Changing aboveground carbon from fire suppression to natural fire regime

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ABSTRACT

Fire suppression started in the early 20th century and has led to high accumulations of surface and ladder fuels. This, combined with the longer droughts and higher temperatures due to climate change, result in large, high-severity fires. The Illilouette Creek Basin (ICB) in Yosemite National Park provides an opportunity to study a mixed conifer ecosystem with a natural fire regime in the Sierra Nevada today. It has been part of Yosemite's Managed Wildfire Program since 1972 and has almost reverted back to a natural fire regime. Previous studies in the ICB have shown how vegetation and water flow have changed as a result of a high-frequency, mixed-severity fire regime, but there is limited knowledge on the impacts on carbon storage. In this study, I evaluate how carbon changes from before the managed wildfire program in 1969 to 2012. Carbon decreases by 24.36% in the whole ICB, mostly due to a decrease in mixed conifer land area, although I suspect the actual decrease in carbon to be much higher. The other three vegetation classes present in the ICB—sparse grassland, dense grassland, and aspen—all increase land area. The fire reduces the amounts of surface and ladder fuels, making the Illilouette Creek Basin less likely to experience high-severity wildfires and enhances its ability of long-term carbon storage. This study can be used as a guide as to what to expect in terms of changes in carbon storage should other mixed conifer ecosystems return to a natural fire regime.

KEYWORDS

Carbon storage, forest restoration, managed fire, mixed conifer, Yosemite, wildfire

INTRODUCTION

Forests have been a topic of interest for sequestering and storing carbon to slow the effects of anthropogenically induced climate change for over a decade. Political documents such as the Kyoto Protocol (Nations 1998), the Paris Climate Agreement (Horowitz 2016), and more locally AB32 (Schwarzenegger 2008) in California focus on managing forests for carbon sequestration in an effort to combat the negative impacts of climate change. Forests can sequester and store large amounts of aboveground carbon (in the leaves and bole), belowground (in the soil and roots), and both in living and dead biomass. However, fire suppression has had a tremendous impact on the fire regime of the Sierra Nevada. Fires tend to be larger and burn at high severities, in part due to the altered frequency, severity, and duration of droughts caused by climate change (Law and Waring 2015). Should forests in the Sierra Nevada not be managed for resiliency in the face of unprecedented high-severity fires, it could mean the loss of several million hectares of the largest carbon sink in the state.

Fire suppression policies were established in the United States in the 20th century, causing the fire regime in the Sierra Nevada to be heavily altered, especially in mixed conifer forests. Over 1 billion megagrams of carbon are stored in live trees over 1 inch in diameter at breast height (DBH), with most of it in public lands (Christensen et al. 2016). However, this storage may be cause for concern. Today's forests have a higher density than forests in pre-colonial times, resulting in an increase in area burned and fire severity when wildfire events occur (Stephens 2005). The low-moderate severity, high-frequency fire regime of the past created a forest dominated by large dominant and codominant trees that were spaced out and reduced the amount of carbon lost by a future wildfire (North et al. 2009, Hurteau and North 2010).

Fire suppression has changed the dynamics of the mixed conifer forests of the Sierra Nevada and its performance as a carbon sink. Sierran forests are now denser with smaller trees and high buildups of ladder and ground fuels that set the stage for high-severity fires. These stands are susceptible to over 75% tree mortality under extreme fire weather conditions compared to managed stands (Stephens et al. 2012). Even trees that have fire resistant bark and other beneficial attributes cannot survive these high temperatures. Oftentimes, thousands of acres will burn in one fire, as in the King Fire of 2014 which burned 97, 717 acres. There has also been an increase in large fires (>4 km^2 per year) since 1984 (Law and Waring 2015). These large-scale fires release several tons of carbon into the atmosphere in one event, contributing to climate change, and create a feedback system that maintains the high-severity fire regime and changes forests to shrublands (Boisrame 2016, Powers et al. 2013).

