Maximizing Carbon Dioxide Storage in Oak Savanna Ecosystems: Identifying the Effects of Ecosystem Disturbances

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ABSTRACT

Identifying opportunities to combat threats of climate change that have important implications for the international community has become a paramount objective for a sustainable future. In order to achieve meaningful mitigation, all of these available opportunities must be explored. Aboveground biomass of terrestrial ecosystems absorbs large quantities of carbon dioxide through photosynthetic processes, and as such, these ecosystems are a good opportunity to increase carbon dioxide sequestration on a large scale. Different ecosystem disturbances have been shown to significantly alter the ability of forest ecosystems to store carbon. However, little literature has considered these disturbances and their associated affects on carbon storage in Oak Savanna ecosystems, which span over large land areas of the United States. This study aims to quantify the effects of ecosystem disturbances, namely grazing and wildfire, on live tree carbon stocks of Oak Savanna ecosystems and provide insight onto how landowners ought to manage disturbances in order to uphold live tree carbon stocks. Data for live tree carbon stocks were analyzed in R and Excel, including summary statistics, Welch's Approximate t-Tests, and regression analysis. There was no significant difference in carbon stocks between ecosystem disturbance histories, as p-values for all pair-wised tests were $>.20$. Regression analysis showed a strong, positive correlation between average tree size and carbon density on a plot scale (r-squared=.91, p-value=.000841).

KEYWORDS

climate change, wildfire, grazing, land management, tree size

INTRODUCTION

In 2007, the International Panel on Climate Change published its fourth assessment report detailing the potential effects of climate change (IPCC 2007). Eight years later, world leaders convened in Paris to make new commitments to prevent now well-understood and rapidly occurring effects of climate change, namely rising sea levels (Vermeer 2009), increased disease due to invasion by species into non-native habitats (Hughes 2000), and irregular weather patterns (IPCC 2007). Importantly, Paris agreements work to target the source of climate change inducing compounds but to accomplish successful, aggressive mitigation scenarios, all opportunities for reducing greenhouse gas concentration must be taken advantage of.

Targeting terrestrial ecosystems is a good opportunity for climate change mitigation as they are large and stable carbon sinks, and the characteristics that determine carbon storage are malleable on short time scales (Smith 2004). Soils alone are estimated to hold as much as 1760 petagrams of carbon globally (Batjes 2014), and estimates for carbon storage in above ground biomass of deciduous forests of the West Coast alone are 43.5 gigatons of carbon (Botkin et al. 1993). Thus, with such large capacity, terrestrial ecosystems must be managed to best uphold their potential for carbon storage. Different ecosystem disturbances can alter carbon stocks by decreasing the abundance of above ground biomass, which affects nutrient cycling. Put another way, decreasing the productivity of ecosystems leads to decreased carbon storage (Jandl et al. 2007). By the opposite mechanism, an absence of ecosystem disturbances leads to densely vegetated areas whose above ground biomass exhibit different characteristics. Increased competition in these areas has been linked to lower average tree size, which is important because we understand live tree carbon stocks to be a function of tree size directly (Dolanc et al. 2014). Importantly, however, neither a higher abundance of trees nor an increased number of larger trees has been explicitly shown to yield higher live tree carbon stocks. Characteristics that determine nutrient cycling and total biomass of terrestrial ecosystems are subject to different land management techniques such as mechanical thinning, grazing, and prescribed burns, which change physical aspects of these ecosystems.

Oak Savannas are important study areas because they are land areas that expand over much of the Pacific Northwest, the Southwest and the Midwest regions of the United States (EPA). Additionally these are ecosystems that experience a variety of disturbances as landowners aim to maintain livestock as well as decrease the chances of high-severity wildfires, the likes of which these ecosystems have faced in recent years. Previous estimates for live tree carbon stocks of terrestrial ecosystems cannot be applied because carbon storage depends on factors such as species composition and dominant physical, chemical, or biological properties of soil which are variable across ecosystems (Johnson and Curtis 2001). Previous studies have also shown that the effects of different management techniques, namely prescribed burning and biomass removal are variable across landscapes. Studies have found that saw log removal increased soil carbon storage, while whole tree removal led to a decrease in carbon storage, however saw log removal techniques are not applied to Oak Savannas (Johnson and Curtis 2001). Other studies show that because tree density is positively correlated with carbon storage, disturbances in ecosystems that decrease tree density will decrease ecosystem carbon (Nowak and Crane 2001). Although the studies on the effects of forest management are robust, these topics are still being explored and little literature has applied these considerations to Oak Savannas.

