The Effects of Forest Management on Carbon Dynamics in California Sierra Nevada Mixed Conifer Forests

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ABSTRACT

Predicted increases in atmospheric carbon dioxide (CO_2) have generated interest in strategies to decrease atmospheric emissions; one such strategy is carbon sequestration in forests and forest products. Forests are an essential part of the carbon cycle and have the potential of storing large quantities of carbon at the stand level and in wood products. The purpose of this study is to better understand the net carbon consequences of even-aged (clear-cuts) and uneven-aged (group selection) management regimes compared to unmanaged reserve stands using long-term data records from the University of California Blodgett Research Forest. I generated growth equations that modeled the stands under a no harvest let-grow scenario and that modeled the regenerated stand. I also conducted a life-cycle analysis of the harvested wood using Stewart and Sharma's (2015) Carbon Calculator for Timber Harvest Plans. I found that both group selection and clear-cut harvesting resulted in higher net carbon benefit than their no-harvest counterparts; with group selection resulting in a higher percent increase in carbon benefit than clear-cut. I also found that when substitution benefits of using wood products instead of CO_2 intensive building material were not included in the carbon benefit analysis, clear-cut did not increase carbon benefit. These findings suggest that the best way to manage forests as carbon sinks for Blodgett Forest is to harvest the stand via group selection.

KEYWORDS

Clear-cut, group selection, carbon sequestration and capture, Jenkins equation, life cycle analysis

INTRODUCTION

Understanding carbon cycling and accurately measuring carbon pools in forests and forest products is critical for estimating future global carbon budgets (Zhang et al. 2012). Worldwide forest ecosystems are enormously important to understanding carbon sinks and currently represent 77 percent of global terrestrial carbon stored aboveground (Goers et al. 2012). In addition to the forests themselves, carbon may be stored for long periods in harvested wood products (HWPs). In 2005, forests and forest products provided net carbon sequestration equal to 10 percent of total U.S. CO_2 emissions (Woodbury et al. 2007). Carbon sequestration in forests and HWPs also offers a more cost effective means of controlling emissions compared to developing new technologies or implementing taxes and other regulations to decrease emissions (van Kooten et al. 2004). Additionally, the substitution of cost-, energy- and emissions-intensive building materials, such as concrete and steel, with forest products may reduce net greenhouse gas (GHG) emissions; these reductions are estimated to be up to 11 times larger than the total amount of carbon sequestered in forest products annually (Larson et al. 2012). Understanding the role of forests and HWPs in the global carbon cycle is therefore vital for the regulation of CO_2 emissions.

California has already begun to incorporate forest and HWPs carbon sinks into their climate action policies. California forests store an estimated 1.12 billion bone-dry tons of above ground carbon, with mixed conifer stands storing the most (Christensen et al. 2007). The Sustainable Forest Target under California’s 2014 Climate Change Scoping Plan sets a state-level target for maintaining and enhancing net carbon sequestration through forest management practices subject to the Forest Practice Act (Climate Change Scoping Plan 2014). Under the this plan, The Forest Carbon Plan mandates that California forests be managed to maintain net carbon storage even in the face of threats from pests, disease, and wildfire (CARB 2014). Under these policies, forest managers must comply with the state's carbon budget and address carbon sequestration when submitting timber harvest plans (Stewart and Sharma 2015). To adhere to these policies, the influence of management practices on carbon sequestration in California forests must be well understood.

Even-aged, uneven-aged, and non-harvest regimes are common management schemes for mixed-conifer forests. When the primary objective is wood production, even-aged clear-cutting is one of the most efficient and economic approaches because all or most trees in a given area are uniformly harvested in a single harvesting operation. Clear-cutting can be an effective tool to regenerate a forest of shade intolerant species such as pines, but can be a controversial method due to the impacts on wildlife and aesthetics (Costello et al. 2000). Maintaining unharvested reserve forests can store a significant quantity of carbon but may become saturated when the forest growth rate slows from competition (Stephens et al. 2009). Allowing the forest to grow without any harvesting or thinning operations may also increase risks to fire, insects and disease (Dolanc et al. 2014). An intermediate approach is uneven-aged management, such as group selection, where groups of trees are harvested as small-scale clear-cuts typically ranging from 0.1 to 1.0 hectares (York et al. 2004). These harvests occur at intervals such that the entire stand is cut within a 40 to 50 year span (York et al. 2004). Group selection treatments can be up to 31.5 percent more costly than clear-cut methods due to equipment requirements (Kellogg et al. 1996).

In this study, I examined the carbon consequences of these three management regimes in the mixed conifer region of the University of California Blodgett Forest Research Station (BFRS). In particular, I estimated the total quantity of aboveground carbon stored in BFRS and determined differences in net carbon benefit among clear-cuts even-aged and group selection even-aged harvesting approaches compared to an unharvested second growth reserve stand. I took into account stand-level carbon and carbon stored in HWPs including substitution benefits. I conducted a life cycle analysis used a recently published carbon sequestration tool for timber harvest plans to estimate the net climate benefits for each harvesting regime (Stewart and Sharma 2015). I hypothesized that actively managed forest stands would remove and store greater amounts of carbon than unmanaged reserve stands when both standing forest and forest products were taken into account. I also hypothesized that uneven-aged management would be more efficient at sequestering carbon than even-aged management. I found that both even-aged clear-cut and uneven-aged group selection management approaches resulted in a higher net carbon benefit than no-harvest reserve stands. My hypothesis that group selection would result in a higher carbon benefit than clear-cut was correct.

METHODS

Study Site

The data for this study was collected from the 1970’s to early 2000’s at the University of California Blodgett Forest Research Station (38°54’45’’ N, 120°39’27” W), located in the north-central mixed-conifer zone of the Sierra Nevada mountain range, approximately 20 km east of Georgetown, California, USA (Olson and Helms 1996). Blodgett Forest’s climate is Mediterranean with dry, warm summers (10-29°C) and mild winters (0-8°C), with an average mean annual precipitation of 165 cm, 85 percent of which occurs between October and March (Stephens et al. 2009, Black and Harden 1995). Blodgett forest species composition includes California black oak (*Quercus kelloggii*), Douglas-fir (*Psuedostuga menziesii*), incense-cedar (*Calocedrus decurrens*), ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), tanoak (*Lithocarpus densiflorus*), white fir (*Abies concolor*), and others (Table 1).

Blodgett forest is divided into approximately 110 compartments, each ranging in size from 8 to 80 hectares; by area, 40% of the compartments are under even-aged management, 40% under uneven-aged management, and 20% are unmanipulated reserves. (Stephens et al. 2009, Battles et al. 2001). The compartments are divided into a 121×121 m grid; with the intersections of the grid lines constituting centers of permanent 1/10th acre circular forest inventory plots (Battles et al. 2001).

Management Regimes

This study focuses on two regeneration methods: clear-cut and group selection, and compares them to no-harvest reserves. Under Blodgett Forest management, compartments under clear-cut plans post-harvest are replanted, targeting at least 340 seedlings per acre with an even species distribution among the five major native conifers; these replantings receive herbicide treatment, a pre-commercial thinning, and then at around age 30, a commercial harvest that thins the trees (Olson and Helms 1996). Approximately every 10 years, 11 percent of the group selection compartments are harvested in small groups with a maximum size of 0.6 ha (Battles et al. 2001). The reserve stands were not harvested. Table 2 details the number compartments analyzed from each management regime and harvest date.

Data Cleaning

The final dataset consisted of 15,310 individual tree measurements. Of these, four had a negative recorded DBH, which I removed from the analysis (Table 3). One tree's recorded species code was XX, indicating that the species was not identified. For this tree I assigned B0 and B1 coefficients for the Jenkins's Equation that corresponded with the most common hardwood species recorded in that stand type, which was incense-cedar.

Forest Carbon Calculations

To determine the quantity of aboveground stored carbon, I used the allometric Jenkins Biomass Equation: ln(biomass)=B0+B1 ln(diameter at breast height (DBH)), with biomass in kg and diameter in cm, to estimate biomass (Chojnacky et al. 2013). I then used the standard heuristic of approximating aboveground stored carbon as 49 percent of the biomass (Woodall et al. 2001). The equation parameters B0 and B1 are specific to the species and specific gravity of green volume basis (Table 1). I determined the family for each inventoried species using calfora.org and found the corresponding specific gravity of green volume of the inventoried species in table 1A of Miles and Smith (2009).

To model the average biomass per hectare for each compartment, I first found the biomass per hectare in each plot and then took the average over all the plots. I did this for each year the compartments were inventoried. To standardize the clear-cut data I organized the data by years since the clear-cut. For the group selection data the intervals between harvesting were not uniform across compartments so I was unable to standardize the data based on harvesting dates. As a result I only analyzed group selection compartment 50 because it had more data points throughout time and compartment 10 had been thinned. For each management practice I conducted weighted regressions to model carbon benefits for the let-grow forest and regenerated forest, weighting by the number of plots surveyed at a given time. The let-grow forest represents what the carbon benefit would have been had the forest never been harvested. I did quadratic and linear regressions and used the regression that rendered the most significant p-value. I first found the growth equation for the reserve stand and used its growth rate to model the let-grow forest for the clear-cut and group selection stands. I used the growth rate of the reserve stand to model the let-grow forest for two reasons: firstly in order to standardize the stands to allow for comparisons and secondly, because both the clear-cut and group selection data did not contain enough long-term data to generate their own observed growth equations. To determine how much carbon was removed from the stand during the clear cut I also conducted a regression. Because most of BFRS was clear-cut between 1900 and 1913, I used 1913 as a data point of zero carbon for the clear-cut compartments in order that there be enough data points to obtain a growth equation (Battles et al. 2001). For the group selection data there was only one inventory before the first harvest. I used this point and the growth rate derived for the reserve stands to model the growth equation for the group selection stands had they been unharvested.

