fire severity, and a composite fire severity-frequency score.

To calculate proportional area change, we extracted area values in hectares for all stands in each year using "calculate geometry" in the attribute tables of the shapefile layers. Proportional change was calculated for two different time periods: the fire exclusion period (1941-1993) and the return of fire period (1993-2017). Periodic proportional change was calculated by dividing the area at the end of the period with the area at the beginning: $\Delta = A_1/A_0$ for both time periods. There were a few stands that were unobservable in 1993 aerial imagery but visible in 2017 after fire, showing that these stands were not completely lost in 1993. These stand areas were coded as 0.003 hectares in 1993, as that is the size of a patch that only includes a single tree, representing the smallest measurable area.

Stand movement was calculated using the Union tool to combine polygons from all three years into one shapefile. This gave us new polygons for areas lost between assessment years, areas gained between years and areas maintained between years for each aspen stand. We then used the calculate geometry function again to get area values for each of these polygons. Stand movement values were calculated as the proportion of a recent year's stand area that was "new" because it was found outside of the previous assessment year's stand area footprint:

$M_{1941\text{-}1993}$ = 1993new_area/1993total_area

$M_{1993\text{-}2017}$ = 2017new_area/2017total_area

For example, a stand that remained entirely within the prior year's footprint would have movement value = 0; a stand that occupied an entirely new location completely outside the prior year's footprint would have movement value = 1 (i.e., maximum movement).

Percent conifer composition was measured using ocular estimates in the imagery from each year. Conifer composition in 1993 and 2017 was observed on imagery in Google Earth and 1941 conifer composition was observed on aerial photos displayed in ArcMap. For each year, the field-derived GPS polygons from the recent field assessments of aspen stand area were overlaid on that year's imagery, along with the digitized stand delineation polygon from that year to account for areas where aspen was observed during ground assessments but not from aerial imagery. A number between zero and one was assigned to each stand in each year based on the conifer crown extent as a percentage of stand area observed within the field-derived and the digitized polygons. Conifer composition change was then calculated by subtracting the percentage for the ending year's conifer composition from the percentage for the starting year's conifer composition for each time period, resulting in a positive number for conifer composition increase and a negative number for conifer composition decrease (e.g., increasing conifer: 50% - 10% = 40% increase; declining conifer 20% - 35% = -15%).

Edge:area ratio was derived in ArcMap. Edge was calculated within the attribute table of individual years using the calculate geometry function to measure perimeter in meters, and calculating the ratio of edge (m) to area (hectares): edge/(area*10,000), where multiplying by 10,000 converts hectares to meters squared.

Fire severity was assigned to each stand using Google Earth. In and around each stand, conifer mortality was assessed by comparing conifer cover in years before and after all fire events. Four fire severity categories were assigned (unburned, low, moderate, high), where low severity had little to no conifer mortality, moderate severity had visible patches of conifer mortality and high severity had 100% conifer mortality (Key and Benson 2005). Severity in stands that burned twice was measured as a cumulative effect, as separate severity for each fire was unobservable. For statistical analysis, low and moderate stands were grouped together as there was only one stand that burned at low severity.

Fire frequency (FF) and fire severity (FS) were combined into a single categorical variable due to singularity: FFFS. Five categories were constructed: unburned, once burned experiencing low/moderate severity, once burned experiencing high severity, twice burned experiencing low/moderate severity and twice burned experiencing high severity.

Spatial Dynamics Modeling

A t-test in R software version 3.5.2 (R Core Team 2018) was used to test for a fire frequency effect on proportional area change when fire was present between years 1993 and 2017. The t-test compared proportional area change in once- versus twice-burned stands.

Linear models were constructed to test for variables influencing three response variables (i) proportional stand area change, (ii) proportional stand movement, and (iii) conifer composition change in each time period. Proportional area change data for the return of fire period were logarithmically transformed to reduce skewness. The lm function was used to model proportional area change. Stand movement was modeled using the betareg function, accounting for data confined by zero and one. Stand movement values of 1 were changed to 0.999999 to use betareg analysis. Two Modoc aspen stands were not included in the stand movement models between 1941 and 1993 due to georeferencing difficulties, leaving 31 stands available for stand movement analysis. The glm function was used to model conifer composition change as a function of candidate explanatory variables (Table 2). Fire severity was not included as a candidate variable for the conifer composition change models as conifer composition before and after fires was used to measure fire severity, making these two variables inherently related. Therefore, fire frequency alone was tested in conifer composition change models.

Backwards eliminations were used for selection of variables used in best models as determined by Akaike Information Criterion corrected for small samples (AICc) (Appendix 3) (Akaike 1974). Pairwise comparisons were performed on categorical variables to determine significant differences among individual categories using the eemeans package in R (Lenth 2018). The coefficients generated from the pairwise comparisons were used to represent least-squares mean and standard error values for each category, and plotted to depict differences among categories of each categorical variable within the best models. Expected values across the range of observed values for each continuous variable were also plotted using the ggplot2 package in R (Wickham 2016).

Table 2. List of candidate explanatory variables for analysis of changes in aspen-conifer stands. Fire severity within the FFFS category are coded as LM for low/moderate severity and H for high severity.

Variable code	Variable description
forest	National forest location of the stand: Lassen, Modoc or Plumas
site	Site type at stand location: upland, riparian or both
FFFS	Fire frequency/fire severity: unburned, 1burn/LM, 1burn/H, 2burns/LM, 2burns/H
area41 area93	Stand area in hectares in 1941 and 1993
edge:area41 edge:area93	Edge to area ratio in 1941 and 1993
%con41 %con93	Percent conifer composition for each year
mov41-93 mov93-17	Stand movement in each time period

RESULTS

On average, our study aspen stands were much larger and had fewer conifers in 1941 than in 1993 (Table 3, Table 4, Appendix 1). Over the 76 year study period (1941-2017), we observed an overall decline in aspen stand area where fire was absent in our study. More recently, however, stands experiencing fire collectively exhibited area expansion. Changes in total aspen stand area (ha) within each fire frequency category were different from each other ($p = 0.0451$) when fire was present between years 1993 and 2017 (Figure 3). Individual stands exhibited variability in how their area changed with and without wildfire disturbances (Figure 4). Stands movement varied widely, ranging from zero movement to full movement into completely different locations. Conifer composition was also highly variable in space and time, but generally increasing from 1941-1993 and decreasing from 1993-2017 (Table 3, Table 4).