The central topic of this study is how different ecosystem disturbances—namely grazing and wildfire—affect the ability of Oak Savannas to store carbon. This study explores the following questions: (1) How do grazing and wildfire affect total live tree carbon? (2) How do grazing and wildfire affect tree size? (3) How is tree size correlated with carbon content of living trees? These are important questions to consider because we expect that land areas that experience grazing and wildfire disturbances will have less biomass and exhibit lower carbon storage. Secondly, live tree carbon stocks are directly a function of tree size, which would lead us to expect tree size will have a strong, positive correlation with carbon density on a plot level. As mentioned before, however, increased tree abundance can also lead to increased carbon density and studies cited earlier show that increasing tree abundance and tree size are incompatible. This is an important aspect of this study because exploring the relationship between average tree size and carbon storage will inform us about the tradeoff between increasing overall tree abundance and increasing overall tree size, and which is more important for carbon storage.

METHODS

Site description

I used the Hopland Research and Extension Center (HREC) to study the effects of different ecosystem disturbances. HREC is located in the northern outskirts of Sonoma County and is an extension of UC Berkeley. The center is exposed to a Mediterranean climate, with average annual rainfall of 1.04 meters and mean temperatures of 21 °C during the summer and 7 °C during the winter (HREC Website). Within the center, disturbances vary greatly but only diverged since the facility's inception in 1951. These conditions allowed a study of the effects of an increasing gradient of disturbances. Three pastures, each with a different disturbance history, were studied (Table 1).

Table 1. Pasture Identity by Treatment Type.

Pasture Identity	Treatment Type
Upper Horse	Currently Grazed & Burned
Figtree	10 Years Since Last Graze & Burned
Cattleguard	Never Grazed & Unburned

Sampling procedure

To determine carbon storage in each study site, I quantified above ground biomass of living trees in each pasture. 5 plots within each pasture were randomly located on a 160m grid in ArcGIS. 10m radius plots were located in the field using Avenza software on an iPhone and a reel tape. Plots within each pasture were numbered by cardinal directions: the northernmost GPS point in a pasture was assigned as plot 1, and plot numbers increased towards the south of each pasture. If two points were equal in latitude, the westernmost point was assigned the lower plot number. If GPS points were inaccessible, they were excluded from data collection.

Determining Biomass of Living Trees

Tree sampling was conducted on all living trees present in the 10m radius study plots. For above ground biomass of trees, I measured diameter at breast height (D.B.H; 1.4m) and tree height. These measurements were made for all living tress greater than 8cm at breast height. In order to measure D.B.H., I used a tape measure that yields diameter measurements directly when wrapped around a tree at 1.4m above the ground (Leverett and Bertolette 2015**)**. To determine tree height, I used a hypsometer that utilizes trigonometry by determining (1) distance from a tree using radio communication and (2) the angle at which it is held from level to a beacon on the tree to the top a tree. If no trees were present in the 10m circular plots, no tree data was collected from these plots but the plots were included in pasture-scale analysis with 0 Mg C / ha of live tree carbon.

Determining Carbon Content of Living Trees

Volume estimates for each tree were generated using species-specific allometric equations that quantify volume as a function of DBH and height. Once an estimate for volume was obtained in ft^3, multiplying this value by the wood density provided for each tree species yielded biomass estimates (FIA 2014). Tree species that were included in data collection were *Quercus agrifolia and Q. alba.* Tree species were determined by comparing pictures taken in the field to the most prevalent tree species listed on the HREC website. Any tree species that were unknown were assigned wood density values from the “other or unknown live tree” column in the FIA index, listed at code #999. After making these estimates for biomass, I adjusted my value by a conversion factor of 50%, which implies that about half of the tree by weight is organic carbon (Ritson and Sochacki 2002). To derive an estimate for weight of carbon per unit area, I calculated the area of 10m radius study plots as π*$10m^2$ which is equal to $314m^2$, and divided carbon stocks in each pasture by this value. These values were converted to hectares and tons to express carbon density as $\frac{Mg\ C}{Ha}$.

