Ponderosa pine forest carbon balance: a synthesis over western North America

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Professional Paper

Master of Forestry

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Abstract

A better understanding of the carbon balance of forested ecosystems is needed in light of rising atmospheric concentrations of carbon dioxide and climate warming resulting from anthropogenic emissions. This study summarizes published literature concerning annual carbon flux and aboveground carbon stocks of ponderosa pine (*Pinus ponderosa*) forests throughout western North America. The objective was to determine relationships between stand density, stand age, and annual carbon flux and aboveground carbon stocks. There was a significant non-linear relationship between stand age and annual carbon flux. Specifically, carbon sink strength increases with stand age until approximately 150 years, and then decreases with stand age after 150 years. Carbon sink strength increases significantly with time since thinning up to approximately 12 years post-thinning. Aboveground carbon stocks increase non-linearly with stand age, which indicates that young stands store less carbon than mid-aged to old-aged stands. There was a positive non-linear relationship between stand density and aboveground carbon stocks, which increase rapidly in low density stands but begin to level out at densities > 100 trees per hectare. Based on the synthesis results here, two options for carbon-focused management are suggested. First, manage for dense old stands; however the risk of intense fire and subsequent deforestation must be weighed. Second, manage for forest structure characterized by a low to moderate density that is composed of medium-aged trees. Use silvicultural treatments to maintain target densities and age classes via thinning, and use the thinned wood for carbon sequestration in long-lived products.

Introduction

Forested ecosystems of the terrestrial biosphere are of great importance to the global carbon cycle. These ecosystems are important for carbon-focused management because they can be influenced by silvicultural practices aimed at promoting carbon storage while still considering other management objectives. Carbon focused management can be defined as being any silvicultural practice aimed specifically at promoting forest structure, composition, or function to offset anthropogenic emissions of carbon and promote overall carbon sequestration. In western North America the ponderosa pine (*Pinus ponderosa*) forest type occupies a vast geographic range and a diversity of growing conditions (Burns and Honkala 1990). Due to this expansive range and variability in growing conditions, ponderosa pine ecosystems are ideal candidates for the study of ecosystem carbon stocks and carbon fluxes. Here, I provide a synthesis of published studies concerning annual carbon fluxes and aboveground carbon stocks of ponderosa pine ecosystems throughout their native range in western North America.

Through a detailed literature search I compiled data from eight published case studies that address carbon dynamics in ponderosa pine dominated forests. The eight case studies provide data on 26 stands throughout the western United States, encompassing a range of diverse growing conditions. I hypothesized that aboveground carbon stocks and annual carbon fluxes would be related to stand age and density. I also hypothesized that there would be variability in the previously stated relationships among regions. I had two objectives for this study: first, compile all available published data regarding annual carbon fluxes and aboveground carbon stocks, and second, analyze the data for relationships between these metrics and various stand characteristics. I limited my investigation of stand characteristics to stand density and stand age as these are the two most common stand metrics reported in all the case studies.

Background

It is important to understand how forest ecosystems fit into the global carbon cycle and specifically how ponderosa pine forests contribute to the global carbon cycle. Global stocks of carbon can be divided into four component pools: sediments and sedimentary rocks (66,000,000-100,000,000 Pg), oceans (37,000 Pg), plants and soil (2,000 Pg), and the atmosphere (816 Pg) (McKinley et al. 2011). Figure 1 displays the component pools of global carbon storage and the annual fluxes of carbon between each pool.

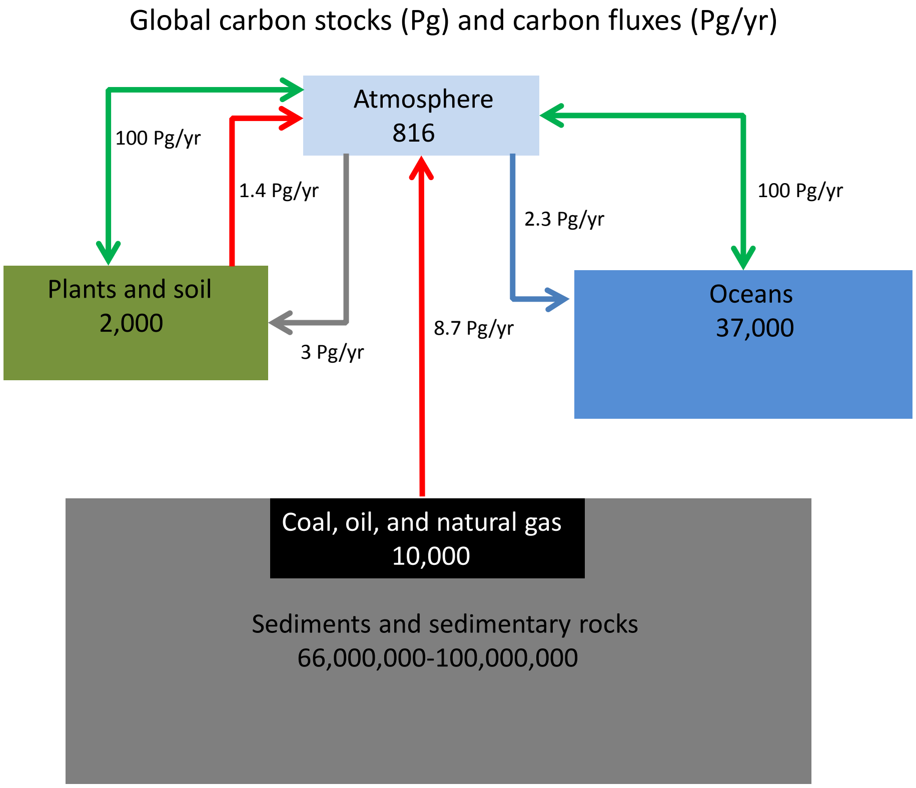

Figure 1. Global carbon pools and associated fluxes of carbon measured in petagrams, Pg. Red arrows display fluxes of carbon to the atmosphere by anthropogenic means, primarily fossil fuel combustion and deforestation. Double-ended green arrows show the historic fluxes of carbon without anthropogenic influence; net uptake is equivalent to net efflux suggesting equilibrium. The gray arrow demonstrates net uptake of carbon by plants and soils attributed mostly to afforestation. The blue arrow displays an increase in carbon uptake by oceans as a result of an increase in atmospheric carbon concentration since the industrial revolution (Figure adapted from McKinley et al. 2011).

Carbon fluxes occur between global carbon pools and fluxes are driven by both natural and anthropogenic disturbances and processes. Within the plants and soil carbon pool forest ecosystems account for approximately 60% of carbon stocks globally (Winjum et al. 1992, McKinley et al. 2011). Just as fluxes of carbon between global pools are mediated by natural and anthropogenic disturbances and processes so are the fluxes of carbon in forest ecosystems. In forest ecosystems the exchange of carbon between the atmosphere and the forest is a result of the interacting processes of photosynthesis, respiration, decomposition, and disturbance (Amiro et al. 2010).

Aboveground carbon stocks of forest types in the Southwestern U.S. increased with increasing elevation (Monson et al. 2002, Huang et al. 2009, Anderson-Teixeira et al. 2011). Lower elevation pinyon-juniper woodlands had an aboveground carbon stock of 0.52 kg C m^{-2} (Huang et al. 2009). Moving up in elevation the smallest recorded aboveground carbon stock for ponderosa pine in the Southwest was 4.2 kg C m^{-2} (Sorensen et al. 2011). At the top of the Southwest elevational gradient in subalpine forests aboveground carbon stocks have been reported to be 26.6 kg C m^{-2} (Teixeira et al. 2011). This trend demonstrates drastic increases in aboveground carbon stocks moving up an elevational and precipitation gradient. Thus, aboveground carbon stocks in ponderosa pine forests are greater than stocks in woodlands but less than stocks in mature subalpine forests.

In ponderosa pine forests several environmental factors influence ecosystem carbon dynamics. Disturbances that influence stand structure and composition include fire, harvesting, disease, and insect infestation (Amiro et al. 2010, McKinley et al. 2011). Climatic conditions, such as temperature and precipitation, are also crucial factors that influence stand characteristics directly related to carbon storage and flux (Law et al. 2002). Environmental conditions and disturbance regimes influence carbon stocks within the ecosystem and component fluxes from the various ecosystem pools of carbon to the atmosphere. Table 1 outlines the component pools of carbon stock within a ponderosa pine ecosystem in northern Arizona.