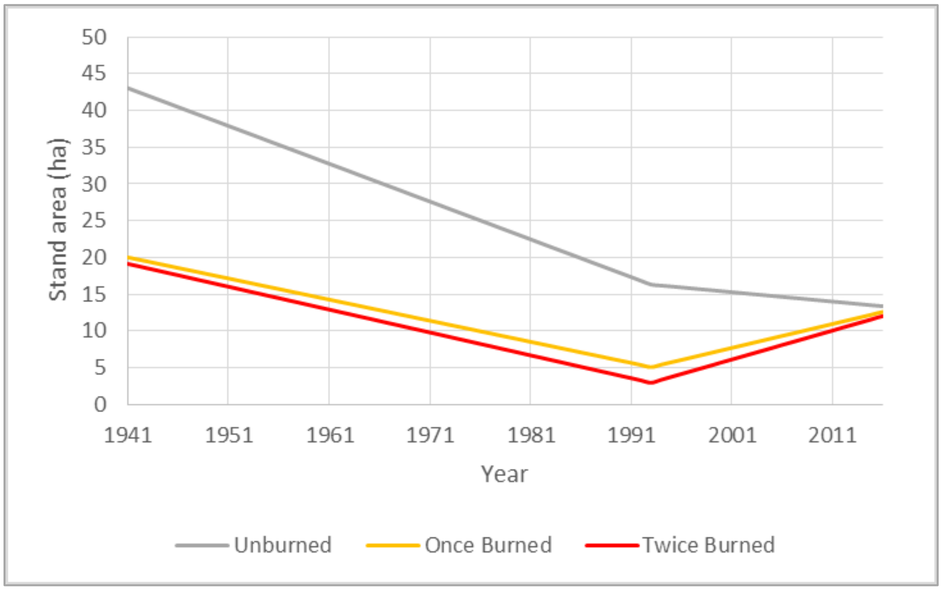

Figure 3. Total aspen stand area in each fire frequency category in 1941, 1993, and 2017, connected by lines depicting average annual change.

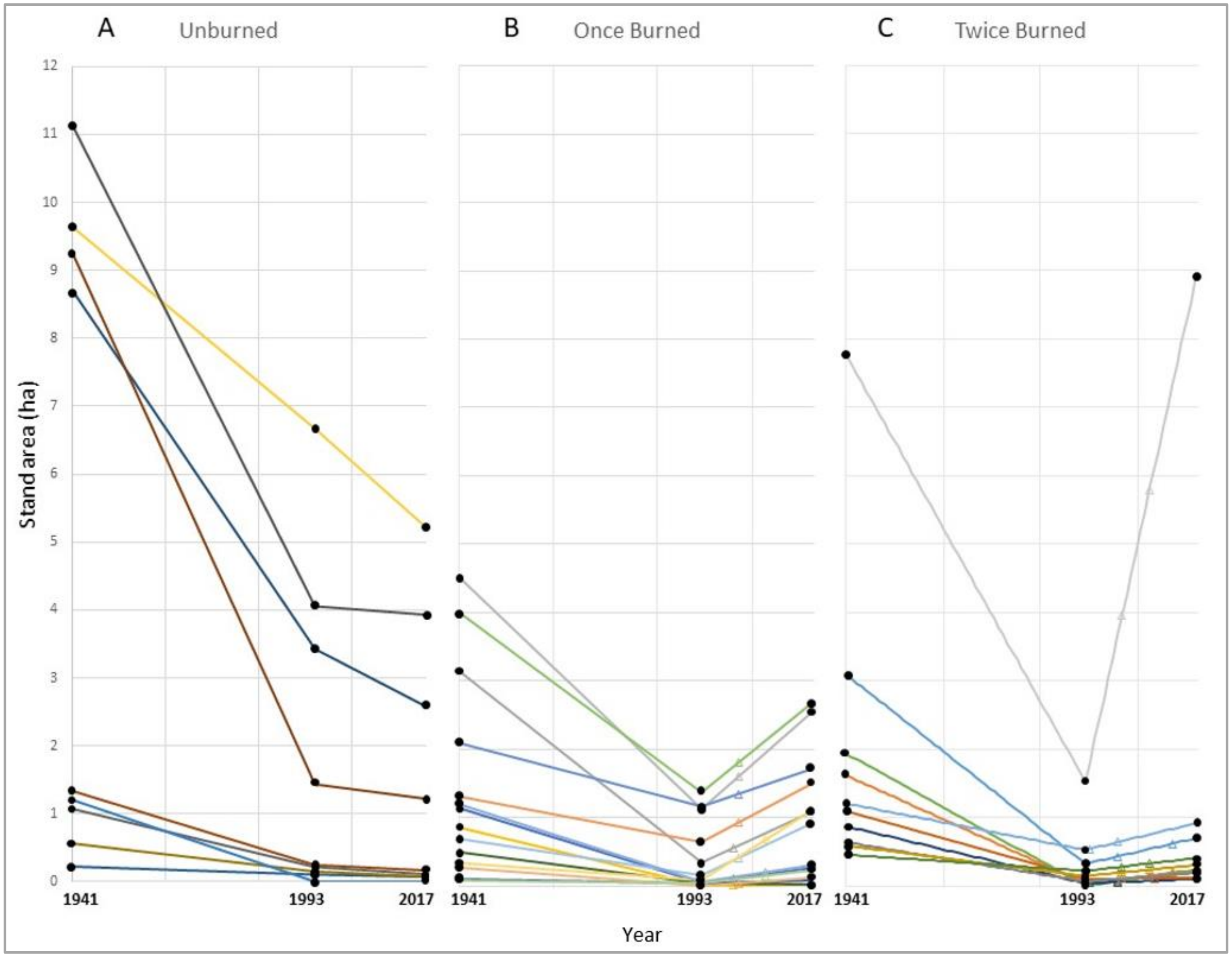

Figure 4. Stand area change over time for individual aspen stands in each fire frequency category: unburned (A), once burned (B) and twice burned (C). Triangles denote years where a stand burned between 1993 and 2017.

Table 3. Summary data for continuous response variables.

Response Variable	Min.	Max.	Mean
Proportional area change: 1941 - 1993	0.00	0.69	0.23
Proportional area change: 1993 - 2017	0.00	14.70	2.64
Stand movement: 1941 -1993	0.00	1.00	0.65
Stand movement: 1993 - 2017	0.17	1.00	0.74
Conifer comp. change: 1941 - 1993	-0.27	0.92	0.29
Conifer comp. change: 1993 - 2017	-0.90	0.18	-0.29

Table 4. Summary data for continuous predictor variables.

Predictor Variable	Min.	Max.	Mean
area41	0.08	11.11	2.49
area93	0.00	6.67	0.73
edge:area41	0.02	0.19	0.08
edge:area93	0.00	0.64	0.18
%con41	0.02	0.65	0.25
%con93	0.05	1.00	0.53

Period of Fire Exclusion (1941 – 1993)

The period of fire exclusion was characterized by decline in area of all aspen stands on all forests. Rate of area decline was greater among stands that had lower edge:area ratios in 1941 ($p = 0.0003$) and smaller stand areas in 1941 ($p = 0.0007$). Aspen stands on the Lassen declined most rapidly, followed by the Plumas and then the Modoc (Figure 5, Table 5).

While their total area declined in the absence of disturbance, the aspen stands also moved over time and began occupying new areas. Smaller stands exhibited more movement than larger stands ($p = 0.0030$) (Figure 6, Table 5).

Throughout the period of fire exclusion, conifer composition increased. We did not detect relationships between composition change and any predictor variables except forest. Specifically, conifer encroachment was higher in stands located on the Lassen, followed by the Plumas and lowest on the Modoc (Figure 7, Table 5).