Statistical analysis

Statistical analysis was conducted between each pair of pastures in the study to determine (1) if there was a significant difference in average live tree carbon stocks between pastures as well as (2) if there was a significant difference in average tree sizes between pastures. The null and alternative hypotheses were as follows:

Live Tree Carbon Stocks

H_0: difference in mean carbon content between pastures is zero

H_A: mean carbon content is different between pastures

Average Tree Size

H_0: difference in mean tree size between pastures is zero

H_A: mean tree size is different between pastures

To determine if there was any significant difference in mean carbon stocks or tree size between pastures, a Welch's Approximate t-Test was conducted in Excel. A standard Student's t-Test was not conducted because it was unclear if variations between groups were the same. The relationship between average tree size and carbon content was also analyzed in a linear regression analysis, with plot average tree size as the explanatory variable and plot carbon content as the response variable, using the lm() function in R.

RESULTS

Live tree carbon stocks by disturbance type

Results for average carbon per hectare (Table 2).

Table 2. Summary statistics for average carbon content by disturbance history

Disturbance type	Average Carbon Content	Standard Deviation
Continuous grazing then wildfire	37.7 MgC ha^{-1}	54.2 MgC ha^{-1}
10 yr since grazing then wildfire	13.1 MgC ha^{-1}	22.7 MgC ha^{-1}
No grazing and no wildfire	83.9 MgC ha^{-1}	110.5 MgC ha^{-1}

From these preliminary results, it is tempting to say that unburned and unmanaged pastures have much higher carbon stocks than any pasture with other disturbances, as the discrepancy here is as much as roughly 50 MgC ha^{-1}. However, the t-tests indicated that there were no significant differences between any of the paired histories (Table 3).

Table 3. Difference in plot scale live tree carbon content by disturbance type

Test	Group 1	Group 2	t-Stat	DOF	P-value
No disturbance vs. continuous grazing then wildfire	No grazing and no wildfire	Continuous grazing then wildfire	0.77	4	.484
No disturbance vs. 10 year since last grazed then wildfire	No grazing and no wildfire	10 yr since grazing then wildfire	1.25	3	.299
10 year since last grazed then wildfire vs. continuous grazing then wildfire	10 yr since grazing then wildfire	Continuous grazing then wildfire	-0.89	5	.414

Tree DBH by pasture type

Averages for DBH by each pasture were calculated (Table 3).

Table 3. Summary statistics for average tree size by disturbance type.

Disturbance type	Average DBH	Standard Deviation
Continuous grazing then widlfire	30.3 cm	4.56 cm
10 yr since grazing then wildfire	24.9 cm	2.64 cm
No grazing and no wildfire	34.2 cm	8.55 cm

Results for the Welch's approximate t-Tests on average tree (Table 4).

Table 4. Difference in plot scale tree size (cm) by disturbance history.

Test	Group 1	Group 2	t-Stat	DOF	P-value
No disturbance vs. continuous grazing and wildfire	No grazing and no wildfire	Continuous grazing then wildfire	0.33	4	.758
No disturbance vs. 10 year since last grazed and wildfire	No grazing and no wildfire	10 yr since grazing then wildfire	0.80	3	.482
10 year since last grazed and wildfire vs. continuous grazing and wildfire	10 yr since grazing then wildfire	Continuous grazing then wildfire	-0.83	5	.444

Relationship between average DBH and carbon content of pastures. To determine if there is a relationship between average tree size, a scatterplot was constructed in R and a linear regression model was run (Figure 1).