Forest and Forest Products Carbon Calculation

For the compartments under clear-cut and group selection management, I included the harvested carbon in the carbon benefits through a life cycle analysis. I used the Bill Stewart and Sharma's (2015) Carbon Calculator for Timber Harvest Plans (CCTHP). This calculator uses California forest data and best practices assumptions. When a forest is harvested, 60 percent of the cut material is processed at the sawmill; at the sawmill 75 percent of the wood is made into wood products with an average half-life of 45 years, 24 percent is used for energy, and 1 percent is mill waste (Figure 1). The remaining 40 percent of harvested carbon that does not go to the mill is accounted for as slash. Of the slash, 25 percent is left on site with a 20-year half-life, and 75 percent is processed for bioenergy (75 percent). The carbon calculator accounts for the emissions released through the harvesting operation, and the substitution benefits of HWPs being used in place of more emissions-intensive materials (e.g. steel and concrete). The CCTHP models the regenerated forest using the Von Bertalanffy growth equation with coefficients based on data collected from private forest plots. I substituted the Von Bertalanffy growth model with the data points derived from the growth equations for the let-grow and regenerated forests. I compared the carbon benefit (tones per hectare) of the let-grow and harvested scenarios to determine which approach resulted in the highest net carbon benefit at the time of the first harvest, 10 years after, 20 years after, and 30 years after.

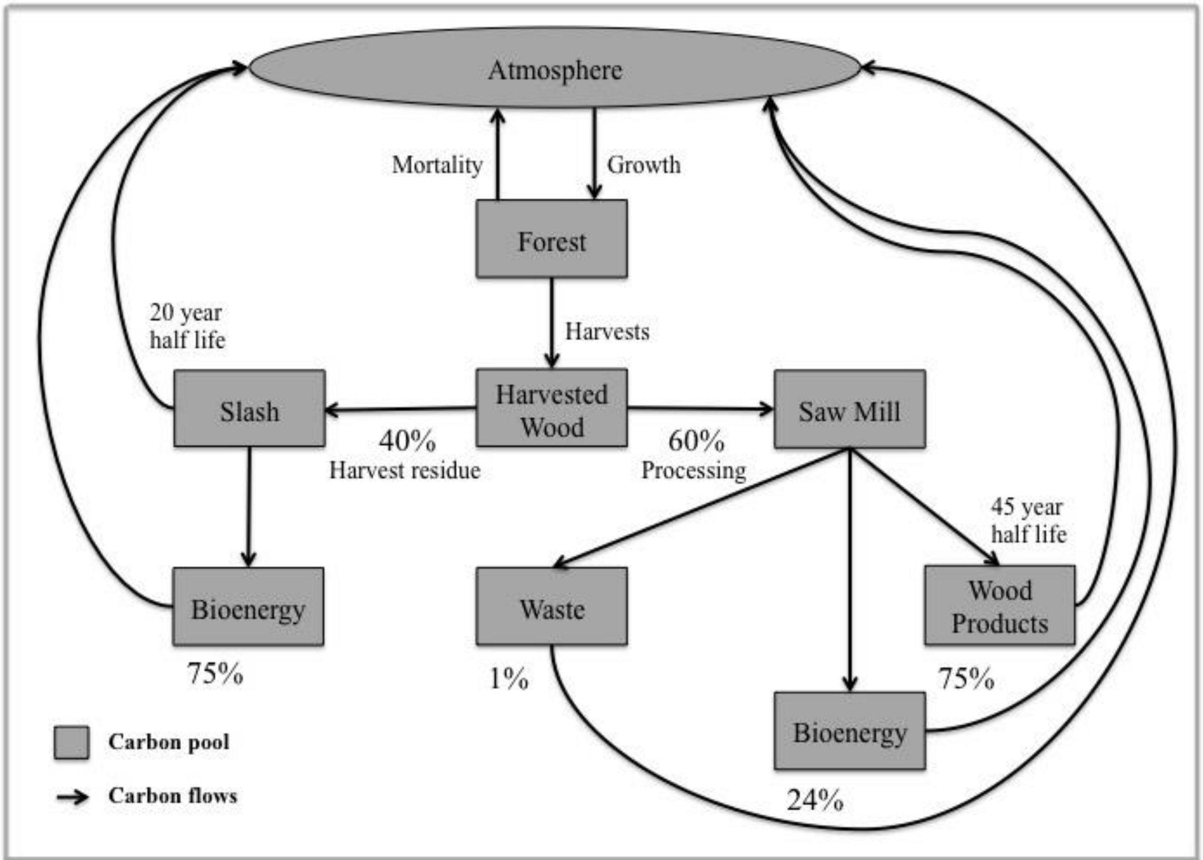


Figure 1. Life cycle of forest carbon. Depicting carbon pools and flows used in Stewart and Sharma's (2015) Carbon Calculator for Timber Harvest Plans.

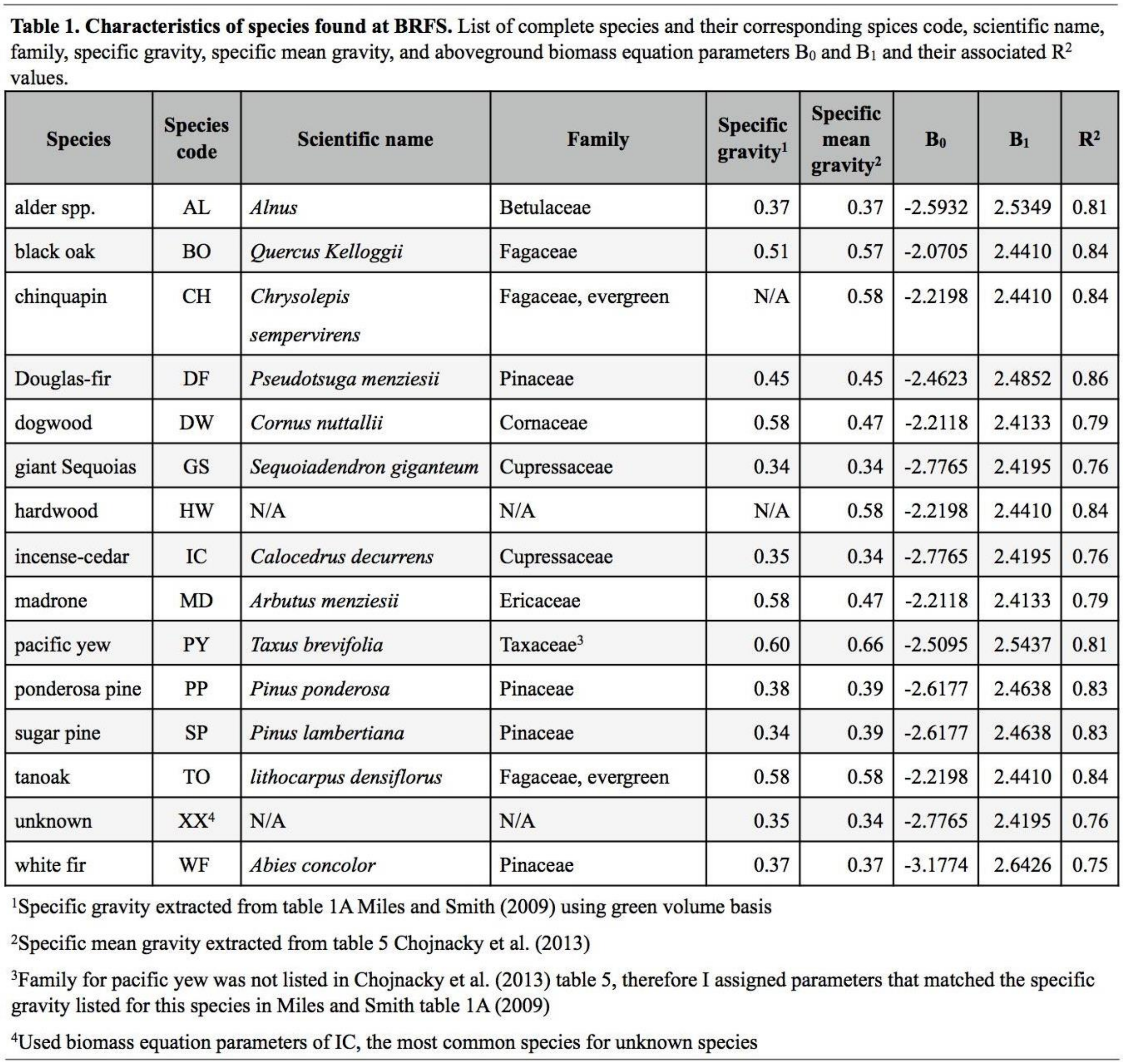


Table 1. Characteristics of species found at BRFS. List of complete species and their corresponding spices code, scientific name, family, specific gravity, specific mean gravity, and aboveground biomass equation parameters B_0 and B_1 and their associated R^2 values.