Prescribed burns, with or without mechanical treatments, reduce the amount of fuels most effectively in Sierran forests (Stephens et al. 2012). Sites that have not been thinned or otherwise treated for fire risk can release 150-170 Mg/ha of carbon from a wildfire, while treated stands release 20-50 Mg/ha of carbon, if not less (Stephens et al. 2012). Although these treatments release carbon into the atmosphere (Hurteau and Brooks 2011) the resulting stands are more fire resistant and can still store large amounts of carbon because large trees are not killed in the fires (Hurteau and North 2009). The treatments of stands require maintenance at least every decade, which is both expensive and time consuming. Given the millions of acres of forest land all over California it is also not feasible to treat all of these stands. The best option would be to go back to a pre-colonial fire regime, but given the high fuel loads and the possible resulting damage to structures and lives, not many places have a natural fire regime today. The Illilouette Creek Basin (ICB) in Yosemite National Park has been experiencing natural and prescribed fires since 1972 (Collins et al. 2007). The fire return interval today is about 6.8 years, which is close to the 6.3 year interval in pre-colonial times (Boisrame 2916, Collins et al. 2007). The ICB gives a rare opportunity to study the effect of a natural fire regime and the resulting change in land cover and carbon storage. Studies in the ICB have shown how vegetation (Boisrame 2016) and fire regime (Collins et al. 2007) change over time, but it is not clear how carbon is impacted. I expect to see a decrease in carbon in the ICB due to a decrease in mixed conifer land area.

In this study, I examine the changes in carbon storage over time, specifically determining how a high frequency, moderate-low severity fire regime affects (1) aboveground carbon and (2) spatial patterns of carbon. Because there will be a reduction of forest cover and stand density in the ICB, I predict that there will be a decrease in the amount of carbon stored aboveground.

However, this management change will create a more fire-resistant forest that will store carbon for longer periods of time.

METHODS

Study site: Illilouette Creek Basin

The ICB, located in the Upper Merced Watershed within Yosemite National Park, was managed for fire suppression from the late 19th century until 1972, when it was chosen for long-term fire study site for Yosemite's managed wildfire program (then called "Natural Fire Management") (Van Wagtendonk 2007) as a result of its rocky boundary that could limit fire spread (Collins et al. 2007). Since then, lightning fires and prescribed fires have been allowed to run their course through the ICB. The fire return interval today is about 6.8 years, which is close to the 6.3 year interval in pre-colonial times (Collins et al. 2007), determined using tree ring records to compare historical fire patterns (Collins and Stephens 2007). Since 1972, there have been 30 fires that burned over 100 acres each in the ICB (Boisrame 2016).

The ICB is $150km^2$, ranging from 1800-3000m in elevation. It has a Mediterranean climate characterized by dry, hot summers, and cold, wet winters. It gets approximately 100cm average annual precipitation, mostly in the form of snow (Boisrame 2016). The basin is characterized by four main types of vegetation: conifer forests (composed mostly of Jeffrey pine, *Pinus jeffreyi*; red fir, *Abies magnifica;* white fir, *Abies concolor;* and lodgepole pine, *Pinus contorta*), shrublands (composed mostly of whitethorn ceanothus, *Ceanothus cordulatus*), and sparse and dense grasslands (Boisrame 2016, Collins et al. 2007). There are also large expanses of rocky outcrops without vegetation. The ICB has never been harvested for timber or had significant impacts from livestock grazing (Collins and Stephens 2007).

Data sources

To calculate carbon change over time, I used the changing vegetation in response to natural fire regime. I used data compiled by Dr. Gabrielle Boisrame (University of California, Berkeley) for the years of 1969/70, 1987/88, 1997, 2005, and 2012 (Boisrame 2016) and LandFire data for 2012 ("LANDFIRE Data Distribution Site"). From here on out I will use only the first year for each data group in tables and graphs (i.e. 1969 instead of 1969/70).

For her study, Boisrame (2016) used a combination of aerial photographs, historical maps, and ground reference data to delineate patches of vegetation with similar characteristics (Figure 1). Aerial photographs varied between 0.5-1m resolution, allowing Boisrame (2016) and her team to manually interpret the images and identify individual trees and large shrubs.

The maps Boisrame (2016) created using aerial imagery show the changes in vegetation for ICB over the study period (Figure 1). The loss in mixed conifer and the increase in sparse grassland and shrublands are the most noticeable landscape changes. The reliability in the assignments of vegetation classes were over 90% accurate, making these maps a good representation of the actual changes in the ICB.