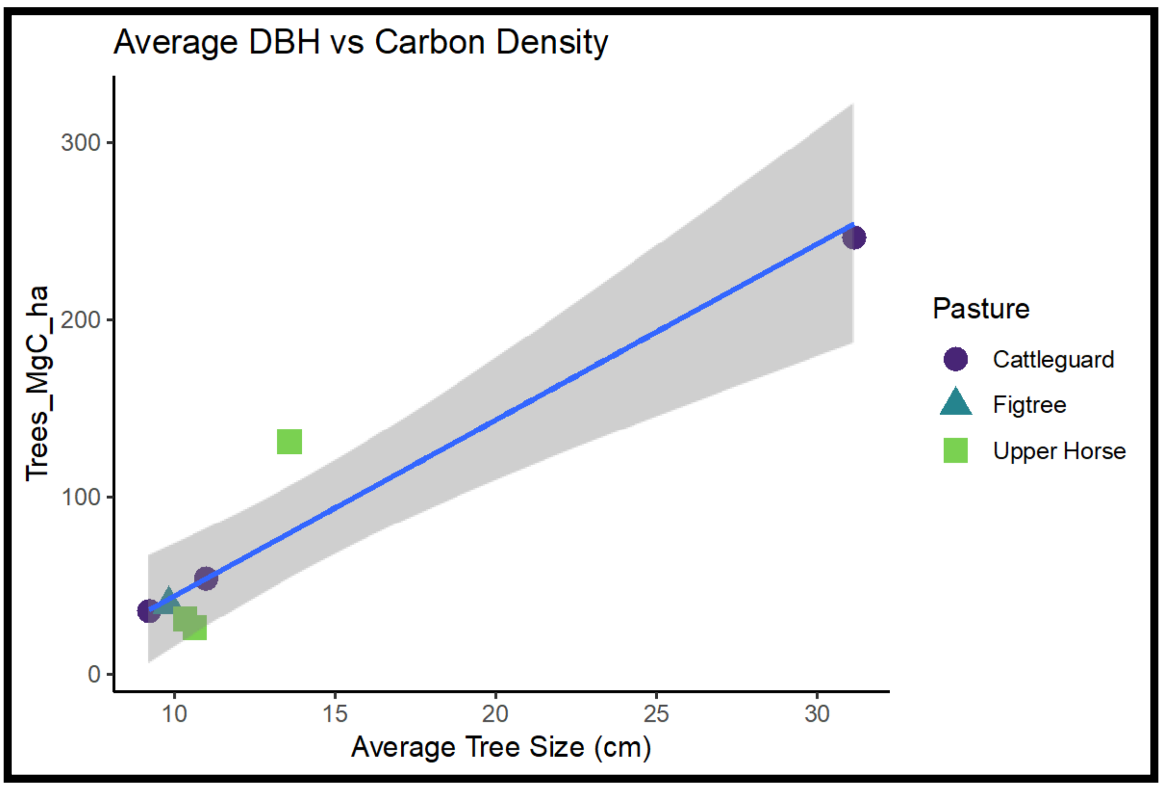

Figure 1. Relationship between average tree size and carbon density at a plot level.

To start the regression analysis, I assumed that (0,0) was a point on this relationship, which is intuitive because a tree size of 0cm means there is no tree, and if there is no tree there will also be no carbon. Results also showed that the slope of the best fit line was 9.94, which means that each increase in DBH of 1cm leads to an increase of 9.94 MgC ha^{-1}. This slope had a p-value of .000841, which suggests that this slope is very unlikely to be observed by chance. This relationship had a standard error of 26.7, which means that at any point on this graph, we expect that a certain DBH will yield a carbon density that is $\pm$ 26.7 MgC ha^{-1} from the actual value.

DISCUSSION

The results of this study have several important implications for disturbance management in Oak Savanna ecosystems. The results suggest that there is no significant difference between carbon stocks in any pastures with different disturbance histories. This did not match my hypothesis or general intuitions about the disturbances analyzed. Wildfire, for instance is expected to reduce carbon stocks by burning biomass and releasing carbon into the atmosphere in the form of carbon dioxide. In this case then, we would expect Cattleguard to have much a much higher carbon content than Figtree and Upper Horse, as the latter two burned in a wildfire. Additionally, grazing should decrease the amount of overall trees in a pasture and thereby the carbon content of those pastures, so Figtree and Upper Horse should be much lower. To understand why this is not the case, it is necessary to explore the effects of disturbances in more depth.

Effects of grazing on tree size

Tree size is an important factor to consider because of its functional role in determining carbon content of living trees, evidenced in allometric equations (FIA Index). Statistical analysis showed that there is no significant difference in average tree size between pastures that are subject to grazing and those that are not (p-value >.05). This means that we fail to reject the null hypothesis that the difference in average tree size is zero, but importantly, this does not mean grazing never affects tree size. Other studies have found, for instance, that higher competition between trees leads to lower growth rates and as such, lower tree size (Vandermeer & Goldberg 2003). In this case, I expected that pastures in HREC would follow this trend, and Upper Horse would have significantly higher tree size, because it is the only pasture that is actively grazed and therefore faces less competition. It is possible that this study found no significant difference due to an insufficient amount of data, which means that there was not enough statistical power to detect any real differences in tree size between disturbance types. However it is also possible that the sheep used at HREC to graze land areas simply prefer grass to oak seedlings, so grazing has no effect on trees. It is also possible however, that there are other factors that limit tree populations such as insect herbivory of seedlings. Other studies have found that insect herbivory can damage or even kill seedlings, and in some instances has been shown to reduce ring size by 30% in *Quercus ilicifoua* trees (Crawley 1989). My study does not explore this directly, so it is unclear if this is what is responsible for results found.