Species	Species code	Scientific name	Family	Specific gravity[1]	Specific mean gravity[2]	B_0	B_1	R^2
alder spp.	AL	*Alnus*	Betulaceae	0.37	0.37	-2.5932	2.5349	0.81
black oak	BO	*Quercus Kelloggii*	Fagaceae	0.51	0.57	-2.0705	2.4410	0.84
chinquapin	CH	*Chrysolepis sempervirens*	Fagaceae, evergreen	N/A	0.58	-2.2198	2.4410	0.84
Douglas-fir	DF	*Pseudotsuga menziesii*	Pinaceae	0.45	0.45	-2.4623	2.4852	0.86
dogwood	DW	*Cornus nuttallii*	Cornaceae	0.58	0.47	-2.2118	2.4133	0.79
giant Sequoias	GS	*Sequoiadendron giganteum*	Cupressaceae	0.34	0.34	-2.7765	2.4195	0.76
hardwood	HW	N/A	N/A	N/A	0.58	-2.2198	2.4410	0.84
incense-cedar	IC	*Calocedrus decurrens*	Cupressaceae	0.35	0.34	-2.7765	2.4195	0.76
madrone	MD	*Arbutus menziesii*	Ericaceae	0.58	0.47	-2.2118	2.4133	0.79
pacific yew	PY	*Taxus brevifolia*	Taxaceae[3]	0.60	0.66	-2.5095	2.5437	0.81
ponderosa pine	PP	*Pinus ponderosa*	Pinaceae	0.38	0.39	-2.6177	2.4638	0.83
sugar pine	SP	*Pinus lambertiana*	Pinaceae	0.34	0.39	-2.6177	2.4638	0.83
tanoak	TO	*lithocarpus densiflorus*	Fagaceae, evergreen	0.58	0.58	-2.2198	2.4410	0.84
unknown	XX[4]	N/A	N/A	0.35	0.34	-2.7765	2.4195	0.76
white fir	WF	*Abies concolor*	Pinaceae	0.37	0.37	-3.1774	2.6426	0.75

[1] Specific gravity extracted from table 1A Miles and Smith (2009) using green volume basis

[2] Specific mean gravity extracted from table 5 Chojnacky et al. (2013)

[3] Family for pacific yew was not listed in Chojnacky et al. (2013) table 5, therefore I assigned parameters that matched the specific gravity listed for this species in Miles and Smith table 1A (2009)

[4] Used biomass equation parameters of IC, the most common species for unknown species

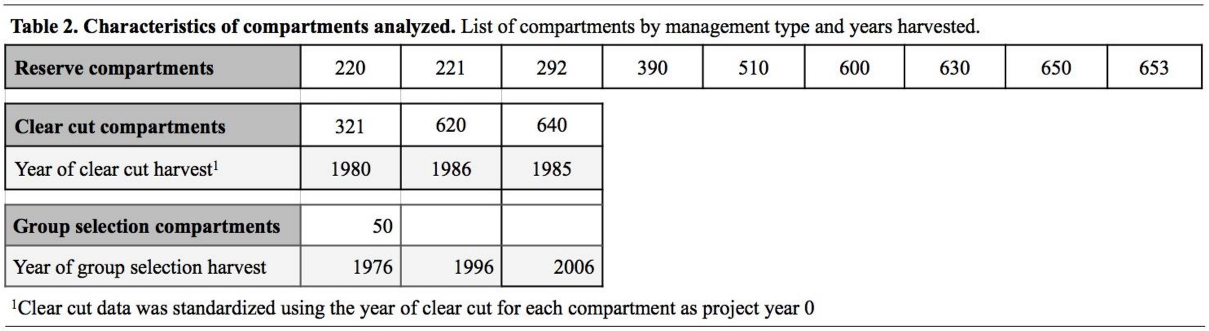


Table 2. Characteristics of compartments analyzed. List of compartments by management type and years harvested.

Reserve compartments	220	221	292	390	510	600	630	650	653

Clear cut compartments	321	620	640
Year of clear cut harvest[1]	1980	1986	1985

Group selection compartments	50		
Year of group selection harvest	1976	1996	2006

[1] Clear cut data was standardized using the year of clear cut for each compartment as project year 0

Table 3. Trees with recorded negative DBH. These were all within the reserve stand data and were not included in the analysis. DBH = diameter at breast height (4.5 feet off the ground).

Compartment	Plots	Year inventoried	Species code
390	5	2004	IC
390	4	2004	IC
220	17	2004	IC
292	8	1994	DF

RESULTS

Forest Carbon

I derived let-grow forest equations for the three management types using the growth rate observed in the reserve stands. I found that a linear regression models the growth in the reserves stand better than a quadratic regression. The linear regression resulted in a p-value of 3.237e-06, which is more significant than the p-value for the quadratic regression, which was 1.346e-05 (Figure 2). The reserve stand had an observed growth rate of 3.2069 carbon (tones/hectare) per year. For the clear cut stand before the harvest the linear regression also had a more significant p-value (p = 0.003474) than the quadratic regression (p = 0.02336) and therefore was the growth equation used to determine how much carbon was harvested at the time of the clear-cut, which was about 126.66 mg/ha (Figure 3). I then used this data point and the growth rate observed in the reserve stand to generate the let-grow forest equation for the clear-cut stand (Table 4). I used the same technique to generate the growth equation for the group selection stand before harvesting operations. Before the first group selection harvest in 1976 there was only one inventory in 1975. I used the average carbon (mg/ha) of this data point and the growth rate from the reserve stand to model the group selection let-grow forest.

I used the same method to determine the growth equations for the regenerated forests. For the clear-cut stand after harvest the linear regression had a more significant p-value (p = 1.513e^-06) than the linear regression (p = 1.256e^-05) and so was chosen to model the clear-cut regenerated forest (Figure 4). The group selection regenerated forest after the first harvesting operation was modeled using the linear regression (p = 0.3069) (Figure 5). The group selection regenerated forest after the second harvesting operation was also modeled using the linear regression (p = 0.2929) (Figure 6). There was not a sufficient amount of data to model the group selection regenerated forests with a quadratic regression (p = NA). The growth equations and associated p-values used for each management time and time interval are summarized in Table 4.

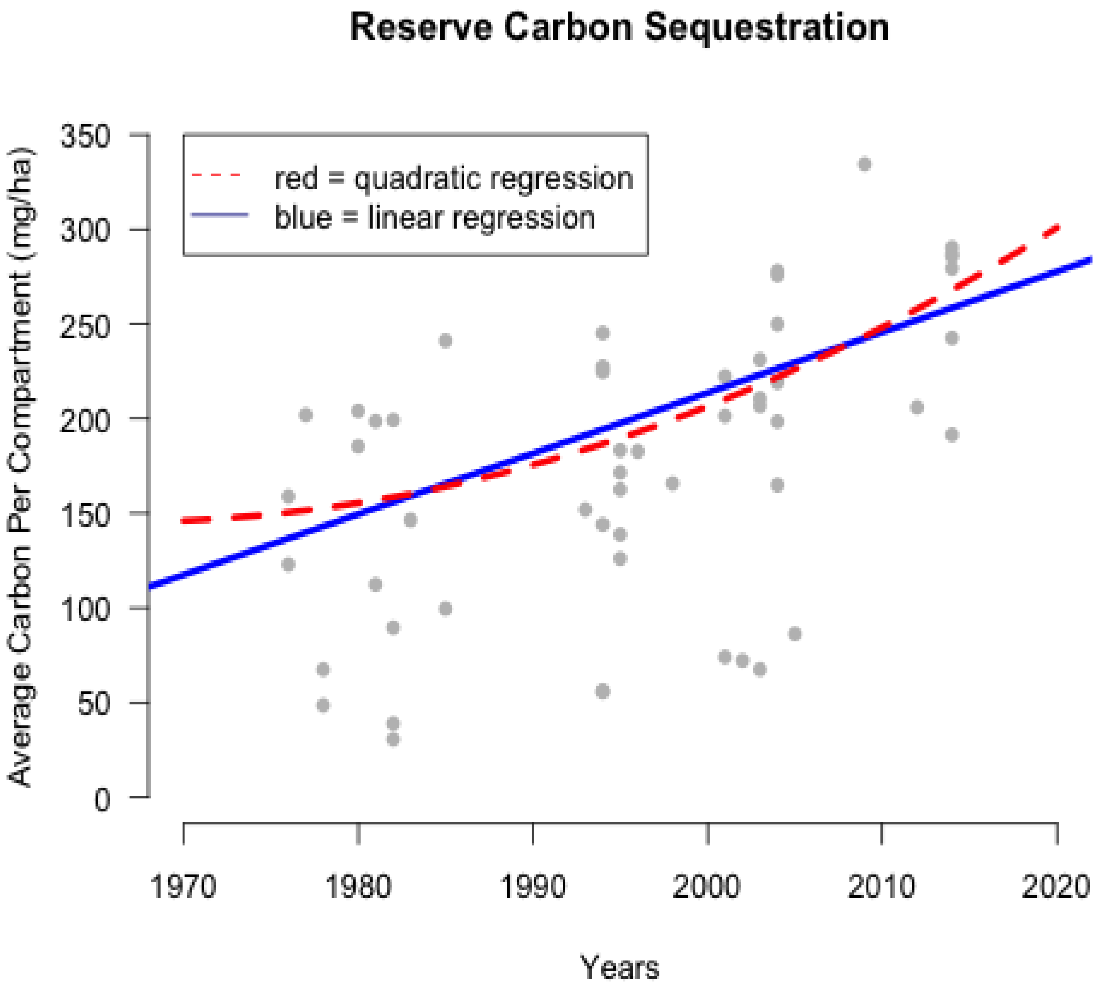


Figure. 2. Average carbon per compartment (mg/ha) in the reserve stand. Each point represents the average carbon in a compartment at a given time. The dashed red line is a best fits quadratic regression and the blue is the best-fit linear line. The linear regression had a more significant p-value than the quadratic regression and thus was chosen as the growth equation.