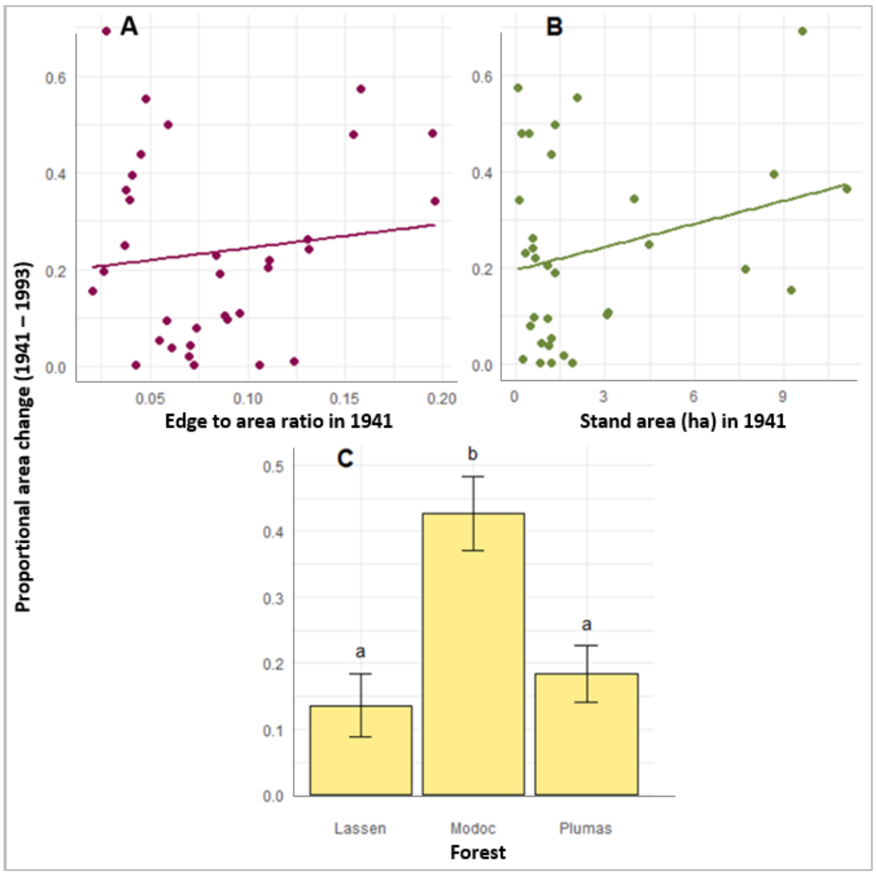

Figure 5. Proportional area change from 1941 to 1993: A) the effect of edge:area ratio in 1941, B) the effect of stand area in 1941 and C) the differences among forests. The plotted dots in A and B are the observed relationship between the two variables, and the lines represent expected area change across range of predictor variable while other variables are held constant at their mean value. The bar graph in C was graphed with pairwise comparison values acquired with emmeans. Error bars represent standard error and letters above each category represent the difference among categories, same letters denoting no significant difference.

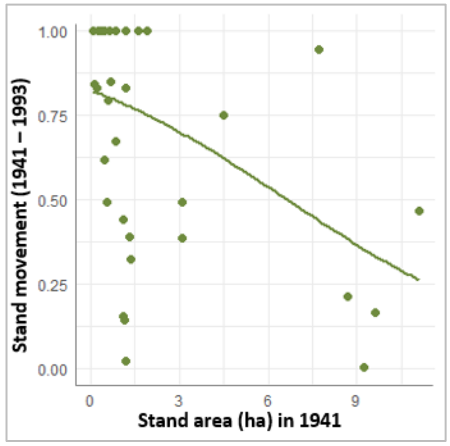

Figure 6. Stand movement from 1941 to 1993 is affected by stand area in 1941. Stand movement on the y-axis represents the portion of a whole stand (1 being the max) that has moved. Plotted dots denote the observed relationship between stand area in 1941 and stand movement between 1941 and 1993. Curve represents expected movement across range of stand areas sampled.

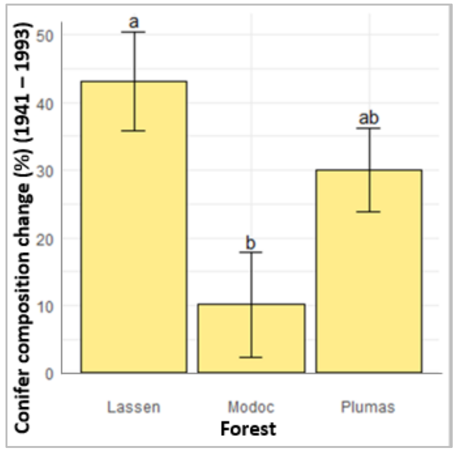

Figure 7. Conifer composition change from 1993 to 1941 differs among forests. Conifer composition on the y-axis shows a change in conifer composition percentage, here all values are positive showing increases among all forests e.g., if a stands conifer composition was 20% in 1941 and 70% in 1993, its' conifer composition change is 50% (e.g. 70-20 = 50%). Error bars represent standard error of least squares means, and same letter denotes no significant difference among categories.

Table 5. Model summaries for selected models in the period of fire exclusion (1941-1993) for 33 stands in the proportional area change and conifer composition change models and 31 stands in the stand movement model. Variance inflation factor (VIF) quantifies multicollinearity, where a value of 10 or above indicates influential multicollinearity (Kutner et al. 2005).

Response	Parameter	Coeff	S.E.	Pr(>|t|)	VIF
Proportional area change	Intercept	-0.26196	0.110	0.0197	
(Adjusted R^2 = 0.41)	Modoc	0.29020	0.080	0.0007	1.5
	Plumas	0.04730	0.060	0.4641	1.5
	edge:area41	3.46814	0.847	0.0003	2.3
	area41	0.04423	0.100	0.0007	1.9
Proportional stand movement	Intercept	1.55167	0.348	<0.0001	
(R^2 = 0.17)	area41	-0.23354	0.079	0.0030	
Conifer composition change (%)	Intercept	0.43100	0.074	<0.0001	
(R^2 = 0.24)	Modoc	-0.32900	0.107	0.0045	
	Plumas	-0.13100	0.097	0.1855	

Period of Return of Fire (1993 – 2017)

Within the time period where fire returned to the study areas, individual stands that were not exposed to fire continued to decline, while stands that burned expanded in area. Once burned stands that experienced high severity fire increased in area significantly ($p = 0.0045$) more than once burned stands that experience low/moderate severity fire and notably had the greatest increase in area across all fire categories. Area increase fluctuated across edge:area ratio in 1993, but more stands with lower edge:area ratios expanded at greater rates. Greater increases in stand area were also associated with areas that had higher conifer compositions in 1993 (Figure 8, Table 6).

Aspen stand movement from 1993-2017 followed the same trend as previous years; smaller stands moved significantly ($p < 0.0001$) more than large stands. Aspen stands also moved significantly ($p = 0.0005$) more when edge:area ratio was lower in 1993 (Figure 9, Table 6).