Table 1. Component pools of carbon within an undisturbed ponderosa pine forest in Arizona. Coarse roots have a diameter greater than 2mm and fine roots have a diameter less than 2mm (Table values adapted from Dore et al. 2008).

Carbon pool			Percent of total forest carbon
Biomass	Aboveground		53%
	Belowground	Coarse root	8%
		Fine root	1%
Mineral soil			27%
Forest floor			6%
Woody debris			5%

It is essential for forest management to be able to measure stocks of carbon within the component pools and the flux of carbon between the forest and the atmosphere. Several techniques are used for measuring carbon stocks and fluxes from forest ecosystems. The first of such techniques for measuring carbon stocks is the use of Lidar (light detection and ranging) and remote sensing imagery to estimate stand characteristics, changes in stand structure, and forest biomass (Turner et al. 2004, Jensen et al. 2006). Remote sensing and Lidar are useful for providing high resolution mapping of forest cover that allows for estimates of biomass, stand age, leaf area index, tree height, tree density, and basal area, all of which are related to forest carbon stocks (Turner et al. 2004). Remote sensing and Lidar data can be coupled with climatic data and incorporated into such models as FOREST-BGC and BIOME-BGC to produce estimates of carbon fluxes (Turner et al. 2004). Remote sensing techniques are useful because they are less time intensive than physically collecting stand level data, and can be used to quickly assess changes in forest structure across a wide range of spatial (10 m to 1 km) and temporal scales (days to years) (Turner et al. 2004, Jensen et al. 2006). However there are some limitations to the accuracy of this data. Accuracy of Lidar and remote sensing techniques is limited on highly diverse terrain and across forests with high species diversity (Nelson et al. 2003, Jensen et al. 2006). When using these techniques with statistical modeling and field data often it is necessary to set a minimum diameter threshold, below which trees are effectively left out of the analysis (Jensen et al. 2006). For large-scale area averaging of forest characteristics these techniques coupled with statistically sound modeling provide an adequately high degree of accuracy (Nelson et al. 2003, Jensen et al. 2006) because most aboveground biomass is stored in standing live and dead trees (Dore et al. 2008).

A second technique used for estimating carbon stocks of a forest ecosystem involves the physical sampling of vegetation to obtain measurements of biomass which can then be converted to amount of carbon (Ter-Mikaelian and Korzukhin 1997, Brown 2002, Kaye et al. 2005). This technique for forest tree species often involves using allometric equations and the diameter at breast height (DBH) of a given tree to predict the total amount of biomass of the tree (Brown 2002, Kaye et al. 2005). Specific allometric equations must be developed for each tree species and region thus requiring a time intensive process of equation development and field sampling (Brown 2002). To date there have been hundreds of allometric equations developed for woody species all over the world; a subset of 65 of these equations for North American tree species has been published by Ter-Mikaelian and Korzukhin (1997). This technique is widely applied in many forest types because it is an inexpensive and accurate way to estimate carbon stocks of individual trees and forest stands. In order to scale up from individual tree measurements to an entire forest stand, predictive relationships based on a subset of sampled trees must be developed (Kaye et al. 2005). These relationships involve using linear regression to relate the diameter at breast height (DBH) and annual incremental growth of sampled trees to the other unsampled trees in the forest stand (Kaye et al. 2005).

A third technique that is growing in application for the measurement of fluxes is the use of eddy covariance flux towers, an instrument-based approach to measuring carbon dioxide exchange between vegetation and the atmosphere (Baldocchi 2003). Eddy covariance techniques provide an accurate and continuous measurement of the exchange of carbon dioxide and water vapor between the land surface and the atmosphere (Baldocchi 2003). The eddy covariance method measures the flux of carbon dioxide on a fine temporal scale (minutes), and the data can then be summed over longer time scales (Baldocchi 2003). This technique works best when the flux towers are located on flat terrain with homogenous underlying vegetation and stable atmospheric conditions (Baldocchi 2003). With the construction of long data records, gaps often form due to variability in atmospheric conditions or instrument failure (Baldocchi 2003). In these instances data gaps are filled with values from statistical and empirical models (Baldocchi 2003). Despite the constraints of the flux towers the eddy covariance technique is gaining widespread use across the globe as an effective way to measure carbon dioxide exchange rates between vegetation and the atmosphere.

In this paper I incorporate data from studies that use biomass inventory, remote sensing, and eddy covariance techniques to synthesize knowledge concerning aboveground carbon stocks and annual carbon fluxes of ponderosa pine ecosystems throughout the western United States.

Methods

Literature Search

In order to formulate a detailed and comprehensive literature synthesis I incorporated all published literature within the scope of this project. To achieve this, the online journal databases (Science Direct, JSTOR, and Google Scholar) from Northern Arizona University's Cline Library were searched using key words, including carbon, annual carbon flux, aboveground carbon stock, ponderosa pine; each set of keywords was searched repeatedly by region and state in order to create a comprehensive search of all published data. In order to limit the scope of this synthesis, only studies reporting aboveground carbon stocks and or annual carbon flux were incorporated. Eddy covariance flux tower locations and associated study groups were located from the Ameriflux data network website (http://www.fluxdata.org/).

Study locations

The case studies utilized in this synthesis come from a vast geographic range across the western United States. Tables 2 - 6 present the relevant stand data reported in each case study and used in this synthesis. Here, annual carbon flux reported as a positive value signifies net ecosystem carbon sink, and a negative flux value indicates a carbon source to the atmosphere. Because ponderosa pine grows across a vast geographic range it is important to understand the climate and growing conditions at each study location.

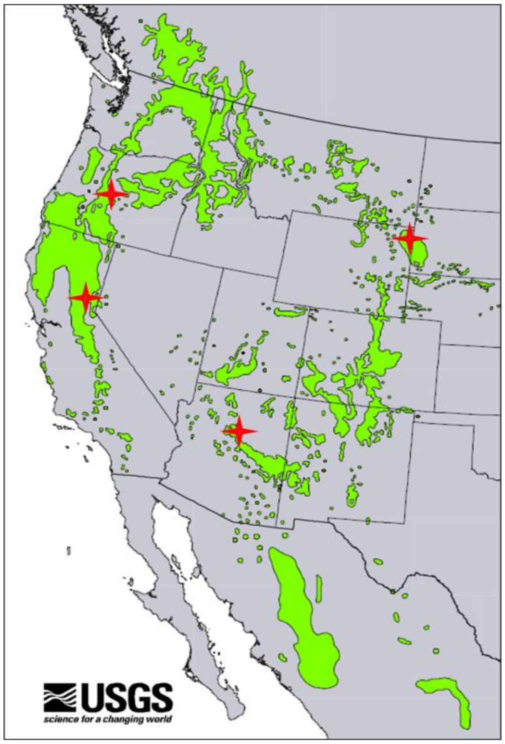

Figure 2. Range of ponderosa pine with study locations identified by a red star

The California study sites reported by Campbell et al. (2009) are considered to be highly productive as compared to ponderosa pine stands in other regions. These study sites are located on the Tahoe National Forest in the western foothills of the Sierra Nevada Mountains (Campbell et al. 2009). The site is located at approximately 1000 m in elevation and experiences an annual precipitation of 950 mm and average annual temperature of 12^{o} C (Campbell et al. 2009). Soils in this area vary from well-drained loam to clay-loam (Campbell et al. 2009). For this study the control stand consists of a fully stocked, nearly pure, ponderosa pine (*Pinus ponderosa*) plantation with a closed canopy (Campbell et al. 2009) The thinned stand from this study consists of a nearly pure ponderosa pine overstory with a dense shrub understory (Campbell et al. 2009). The thinning treatment in this study was accomplished with a thin from below, retaining larger crown classes in order to achieve a final spacing of approximately 7.6 m, with an average reduction in basal area of 50% (Campbell et al. 2009).