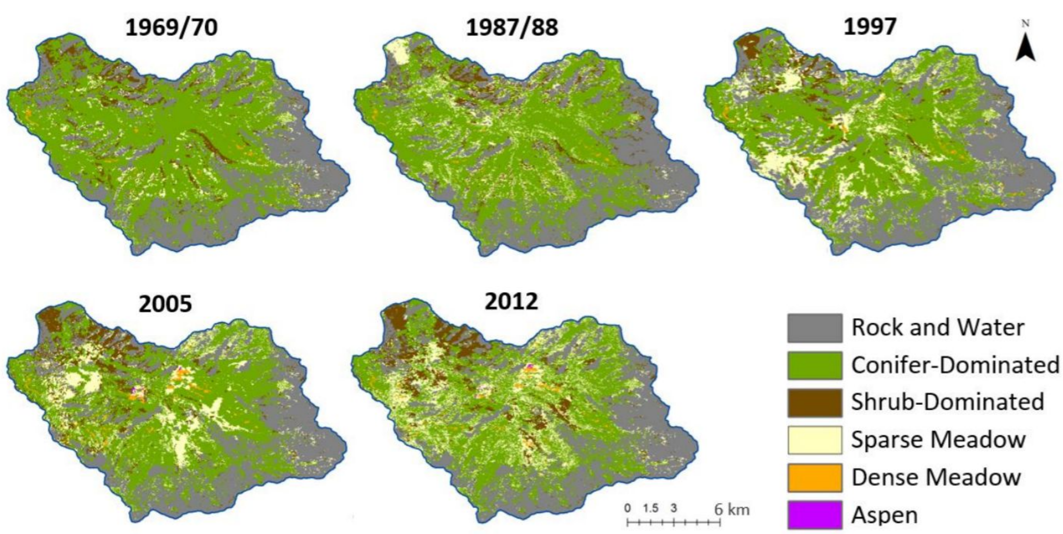

Figure 1. Maps of Illilouette Creek Basin vegetation. These maps, created by Boisrame (2016) show the changes in vegetation over the years of the 5 vegetation classes.

To determine the vegetation classes within in the ICB, Boisrame (2016) used aerial photographs taken by Cartwright Aerial Surveys in 1969 and 1970, the National Aerial Photography Program (NAPP) from 1987, 1988. and 1997, and the National Agriculture Imagery Program (NAIP) from 2005 and 2012 (“NAIP Imagery” n.d.). The two Cartwright Aerial Survey photographs and the 1987 and 1988 NAPP photographs were combined to cover the expanse of the ICB. Boisrame (2016) also used ERDAS Imagine Leica Photogrammetry Suite (www.hexagongeospatial.com/ products/ producer-suite/ erdas-imagine), NAIP imagery for reference, and a LiDAR elevation map (Kane et al., 2015) to orthorectify all images except those from the NAIP. She used existing vegetation maps of Yosemite to assist with mapping the vegetation.

To classify the vegetation classes, Boisrame (2016) used eCognition (available at ecognition.com), a remote sensing software that uses color band values, texture, and shape to identify objects in photographs and classify them into similar groups . All years were classified into 7 vegetation cover classes, but here I focus on the following four: mixed conifer forest, shrub, sparse meadow, and dense meadow. Aspen was also detected in the 1997 NAPP and both NAIP images, which I also take into account for a total of five vegetation classes for all dates including and after 1997. I chose to focus on these five because I am looking at the changes in aboveground carbon which require aboveground vegetation. The other cover classes had no aboveground vegetation (i.e. water, rocks, etc).

To test the accuracy of this vegetation identification and classification Boisrame (2016) validated the 2012 map using 164 ground reference points mapped in 2013-2015 with a handheld Garmin GPS unit and manually classified another 300 randomly selected points from the photographs (Boisrame 2016, Naranjo 2015). Overall, accuracy of the remotely sensed images was 92.9% (Naranjo 2015). Ground-based mapping was limited to within 1.5km of hiking trails due to difficult terrain.

To identify landscape change, Boisrame (2016) calculated the total cover for each vegetation type in each image, adjusting for the steep topography of the area to avoid underestimating vegetation cover in steep slopes (Dorner et al. 2002). This vegetation dataset forms the basis of my aboveground carbon study.

Data Analysis

Biomass and carbon calculations

Carbon calculation requires integrating multiple datasets to characterize biomass density and carbon storage. To determine total area of each vegetation type, I used the 'calculate geometry' tool on ArcMap on Boisrame's (2016) maps with the 5 vegetation classes (aspen, mixed conifer, shrub, dense grassland, and sparse grassland) for each of the 5 data years (Figure 2). The following steps were only performed on data from 2012 because that was the only year with matching data from LandFire ("Data Distribution Site" 2012) and Boisrame (2016). Therefore, I used the breakdown of existing vegetation types (EVTs) by LandFire vegetation types in 2012 as the basis for all years.

To get the stand characteristics for 2012 I used the overlay tool in ArcMap to display Boisrame's (2016) map with the 5 vegetation classes over the 2012 LandFire map with the multiple EVTs, heights, and % covers (Figure 2). I then clipped the LandFire data to match each of the 5 vegetation classes. As some of the LandFire EVTs made up very small percentages within a vegetation class, I only used the ones that together cover at least 90% of the area within that vegetation class ("LANDFIRE Data Distribution Site" 2012).