Conifer composition change was highly influenced by fire frequency; all stands that experienced fire also experienced a decrease in conifer composition. Twice burned stands exhibited a greater average decline in conifer composition than once burned stands, but the difference was not statistically significant. After accounting for the influences of disturbance type and site type in the regression analysis, stands on the Modoc experienced a small average increase in conifer composition while the Lassen and Plumas stands experienced large decreases in conifer composition. Pure riparian and upland stands both showed significantly ($p = 0.0284, 0.0332$) more conifer loss than mixed type stands but did not differ significantly (p = 1.0) from each other (Figure 10, Table 6).

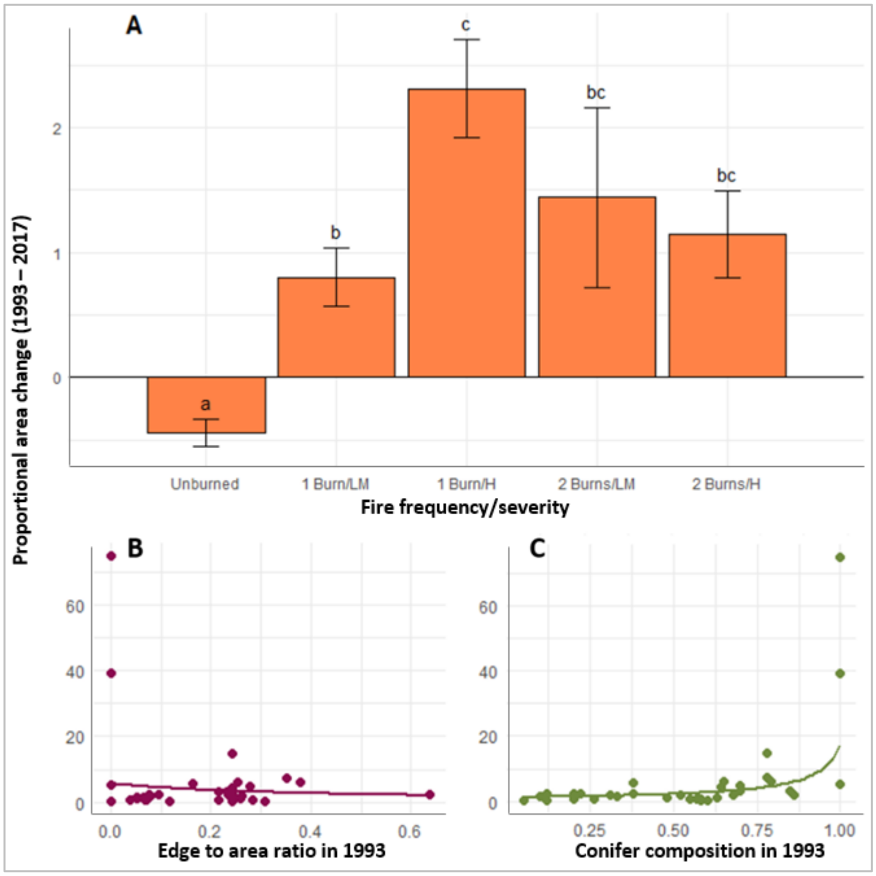

Figure 8. Proportional area change between 1993 and 2017: A) Fire frequency and severity category least squares means and standard errors, B) the effect of edge:area ratio in 1993 and C) the effect of conifer composition in 1993. Error bars represent standard error and letters above each category represent the difference among categories, same letters denoting no significant difference. The plotted dots in B and C are the observed relationships between the two variables, and the curves superimposed over stand data represents expected values across range of predictor variable while other variables are held constant at their mean value.

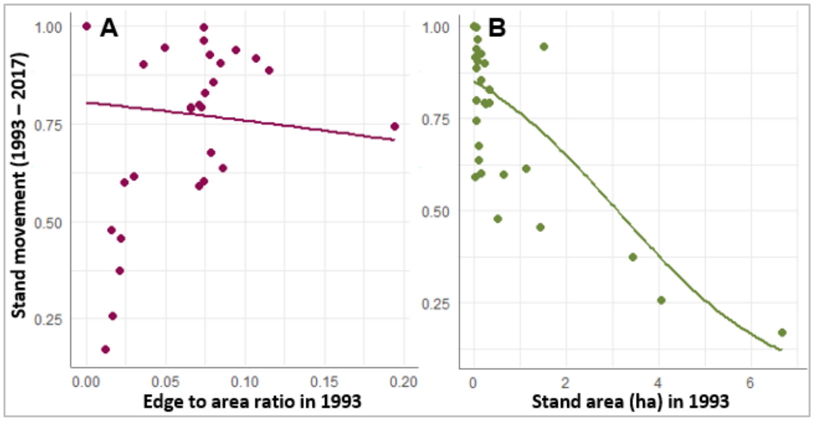

Figure 9. Stand movement from 1993 to 2017: A) the effect of edge to area ratio in 1993 and B) the effect of stand area in 1993. Stand movement on the y-axis represents the proportion of a whole stand area that has moved (1= max.). The curve superimposed over stand data represents expected values across range of predictor variable with the other variable held constant at its mean value.

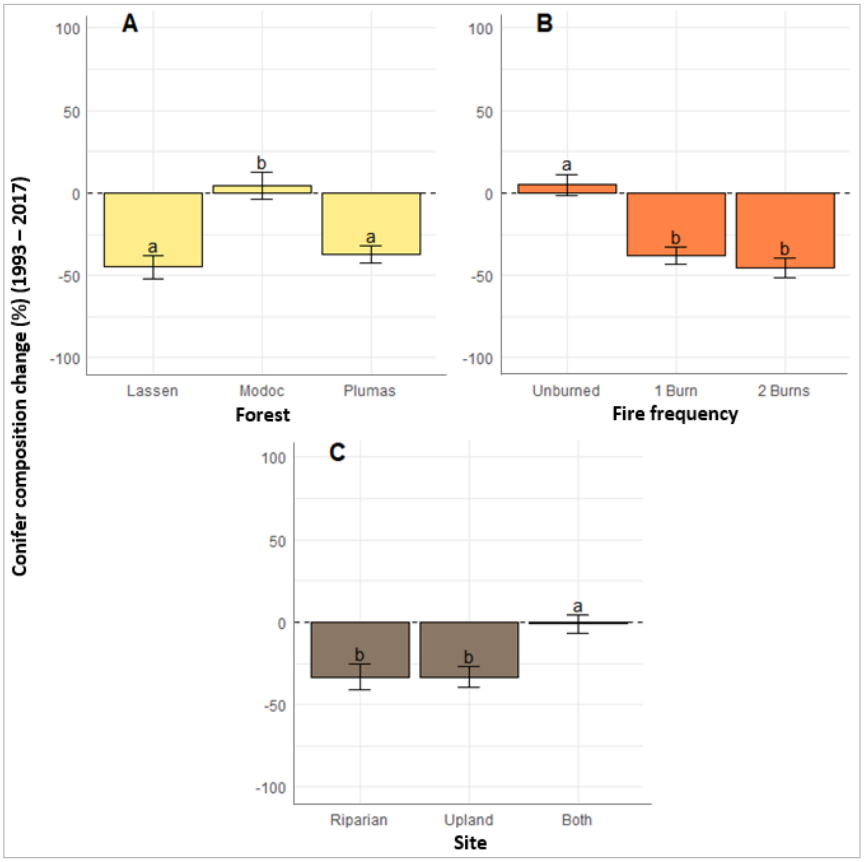

Figure 10. Conifer composition change between 1993 and 2017: A) differences among forest, B) fire frequencies and C) site types, e.g. if a stand's conifer composition was 50% in 1993 and 10% in 2017, it's conifer composition change was -40%. Graphed values are from pairwise comparisons acquired with emmeans. Error bars represent standard error. Categories with same letter were not significantly different.