The second study sites in California reported by Mission et al. (2005) were located on a young ponderosa pine plantation owned and operated by Sierra Pacific Industries adjacent to the Blodgett Forest Research Station in the Sierra Nevada Mountains (Goldstein et al. 2000). The Blodgett Forest Research Station is a research forest of the University of California at Berkeley. This site is part of the Ameriflux network of eddy covariance flux tower sites. The site was located at approximately 1315 m in elevation and experiences an annual precipitation of 1290 mm and an average annual temperature of 12^{o} C (Mission et al. 2005). Soils in this area are primarily sandy-loam (Mission et al. 2005). The stand investigated here was a pure ponderosa pine plantation, planted following clearcut, with a dense shrub understory (Mission et al. 2005). The treatment investigated here involved the cutting of all shrubs at the base, which were then left onsite to decompose. The pine overstory underwent precommercial thinning by mastication and achieved a reduction in basal area of 30% (Mission et al. 2005).

Table 2. Reported stand data from the two California study sites published by Campbell et al. (2009) and Mission et al. (2005), respectively. Table includes location, stand age, tree density, aboveground carbon stock (C stock), annual carbon flux (C flux), treatment/ stand ID (as reported in publication), and relevant citation for each study.

Location	Stand age(years)	Density (tph)	C stock (kg C m^2)	C flux (g C m^2 yr^{-1})	Treatment/ Stand ID	Reference
California	36	554	13	294	Control	Campbell et al 2009
California	37	186	7.1	107	3 yr post thin	Campbell et al 2009
California	37	191	8	256	16 yr post thin	Campbell et al 2009
California	9	1275	-	201	Prethinning	Mission et al 2005
California	10	765	-	-13	Year of treatment	Mission et al 2005
California	11	765	-	97	1 yr post treatment	Mission et al 2005
California	12	765	-	172	2 yr post treatment	Mission et al 2005

The 12 Oregon study sites reported by Law et al. (2003) were located within a 100 km^2 area in the Metolius River Basin in central Oregon, on the Willamette National Forest. The region is considered to be semi-arid with an average annual precipitation of 550 mm, an average annual temperature of 8^o C (WRCC 2011) and stand elevations ranging from 887 - 1232 m (Law et al. 2003). The soils of this area are primarily sandy-loam (Law et al. 2003). Three of the study sites are Ameriflux network sites with eddy covariance flux towers (Law et al. 2003). All stands incorporated in this study have an overstory dominated by ponderosa pine with varying amounts of incense cedar (*Calocedrus decurrens)*, grand fir (*Abies Grandis)*, and western larch (*Larix occidentalis)* (Law et al. 2003). All stands have a shrub-dominated understory, which is most dense in the youngest age class of stands (Law et al. 2003). All stands regenerated naturally, with varying amounts of silvicultural thinning in all but the oldest stands and stand 26 (Law et al. 2003).

Table 3. Stand data from a chronosequence study in Oregon (Law et al. 2003). Table includes location, stand age, stand density, aboveground carbon stock (C stock), annual carbon flux (C flux), and treatment/ stand ID (as reported in publication). Letters in parenthesis indicate stand age class: Initiation (I, 9-20yrs); Young (Y, 56-89yrs); Mature (M, 95-106yrs); Old (O, 190-316yrs).

Location	Stand age(years)	Density (tph)	C stock (kg C m^{2})	C flux (g C m^{2} yr^{-1})	Treatment/ Stand ID
Oregon	23	431	11.5	-83	Stand 25 (I)
Oregon	9	272	16.9	-244	Stand 26 (I)
Oregon	16	241	7.9	-44	Stand 27 (I)
Oregon	69	349	10.1	177	Stand 28 (Y)
Oregon	56	237	16.5	60	Stand 29 (Y)
Oregon	89	325	20.1	117	Stand 30 (Y)
Oregon	106	581	26.6	190	Stand 31 (M)
Oregon	93	1281	20	-40	Stand 32 (M)
Oregon	96	1070	30	359	Stand 33 (M)
Oregon	190	574	23.9	168	Stand 34 (O)*
Oregon	251	116	22.1	4	Stand 35 (O)
Oregon	316	732	30.4	-67	Stand 36 (O)$^{\#}$

* 2 layer canopy, dominant trees 190 years old with second growth understory

The four Wyoming study sites reported by Chatterjee et al. (2009) and Tinker et al. (2010) were all located on Wyoming State Forestry land adjacent to the Black Hills National Forest. The region is a continental type climate (Chatterjee et al. 2009) with an average annual precipitation of 384 mm and an average annual temperature of 8^{o} C (WRCC 2011). All stands in this study ranged in elevation from 1900 to 2200 m (Tinker et al. 2010). The soils on the limestone plateau where all stands were located ranged from Citadel loam to McCaffery loamy sand (Chatterjee et al. 2009). All stands were nearly pure ponderosa pine with small amounts of quaking aspen (*Populous tremuloides)* and white spruce (*Picea glauca)* occurring on more mesic sites (Tinker et al. 2010). Understory vegetation consisted of varying densities of herbaceous species. All stands, except unmanaged, have undergone variable intensities of silvicultural thinning

(Chatterjee et al. 2009, Tinker et al. 2010). The reader is referred to Tinker et al. (2010) for specific stand details on the thinning and harvest treatments. These studies focused on examining the impact of management history on ecosystem carbon stocks, and thus annual carbon flux data was not reported and is not included here.

Table 4. Stand data from two studies in the Black Hills of Wyoming from Chatterjee et al. (2009) and Tinker et al. (2010) looking at the influence of various management histories on carbon stocks. Table includes location, stand age, stand density, aboveground carbon stock (C stock), treatment/ stand ID (as reported in publication), management action, and relevant references.

Location	Stand age(years)	Density (tph)	C stock (kg C m^2)	Treatment/ Stand ID	Management action
Black Hills	96	3344	24.9	Unmanaged	No active management
Black Hills	46	1390	16.4	Even-aged	Commercial thinning
Black Hills	114	342	17	Uneven-aged	Precommercial thinning
Black Hills	95	478	20	Intensive harvest	Precommercial thinning

The six Arizona stands reported by Sorensen et al. (2011), Finkral and Evans (2008), and Dore et al. (2012) were located near Flagstaff, AZ. Of the six stands in northern Arizona, two, Government Hill and Horse Pine, were located on the Kaibab National Forest, Mountainaire was located on the Coconino National Forest, and the last three, Rogers North, Restoration and Undisturbed were all located on Northern Arizona University's Centennial Forest (Sorensen et al. 2011, Finkral and Evans 2008, Dore et al. 2012). The climate of the region is characterized as having a distinct dry period in the late spring/early summer followed by a distinguished monsoonal season in the late summer, and snow in the winter (Sheppard et al 2002). The Flagstaff region where all stands were located has an average annual temperature of 7.8^{o} C and an average annual precipitation of 537.5 mm (WRCC 2011). For all six stands elevation ranged from 2110 - 2390 m (Finkral and Evans 2008, Sorensen et al. 2011, Dore et al. 2012). The soils across all stands were variable and ranged from fine to gravely clay-loam and cobbly to skeletal fine sandy-loam (Finkral and Evans 2008, Sorensen et al. 2011, Dore et al. 2012).

Four of the Arizona stands reported by Sorensen et al. (2011), Government Hill, Horse Pine, Mountainaire, and Rogers North, were dominated by nearly pure ponderosa pine with fairly continuous canopy cover. These stands also include small scattered pockets of quaking aspen (*Populous tremuloides),* Douglas-fir *(Pseudotsuga menziesii),* white fir *(Abies concolor),* southwestern white pine *(Pinus strobiformis),* Gambel oak *(Quercus gambelii),* alligator juniper *(Juniperus deppeana),* Arizona cypress *(Cupressus arizonica),* and pinyon pine *(Pinus edulis)* (Sorensen et al. 2011). All four stands are assumed to have regenerated in the 1919 cohort which is typical of the region, and data in Table 5 represents pre- and post-thinning treatment aboveground carbon stocks (Sorensen et al. 2011). The study by Sorensen et al. (2011) did not include annual carbon flux data and therefore the flux data is not reported here.