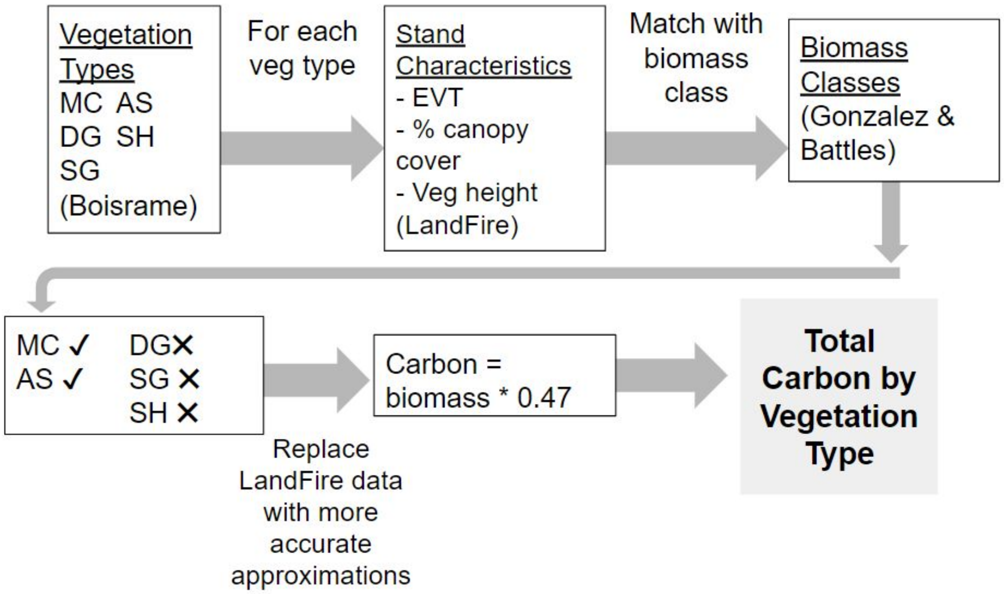

Figure 2. Flowchart of method steps to calculating carbon by vegetation type.

To identify the most fitting biomass class (Gonzalez et al. 2015, Battles, unpublished data) I used the EVT, height, and percent cover from LandFire ("LANDFIRE Data Distribution Site" 2012), (Figure 2). Each of these EVTs has multiple land cover pairings in Landfire/Gap (LandFire 2012). Battles et al. (2014) calculated the aboveground main biomass (Mg/ha) for the land cover types in Landfire that exist in California, including those in the ICB (Gonzalez et al. 2015). I calculated the weighted biomass and carbon stock for each of the 5 years that were included in Boisrame's (2016) study: 1969, 1987, 1991, 2005, and 2012. The only vegetation class that did not have all 5 years on record was aspen, occurring only since 1997. I assumed that the breakdown of LandFire EVT, percent canopy cover, and vegetation cover remained the same throughout the years for each of the 5 vegetation classes. To project total biomass backwards in time, I used 2012 biomass values per hectare for each of the 5 vegetation classes with Boisrame's (2016) land areas for the other 4 data years (1969, 1987, 1997, and 2005).

However, the results from the LandFire data ("LANDFIRE Data Distribution Site" 2012) did not match Boisrame's (2016) data for 3 vegetation classes: shrubs, sparse grassland, and dense grassland (Figure 2). LandFire EVT 'Mediterranean California Red Fir Forest' constituted the highest percent of area covered for all vegetation classes. Although this EVT is appropriate for the forest ecosystems, it should not have been the case for the other 3 vegetation classes (shrubs, dense grassland, and sparse grassland). Because Boisrame's (2016) data was ground truthed to an accuracy ranging of 87-94% (Boisrame 2016, Naranjo 2015) and LandFire does not distinguish between dense and sparse meadows, I used a more fitting biomass number according to the vegetation described for these areas in her paper that would more accurately estimate carbon (John Battles, in person communication).

I used these biomass numbers to calculate the weighted total carbon (MgC) per vegetation class. Area per vegetation type was calculated from the shapefiles. I assumed carbon to be 47% of the biomass, as this is a standard value applied when carbon is not directly measured (Gonzalez et al. 2015, McGroddy et al. 2004).

RESULTS

Vegetation Change and Carbon Storage

Changes in vegetation area and carbon

Mixed conifer area decreased over the study period and area increased in every other vegetation class (Figure 3) but, mixed conifer remained the largest vegetation class at the ICB. Over the study period, conifer covered decreased by 2,080ha (24.39%), shrubs increased by 360ha (35.84%), dense grassland increased by 136 ha (211.94%), sparse grassland increased by 1527ha (189.39%) and aspen increased by 1.8ha (20.33%).