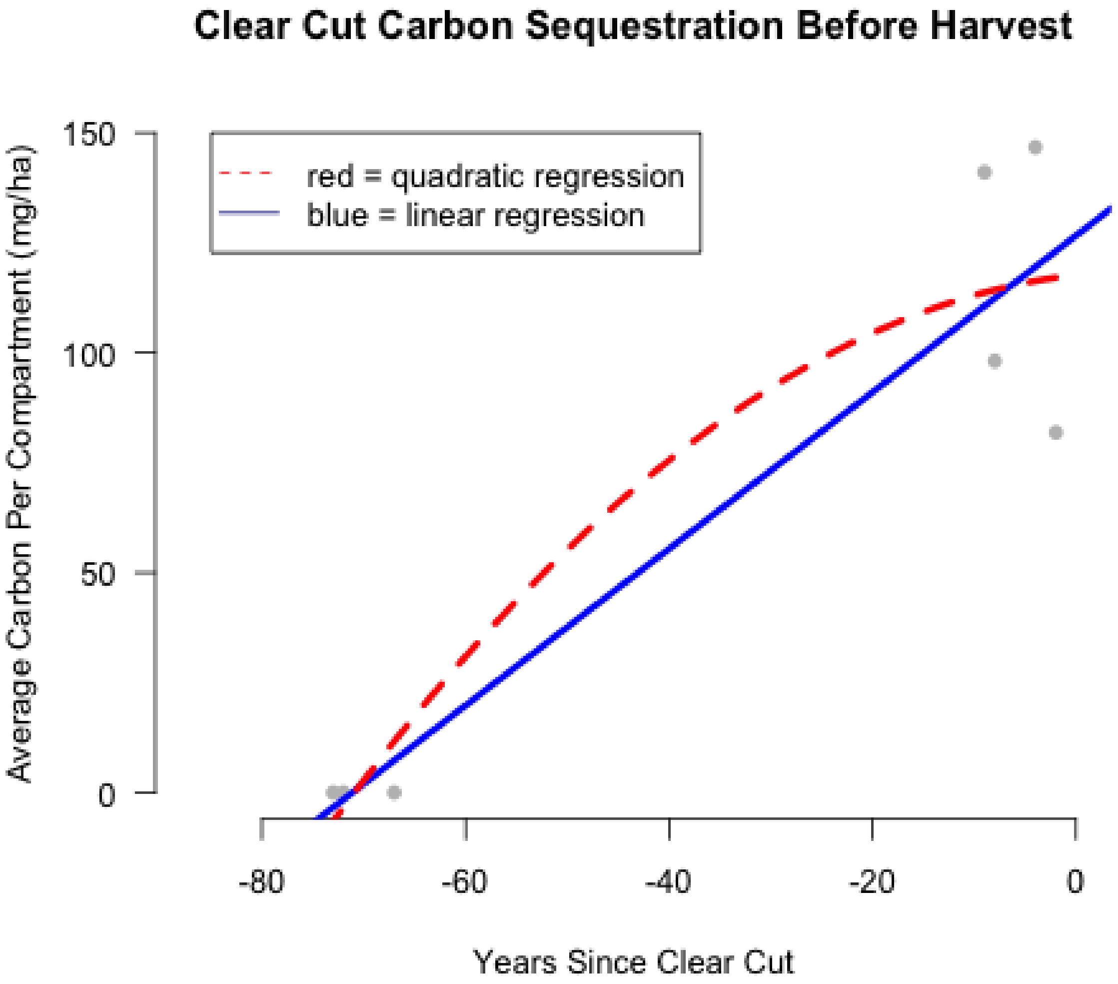


Figure. 3. Average carbon per compartment (mg/ha) in the clear-cut stand before harvest. Each point represents the average carbon in a compartment at a given time. The dashed red line is a best fits quadratic regression and the blue is the best-fit linear line. The linear regression had a smaller p-value and was used to determine how much carbon was removed from the stand at harvest.

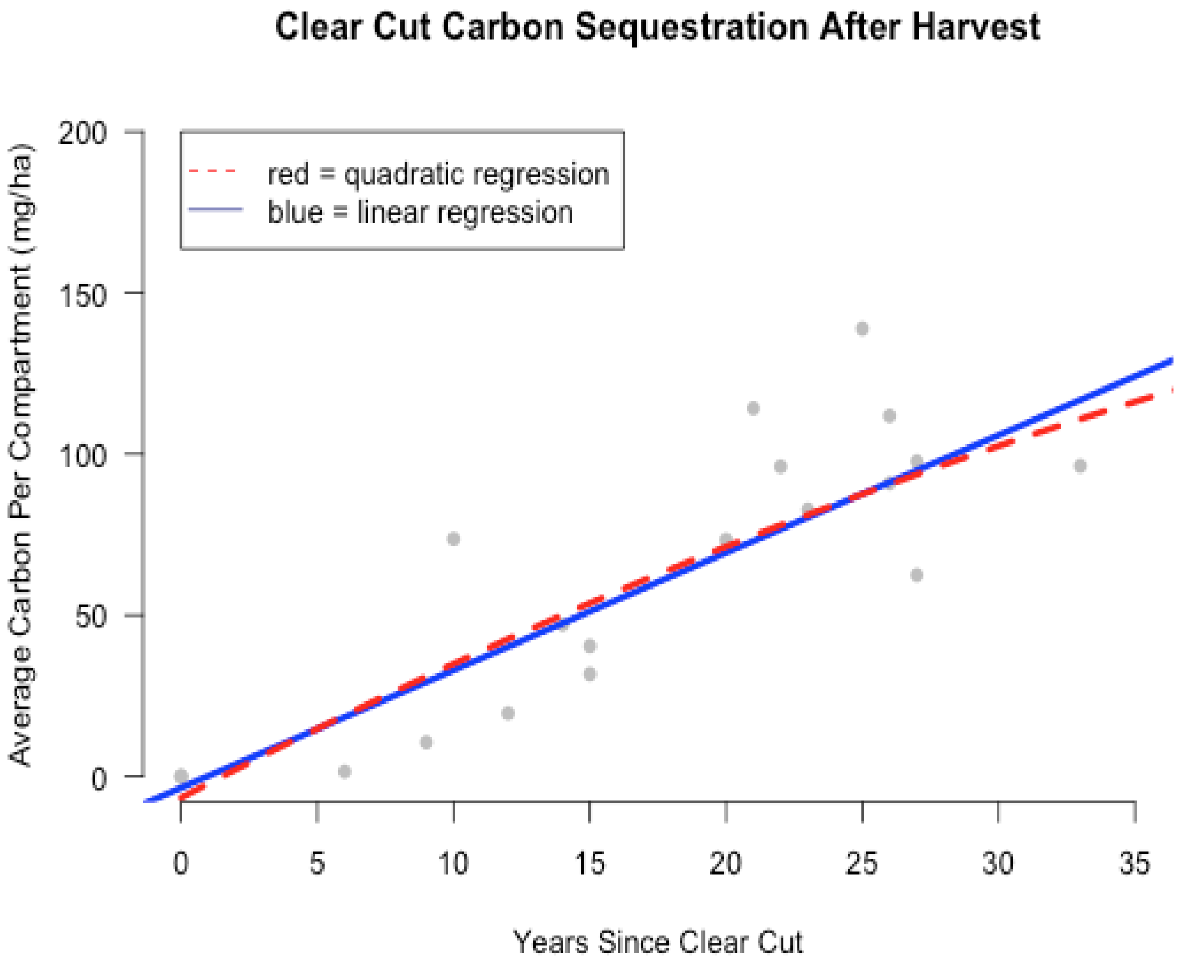


Figure. 4. Average carbon per compartment (mg/ha) in the clear-cut stand after harvest regenerated forest. Each point represents the average carbon in a compartment at a given time. The dashed red line is a best fits quadratic regression and the blue is the best-fit linear line. The linear regression had a smaller p-value and was used to model the regenerated clear-cut forest.

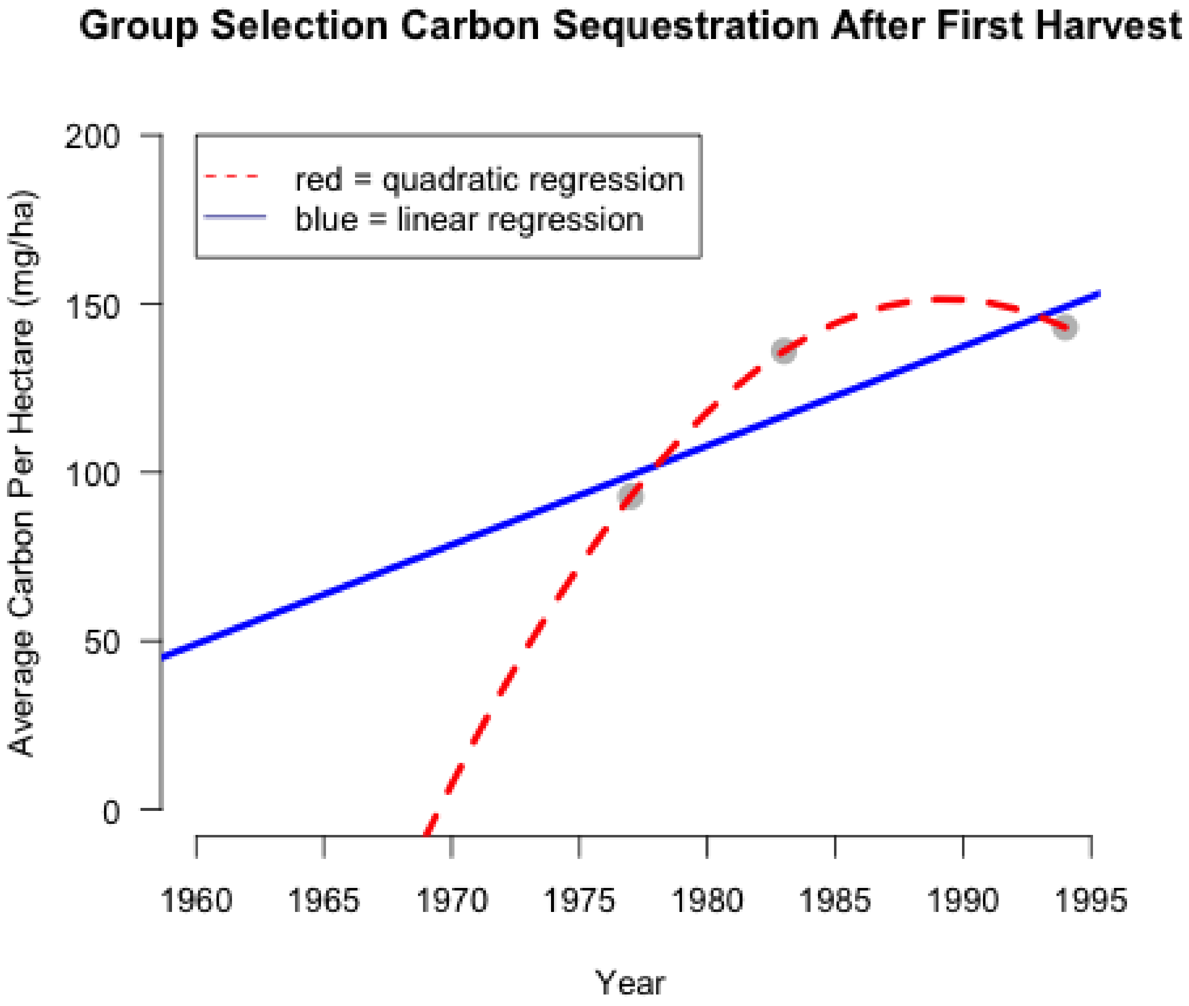


Figure. 5. Average carbon per compartment (mg/ha) in the group selection stand after first harvest regenerated forest. Each point represents the average carbon in a compartment at a given time. The dashed red line is a best fits quadratic regression and the blue is the best-fit linear line. The linear regression was used to model the regenerated forest after the first harvest.