Table 5. Pre- and post-thinning data from four stands in north central Arizona reported by Sorensen et al. (2011). Table includes location, stand age, stand density, aboveground carbon stock (C stock), and treatment/ stand ID (as reported in publication).

Location	Stand age(years)	Density (tph)	C stock (kg C m^2)	Treatment/ Stand ID
N. Arizona	91	430	10.009	Pre thin Government hill
N. Arizona	91	76	5.641	Post thin Government hill
N. Arizona	91	389	7.482	Pre thin Horse pine
N. Arizona	91	143	5.159	Post thin Horse pine
N. Arizona	91	219	6.709	Pre thin Mountainaire
N. Arizona	91	79	4.237	Post thin Mountainaire
N. Arizona	91	284	7.336	Pre thin Rogers north
N. Arizona	91	202	5.798	Post thin Rogers north

The final two Arizona stands reported by Finkral and Evans (2008) and Dore et al. (2012), restoration and undisturbed, were both dominated by nearly pure ponderosa pine with a minor scattered Gambel oak component and were assumed to have regenerated in the 1919 cohort. The restoration stand has had several timber harvests on site between 1914 and 2006 when the restoration thinning occurred (Finkral and Evans 2008). This stand had almost continuous canopy cover and understory vegetation typical of the region, which was dominated by grass and forb species (Finkral and Evans 2008). The undisturbed stand has been excluded from silvicultural treatments and fire over the past century; it has a continuous ponderosa pine canopy and a sparse understory (Dore et al. 2012).

Table 6. Stand data for five years of data collection for the restoration and undisturbed stands from Finkral and Evans (2008) and Dore et al. (2012). Table includes location, stand age, stand density, aboveground carbon stock (C stock), annual carbon flux (C flux), treatment/ stand ID (as reported in publication) and relevant references.

Location	Stand age(years)	Density (tph)	C stock (kg C m^2)	C flux (g C m^2 yr^{-1})	Treatment/ Stand ID	Reference
N. Arizona	87	579	5.756	118	Pre thin Restoration 2006	Finkral and Evans 2008 Dore et al 2012
N. Arizona	88	163	4.488	-51	1 yr post thin Restoration 2007	Finkral and Evans 2008 Dore et al 2012
N. Arizona	89	163	-	114	2 yr post thin Restoration 2008	Dore et al 2012
N. Arizona	90	163	-	116	3 yr post thin Restoration 2009	Dore et al 2012
N. Arizona	91	163	-	225	4 yr post thin Restoration 2010	Dore et al 2012
N. Arizona	87	853	12.319	174	Undisturbed 2006	Dore et al 2012
N. Arizona	88	853	12.378	58	Undisturbed 2007	Dore et al 2012
N. Arizona	89	853	-	142	Undisturbed 2008	Dore et al 2012
N. Arizona	90	853	-	19	Undisturbed 2009	Dore et al 2012
N. Arizona	91	853	-	170	Undisturbed 2010	Dore et al 2012

In order to infer regional trends in annual carbon fluxes and aboveground carbon stocks I grouped the western US into four regions: Northwest, California, Intermountain, and Southwest. Each study reported here represents a distinct region and the growing conditions therein. The Oregon study sites from Law et al. (2003) were used for the Northwest region, the California study sites from Campbell et al. (2009) and Mission et al. (2005) were used for the California region, the Wyoming study sites from the Black Hills described by Chatterjee et al. (2009) and Tinker et al. (2010) were used for the Intermountain region, and the Arizona study sites described by Sorensen et al. (2011), Finkral and Evans (2008) and Dore et al. (2012) were used for the Southwest region.

Data analysis

From the literature search I compiled stand-level carbon data and fit regression lines to the data to assess relationships between stand age, stand density, and the fluxes and stocks of carbon. Significance of all statistical relationships was determined at the $p < 0.05$ level. Multiple regression models were tested for each relationship and the best fit model was selected by the highest R^2 value. Adjusted R^2 values were also calculated to determine the quality of each model tested. The presence of negative R^2 values indicated that the model in question was not capable of predicting the response based on the predictor variable. Table 7 provides a summation and comparison of all models tested.

Table 7. Summary and comparison of all models tested based on the relationship of study variables. Table includes variables in each relationship, type of model tested, R^2 value, adjusted R^2 value, sample size, and P value associated with each model. Models used for analysis here are highlighted in red and significance is denoted by an asterisk (*).

Predictor variable	Response variable	Model	R^2	Adjusted R^2	Sample size	P value
Stand age	Annual carbon flux	Linear	0.0049	-0.03195	29	0.7132
		Logarithmic	0.0247	-0.0114	29	0.4069
		Polynomial	0.1596	0.1285	29	0.0287*
Stand age	Annual carbon flux (CA)	Linear	0.2773	0.1328	7	0.1800
		Logarithmic	0.2757	0.1308	7	0.1814
		Polynomial	0.2862	0.1434	7	0.1719
Stand age	Annual carbon flux (NW)	Linear	0.0118	-0.0870	12	0.7240
		Logarithmic	0.2249	0.1474	12	0.1016
		Polynomial	0.5906	0.5497	12	0.0021*
Stand density	Annual carbon flux	Linear	0.033	-0.0028	29	0.3367
		Logarithmic	0.0302	-0.0057	29	0.3584
		Polynomial	0.0346	-0.0012	29	0.3250
Years since thinning	Annual carbon flux with outlier	Linear	0.4406	0.3707	10	0.0259*
		Polynomial	0.5748	0.5217	10	0.0068*
Years since thinning	Annual carbon flux no outlier	Linear	0.4233	0.3409	9	0.0416*
		Polynomial	0.452	0.3737	9	0.0332*
Stand age	Aboveground carbon stock	Exponential	0.1553	0.1262	31	0.0256*
		Linear	0.2567	0.2311	31	0.0031*
		Logarithmic	0.1168	0.0863	31	0.0555*
		Polynomial	0.2687	0.2435	31	0.0024*
		Power	0.052	0.0193	31	0.2095
Stand density	Aboveground carbon stock with outlier	Exponential	0.2824	0.2576	31	0.0018*
		Linear	0.3063	0.2824	31	0.0010*
		Logarithmic	0.4219	0.4019	31	0.0001*
		Polynomial	0.4129	0.3926	31	0.0001*
		Power	0.4529	0.4340	31	0.0001*
Stand density	Aboveground carbon stock no outlier	Exponential	0.3004	0.2754	30	0.0014*
		Linear	0.2681	0.2419	30	0.0028*
		Logarithmic	0.3063	0.2815	30	0.0012*
		Polynomial	0.333	0.3092	30	0.0007*
		Power	0.3782	0.3559	30	0.0002*
Stand density	Aboveground carbon stock (SW)	Exponential	0.7217	0.6939	12	0.0002*
		Linear	0.7656	0.7422	12	0.0001*
		Logarithmic	0.6681	0.6349	12	0.0006*
		Polynomial	0.7703	0.7473	12	0.0001*
		Power	0.6869	0.6556	12	0.0005*

Results and Discussion

Annual carbon fluxes

I compared reported stand age, density, and time since thinning to annual carbon flux of ponderosa pine dominated stands across the western United States. I determined that the relationship between stand age and annual carbon flux was non-linear (Figure 3).

