Final Report

Carbon cycling at the landscape scale: the effect of changes in climate and fire frequency on age distribution, stand structure, and net ecosystem production.

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Michael G Ryan
USDA Forest Service
Rocky Mountain Research Station
240 West Prospect RD
Fort Collins, CO 80526

Daniel M. Kashian
Department of Biological Sciences
Wayne State University
Detroit, MI 48202

Erica A. H. Smithwick
Department of Geography and Intercollege Graduate Program in Ecology
The Pennsylvania State University
University Park PA 16802

William H. Romme
Department of Forest, Rangeland, and Watershed Stewardship, and Graduate Degree Program in Ecology
Colorado State University
Fort Collins, CO 80523

Monica G. Turner
Department of Zoology
University of Wisconsin
Madison, WI 53706

Daniel B. Tinker
Department of Botany
University of Wyoming
Laramie, WY 82071

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Introduction

Understanding the interactions between climate, fire and forest characteristics--and how carbon dynamics are affected by these factors--remains an important challenge in ecology. As the size and severity of fires in the western US continues to increase (Westerling et al. 2006), it has become increasingly important to understand carbon dynamics in response to fire. In this study, we investigated these key interactions in the landscape of Yellowstone National Park (YNP). We asked how initial post-fire heterogeneity in forest structure (especially tree density and stand age) controls carbon dynamics over the full life cycle of individual forest stands, and how climate-mediated changes in the fire regime might potentially alter the behavior of the YNP ecosystem as a net sink or source of carbon in the global carbon cycle. We focused on net ecosystem production (NEP), which is the annual net change in carbon stored in the ecosystem—that is, the difference between net primary production (NPP) and heterotrophic respiration. Our research embraced a landscape perspective by considering how NEP varies with spatial variability in structure and forest development. To address our overarching question, we combined a broad-scale chronosequence study of 77 stands distributed widely across the YNP landscape with simulation modeling that incorporated projected climate change. We also developed new allometric equations to predict biomass of the lodgepole pine trees in this region, since existing equations (developed in other regions) were found to be inadequate. Our research has produced one MS thesis (Arcano 2005), two peer-reviewed journal articles to date (Kashian et al. 2006, Smithwick et al. 2008), one submitted manuscript (Tinker et al. Submitted), two in draft form (Kashian et al. Draft, Smithwick et al. Draft), and six manuscripts are in preparation. In the remainder of this report, we highlight some of the key findings.

Synopsis of Research Findings

In a landscape characterized by a natural stand-replacing fire regime, equilibrium carbon storage will change only minimally--as long as the forest regenerates after a fire.

We hypothesized in our proposal that the large differences in stand density seen after the 1988 Yellowstone National Park (YNP) fires and an estimated extended recovery time for aboveground biomass would yield large differences in equilibrium carbon storage on the YNP forested landscape if fire frequency increased. Our data show that productivity and carbon storage reached equilibrium fairly quickly (between 70-100 years), independent of initial or current stand density (Kashian et al. 2006, Kashian et al. Draft). Because carbon storage in stands 70-100 years is similar to pre-fire carbon storage, a fire regime that changes the distribution of age classes and/or tree density classes on the landscape would have little effect on landscape carbon storage unless stand-replacing fires occurred much more frequently (e.g., < 50 years rather than the 150-300 years common today). Thus, as long as forests regenerate after fire and avoid conversion to grasslands or savannas, landscape carbon storage is very resistant to changes in fire frequency and moderate changes in stand density (Figure 1).