Sparse grassland had the most growth in terms of total area covered, with most of this increase in area occurring between 1969 and 1997. Coincidentally, mixed conifer had the greatest decrease in land cover during those years as well. Both vegetation classes continued to increase and decrease in area, respectively, but not as quickly as during the first 31 years of the study.

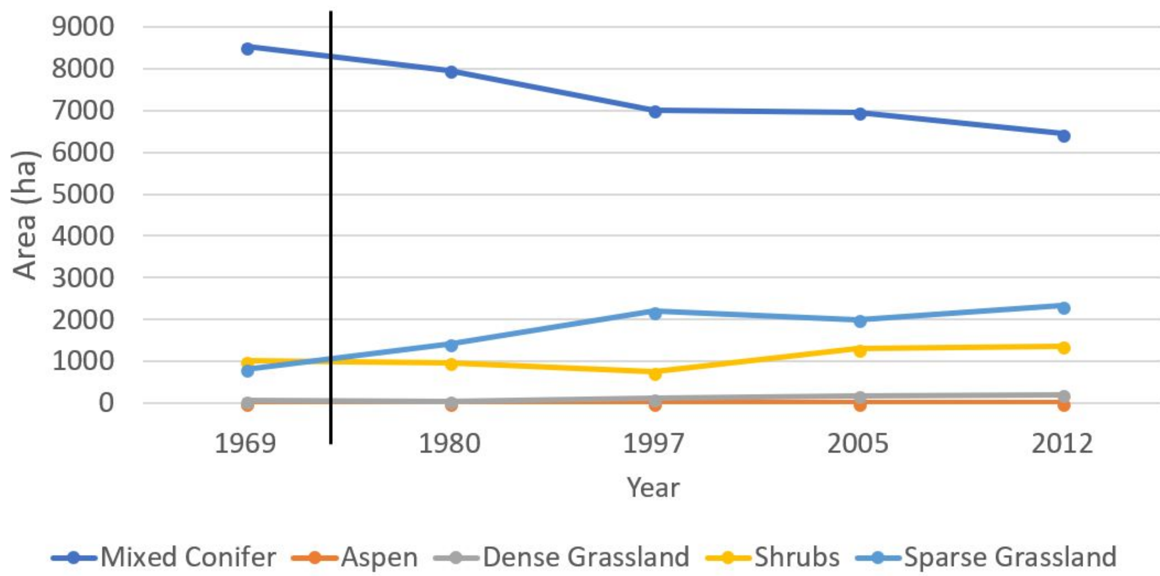

Figure 3. Area by Vegetation Type. I used ArcMap to calculate the area in hectares of the five vegetation classes. The black line represents 1972, the year Yosemite's managed wildfire program was established.

The changes in area are closely reflected in the changes in carbon stored for the ICB. The density of aboveground carbon is much higher for mixed conifer than for any other vegetation class (Table 1). Weighted mean carbon varied from 97.13Mg/ha for mixed conifer to 0.36Mg/ha for sparse grassland.

Table 1. Carbon density by vegetation class and change in carbon. I determined weighted mean carbon per hectare by using biomass values from Gonzalez *et al*. (2015). Change in carbon is calculated between 1969 and 2012, except for aspen which is calculated between 1997-2012.

Vegetation Type	Weighted Mean Carbon (Mg/ha)	Change in Weighted Mean Carbon (Mg/ha)	Change in Carbon (%)
Mixed Conifer	97.13	-202,078.23	-24.36%
Aspen	59.99	111.45	+20.33%
Shrubs	14.79	5324.68	+35.84%
Dense Grassland	0.96	103.91	+211.91%
Sparse Grassland	0.36	552.49	+189.39%

Therefore, reducing area in mixed conifer, even if it is replaced by other vegetation classes, does not make up for the overall loss of carbon (Figure 4) resulting in a 24.36% loss of carbon in the ICB during from 1969 to 2012 (Figure 5). There was an overall loss of land area in the mixed conifer vegetation class, with some land converted from shrubs, grasslands, or aspen to mixed conifer.