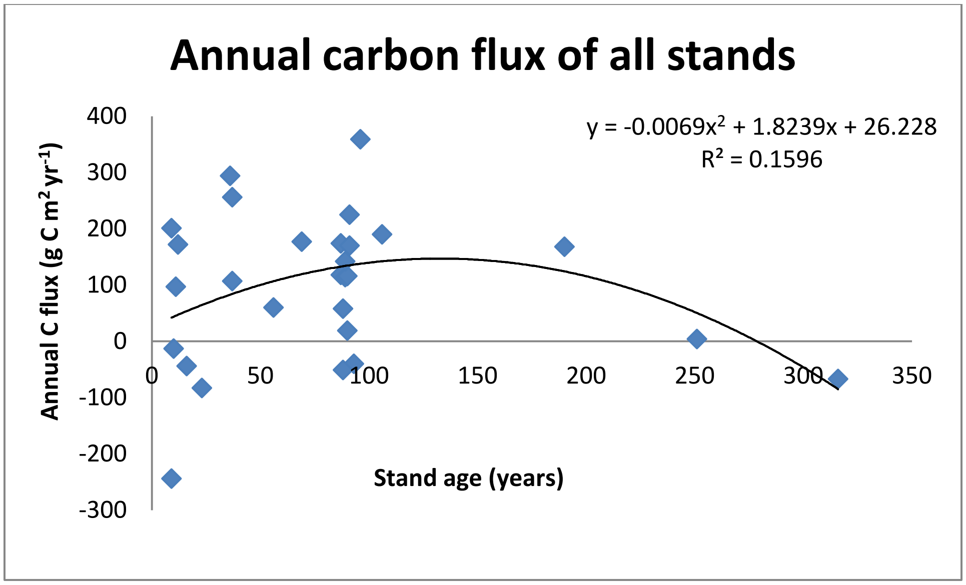

Figure 3. Relationship between stand age and annual carbon flux pooled across 29 ponderosa pine dominated stands from the California, Northwest and Southwest regions. The fitted line and equation display the best fit regression ($p = 0.028$). Positive values signify net carbon sink.

This relationship indicates increasing sink strength with stand age until approximately 150 years and then carbon sink strength decreases with stand age after 150 years. In the absence of disturbance stand carbon sink strength (i.e. the ability to uptake and store carbon) increases until approximately 150 years old. At this age in the absence of treatment or disturbance the sink strength declines as the stand progresses into an old growth structure. I compared stand age and annual carbon flux by region as well (Figure 4). The only significant relationship was in the Northwest region (Figure 4). However, due to a lack of published studies in regions other than the Northwest it is difficult to confirm the non-linear relationship in individual regions. A weak and non-significant linear relationship was found in the California region (Figure 4) represented by the blue dashed line (p = 0.1800).

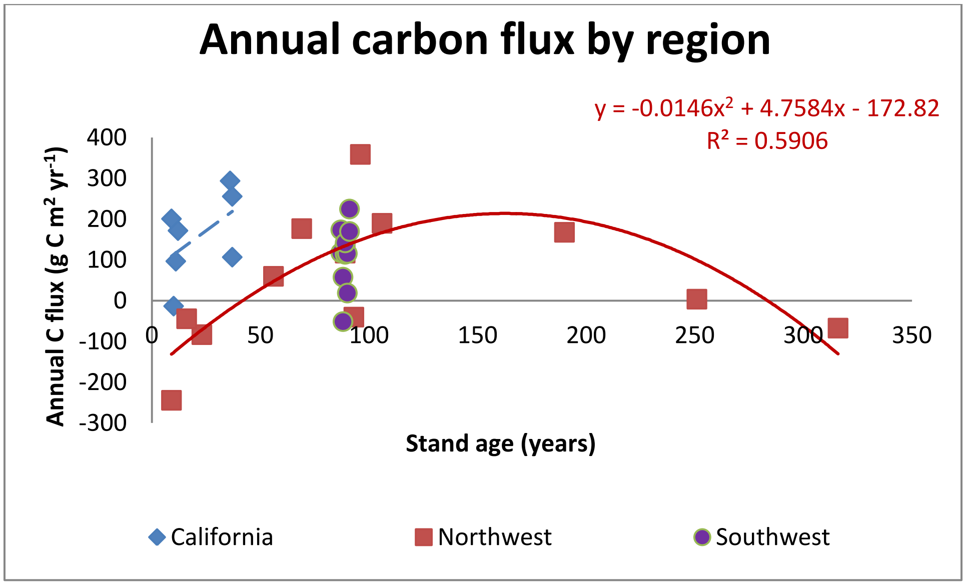

Figure 4. Relationship between stand age and annual carbon flux for ponderosa pine dominated stands, separated by region. Individual region sample sizes are n = 7, 12, and 10 for the California, Northwest, and Southwest regions, respectively. The only region that exhibited a statistically significant relationship was the Northwest, for which a regression line and equation were fitted (p = 0.0021) shown here in red. Positive values signify net carbon sink.

Distinct differences in the annual carbon flux of young stands occurred between the California and Northwest regions. Annual flux values for young California stands were greater than the values for young stands in the Northwest region.

The relationship between stand density, measured in trees per hectare (tph), and annual carbon flux was weak and not statistically significant (Figure 5).

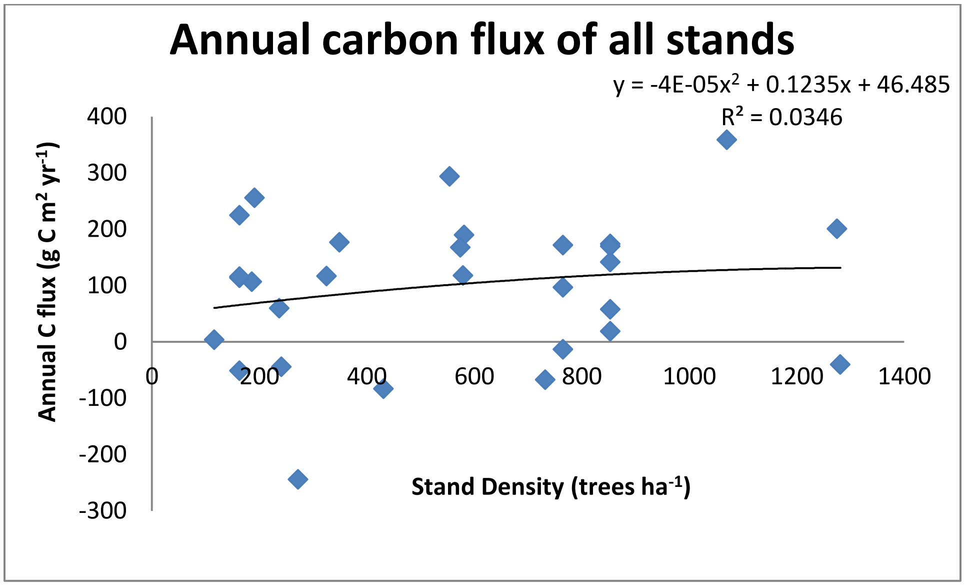

Figure 5. Relationship between stand density and annual carbon flux pooled across 29 ponderosa pine dominated stands from the California, Northwest, and Southwest regions. The fitted line and equation displays the best fit regression which was not significant ($p = 0.3250$). Positive values signify net carbon sink.

The relationship between density and annual carbon flux was even weaker when examined by individual region due to small sample size (Figure 6).

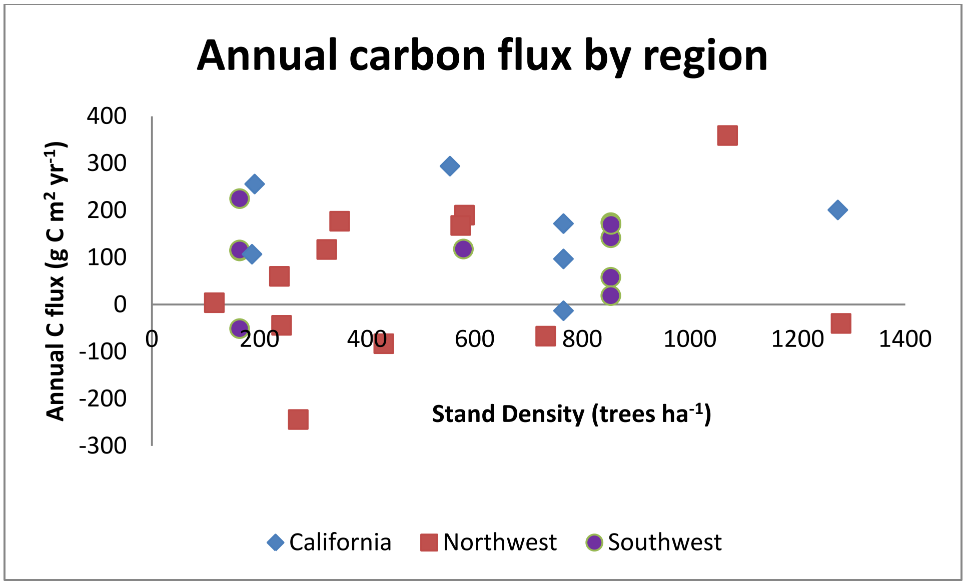

Figure 6. Relationship between stand density and annual carbon flux for ponderosa pine dominated stands, separated by region. Individual region sample sizes are n = 7, 12, and 10 for the California, Northwest, and Southwest regions respectively. No significant relationships were detected. Positive values signify net carbon sink.