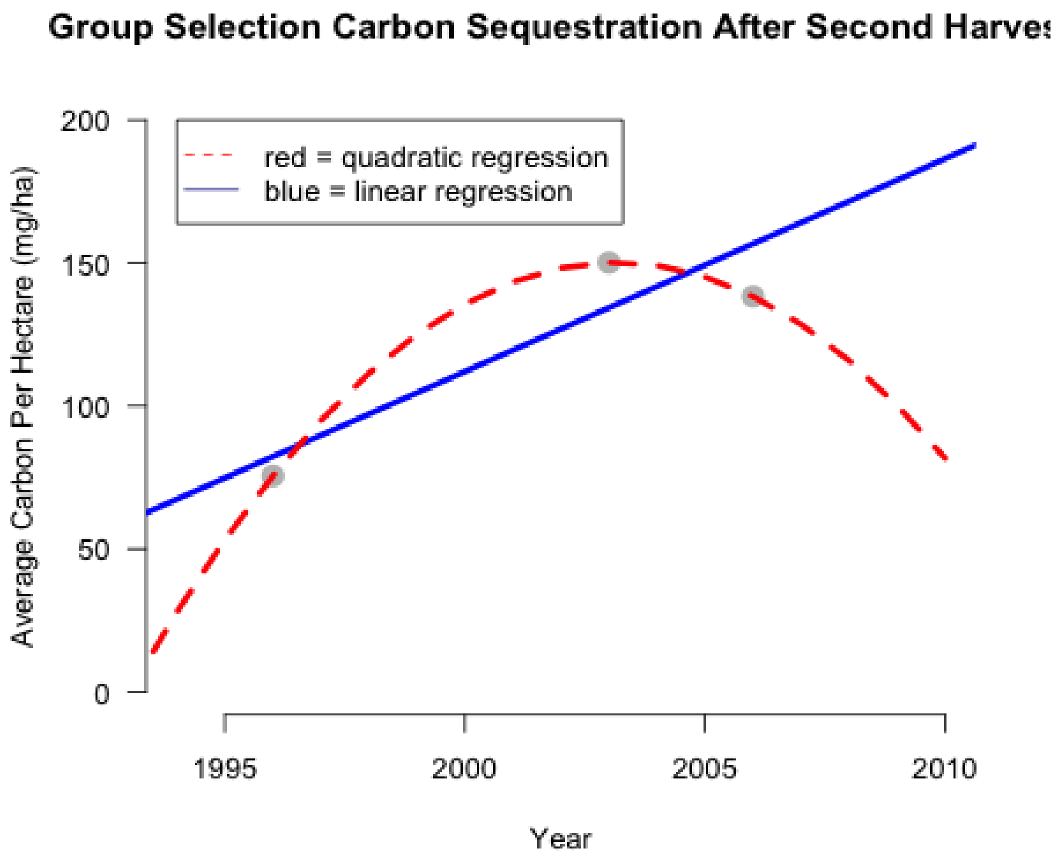


Fig. 6. Average carbon per compartment (mg/ha) in the group selection stand after second harvest regenerated forest. Each point represents the average carbon in a compartment at a given time. The dashed red line is a best fits quadratic regression and the blue is the best-fit linear line. The linear regression was used to model the regenerated forest after the second harvest.

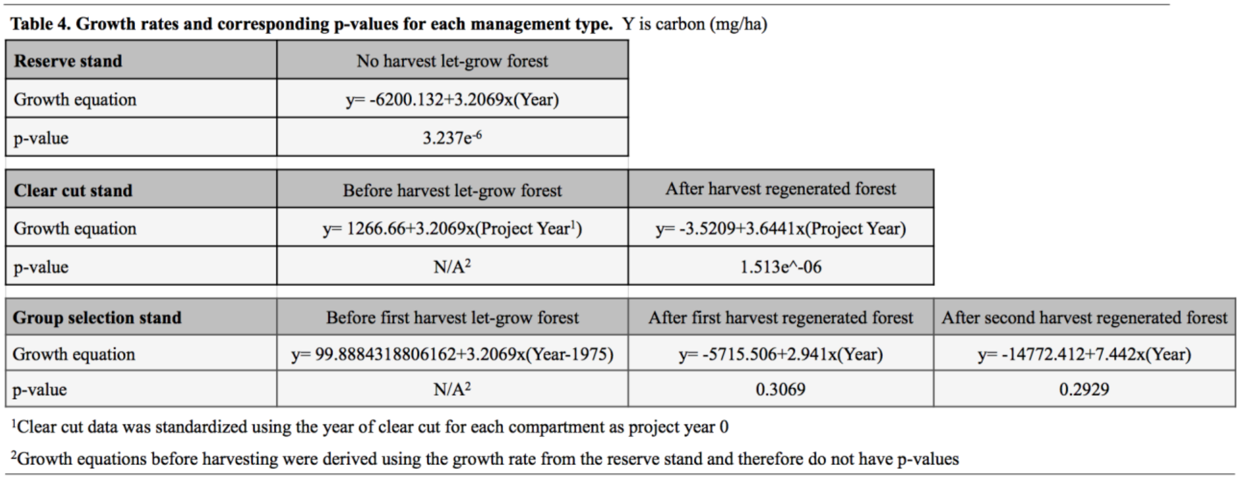


Table 4. Growth rates and corresponding p-values for each management type. Y is carbon (mg/ha)

Reserve stand	No harvest let-grow forest
Growth equation	y= -6200.132+3.2069x(Year)
p-value	$3.237e^{-6}$

Clear cut stand	Before harvest let-grow forest	After harvest regenerated forest
Growth equation	y= 1266.66+3.2069x(Project Year[1])	y= -3.5209+3.6441x(Project Year)
p-value	N/A[2]	1.513e^-06

Group selection stand	Before first harvest let-grow forest	After first harvest regenerated forest	After second harvest regenerated forest
Growth equation	y= 99.8884318806162+3.2069x(Year-1975)	y= -5715.506+2.941x(Year)	y= -14772.412+7.442x(Year)
p-value	N/A[2]	0.3069	0.2929

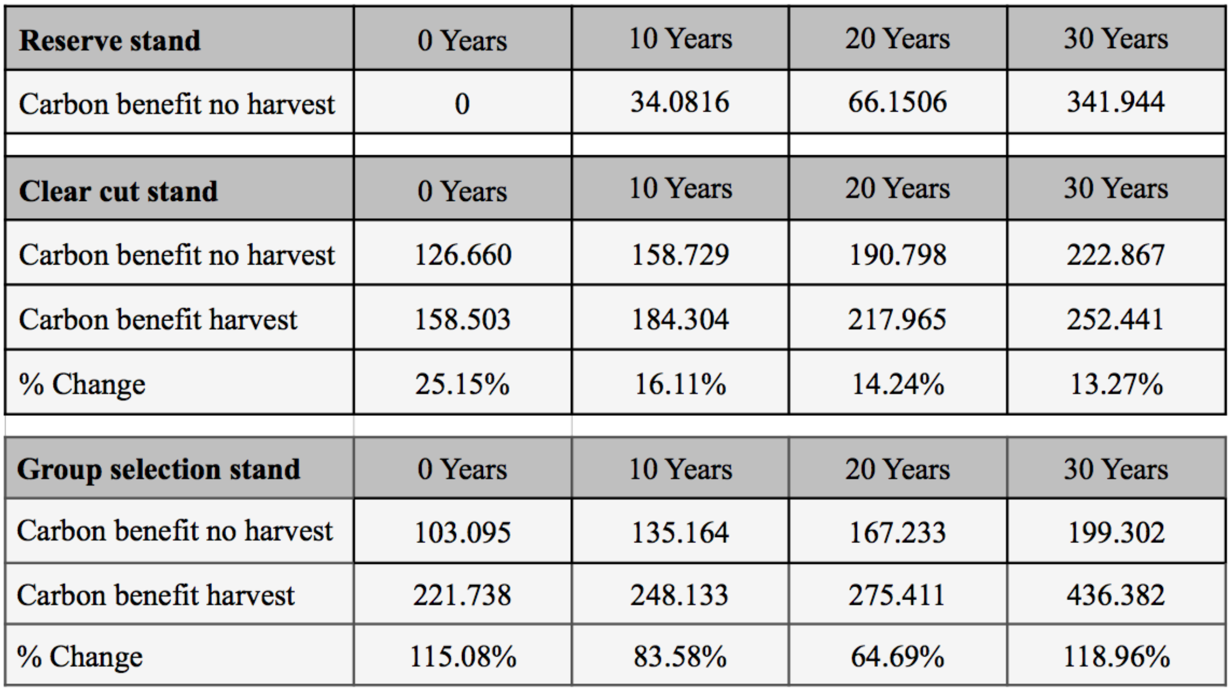
[1] Clear cut data was standardized using the year of clear cut for each compartment as project year 0

[2] Growth equations before harvesting were derived using the growth rate from the reserve stand and therefore do not have p-values

Forest and Forest Products Carbon

Using the CCTHP I found that both harvesting regimes resulted in higher carbon benefits than their no harvest let-grow counterparts (Table 5). This trend was recorded up to 30-years after the first harvesting operation. Group selection harvesting resulted in a higher percent change between the no harvest and harvest scenario than clear-cutting. Figures 7-9 depict the carbon benefits of the different management regimes. When substitution benefits of harvesting were ignored and only carbon sequestration and capture was analyzed clear-cutting did not result in a higher carbon benefit than the no harvest let-grow model, whereas group selection did (Table 6). Figures 10 and 11 depict the carbon benefits of the different management regimes when substitution benefits of the harvest are ignored.