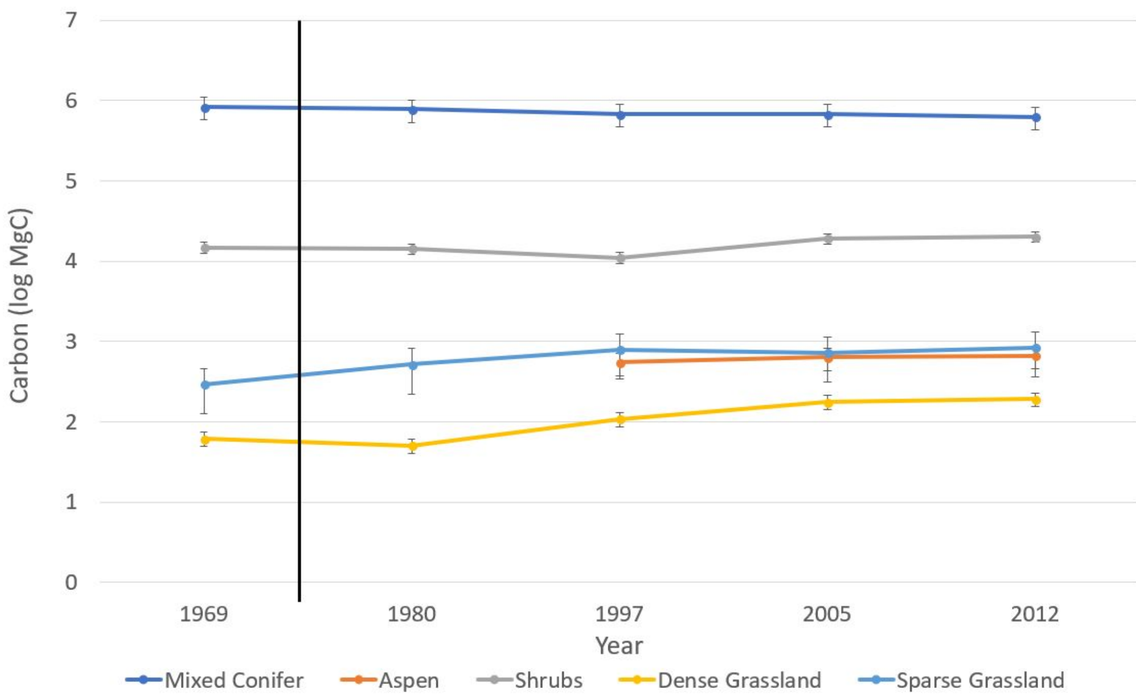

Figure 4. Carbon per vegetation class. The carbon stored within mixed conifer far exceeds that stored within the other vegetation classes. The error bars are plus or minus one standard error based on inaccuracies in biomass class assignments. Error bars are calculated from the standard errors in the biomass classes.

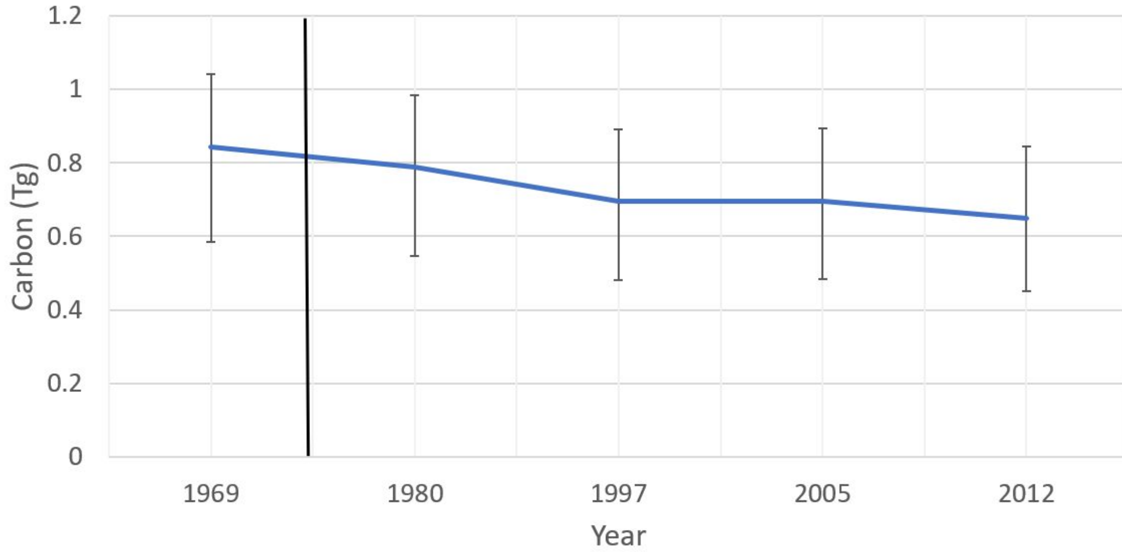

Figure 5. Carbon storage in the Illilouette Creek Basin. There is a nearly constant decrease in carbon in the whole ICB over the study period. Error bars are calculated from the standard errors in the biomass classes.