Figures 7A and 7B display two possible post-treatment carbon flux scenarios resulting from different durations of time reported following treatment. Panels A and B display the same relationship with and without the outlier point at sixteen years.

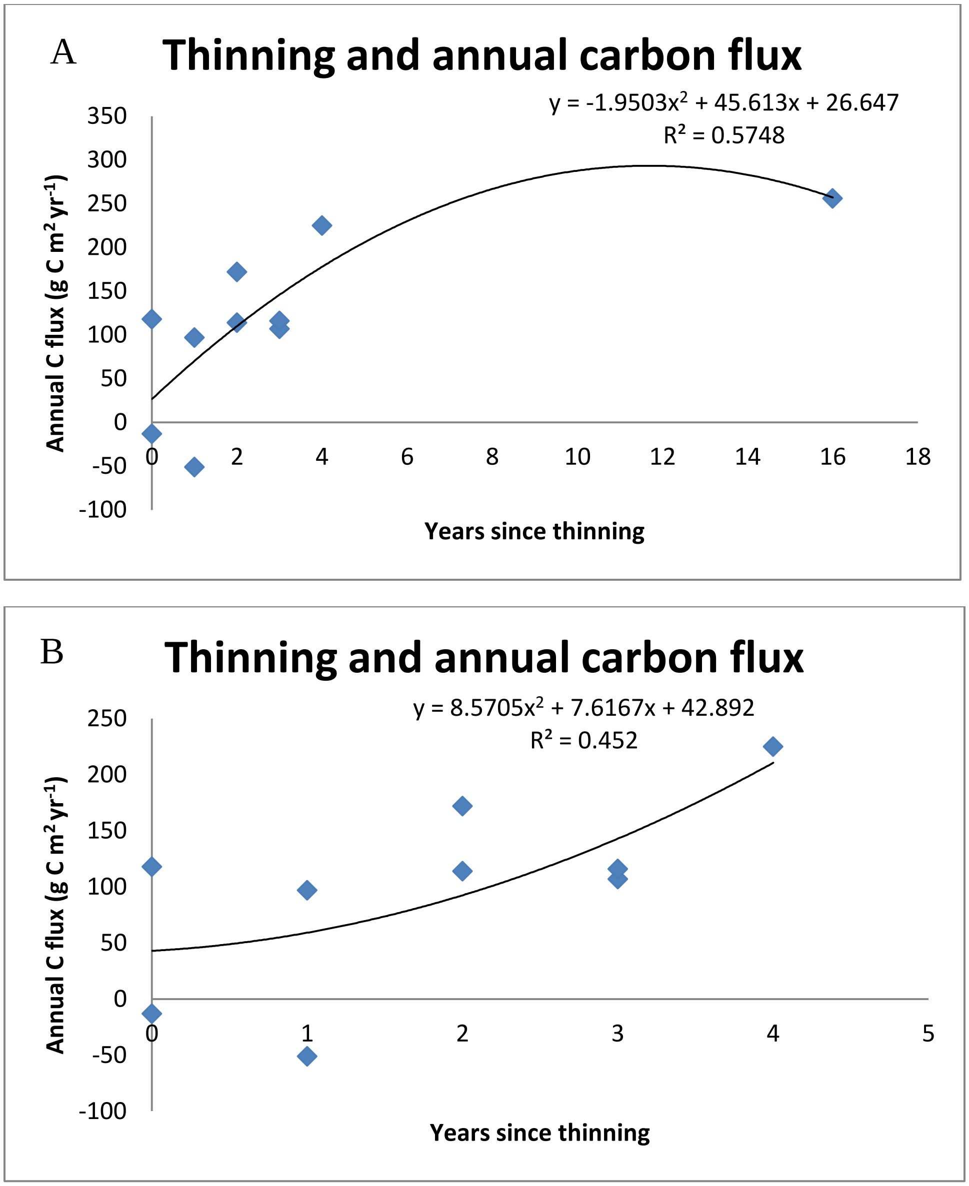

Figure 7. Relationship between time since thinning and annual carbon flux pooled across 10 (A) and 9 (B) ponderosa pine dominated stands from the California and Southwest regions. A significant non-linear relationship is displayed by the best fit regression line and equation for each panel (p = 0.0068 and p = 0.0332 for A and B, respectively). Positive values signify net carbon sink.

In panel A there is a large data gap between four and sixteen years resulting in an influential outlier point at sixteen years. Panel B displays the same relationship without the outlier point at sixteen years. With a small data set and incomplete reporting on number of years since thinning, it is difficult to elucidate which relationship is most representative of the recovery of carbon sink strength following thinning. Both relationships were significant and demonstrate that sink strength increases within two years following thinning treatment, as reported previously by Dore et al. (2012), Campbell et al. (2009), and Mission et al. (2005) In panels A and B of Figure 7, sink strength continues to increase for at least four years following thinning, but with limited reported results it is difficult to predict how long thinning-induced increases in sink strength will continue. In fire-adapted ecosystems such as ponderosa pine, thinning treatments can help to maintain sink strength while reducing the risk of intense wildfire (Finkral and Evans 2008, Campbell et al. 2012). Silvicultural thinning is also used to increase individual tree growth to promote health and economic value (Daniel et al. 1979, Dore et al. 2012). The thinning treatment from Dore et al. (2012) was implemented for ecological restoration, a common silvicultural thinning treatment used in the American Southwest (Covington et al. 1997, Allen et al. 2002). On the other hand, the thinning treatments investigated by Campbell et al. (2009) and Mission et al. (2005) from California were used to promote individual tree growth for economic value.

Aboveground carbon stocks

I compared reported stand age, density, and time since thinning with aboveground carbon stocks of ponderosa pine dominated stands across the western United States. Aboveground carbon stocks increased in a non-linear fashion with stand age for sites pooled over regions (Figure 8).

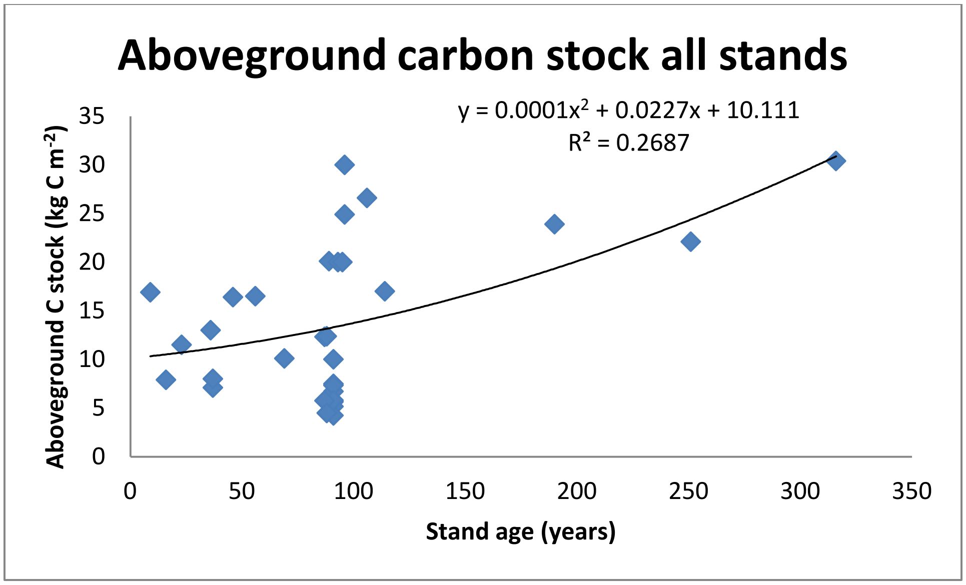

Figure 8. Relationship between stand age and aboveground carbon stock pooled across 31 ponderosa pine dominated stands from the California, Northwest, Intermountain, and Southwest regions. The fitted trend line and equation displays the best fit regression which was significant (p = 0.0024).