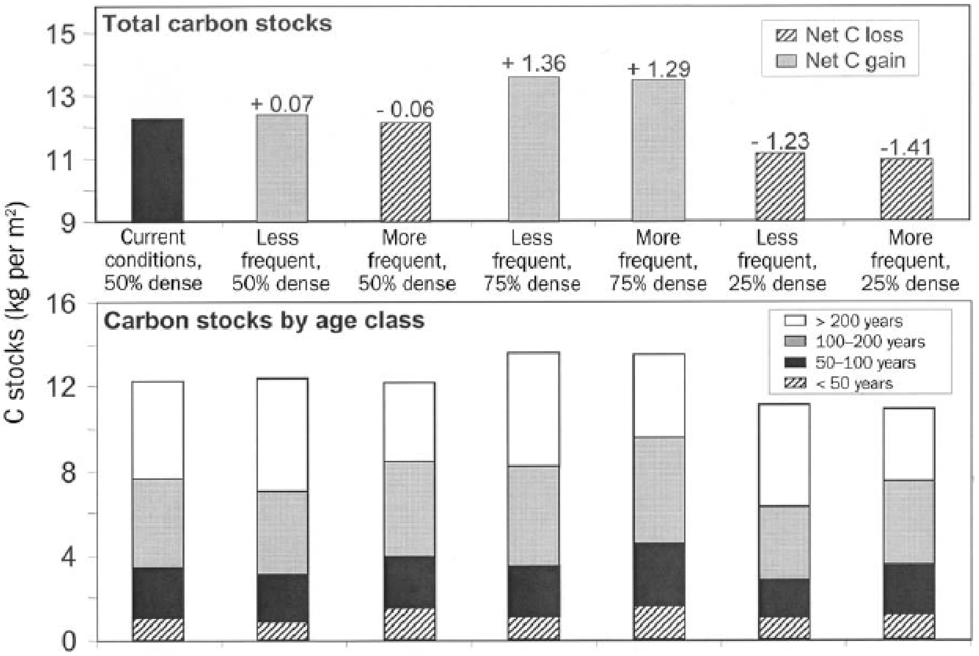

Figure 1. Ecosystem carbon stocks (top) and C stocks by age class (bottom) of an 80,000 ha YNP landscape under more and less frequent fires and differences in tree density. Carbon stored on the landscape is very resistant to changes in fire frequency or tree density, as long as the forest regenerates.

This study identified successful tree regeneration as a much more critical factor than stand age class distribution (resulting from different fire return intervals) or tree density (resulting from pre-fire serotiny and fire intensity). As long as post-fire lodgepole pine stands support enough trees to have the structural characteristics of forests rather than shrublands, grasslands, or other kinds of non-forest vegetation, they will recover pre-fire carbon stocks quickly and the landscape will be resistant to long-term changes in carbon storage.

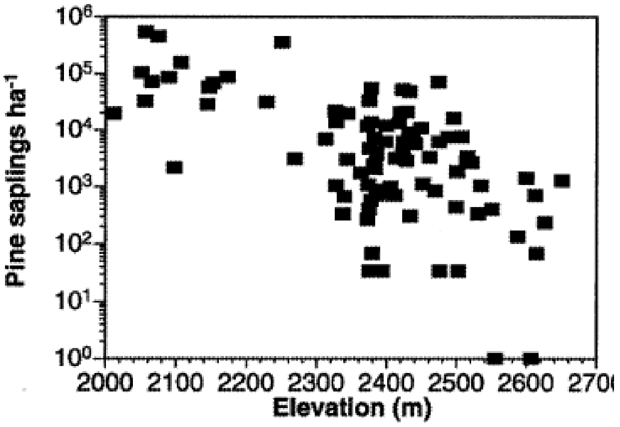

Figure 2. Lodgepole pine seedlings versus elevation in 90 sample plots. From Turner et al. (2004).

In ecosystems with a historical fire regime featuring frequent surface fires or surface- and mixed-severity fires, a stand-replacing fire can lead to poor or no regeneration and conversion of forests to shrublands or grasslands. Such conversion will move the carbon in live and dead wood from the forest to the atmosphere, possibly for centuries. The majority of the YNP landscape burned in the 1988 fires had forest regeneration that would yield fully stocked stands or overstocked stands. To complete the fire and carbon story, there is a need for research on carbon storage in ecosystems where stand-replacing fires may lead to land cover conversion.

Because the question of regeneration success is so important, we include in this report information from prior studies at YNP by participants in this study. One thousand seedlings per hectare equals about 400 seedlings per acre, the current requirement for lodgepole pine regeneration that would lead to a ‘fully stocked’ stand. A survey of regeneration on the YNP landscape (Kashian et al. 2004, Turner et al. 2004) after the 1988 fires showed that at least 64% of stands sampled had > 1000 stems per hectare (Figure 2). Additionally, lodgepole pines reach reproductive maturity quite early (~15 years), and many of the stands that regenerated after the 1988 fires are already producing cones (Turner et al. 2007). The presence of any ongoing recruitment will increase regeneration success in the long term (Kashian et al. 2005).