Table 6. Models of change over the return-of-fire period (1993-2017) for 33 aspen stands experiencing different fire frequencies and severities: unburned, once burned experiencing low/moderate severity fire (1burn/LM), once burned experiencing high severity fire (1burn/H), twice burned experiencing low/moderate severity fire (2burns/LM) and twice burned experiencing high severity fire (2burns/H). Variance inflation factor (VIF) quantifies multicollinearity, where a value of 10 or above indicates influential multicollinearity (Kutner et al. 2005).

Response	Parameter	Coeff	S.E.	Pr(>|t|)	VIF
log(Proportional area change)	Intercept	-0.876400	0.347	0.0180	
(Adjusted R^2 = 0.69)	1burn/LM	1.328800	0.324	0.0003	1.6
	1burn/H	2.417500	0.441	<0.0001	1.6
	2burns/LM	1.880800	0.408	<0.0001	1.6
	2burns/H	1.548100	0.420	0.0110	1.6
	edge:area93	-2.212800	0.963	0.0299	1.2
	%con93	1.630800	0.507	0.0034	1.4
Proportional stand movement	Intercept	2.899200	0.423	<0.0001	
(R^2 = 0.39)	area93	-0.788700	0.145	<0.0001	1.4
	edge:area93	-15.805300	4.601	0.0005	1.3
Conifer composition change (%)	Intercept	0.005887	0.072	0.9361	
(R^2 = 0.78)	Modoc	0.494151	0.110	<0.0001	2.5
	Plumas	0.074944	0.086	0.3935	2.5
	FF (1)	-0.426577	0.079	<0.0001	1.2
	FF (2)	-0.503539	0.086	<0.0001	1.2
	riparian	-0.219728	0.094	0.0284	2.6
	upland	-0.218798	0.097	0.0332	2.6

DISCUSSION

The Role of Wildfires in Declining and Expanding Aspen Stands

We observed spatial changes in aspen stands in the absence and presence of wildfire. Without fire on the landscape, aspen stand areas declined across all stands and on all forests studied. During our study period of 52 years without wildfires, aspen stand areas declined by 76% on average. Four of our 32 studied stands were completely undetectable in 1993 aerial photography. Di Orio et al. (2005) observed aspen decline on the Modoc National Forest, also within a similar time range (1946-1994), finding a 24% decline in total area studied. This was lower than our observations of decline on the Modoc which had the least decline of our three study areas at about 54% (1941-1993). Aspen on the Lassen and the Plumas National Forests had higher rates of decline (90%, 73%) over the same 52-year period. Bartos (2000) studied a century of decline across all western states and observed decline from 49% to 95%.

The observed decline was seemingly related to the process of succession to conifers within these aspen-conifer stands. In the absence of fire, conifer composition increased by 29% on average over 52 years. McCullough et al. (2013) conducted a thorough 50-year study that observed yearly increase in conifer encroachment and associated aspen decline at Lassen Volcanic National Park in northeastern California. They found that within stands that had significant encroachment by conifers, mean conifer cover had increased by 46% at the end of their study period. Correspondingly, mean aspen cover in these stands decreased by 29%. The increase in conifer composition found by McCullough et al. (2013) was higher than what we found in our study, possibly because McCullough's study excluded stands that had less than 10% conifer increase from their encroachment average.

The steady establishment of conifers within the aspen stand footprints is assumed to be correlated to lack of disturbance. Our study observed a significant increase in conifer composition during the period when fire was absent, and a significant decrease in conifer composition when fire was present. This suggests that lack of fire or other disturbance as a stimulant and release from competition is a driving cause for aspen decline in these areas. Restoration treatments found to promote aspen regeneration and growth include conifer removal alone (Jones et al. 2005, Berrill et al. 2017) or combined with prescribed fire (Krasnow et al. 2012). Expansion between 1993 and 2017 was also affected by the percentage of conifers present in 1993. During the return-of-fire period, burned stands experienced greater expansion where conifer composition was higher at the beginning of the period. In the presence of fire, these stands may have experienced a greater release from conifer competition as well as stimulation of regeneration by fire, in turn resulting in a greater rate of expansion over our study period.

In the presence of fire, aspen stands expanded and presumably started to occupy areas of former stand footprints and new areas. Total stand area that experienced a single fire event within the 24-year period of return of fire increased in stand area by 60% from total area in 1993. Total stand area that burned twice between 1993 and 2017 increased in stand area by 75%. Even after expansion, these new areas were still only a fraction of observed stand sizes in 1941. It is uncertain whether expansion will continue in the future. These observations assume greater changes than our statistical conclusions because we incorporated other explanatory variables that may affect the explained growth, so we cannot fully claim that the larger expansion of twice burned stands is due solely to the compound disturbance. For this to be better explored, a larger sample size of aspen stands would need to be studied.

Expansion where fire has occurred may also be a consequence of the removal of conifers due to high severity fire. Stands that burned at low or moderate severity increased in stand area by 52% from 1993 to 2017, and stands that burned at high severity increased by 82%. A major consequence of fire severity is conifer removal, as high severity stands were classified as having 100% conifer mortality within the period of return of fire. In the absence of high-severity fire, Berrill et al. (2016) found that the heavy or frequent conifer removals would be needed to restore aspen dominance in stands undergoing succession from aspen to conifer. Fire severity also correlates with enhanced re-sprouting of other vegetation such as black oak (*Quercus kelloggii*) in this forest type (Crotteau et al. 2015), especially after reburn (Coppoletta et al. 2016, Hammett et al. 2017, Nemens et al. 2018).

We also observed greater area expansion in aspen stands that had lower edge:area ratios, or less edge. Aspen stands with greater amounts of edge in comparison to their total area may be more vulnerable to outside inhibitors. Where large populations of ungulate grazers are present, aspen stands with greater edge are less likely to successfully regenerate (Alverson et al. 1988). Greater edge was more commonly observed in aspen stands that were broken up by conifers, or stands that were not pure aspen. Aspen regeneration and recruitment decreases when more conifers are present in a stand (Calder and St. Clair 2012, Berrill and Dagley 2014).

The greater movement of small aspen stands compared to larger stands may indicate that smaller stands are more vulnerable to change. If small stands are easily outcompeted, they may tend to migrate into other spaces when available. Within our return-of-fire period, aspen stands also moved more when they had a lower edge:area ratio at the beginning of the time period. This, again, may be due to the increase in competition that stands with more edge experience in comparison to stands that are closer to pure aspen. Pure aspen stands with a simpler shape are more likely to recruit to the adult age classes (Berrill and Dagley 2014). When the older trees die, the clone sends out root suckers in other available areas, leaving an opening where previous aspen were (Baker 1925).