Table 5. Net carbon benefit (mg/ha) projected with and without harvest. After a certain amount of years after first harvest.



Reserve stand	0 Years	10 Years	20 Years	30 Years
Carbon benefit no harvest	0	34.0816	66.1506	341.944
Clear cut stand	0 Years	10 Years	20 Years	30 Years
Carbon benefit no harvest	126.660	158.729	190.798	222.867
Carbon benefit harvest	158.503	184.304	217.965	252.441
% Change	25.15%	16.11%	14.24%	13.27%
Group selection stand	0 Years	10 Years	20 Years	30 Years
Carbon benefit no harvest	103.095	135.164	167.233	199.302
Carbon benefit harvest	221.738	248.133	275.411	436.382
% Change	115.08%	83.58%	64.69%	118.96%

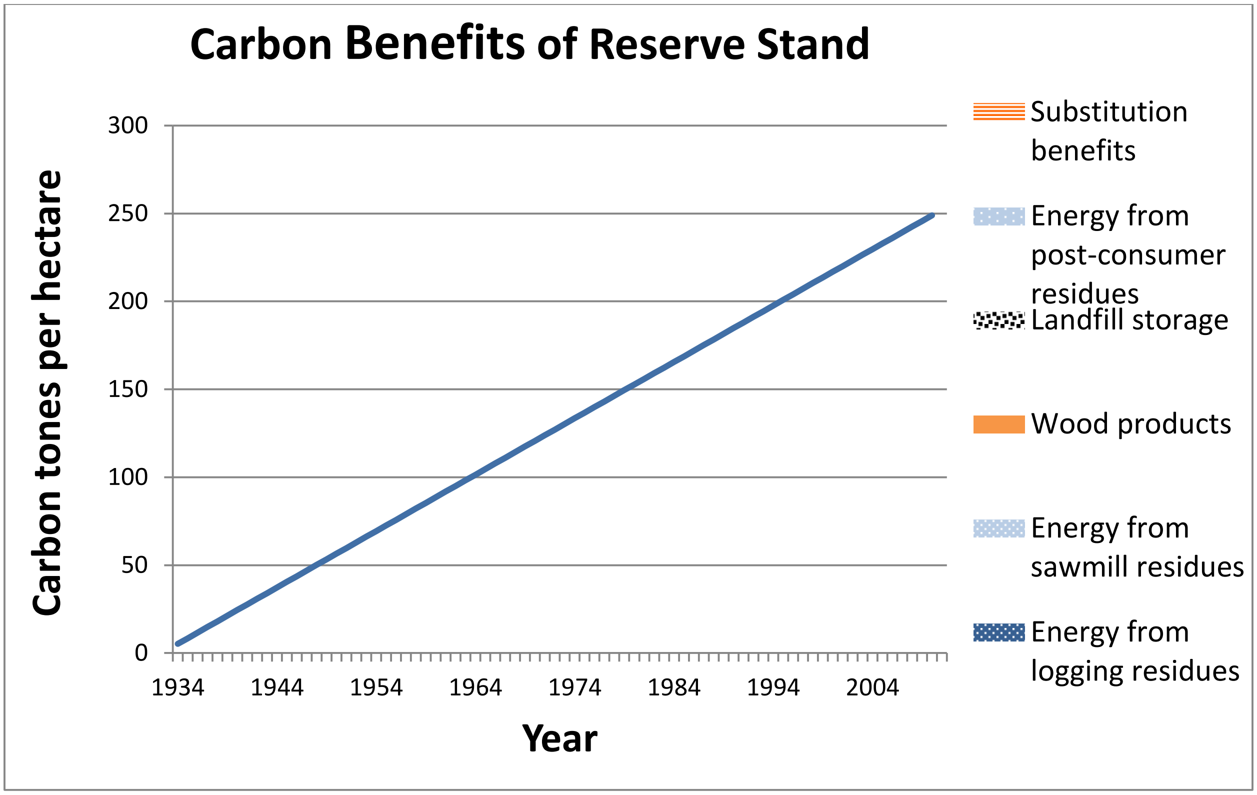


Figure. 7. Carbon benefit of no harvest reserve management.

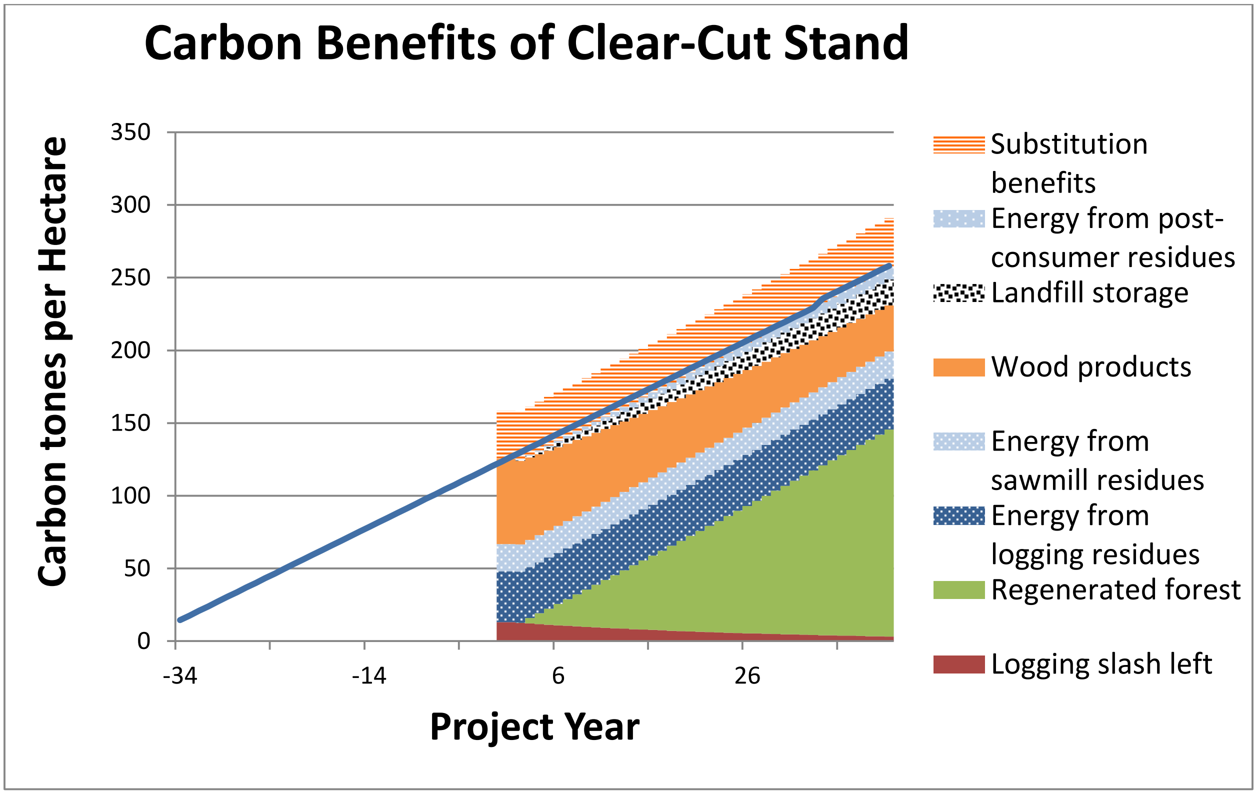


Figure 8. Carbon benefit of clear-cut management.