The carbon lost in the 1988 fire and in the subsequent decomposition of the trees killed in the fire will be recovered quickly, relative to the current fire interval.

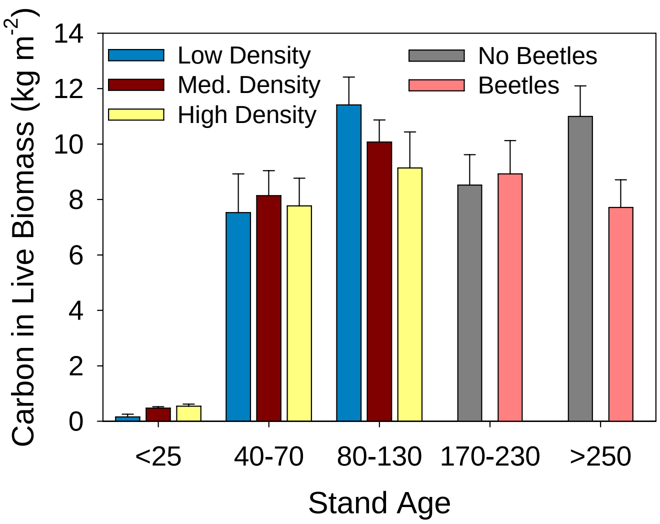

Figure 3. Carbon in live biomass from 77 lodgepole pine stands in a replicated chronosequence across the Yellowstone plateau. Live biomass includes tree foliage, aboveground wood, branches and twigs, coarse and fine roots, and understory vegetation. Older stands (170+ yr) do not vary greatly in density, except where mountain pine beetles killed 20-70% of the dominant canopy trees in the 1970s-1980s (Romme et al. 1986). The most striking pattern is that carbon in live biomass recovers to pre-fire levels in 70-100 years.

Carbon storage in lodgepole pine stands will stabilize after about 70-100 years. First, as seen in the years following the 1988 fires, regeneration after the 1988 fires will lead to fully or overstocked stands (Kashian et al. 2004, Turner et al. 2004). Immediate fully-stocked regeneration ensures relatively rapid recovery of pre-fire carbon stocks following a fire. Second, examining the stand history of stands in YNP in 1988 shows that where regeneration was low after a stand replacing fire, subsequent regeneration fills in gaps and stand density converges after about 70-100 years (Kashian et al. 2005). Carbon and production converge more quickly than stand density, and carbon is recovered by 70-100 years.

Third, once regeneration is established, the dynamics of production and decomposition produce relatively stable carbon storage in about 70-100 years (Figures 3, 4, and 5, Kashian et al. Draft). The more densely stocked stands will accumulate carbon more quickly and the very sparse stands more slowly, but those differences diminish by 70 yrs. These field data are similar to our results for dense regeneration stands from a modeling study of the effects of climate change and fire frequency on ecosystem carbon storage (Smithwick et al. 2008), and similar to that found in a landscape study of carbon distribution in subalpine forest landscapes in response to forest age and elevation (Bradford et al. 2008).

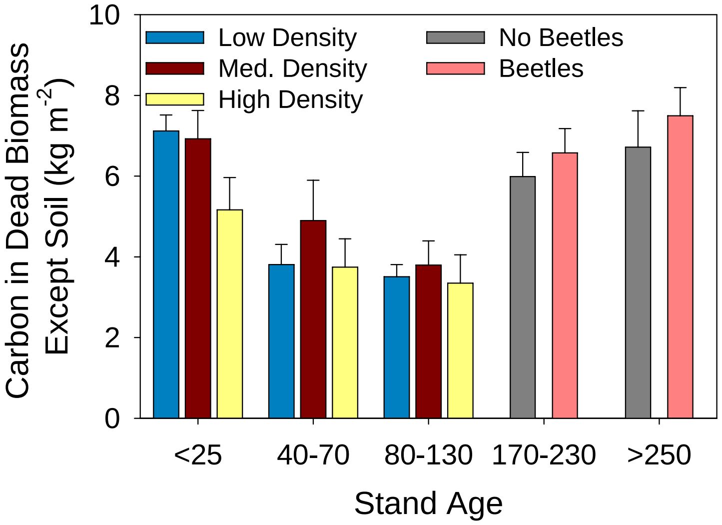

Figure 4. Carbon in dead biomass from 77 lodgepole pine stands in a replicated chronosequence across the Yellowstone subalpine plateau. Dead biomass includes snags, down wood, stumps, and the soil organic layer (litter)—but not carbon in mineral soil. Carbon in dead biomass recovers to pre-fire levels in 70-100 years.