With future technological advances, our methods of observing spatial changes in aspen stands using a time series of remotely sensed data may become more straightforward or streamlined. Di Orio et al. (2005) studied aerial imagery in 1946 and 1993 and reported aspen stand decline between these years. We adopted a similar approach and added observation of stand area change after disturbance in an attempt to identify corollaries or patterns of stand area change. McCullough et al. (2013) also measured aspen decline by cause of conifer encroachment using an aerial photo series. They used an annual time series spanning the years 1952 and 1998. By assessing decline prior to the disturbances at our study sites, we created a baseline of change against which to compare subsequent aspen stand expansion detectable in the remotely sensed imagery.

When using aerial photo sets from different years, with different quality and resolution, we encountered a problem with a confounding of time and technology. With the improvement of technology throughout time, photo quality increased progressively. Because of this, decisions on whether or not to delineate areas of aspen had to be consistent with what was visible within the oldest photos (1941), even though much younger trees were observable in the most recent imagery. This resulted in the exclusion of small, young individuals in all years to avoid bias towards including more aspen area in later years that may only be detectable due to better photo quality. We were also limited by choosing stands that were present at the time of recent field delineation, as we used these recent GPS polygons to locate areas of aspen in the historical imagery. This may have prevented us from observing stands that were present in previous years and had since been lost from our study areas within our study period.

Another limitation appeared when trying to isolate the effect of time since fire had burned a stand in our models for the period of return of fire. Including a variable that was the number of true years since fire was not possible while trying to compare to the unburned stands as the last year they had burned is unknown. Because of this, we expect that there may be an effect of fire date from the forest where stands were located. We also may have seen a lesser effect in twice burned stands due to these later fire dates in overlapping fire areas. Each forest had different years of fire even though they were all within the study period. The longest time between the latest fire and the aerial imagery date was on the Modoc (16 years), and the shortest time since fire was on the Lassen (5 years). Therefore, twice burned aspen regenerating after fire on the Lassen had fewer growing seasons to respond to the effect of fire and would not be as large or visible after the more recent fire. Field assessment of the same aspen stands on the Lassen revealed many areas with small new root suckers that were not included in aspen stands delineated by remote sensing. If the Lassen stand areas had included these suckers, their post-fire area expansion may have been even greater.

Implications for the Future

Aspen stands that have burned both once and twice appear to be on a post-fire trajectory of expansion towards pre-fire exclusion stand areas. However, the sustainability of this upward trend is unknown. Monitoring these stands into the future would be required to fully understand how often these stands need to burn to maintain or enhance their area into the future. The continued decline of stands that did not burn during the entire study period (1941-2017), suggests that these stands may be lost without restoration efforts. Although our study has shown how wildfire disturbances favor aspen over conifer, fire may not be the easiest or safest restoration tool to use. For stands that are nearing complete loss, prescribed fire or fire surrogates such as thinning may provide an immediate benefit needed to promote aspen regeneration and growth by reallocating growing space to aspen. Regeneration from suckering may be promoted from options other than fire as well, including manual breakage of the roots (DeByle and Winokur 1985). In areas where aspen is present and wildfires are expected in the future, land managers should have wildland fire use plans in place in preparation for the opportunity to introduce natural fire into aspen stands. If declining stands are not exposed to fire or fire surrogates, the effects of succession to conifers may lead to complete overtopping of aspen and loss of entire aspen stands. Conversely, the clear benefits of wildfire to aspen stands in our study highlights the potential to reverse aspen decline in this region.

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APPENDIX A

Appendix A. Study stand attributes

Stand	Forest	FF	FS	Site	Stand area (ha) 1941	Stand area (ha) 1993	Stand area (ha) 2017	Edge:area ratio 1941	Edge:area ratio 1993	Edge:area ratio 2017	% conifer 1941	% conifer 1993	% conifer 2017	# polygons 1941	# polygons 1993	# polygons 2017
1	Lass	2	LM	both	3.07	0.32	0.70	0.09	0.25	0.22	35	52	12	5	8	12
2	Lass	2	H	both	1.61	0.03	0.23	0.07	0.35	0.35	42	78	5	3	2	10
3	Lass	1	LM	both	3.11	0.34	1.08	0.10	0.22	0.13	22	85	68	7	5	11
4	Lass	1	LM	both	0.84	0.00	0.02	0.11	0.00	0.51	8	100	62	2	0	1
5	Lass	1	H	upl	1.12	0.04	0.27	0.06	0.38	0.11	27	65	2	1	2	1
6	Lass	2	LM	both	1.92	0.00	0.22	0.07	0.00	0.19	15	100	10	3	0	3
7	Lass	0	U	both	0.22	0.10	0.07	0.15	0.28	0.34	10	57	67	3	3	4
8	Lass	0	U	rip	1.33	0.26	0.18	0.09	0.22	0.29	38	55	42	2	2	4
9	Lass	0	U	both	1.08	0.22	0.11	0.11	0.12	0.41	40	58	70	3	1	9
10	Lass	0	U	both	0.56	0.15	0.07	0.13	0.24	0.28	42	60	55	3	3	2
11	Mod	2	LM	upl	0.87	0.04	0.10	0.07	0.64	0.41	10	22	18	3	9	9
12	Mod	1	LM	upl	0.48	0.04	0.02	0.07	0.31	0.58	3	12	9	1	1	2
13	Mod	2	LM	upl	1.20	0.52	0.92	0.05	0.05	0.05	15	33	12	1	1	1
14	Mod	1	LM	both	1.30	0.65	1.50	0.06	0.08	0.06	12	20	15	2	1	1
15	Mod	1	LM	upl	4.48	1.12	2.54	0.04	0.10	0.07	3	12	8	2	2	3
16	Mod	0	U	upl	9.64	6.67	5.21	0.03	0.04	0.05	11	20	38	3	4	4
17	Mod	1	LM	upl	2.09	1.16	1.72	0.05	0.07	0.04	13	10	13	1	1	1
18	Mod	1	LM	upl	3.96	1.36	2.67	0.04	0.08	0.04	5	31	6	1	2	1
19	Mod	0	U	upl	1.20	0.00	0.00	0.04	0.00	0.00	2	5	7	1	0	0
20	Plum	2	H	rip	1.09	0.10	0.11	0.06	0.26	0.33	12	63	3	1	1	3
21	Plum	2	H	rip	0.63	0.06	0.19	0.09	0.23	0.12	32	70	0	2	1	1
22	Plum	2	H	rip	0.58	0.14	0.30	0.13	0.26	0.23	47	68	7	3	4	5
23	Plum	1	LM	rip	0.10	0.04	0.09	0.20	0.23	0.16	28	38	10	1	1	1
24	Plum	2	LM	rip	0.45	0.22	0.41	0.19	0.24	0.20	30	86	34	4	3	4
25	Plum	1	H	rip	0.68	0.15	0.91	0.11	0.25	0.12	47	79	0	3	2	5
26	Plum	1	H	rip	0.26	0.00	0.12	0.12	0.00	0.28	31	100	15	2	0	3