Illilouette Creek Basin Carbon Maps

To better visualize the spatial changes in carbon in the ICB, I created carbon cover maps (Figure 6), based on the vegetation changes from Boisrame's (2016) maps (Figure 1) and the biomass estimations from Gonzalez *et al.* (2015). The maps show the changes in carbon density throughout the years due to vegetation change and were created using the carbon densities from Table 1. The darker the color, the more carbon density that area holds. The lighter colors represent less carbon density, or no carbon density in the case of water and rock. When comparing 1969 to 2012, the area covered in dark red has visibly diminished.

Estimating exact changes in carbon is difficult because LandFire data is grouped into categories, so if there is a change in stand characteristics (EVT, cover height, and %cover) that is not a large enough change to switch categories, it will not be detected.

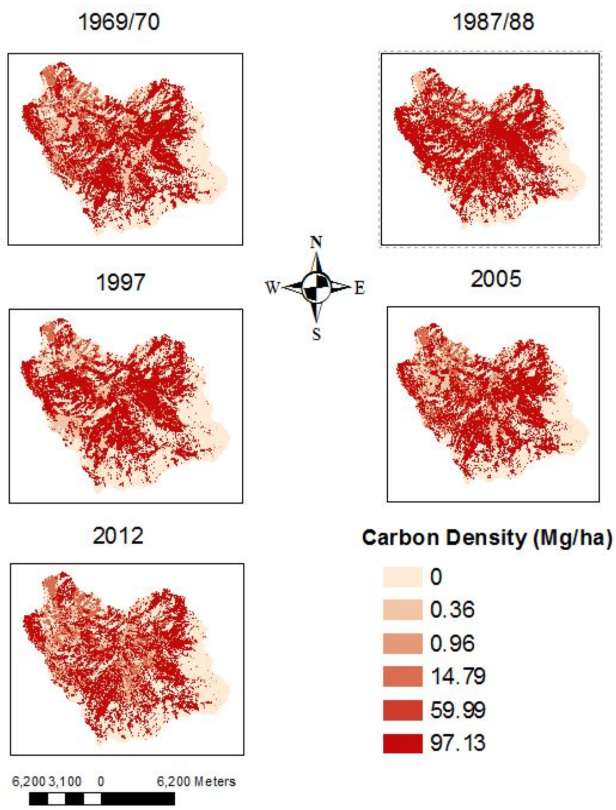

Figure 6. Carbon density map. These maps track the spatial changes in carbon using vegetation changes.

DISCUSSION

There was an overall decrease in carbon in the ICB due to a decrease in the area of mixed conifer, proving my hypothesis correct. The high carbon density in mixed conifers makes it so that any changes in its land area greatly affect the carbon storage in the ICB as a whole. The main vegetation conversions were from mixed conifer to either sparse grassland or shrubs (Boisrame 2016). However, 61-73% of mixed conifer area in 1969 remained so in 2012, either because it had not experienced a stand-replacing fire or conifer had regrown post-fire (Boisrame 2016).

The carbon calculations only took into account aboveground, live carbon but ignored below-ground carbon (roots and soil) and other carbon pools (dead and down wood, litter, etc.). Grasslands tend to store most of their carbon in the soil, as do wetlands and meadows, all of which increased in area from 1969 to 2012. Dense meadows mostly increased in area, but had a slight decrease between 2005 to 2012, probably due to the drought in California at the time (http://droughtmonitor.unl.edu/). Aspen is first seen in the data in 1997 because it was restored through the removal of conifer trees by fire (Jones et al. 2005).

Although this study shows that aboveground carbon decreased, it is not a complete account of all the carbon in the basin. I expect carbon storage to further decrease should all carbon pools be take into account. Biomass was calculated solely based on 2012, when the fire regime had almost reverted back to its pre-colonial frequency resulting in less dense forests with less biomass. The ICB in 1969 likely had more biomass than is estimated with the 2012 data, and therefore the reduction in biomass between 1969 and 2012 is greater than what I have estimated in this study. Therefore, the loss of carbon is also likely much higher than the estimations in this study.