Effects of wildfire on live tree carbon stocks

That there was no significant difference in carbon stocks between pastures (p-value>.05) that burned and pastures that did not is an especially striking result. Intuition and research tells us that wildfires that burn biomass will reduce live tree carbon stocks, depending on their intensity. For instance, studies conducted in mix-conifer forests have found that high-severity wildfires decrease carbon storage of an area by as much as 80.2 MgC ha^{-1} (North and Hurteau 2001). Normally, we might be able to identify higher average tree size as an explanation for the apparent discrepancy between previous results and the results of this study. Instead, we should recognize the effects of grazing on vegetation density as the explanatory factor at play here. Grazing could reduce the amount of overall vegetation in an area of land, which prevents high-intensity wildfires by decreasing the amount of fuel available, leading to fewer live trees being burned. Given these factors and that Upper Horse is currently grazed, it is perfectly reasonable that this pasture did not have significantly lower carbon content.

Relationship between average tree size and carbon content

Despite a lack of evidence for differences in carbon stocks between disturbance types, it is still valuable to consider the relationship between average tree size and carbon content. The two possible relationships to pursue in order to maximize carbon stocks are: (1) increase the average abundance of trees, in order to increase amount of sequestration from individual trees or (2) increase the average size of trees while neglecting overall tree abundance, with the hopes that larger trees sequester significantly more carbon. With a p-value was of .00084, there is overwhelming evidence that carbon density at a plot level is strongly correlated with tree size. This means that higher average DBH leads to more plot carbon, so higher average tree size does not reduce abundance enough to cause a net negative effect on plot carbon. Analysis was first done with all data points (carbon stocks and average tree size for each plot), but to ensure that two extremely high values did not skew the relationship, they were removed from analysis. Even without these high values, the relationship was still significant. An r-squared value of .91 indicates that 91% of the variations in live tree carbon stocks at a plot level can be explained by average DBH. This result suggests that regardless of disturbances observed here (given that none of them had a significant impact on tree size), in order to maximize carbon storage, disturbances should be managed to maximize tree size.

Limitations & future directions

Several limitations in this study need to be recognized, and as such, more comprehensive research needs to be done to develop a disturbance management plan that maximizes carbon storage. Crucially, this study had a limited number of data points due to lack of time and resources, so the conclusions may not accurately reflect disturbances analyzed and associated ecosystem responses. Additionally, this study was limited to analysis of stems of living trees, and other characteristics of forest ecosystems such as canopy size as well as smaller shrubs, grasses and soils play an important role in carbon stocks and nutrient cycling. Thus, to get a more accurate picture of total carbon stocks in future studies, these factors should be included.

Any further research on this topic should emphasize collecting more data, which would increase statistical power to detect any real-world effects of disturbance on average tree size and carbon content. Future studies should also analyze more explicitly the tradeoff between increasing overall abundance of trees and increasing tree size. Though the results of this study show that higher average tree size leads to higher carbon content, it did not focus on comparing the carbon content of pastures with higher average tree size against pastures with a higher abundance of trees. This analysis will provide a more pointed explanation of how these factors should be weighed against each other.

Broader implications

Current global warming trends demand that all present opportunities for mitigation be pursued. This study finds that one of these opportunities is to increase average tree size in land areas to increase carbon stocks in terrestrial ecosystems as much as possible. The scale at which terrestrial ecosystems can mitigate climate change still needs to be explored, but preliminary results suggest that this is a worthy avenue to take. If studies find that increases in carbon stocks from increased tree size are too big to be ignored, land use policy could soon change to reflect these findings. As global warming increases, so do the threats of drought and subsequently wildfire, which directly influence live tree carbon stocks in any ecosystem. It is important then, to understand and implement the practices that will mitigate potential losses in carbon. Droughts will diminish the ability of ecosystems to support a variety and abundance of above ground biomass. Increased temperatures will lead to drier ecosystems and higher potential for wildfire. This suggests that land areas should be managed to decrease increased risk of wildfire, at the highest priority. If further studies find that wildfire significantly decreases carbon stocks in the long term, then it is imperative that land owners increase grazing to decrease small shrubs that serve as fire fuel.

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