Stand	Forest	FF	FS	Site	Stand area (ha) 1941	Stand area (ha) 1993	Stand area (ha) 2017	Edge:area ratio 1941	Edge:area ratio 1993	Edge:area ratio 2017	% conifer 1941	% conifer 1993	% conifer 2017	# polygons 1941	# polygons 1993	# polygons 2017
27	Plum	2	H	both	7.72	1.52	8.84	0.03	0.16	0.07	65	38	16	2	10	7
28	Plum	1	H	upl	0.33	0.08	1.11	0.08	0.24	0.10	62	78	8	1	1	2
29	Plum	1	H	upl	1.18	0.06	0.31	0.05	0.28	0.18	15	70	0	2	2	2
30	Plum	1	LM	both	0.08	0.05	0.22	0.16	0.24	0.21	59	64	32	1	1	2
31	Plum	0	U	both	8.69	3.43	2.58	0.04	0.07	0.08	11	26	37	1	3	4
32	Plum	0	U	upl	9.23	1.43	1.22	0.02	0.07	0.06	7	58	58	1	2	2
33	Plum	0	U	both	11.11	4.05	3.93	0.04	0.05	0.05	20	48	52	6	4	3

APPENDIX B

Appendix B: Information for each studied forest.

Forest	Fire year 1	Fire year 2	Mean unburned stand size (ha)	Mean once burned stand size (ha)	Mean twice burned stand size (ha)	Mean # polygons 1941	Mean # polygons 1993	Mean # polygons 2017
Lassen	2000	2012	0.88	1.69	2.20	3	3	6
Modoc	1994	2001	5.42	2.46	1.03	2	2	2
Plumas	2001	2008	9.68	0.44	2.10	2	3	3

APPENDIX C

Appendix C: Skewness values before and after proportional area change transformations.

	Skewness of untransformed variable	Skewness of log transformed variable
Proportional Area Change: 1941 - 1993	0.63	
Proportional Area Change: 1993- 2017	4.20	0.88
Stand Movement: 1941 - 1993	-0.54	
Stand Movement: 1993 - 2017	-0.77	
Conifer Comp Change: 1941 - 1993	0.59	
Conifer Comp Change: 1941 - 1993	-0.35	
Edge:area41	0.86	
Edge:area93	0.90	
Area41	1.64	
Area93	2.87	
%conifers41	0.67	
%conifers93	-0.08	

APPENDIX D

Appendix D: Model selection: comparing full model and reduced models, with best model highlighted in gray (variable codes listed in Table 2).

Proportional area change from 1941 to 1993	AICc	AIC weight
Forest + Site + edge.area41 + %con41 + area41 + mov41-93	-17.14	
Forest + edge:area41 + %con41 + area41 + mov41-93	-22.55	0.38
Forest + edge:area41 + area41 + mov41-93	-22.03	0.29
Forest + edge:area41 + area41	-22.26	0.33

Stand movement from 1941 to 1993		
Forest + Site + edge:area41 + %con41 + area41	-132.80	
Forest + Site + area41	-137.91	0.01
Site + area41	-142.06	0.11
area41	-146.34	0.88

Conifer composition change from 1941 to 1993		
Forest + Site + edge:area41 + area41 + mov41-93	17.87	
Forest + Site + area41	10.64	0.03
Forest + Site	7.82	0.12
Forest	3.93	0.85

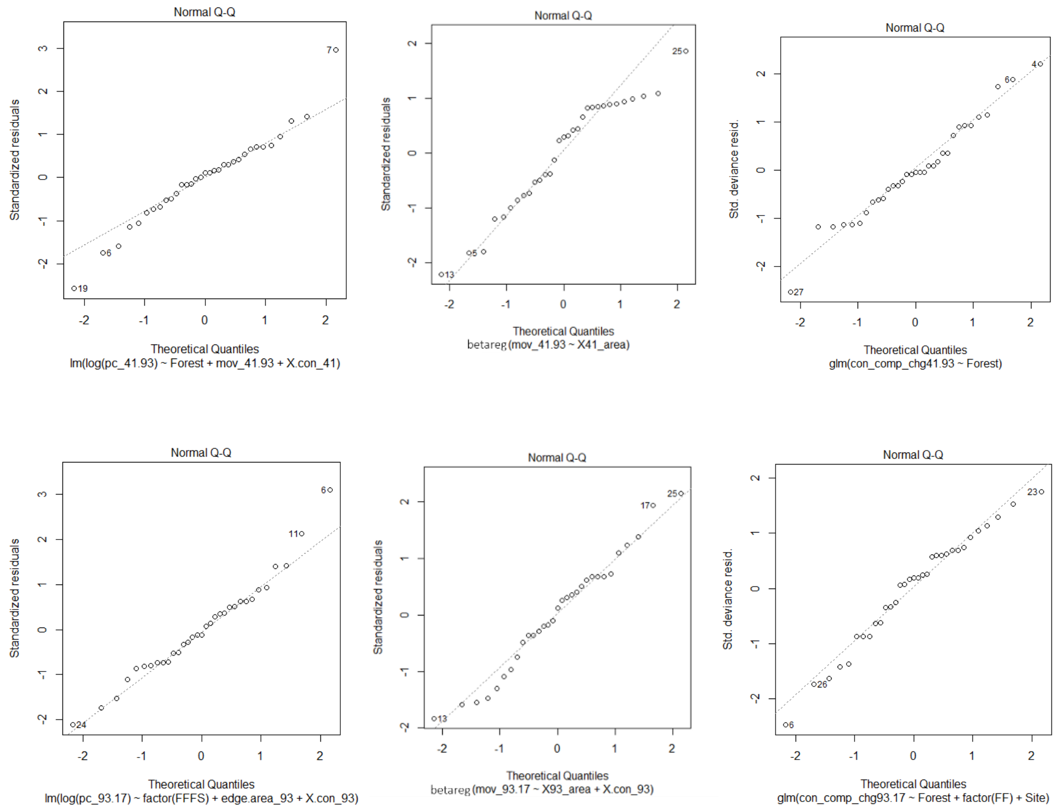
Proportional area change from 1993 to 2017		
Forest + FFFS + Site + edge:area93 + %con93 + area93 + mov93-17	104.62	
FFFS + Site + edge:area93 + %con93	85.71	0.16
FFFS + edge:area93 + %con93	82.80	0.66
FFFS + %con93	85.37	0.18

Stand movement from 1993 to 2017		
Forest + FFFS + Site + edge:area93 + %con93 + area93	-58.98	
Forest + edge:area93 + %con93 + area93	-81.79	0.03
edge:area93 + %con93 + area93	-85.64	0.25
edge:area93 + area93	-87.79	0.72

Conifer composition change from 1993 to 2017		
Forest + FF + Site + edge:area93 + area93 + mov93-17	-2.91	
Forest + FF + Site + edge:area93 + mov93-17	-6.26	0.44
Forest + FF + Site + edge:area93	-5.51	0.31
Forest + FF + Site	-5.13	0.25

APPENDIX E

Appendix E. QQ plots for all models, top row for years 1941 – 1993 and bottom row for years 1993 – 2017. From left to right are proportional area change, stand movement and conifer composition change.



APPENDIX F

Appendix F. R code for creating each model and associated figure.