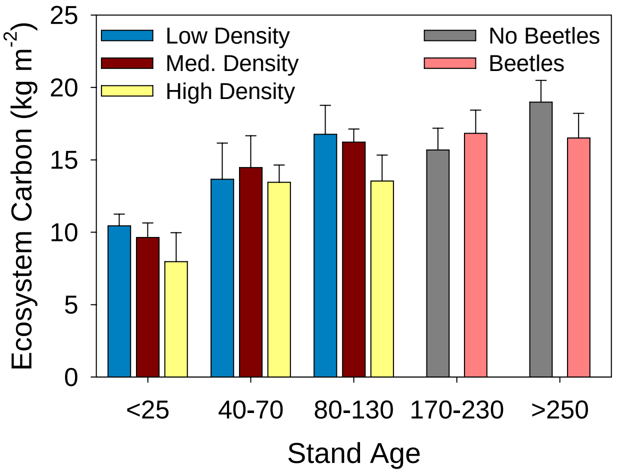

Figure 5. Ecosystem carbon from 77 lodgepole pine stands in a replicated chronosequence across the Yellowstone subalpine plateau. Ecosystem carbon recovers to pre-fire levels in 50-100 years. The difference in carbon stocks between stands older than 80 years (~ 15 kg C m^{-2}) and that in the stands regenerating after the 1988 fires (~8 kg C m^{-2}) is greater than the amount lost through combustion (~3 kg C m^{-2}) because the older stands available for assembling the chronosequence had higher average basal area than the stands that burned (see below).

Climate change projected for the next 100 years in YNP (more precipitation and warmer temperatures) will increase the production and carbon storage of YNP lodgepole pine forests.

The CENTURY model, fit to current data, suggests that the increased precipitation and warmer temperatures projected for the YNP area in the next 100 years will increase forest growth rates (Smithwick et al. 2008). These increased growth rates will lead to more carbon stored in mature forests (> 100 years old) and lead to quicker recovery of carbon from fire (Figure 6).

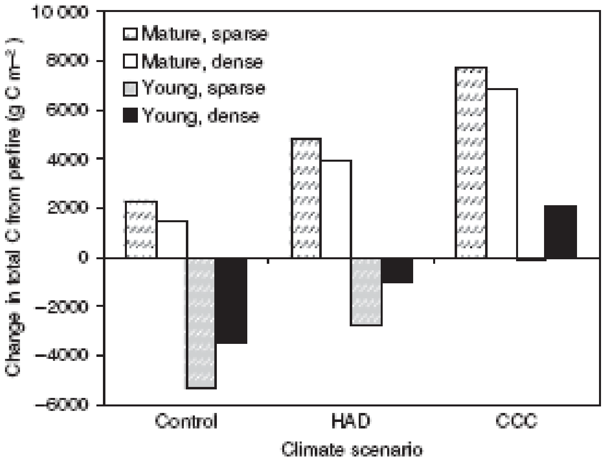

Figure 6. Projected differences in carbon from mature stands prior to 1988 for control climate, and two future climate scenarios. Both climate scenarios suggest forest will be more productive and store more carbon.

Carbon storage on the YNP landscape would be reduced only if stand-replacing fires become much more frequent (e.g., return intervals < 50 yrs) than is projected.

The current fire return interval in the YNP landscape is 135-185 years at lower elevations and 280-310 years at higher elevations (Schoennagel et al. 2003). Because the recovery time for the stand carbon stocks is less than 100 years (Kashian et al. Draft), and that for the landscape is 100-230 years (Kashian et al. 2006, Smithwick et al. 2008), it would take a large decrease of the fire return interval (to < 50 years) to substantially affect C stocks on the landscape as long as the forest regenerates after a fire. Given that more frequent fires likely select for trees with serotinous cones (Schoennagel et al. 2006), more frequent fires would likely lead to greater regeneration after fire—and hence more rapid recovery of carbon.