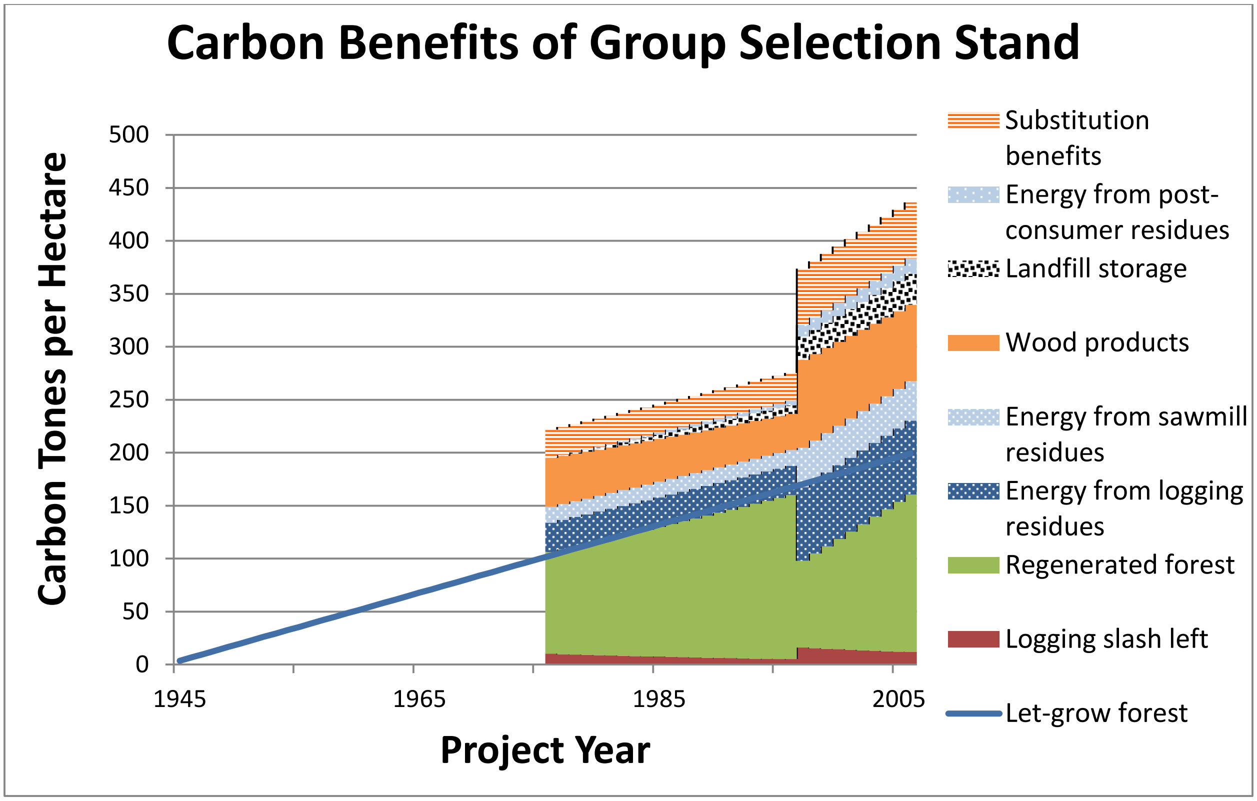


Figure 9. Carbon benefit of group selection management.

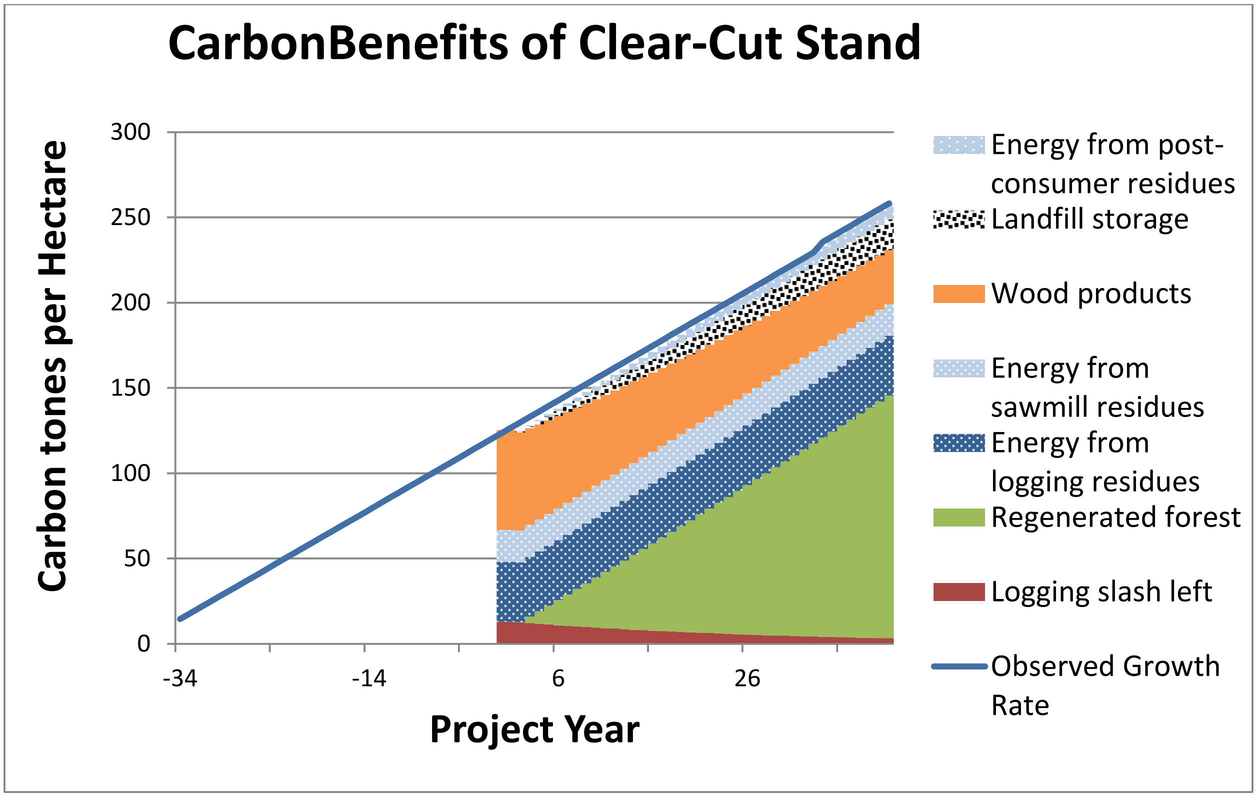


Figure 10. Carbon benefit of clear-cut management ignoring substitution benefits.

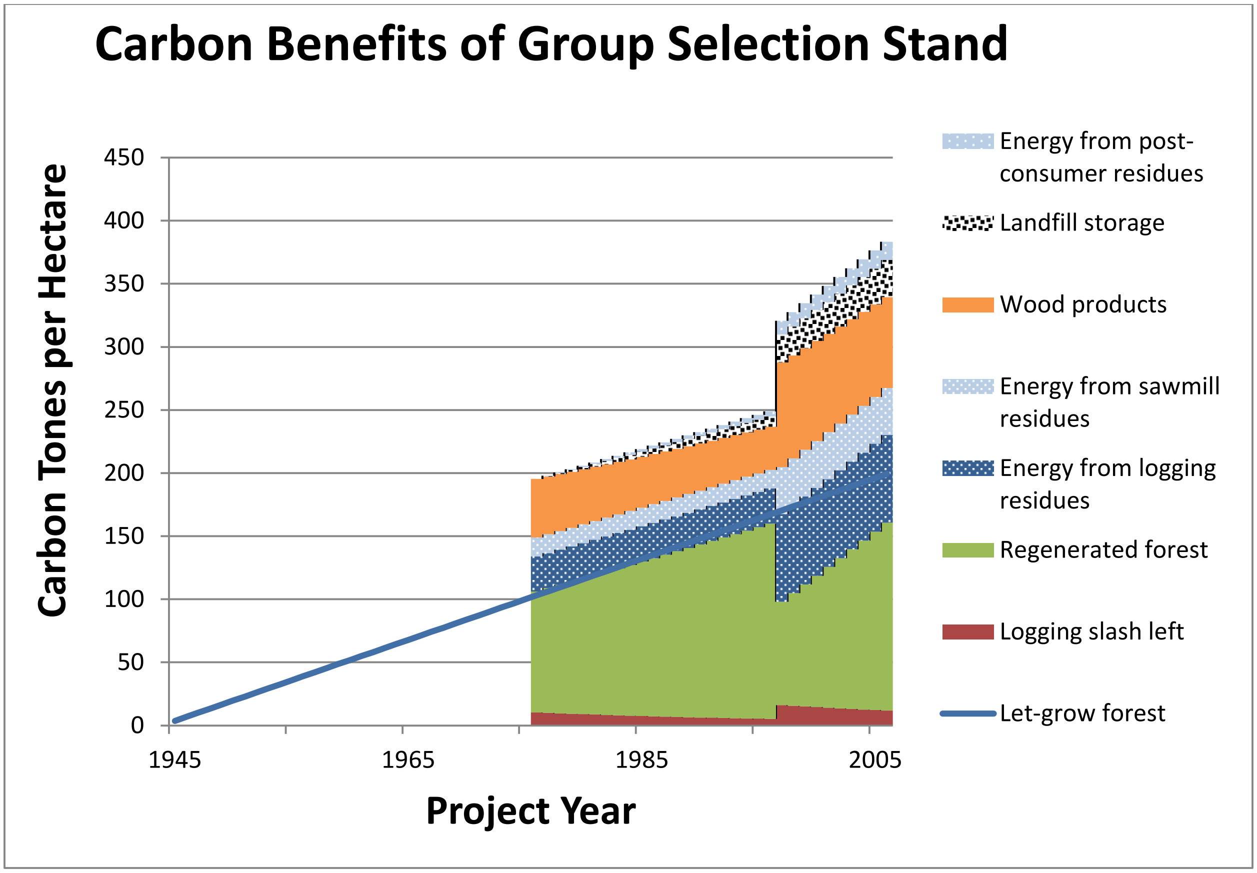


Figure 11. Carbon benefit of clear-cut management ignoring substitution benefits.