	Proportional area change	Proportional stand movement	Conifer Composition Change
1941 - 1993	lm(pc_41.93~Forest+edge.area_41+X41_area) aspendata$predicted <- predict(pc41-93, aspendata) g1b <- ggplot(prefire5a, aes(edge.area_41, pc41.93_y))+ geom_point(size = 2, color = "deeppink4")+ geom_smooth(method = lm, se = FALSE, color = "deeppink4")+ theme_minimal()+ labs(x = "Edge to area ratio in 1941", y=element_blank()) g2b <- ggplot(prefire5a, aes(X41_area, pc41.93_y))+ geom_point(size=2, color = "darkolivegreen4")+ geom_smooth(method = lm, se = FALSE, color = "darkolivegreen4")+ theme_minimal()+ labs(x = "Stand area (ha) in 1941", y = element_blank()) g5 <- ggplot(data = comp, aes(x=forest1, y=mean1))+	betareg(mov_41.93~X41_area, link = "logit") aspenmov$predict41 <- predict(mov41, type = "response") p41 <- ggplot(data=aspenmov,aes(x=X41_area, y = mov_41.93)) geom_point(size = 2, color="darkolivegreen4") geom_smooth(data = aspenmov, aes(X41_area, predict41), method = "glm", method.args = list(family = "binomial"), se = FALSE, color = "darkolivegreen4") theme_minimal() labs(x = "Stand area (ha) in 1941", y = "Stand movement (1941 - 1993)")	glm(con_comp_chg41.93~Forest) g4 <- ggplot(data = comp, aes(x=forest, y=mean))+ geom_bar(stat="identity", color = "black", fill = "lightgoldenrod1", position = position_dodge())+ theme_minimal()+ labs(x = "Forest", y = "Conifer composition change (%)")+ geom_errorbar(aes(ymin=mean-se, ymax=mean+se), width=0.2, position=position_dodge(0.9))+ geom_text(aes(y=mean+se+0.05,label= pair),position=position_dodge(width=0.9),vjust=-0.25)

	geom_bar(stat="identity", color = "black", fill = "lightgoldenrod1", position = position_dodge())+ theme_minimal()+ labs(x = "Forest", y = element_blank())+ geom_errorbar(aes(ymin=mean1-se1, ymax= mean1+se1),width=0.2, position=position_dodge(0.9))+ geom_text(aes(y=mean1+se1+0.05,label=pair1), position=position_dodge(width=0.9),vjust=-0.25)		
1991 - 2017	lm(log(pc_93.17)~factor(FFFS)+edge.area_93+X.con_93) aspendata$predicted <- exp(predict(pc93-17, aspendata)) p1 <- ggplot(data = model1, aes(x = edge.area_93, y = log(pc_93.17)))+ geom_point(size = 2, color = "deeppink4")+ geom_smooth(data = aspendata, aes(edge.area_93, predicted, color = as.factor(FFFS)), method = "glm",method.args = list(family = "Gamma"), se=FALSE, color="deeppink4")+ theme_minimal()+ labs(x = "Edge to area ratio in 1993", y = element_blank()) f1 <- ggplot(data = fire, aes(x=FFFS, y=value))+	betareg(mov_93.17~X93_area+edge.area_93, link = "logit") aspenmov$predict93 <- predict(mov93a, type = "response") p93a <- ggplot(data=aspenmov,aes(x=X93_area, y = mov_93.17)) geom_point(size = 2, color="darkolivegreen4") geom_smooth(data = aspenmov, aes(X93_area, predict93), method = "glm", method.args = list(family = "binomial"), se = FALSE, color = "darkolivegreen4") theme_minimal() labs(x = "Stand area (ha) in 1993", y = "Stand movement (1993 - 2017)") p93b <- ggplot(data=aspenmov,aes(x=edge.area_93, y = mov_93.17)) geom_point(size = 2, color = "deeppink4")	glm(con_comp_chg93.17~Forest+factor(FF)+Site) g4 <- ggplot(data = comp, aes(x=forest, y=mean))+ geom_bar(stat="identity", color = "black", fill = "lightgoldenrod1", position = position_dodge())+ theme_minimal()+ labs(x = "Forest", y = "Conifer composition change (%)")+ geom_errorbar(aes(ymin=mean-se, ymax=mean+se), width=0.2, position=position_dodge(0.9))+ geom_text(aes(y=mean+se+0.05,label= pair),position=position_dodge(width=0.9),vjust=-0.25) pc2 <- ggplot(data = fire, aes(x=cfs, y=cem2))+ geom_bar(stat="identity", color = "black", fill = "sienna1", position = position_dodge())+

	geom_bar(stat="identity", color = "black", fill = "sienna1", position = position_dodge())+ theme_minimal()+ geom_hline(yintercept = 0)+ labs(x = "Fire frequency/severity", y = element_blank())+ scale_x_discrete(limits = c("Unburned", "1 Burn/LM", "1 Burn/H", "2 Burns/LM", "2 Burns/H"))+ geom_errorbar(aes(ymin=value-fferror, ymax=value+fferror), width=0.2, position =position_dodge(0.9))+ geom_text(aes(y=value+fferror+0.05, label = letter), position=position_dodge(width=0.9), vjust=-0.25) p1 <- ggplot(data = model1, aes(x = X.con_93, y = pc_93.17))+ geom_point(size = 2, color = "darkolivegreen4")+ geom_smooth(data = aspendata, aes(X.con_93, predicted), method = "glm", method.args = list(family = "Gamma"), se = FALSE, color = "darkolivegreen4")+ theme_minimal()+ labs(x = "Conifer composition in 1993", y = element_blank())	geom_smooth(data = aspenmov, aes(edge.area_93, predict93), method = "glm", method.args = list(family = "binomial"), se = FALSE, color = "deeppink4")+ theme_minimal() labs(x = "Edge to area ratio in 1993", y = "Stand movement (1993 - 2017)")	theme_minimal()+ labs(x = "Fire frequency", y = element_blank())+ scale_x_discrete(limits = c("Unburned", "1 Burn", "2 Burns"))+ scale_y_continuous(limits = c(-100,100))+ geom_hline(yintercept = 0, linetype="dashed")+ geom_errorbar(aes(ymin=cem2-cse2, ymax=cem2+cse2), width=0.2, position=position_dodge(0.9))+ geom_text(aes(y=cem2+cse2+0.05, label=cpair2),position=position_dodge(width =0.9),vjust=-0.25) pc3 <- ggplot(data = fire, aes(x=cste, y=cem3))+ geom_bar(stat="identity", color = "black", fill = "peachpuff4", position = position_dodge())+ theme_minimal()+ labs(x = "Site", y = element_blank())+ scale_x_discrete(limits = c("Riparian", "Upland", "Both"))+ scale_y_continuous(limits = c(-100,100))+ geom_hline(yintercept = 0, linetype="dashed")+ geom_errorbar(aes(ymin=cem3-cse3, ymax=cem3+cse3), width=0.2, position=position_dodge(0.9))+ geom_text(aes(y=cem3+cse3+0.05, label=cpair3),position=position_dodge(width =0.9),vjust=-0.25)