This relationship indicates that young stands store less carbon than mid-aged and old-aged stands and this trend increases slightly with age. A regional comparison in Figure 9 showed that stands of similar age differ in aboveground carbon stocks between regions.

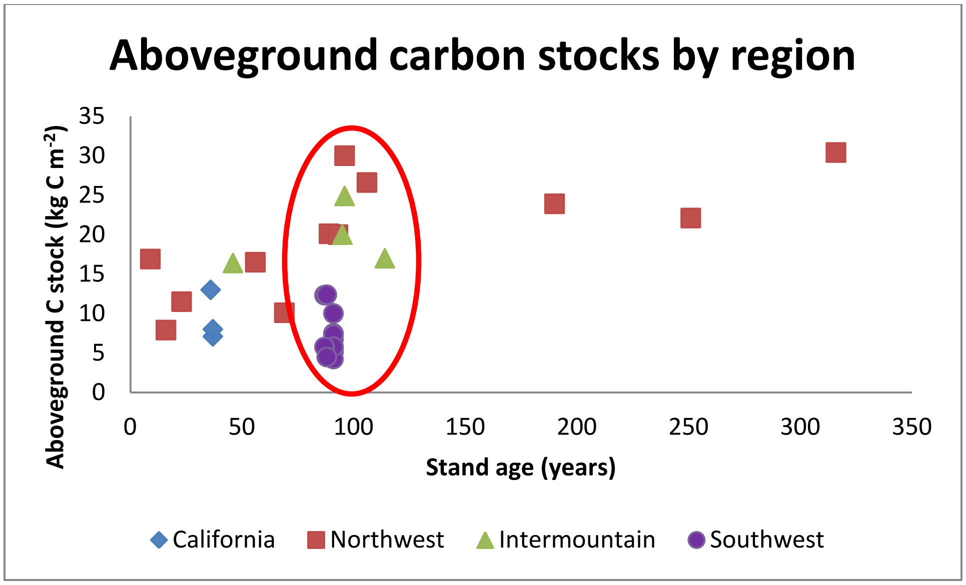

Figure 9. Relationship between stand age and aboveground carbon stock in ponderosa pine dominated stands, separated by region. Individual regional sample sizes are n = 3, 12, 4, and 12 for California, Northwest, Intermountain, and Southwest, respectively. The area in the red circle highlights a regional difference in carbon stocks of similar aged stands.

Stands of approximately 100 years old in the Southwest contain a smaller aboveground carbon stock than stands in the Northwest and the Intermountain regions in Figure 9. Based on observed trends here and results from Law et al. (2003), in the absence of severe disturbance aboveground carbon stocks increase with stand age.

The relationship between stand density, measured in trees per hectare (tph), and aboveground carbon stocks increases non-linearly (Figure 10). This relationship was plotted twice, with (A) and without (B) the outlier. The outlier point was an extremely dense stand that had 3,344 tph.

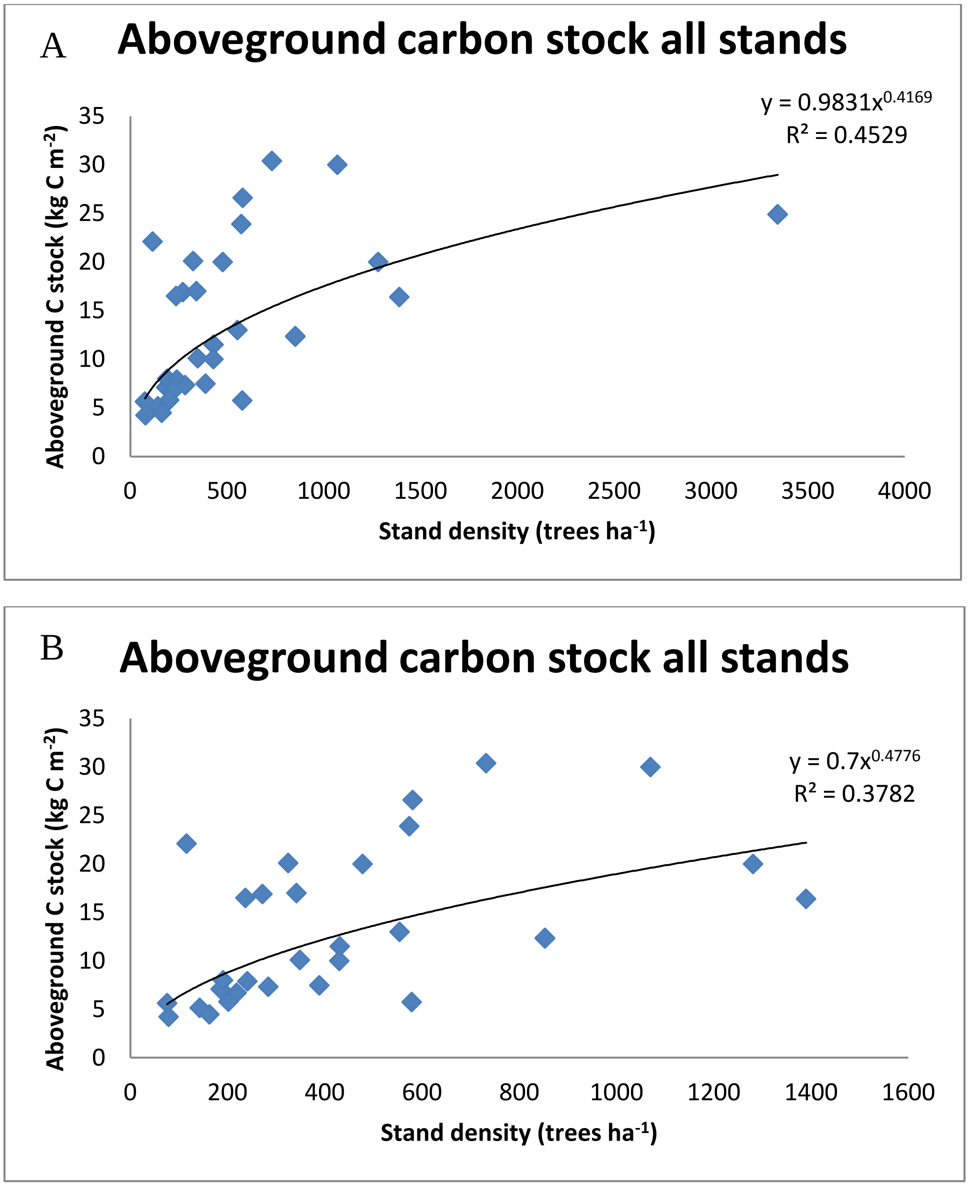

Figure 10. Relationship between stand density and aboveground carbon stocks pooled across 31 (A) and 30 (B) ponderosa pine dominated stands from the California, Northwest, Intermountain, and Southwest regions. The fitted trend lines and equations show the best fit regressions, which were significant ($p = 0.0001$ and $p = 0.0002$ for A and B, respectively).

The relationships shown in panels A and B of Figure 10 demonstrate a similar relationship between stand density and aboveground carbon stock regardless of the outlier point. This similarity confirms the non-linearity of the relationship even in the presence of a large data gap between densities of 1500 and 3,300 tph as seen in panel A of Figure 10.

When aboveground carbon stocks were compared by region (Figure 11) the Northwest region stands out for supporting high carbon stocks at moderate tree density, shown here in the red circle. The only significant relationship between aboveground carbon stocks and stand density occurred in the Southwest region.