Recovery of the carbon lost in the 1988 fires is projected to occur in 100-230 years, depending on modeling approach used and the simulated post-fire stand density.

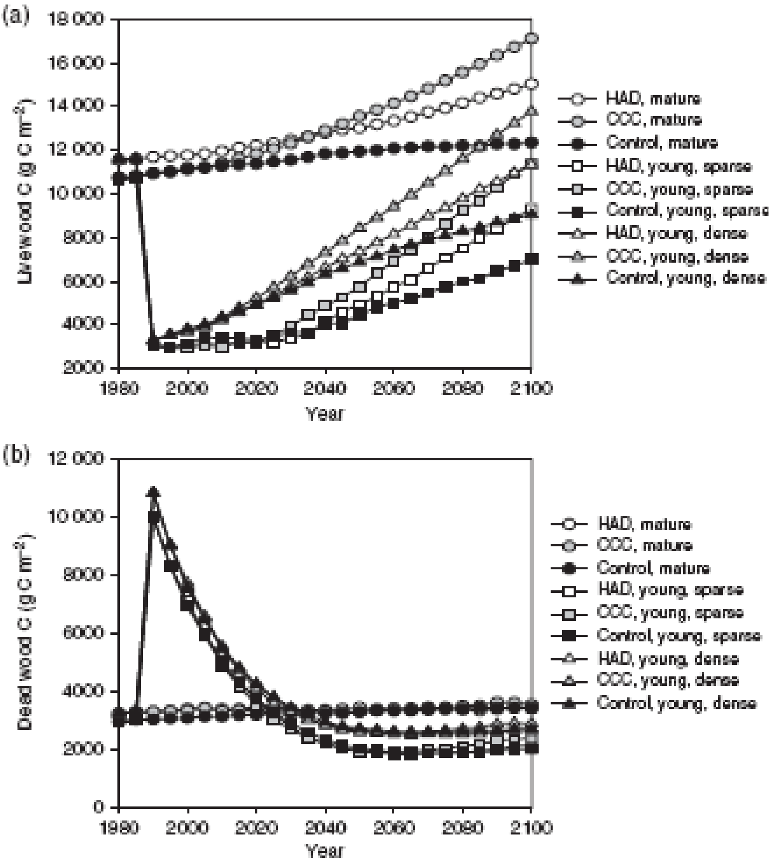

Figure 7. CENTURY simulations show that the carbon stored in mature forest will increase in the next 100 years, but total carbon storage will be little affected because increased decomposition will lower the amount of dead wood. Stands regenerating after the fire are projected to grow faster under climate change over the next 100 years (Smithwick et al. 2008).

Smithwick et al. (2008), using the CENTURY model with two different climate simulations, suggests that changes in temperature and precipitation over the next one hundred years will speed the recovery of carbon stocks on the landscape over the control or past climate (Figure 7). CENTURY-simulated net ecosystem carbon balance turns positive in about 50 years for stands with dense regeneration and in about 60 years for stands with sparse regeneration. Kashian et al. (2006) estimated 35 years. To store the same carbon as was stored before the 1988 fires would require 94 years (for stands with dense regeneration and the ‘CCC’ future climate) or ~ 200 years for the ‘HAD’ future climate or past climate. These are comparable to the time estimated by Kashian et al. (2006) for the landscape as a whole with a mixture of stands with dense and sparse regeneration (~230 years). However, our chronosequence data (Figures 3-5) suggest that the recovery of pre-1988-fire carbon stocks would occur in 70-100 years under past climate. We think that the more rapid recovery is more plausible because it is based on broad sampling that shows that regeneration effects on carbon stocks disappear by age 40-70—suggesting that our models of recovery for the stands with sparse regeneration were too slow.

Recovery of nitrogen content in post-fire lodgepole pine ecosystems mirrors that of carbon, and forests > 100 years old do not appear to be nitrogen limited.