Political attention is focused on short-term storage or sequestering carbon, but major consideration should be given to long-term storage to make a difference in the trajectory of climate change. With this re-established mixed severity, high frequency fire regime carbon will be stored for longer periods of time because it is less likely to experience a stand replacing fire and be more resilient to forest fires (Fulé and Laughlin 2007). vegetation classes become more equally represented on the landscape in similar sized patches resulting from fragmentation and reduction of conifer forests in the ICB (Boisrame 2016). This increased fragmentation and reduced patch sizes decrease connectivity of available fuels (Miller and Urban, 2000a), reducing the risk of extreme fire in the ICB. However, an increase in dense shrubland patch sizes could counteract the reduction fire risk from mixed conifer fragmentation (Boisrame 2016).

Not only that, but the natural fire regime has restored the sparse canopy cover in the forest that leads to a reduction in water loss from transpiration and canopy evaporation and an increase in snow retention (Boisrame 2016). As a result there are increased streamflow yields from Sierra Nevada watersheds and there is less competition for water sources in forests (Boisrame 2016, Grant et al. 2013), meaning that forests will be less stressed during times of drought. Since lightning fires do not require as much intense planning as prescribed fires or mechanical thinning, the cost of fire and forest management, fire suppression, restoration and fuel treatments is reduced and firefighter safety increase (Collins 2007, Ingalsbee 2001, USDA/USDI 2006). The ICB is now more resistant to disturbances such as insects and disease outbreaks, as well as possible changes in the climate (Collins 2007). The fire-induced mortality in the ICB today is similar historical patterns (Collins 2007). In addition to reducing fuels, fire also creates pockets of high mortality where space in the canopy opens up. This serves to increase growing space and light availability, favoring the growth of shade-intolerant species like ponderosa pine (*P. ponderosa*) and sugar pine (*P. Lambertiana*) which have been in decline since fire suppression started.

Sources of Error

The main sources of error for carbon estimates resulted from the assignment of biomass classes because (1) LandFire data which at times contradicts itself and (2) I could not use all of the LandFire EVTs within each of the 5 vegetation classes. LandFire (2012) vegetation data is broken down into three categories: EVT, vegetation height, and % cover. In many cases an EVT of a forest-type vegetation height would have a corresponding vegetation in terms of shrub height or herb height instead of forest height, making it impossible to match to a biomass class in Gonzalez et al. (2015) or Battles et al. (2014). Similarly, an EVT of a forest-type vegetation would have a corresponding % canopy cover in terms of shrub or herb cover, again making it impossible to match to a biomass class. Battles et al. (2014) only had biomass classes for vegetation classes in which all three LandFire data categories matched (i.e. forest vegetation, forest height, forest cover). The LandFire categories were a limitation I encountered while analyzing the data and I assumed that the EVT was correct and chose the second most prevalent vegetation height and percent cover that matched the EVT.

The second source of error arose from having multiple LandFire EVTs per each of Boisrame's (2016) vegetation classes. For example, mixed conifer contained 29 EVTs ranging from red fir forests (61.62%) to lodgepole pine forest and woodland (7.63%) to annual grasslands (0.02%). The percents represent the amount of area the EVT occupies within the mixed conifer land area. To simplify the calculations, and because some of these EVTs represented such a small percentage of the mixed conifer area, I used only the EVTs summed to at least 90% of the area. This left the calculation with 6 EVTs that made up 91.18% of the mixed conifer area. I made this calculation for each of the 5 vegetation classes, but it only worked for mixed conifer and aspen. The standard errors from the biomass classes were then extrapolated to the carbon calculations.

Another source of error is the assignment of one EVT to the entire of area of shrubs, sparse grassland, and dense grassland based on the description of vegetation in Boisrame (2016) and suggestions from Battles (personal communication). This was done because LandFire cannot distinguish between dense and sparse meadow and Boisrame (2016) had a high level of accuracy in vegetation identification.

CONCLUSION

Although the fire regime has almost reverted back its natural frequency and severity, the ICB is just beginning to return to its pre-fire suppression conditions (Boisrame 2016). Frequent, mixed severity fires have increased the heterogeneity of the ICB, reduced its risk of stand-replacing wildfires, created a more open forest with less fuel and lower density, and increased the amount of water in Sierran watersheds. Although aboveground carbon was lost, there are other pools of carbon that must be accounted for, as well as considering the long-term storage of carbon and the multiple benefits that a fire brings. The fire regime in ICB changed in 43 years, as did the vegetation profile. Other forests that have been under fire suppression for longer may take over 200 years to revert back to a natural fire regime to be restored (Miller and Urban, 2000b), without taking into account climate change. However, this change is a necessary step to prevent further loss of timber, carbon, life, and structures in high severity wildfires that are difficult to control. The ICB can serve as a guide for what to expect when trying to re-introduce a natural fire regime to other Sierran forests, as well providing a reason to implement policy and management plans that will increase the use of prescribed fires throughout the state.

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