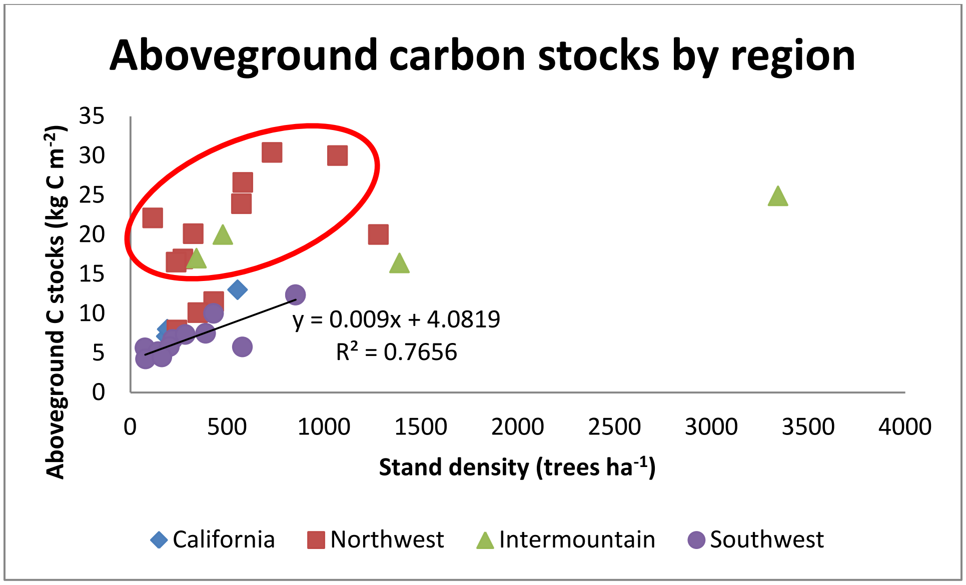

Figure 11. Relationship between stand density and aboveground carbon stocks in ponderosa pine dominated stands, separated by region. Individual regional sample sizes are n = 3, 12, 4, and 12 for California, Northwest, Intermountain and Southwest, respectively. This figure demonstrates that the Northwest region supports high carbon stocks at low to moderate stand densities. The fitted trend line and equation show the best fit regression only for data from the Southwest region, which was significant ($p = 0.0001$).

Due to incomplete reporting it is difficult to know whether these higher carbon stocks in the Northwest region represent a treatment effect (release from competition) or if they are higher due to higher productivity or some other unknown factor.

Management considerations

Through this synthesis study I found several significant relationships between stand age, stand density and aboveground carbon stocks and annual carbon fluxes in ponderosa pine forests. Here I list five key relationships that will be important for carbon focused management.

1. There is a significant non-linear relationship between stand age and annual carbon flux. Specifically, carbon sink strength increases with stand age until approximately 150 years and decreases with stand age after 150 years.

2. Carbon sink strength increases within two years following treatment, and continues to increase up to four years after treatment. Due to limited data it is difficult to say how long thinning induced sink strength will last.

3. Aboveground carbon stocks showed a significant positive non-linear trend in relation to stand age. This trend indicates that young stands store less carbon than mid-aged to old-aged stands.

4. There are regional variations in aboveground carbon stocks in relation to stand age and stand density. The Northwest region supports the highest carbon stocks, followed by the Intermountain, then California, and finally the Southwest region had the lowest aboveground carbon stocks.

5. There is a significant positive non-linear relationship between stand density and aboveground carbon stocks. Carbon stocks increase rapidly in low density stands but begin to level out at densities > 1000 trees per hectare.

The results of my analysis can be used to inform carbon-focused management. First, the observed relationship between stand age and annual carbon flux could be used to coordinate the timing of thinning treatments. I demonstrate here that sink strength is highest at a stand age of approximately 150 years. Thinning at this time may increase the stand vigor and thus rejuvenate the carbon sink strength beyond the approximate 150 year threshold. Pre-commercial thinning early in the life of a stand is often used to reduce fire hazard and promote individual tree growth to produce large commercial sized saw timber (Oliver 1972, Finkral and Evans 2008, Hurteau and North 2009, Campbell et al. 2009, Campbell et al. 2012). Pre-commercial thinning also may increase the carbon sink strength of younger stands beyond that of untreated stands while protecting them from intense fire (Rhodes and Baker 2008, Campbell et al. 2012). Stands having undergone pre-commercial thinning initially have lower aboveground carbon stocks but will be able to support higher carbon stocks and have greater sink strength in the long term due to increased growth of residual trees resulting from the thinning treatments.

With the understanding that carbon sink strength increases with time since thinning it is also possible to address a variety of management objectives with the use of thinning treatments. Forest thinning has been shown to reduce wildfire hazard, increase tree-level wood production, increase resistance to pests, and aid in ecological restoration (Oliver 1972, Allen et al. 2002, Finkral and Evans 2008, Hurteau and North 2009, Campbell et al. 2009, Campbell et al. 2012). Thus, thinning can promote stand-level carbon sink strength and other management goals. For instance thinning can support economic incentives such as timber production, as well as promoting increased tree-level wood production that will sequester additional carbon in residual trees, and reduce the risk of intense fire (Oliver 1972, Hurteau and North 2009).

Thinning treatments aimed at promoting and protecting carbon sink strength should support management goals associated with offsetting anthropogenic carbon emissions in the form of carbon sequestration in forest biomass and forest products. Carbon sequestration goals would be promoted by using wood from thinning to produce long-lived forest products such as housing materials. On the other hand, wood used for short-lived products, such as firewood and paper, releases carbon to the atmosphere quickly (Skog and Nicholson 1998, Finkral and Evans 2008, Sorensen et al. 2011). Long-term carbon sequestration in forest biomass can also be achieved by managing for old growth or restoration (pre-settlement) stand structures that are resistant to wildfire and forest pests while still supporting valuable ecosystem services (Allen et al. 2002, Luyssaert et al. 2008).

The benefits associated with thinning treatments also come with a price, in the form of carbon emissions associated with harvesting machinery, trucking to mills, processing, and the treatment of logging slash on site, often by burning (Markewitz 2006, Finkral and Evans 2008). The carbon emissions associated with the thinning treatment should be offset in order for the treatment to be a net benefit for the forest carbon balance. The increased growth and carbon storage of residual trees following thinning, coupled with long-term storage in wood products, could potentially be sufficient to offset carbon emissions associated with thinning treatments (Markewitz 2006, Sorensen et al. 2011, Dore et al. 2012).

A recent study by Campbell et al. (2012) described how thinning treatments aimed at fire hazard reduction compare to high intensity wildfire in terms of total carbon release to the atmosphere.

In intense or stand replacing wildfire events occurring in high density stands that experience fire suppression, an average of 12-22% of aboveground carbon stocks was released to the atmosphere (Campbell et al. 2007, Meigs et al. 2009, Campbell et al. 2012). On the other hand stands that were treated for fire hazard reduction using a variety of thinning only methods removed an average of 30% of aboveground carbon stocks (Campbell et al. 2012). The study by Campbell et al. (2012) also found that for fire hazard reduction to be effective on one hectare of forest about ten hectares had to be treated in total.

Overall, my analysis suggests that there are many ways that silviculutral practices can incorporate carbon focused managment as one of many objectives. First, there exists a carbon storage and wildlife benefit associated with high stand densities. These stands are able to support large carbon stocks and provide ideal habitat for various wildlife species including squirrels, birds and ungulates (Reynolds 1969, Dodd 2003, Kalies et al. 2010). Management actions in these stands can help protect them from intense wildfire by incorporating a silvicultural treatment that maintains high density but raises canopy base height to reduce the risk of a catastrophic fire starting in the stand (Miller and Urban 2000, Fulé et al. 2004, Agee and Skinner 2005, Hurteau and North 2009, Campbell et al. 2012). The risk of a crown fire still exists but in such a treatment, the crown fire would have to spread into the treated stand from adjacent forested areas. Second, increased silvicultural management in the form of intense regular harvesting can support carbon sequestration and sink strength in the form of long-lived timber products and large diameter residual trees that have a greater spacing and reduce overall fire hazard (Skog and Nicholson 1998, Finkral and Evans 2008, Sorensen et al. 2011). These lower density stands are more protected from catastrophic fire events that start within the stand or that spread from adjacent stands. Lower density stands also have residual trees that show increased vigor which supports a greater sink strength. For carbon focused management to be truly effective it would need to be implemented on a landscape scale, because individual stands of trees on their own are not capable of creating a significant impact in terms of offsetting anthropogenic emissions of carbon (Campbell et al. 2012). Thus the incorporation of landscape scale carbon focused management can adequately support a wide array of management objectives that are both sustainable and ecologically sound.

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