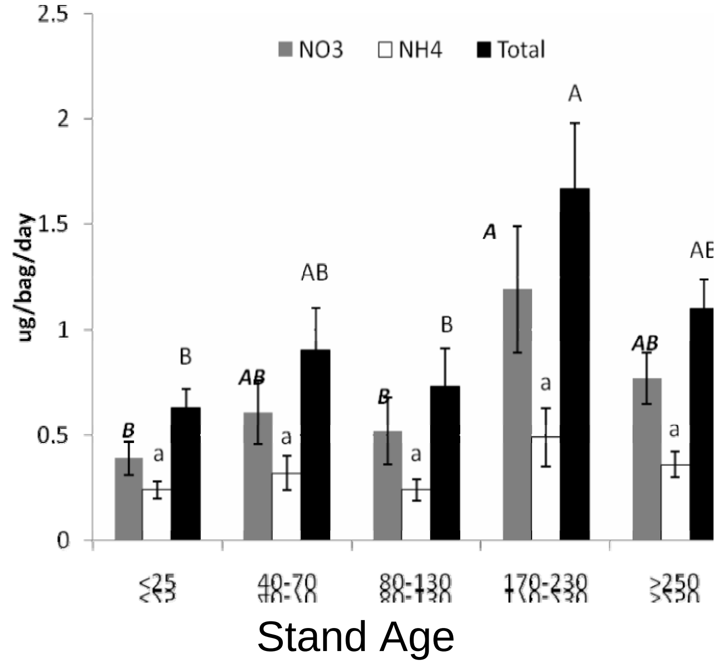

Figure 8. Available N as measured by resin bags in a lodgepole pine chronosequence in Yellowstone National Park shows that available N as nitrate (NO_3) increases with stand age (Smithwick et al. Draft).

Nitrogen availability, as measured by resin bags, increased with forest age, largely due to increases in nitrate availability, and was lower in dense versus sparse stands (Figure 8). Nitrogen availability did not differ among beetled-killed and non beetle-killed stands. Total ecosystem Nitrogen was lowest in the <25 yr age-class and did not increase significantly beyond 40 yrs. Nitrogen in live biomass ranged from 4% (<25 yr) to 53% (80-130 yr) of total ecosystem N; soil N was 50% of ecosystem N in the <25-yr age-class, but 25 to 29% >80 years. Statistical models that best explained patterns in soil N availability included pH, soil P, and litterfall N. The lack of observed decreases in soil N availability in older stands suggests factors in addition to N may limit lodgepole pine productivity. The lack of changes in total ecosystem N beyond the 40-70 yr age-class suggests that increased fire frequency in these forests would have a minimal effect on soil N accumulation and would be unlikely to cause nitrogen limitation for lodgepole pine forests (Smithwick et al. Draft).

Allometric equations developed for this study reflected the effects of age and tree density and performed better than other published equations for lodgepole pine.

Stand age and tree density influenced individual aboveground and belowground biomass components. However, equations that predict total tree and total aboveground biomass were not influenced by either age or density. Allometric equations developed for lodgepole pine elsewhere - in southeastern Wyoming and British Columbia – consistently produced poorer estimates of biomass for mature lodgepole pine in the GYE, supporting the idea that many allometric relationships in forested systems are site-specific.

Chronosequence studies are not perfect, even in a 'pristine' landscape such as the Yellowstone plateau.

We were drawn to the YNP landscape because it has received much study and because all of the components of the carbon cycle were preserved (no wood removals that would complicate developing an understanding of all components of the carbon cycle). However, we discovered that even in such a pristine landscape, it is difficult to assemble a perfect chronosequence. Our data show that the critical time for changes in the carbon cycle for lodgepole pine is the first 100 years after a fire. However, because of climate and fire suppression, stands older than the ones originating in 1988 and younger than 100 years were very difficult to find. Therefore, we had to lump stands into very broad age classes that likely obscured some important patterns. We also discovered that the amount of carbon in our older stands minus good estimates of carbon lost in combustion for the 1988 fires was substantially greater than the carbon that remained in the post-1988 stands we sampled (~4 kg C m^{-2}). This encouraged a 3rd field season to uncover the reason for the discrepancy. We found with this additional sampling that our original sampling was correct – our post 1988 stands had the amount of carbon established in the original sample and our stands older than 130 years old matched the basal area of stands in random survey of stands. However, the discrepancy occurred because the fire likely mostly burned younger, lower elevation stands, and the older stands in YNP are largely restricted to higher elevations, where historical fire intervals were longer, and where total stand biomass tends to be greater than average because of greater precipitation. We will need to adjust our chronosequence models to make them compatible with these observations, but our imperfect chronosequence does not invalidate our primary results: that these ecosystems are good at storing carbon, and as long as regeneration occurs, the landscape is resistant to changes in carbon storage resulting from fire.