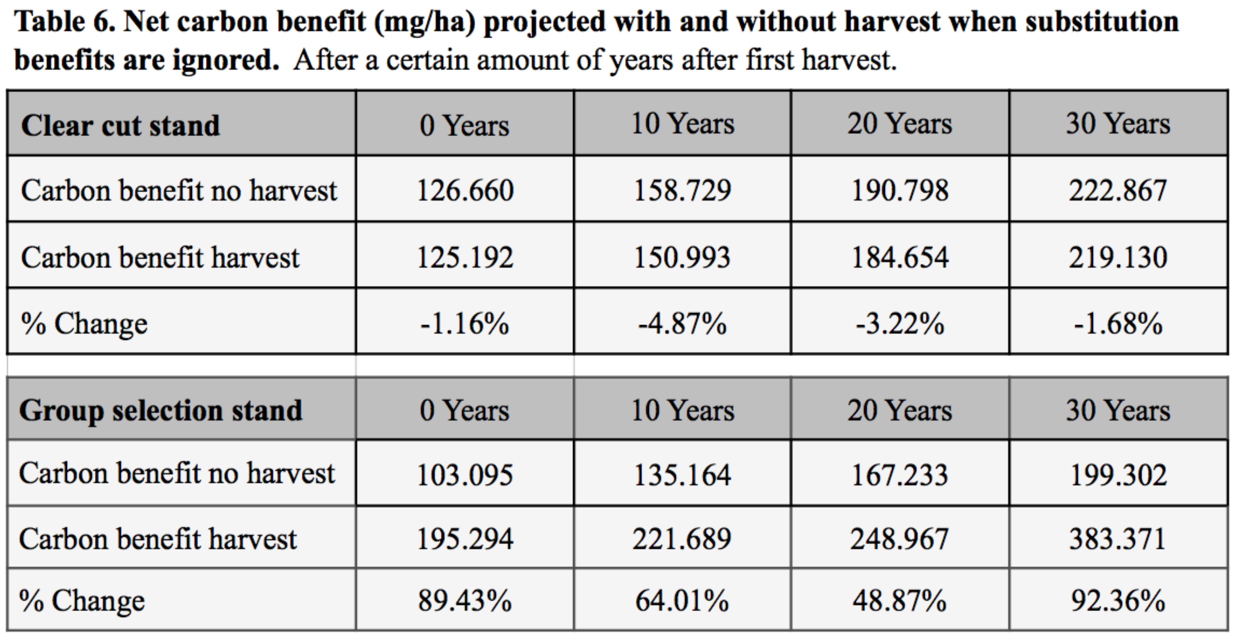


Table 6. Net carbon benefit (mg/ha) projected with and without harvest when substitution benefits are ignored. After a certain amount of years after first harvest.

Clear cut stand	0 Years	10 Years	20 Years	30 Years
Carbon benefit no harvest	126.660	158.729	190.798	222.867
Carbon benefit harvest	125.192	150.993	184.654	219.130
% Change	-1.16%	-4.87%	-3.22%	-1.68%

Group selection stand	0 Years	10 Years	20 Years	30 Years
Carbon benefit no harvest	103.095	135.164	167.233	199.302
Carbon benefit harvest	195.294	221.689	248.967	383.371
% Change	89.43%	64.01%	48.87%	92.36%

DISCUSSION

Given the consensus that carbon dioxide emissions have a significant influence on global climate change, it is important to understand how forest management affects forest carbon sequestration (Zhang et al. 2012). This study found that group selection and clear-cut regimes can be used to increase net carbon benefit when the life cycle of the harvested wood is considered. Group selection resulted in a larger increase in carbon benefit compared to the no harvest scenario than clear-cutting. When substitution benefit was not included clear-cutting did not result in an increase in carbon benefit; however this finding is heavily dependent on the growth rate of the let-grow forest.

Managed versus Unmanaged Stands

I found that actively managed forest stands store greater amounts of carbon than unmanaged reserve stands when both standing forest and forest products are taken into account. Both even-aged clear-cut and uneven-aged group selection management approaches resulted in higher net carbon benefits than the no-harvest reserve stands. When deciding to how to manage a forest it is important to consider the other benefits that accompany the regimes outside of carbon sequestration and capture. Although I found that the no-harvest regime did not maximize net carbon benefit, this approach helps maintain biodiversity through habitat preservation and preservation of ecosystem services such as climate regulation, recreation, and air and water purification (Larson et al. 2012). Not harvesting the forest can increase fuel loads and fuel continuity, leaving forests vulnerable to catastrophic fires, which have the potential of releasing large quantities of carbon instantly into the atmosphere (Anderson and Moratto 1996). In 2014, the ten largest forest fires cost more than $320 million to contain and between 2014 and 2015, the U.S. Forest Service had to cut funding to restoration and land management programs in order to expand the fire suppression budget by $115 million (United States Department of Agriculture 2015). These costs are projected to increase as the fire season continues to lengthen and become more dangerous, with the cost of fire suppression expected to grow to $1.8 billion by 2025 (United States Department of Agriculture 2015). The use of harvesting regimes could help lower costs and carbon loss by preventing large catastrophic forests fires. Harvesting not only increases carbon sequestration, it decreases risks, from fire, insects, and diseases (Dolanc et al. 2014).

Uneven versus Even-aged Management

I found that for BFRS uneven-aged management was more efficient at sequestering carbon than even-aged management. My hypothesis that group selection would result in a higher carbon benefit than clear-cut was correct. In addition to carbon benefits, uneven-aged management can be more economical than even-aged management in some cases because of its use of natural regeneration as opposed to artificial regeneration and its consistent production of harvested wood products (Pukkala et al. 2011). Other co-benefits of uneven-aged management compared to even-aged management include: reduced forest fragmentation, aesthetics, and a more diverse forest structure, which provides habitat for many species (United States Forest Service 1995). Uneven-aged management also does not come with the same erosion risks that even-aged management has, which causes excessive sedimentation in stream channels, damaging aquatic habitats (Robinson 2013). However, both group selection and clear-cut regimes can be designed to encourage the regeneration of shade-intolerant species that cannot compete in mature forests and can help reestablish a natural vegetation composition (Webster and Lorimer 2002). The harvested area can also provide early successional plants and wildlife species habitat and be used to mimic natural stand-replacing disturbances such as wildfires (Tennessee Valley Authority 1993, Toivane and Kotiaho 2007).

Substitution Benefits

When substitution benefits were included, clear-cut management resulted in an increase in net carbon benefit; however when they were excluded, there was a slightly negative net carbon benefit. This implies that the magnitude of the substitution benefit greatly affects whether clear-cutting is an effective tool for increasing carbon sequestration.

The CCTHP assumes that 57 percent of harvested wood products are used as building materials, and have a 1:1 substitution benefit. A 1:1 ratio implies that every wood product displaces the use of non-wood, CO_2 intensive materials. It is not accurate to assume that a CO_2 reduction will result from the use of every piece of wood used (Sathre and O’Connor 2010). In the U.S., wood-based materials already dominate the market for exterior structural support building materials. In 2001, steel accounted for two percent of the market, and concrete represented about nine percent, indicating that the U.S. already captures about 90 percent of the carbon benefits associated with using wood-based building materials (Upton et al. 2008). It is also important to consider which materials are being displaced when estimating the substitution benefit. The displacement of steel materials results in a greater substitution benefit than concrete (Upton et al. 2008). The CCTHP does not consider which materials are displaced or how much is displaced, which affects the displacement benefit. Since this study is based on the assumption that all wood products used in construction results in the displacement of a CO_2 intensive building material, the results may overestimate substitution benefits.

Synthesis

When considering forest management approaches it is important to consider the life-cycle analysis of harvested wood, possible carbon substitution benefits, and other co-benefits. The findings of this study suggest that when these factors are taken into account, forest management should consider harvest plans, and in particular, group selection, in order to maximize carbon sequestration.

Limitations

The data set used in this study was not originally designed for carbon sequestration monitoring of management regimes. There was not enough data before the first harvesting operations to determine management specific growth rates for the let-grow forest; therefore, the reserve stand growth rate was used to model the let-grow forest for clear-cut and group selection. Thus, the results of this study are based on the assumption that the clear-cut and group selection compartments grow at the same rate as the reserve stand. It is not possible with the available data to test if this assumption is correct; however, given that the compartments analyzed are in the same geographical location with the same climate and soil type, it is likely they have similar growth rates. These results are also site specific to BFRS and do not necessarily represent California forests. BFRS is the most productive forest in California, so if this analysis were to be conducted for other forests in California the growth rate would be lower; for such forests it is likely that that clear-cutting would have a higher carbon benefit than the let-grow forest, even when substitution benefits are not included (Black and Harden 1995).

Because of the available data and time constraints, only one group selection compartment was analyzed. This study also only quantified aboveground carbon stored in trees and in harvested wood. A more complete accounting would consider all sources of organic carbon in forests. Most of the carbon stored in an average forest in the U.S. is found in the soil and accounts for 59 percent of the carbon stored in the forest (Forest Service 1992). The results from this study are a conservative estimate of BFRS carbon benefit because it only examined aboveground carbon.

Future Directions

The findings of this study suggest harvesting regimes as a method to increase net carbon benefit of forests; however, future research is needed to incorporate probability analysis of stand-terminating disturbances such as wildfires, which would reduce long-term carbon sequestration. In the United States alone, carbon emissions released from forest fires account for between four and six percent of annual anthropogenic carbon emissions; during the California wildfires of October 2003, more than 750,000 acres burned, releasing an equivalent 49 percent of the monthly fossil fuel carbon emissions throughout the entire state (Wiedinmyer and Neff 2007). Increased wildfire activity has occurred throughout the western United States in recent years; this increase has been especially severe in northern California and in the Sierra Nevada mountain range (Westerling and Bryant 2008). Under current climatic scenarios these trends are predicted to worsen, which will in turn contribute to the occurrence of large, severe forest fires (Westerling and Bryant 2008). Forest management is tasked with the goal of maximizing carbon storage while also minimizing fire risks, all under a changing global climate.

Broader Implications and Conclusions

The results of this study add to the research of forest carbon market systems. Forest carbon offsets and carbon credit programs provide financial incentives for preserving forests and not harvesting them as a way to increase carbon sequestration and capture (UN-REDD 2011). In these markets emitting agents can offset their emissions by purchasing carbon credits or offsets (UNFCCC 2011). However, this study suggests that harvesting forests can sequester more carbon than if otherwise left to grow. California's Forest Project Protocol establishes a carbon market more inline with the finding of this study. Under this program harvested forests can also serve as a carbon offset if the harvesting is sustainable and meets the criteria that more carbon is being sequestered through the harvest compared to the case in which the forest was never harvested (CARB 2014). This market system provides an incentive for forest managers to maximize carbon sequestration and capture in their management regimes. The results of this study suggest the use of group selection management as the best means to maximize net carbon benefits.

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