Future Directions

Regeneration after crown fires in ecosystems with historical surface fire regimes. In ecosystems with a historical fire regime featuring frequent surface fires or surface and mixed severity fires, a stand-replacing fire can lead to poor or no tree regeneration and conversion of forests to shrublands or grasslands. Such conversion will move the carbon in live and dead wood from the forest to the atmosphere, possibly for centuries. For example, in ponderosa pine ecosystems, regeneration after large crown fires is often poor because the fire kills the seeds, seeds are heavy and do not move far from the surviving parent trees, and weather favoring successful germination and survival of seedlings is rare. If shrubs were present prior to the fire, they can resprout profusely and out compete overstory trees. To estimate the carbon consequences of these fires will require studies on long-term, landscape-level regeneration and the decomposition of the trees killed by the fire.

Landscape effects of fuels treatments on forest carbon storage. At the stand level, restoration to historical stand structure and density can dramatically reduce carbon losses in fire (Hurteau et al. 2008). However, treatment of an entire landscape, while desirable for many reasons, may cause a permanent carbon loss to the atmosphere. To reduce crown fire risk often requires 60% or more of the biomass to be removed—a permanent transfer of carbon from the forest to the atmosphere unless the removed biomass is used to displace fossil fuel. So, in the absence of treatment, more than 60% of the landscape would need to be consumed by a crown fire with no regeneration for the treatments to be carbon neutral. Since the average fire return interval for the US is 100 years (1% of the forested landscape will burn each year, though not all with stand replacing crown fires), it seems unlikely that fuels treatments will increase forest carbon stores on the landscape. However, to fully understand the carbon consequences of fuels treatments would require a landscape scale study of current and projected fire return intervals and fire sizes and information mentioned above on regeneration.

Summary

The lodgepole pine forests of the Yellowstone Plateau store about 16 kg C m^{-2}. Fire has been part of this landscape throughout the Holocene, and carbon storage in Yellowstone appears to be remarkably resilient to fire—even fires as extensive as those of 1988. In the short-term, burned forests do lose carbon to combustion and subsequent decomposition, but the forests recover their carbon stores relatively quickly (70-100 yrs) compared to current fire interval (170-300 yrs). In the long-term, this magnitude of carbon storage is likely to remain relatively constant on the Yellowstone landscape. Under current climate projections including more frequent fires, the Yellowstone landscape does not seem likely to become a net carbon source over the long run. However, our results do suggest that, in forest types that are not adapted to stand-replacing fire, conversion from forest to non-forest vegetation could result in an ecosystem switching from a net carbon sink to a net carbon source. Future studies should elucidate the conditions that might result in this kind of state change. For Yellowstone, however, even somewhat more frequent fire is unlikely to qualitatively alter the role of the landscape as a carbon sink.

Field Location and Methods

Our field location was the subalpine plateaus of Yellowstone National Park (YNP) in northwest Wyoming. Current forested elevation range is from 1900 to 2900 m. Approximately 80% of the park is dominated by lodgepole pine (*Pinus contorta*) forest, but subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii* Parry), whitebark pine (*P. albicaulis*) and Douglas-fir (*Pseudotsuga menziesii*) may be locally abundant. Understory communities in YNP are generally dominated by resprouting perennials, with fire-intolerant perennials increasing in stands with longer fire intervals. Annual average precipitation is 62 cm (9/1978-9/2005 Normals, Western Regional Climate Center, Old Faithful). Average total snowfall is 540 cm, with an average depth of 33 cm. Average monthly maximum temperature is 9.6 °C (-2.0 °C in January and 23.6 °C in July) and average monthly minimum temperature is –7.4 °C (-17.8 °C in January and 3.9 °C in July). Soils in Yellowstone National Park are derived from relatively infertile rhyolitic substrates, intermixed with small areas of more mesic and fertile soils derived from andesitic substrates and lacustrine sediments.

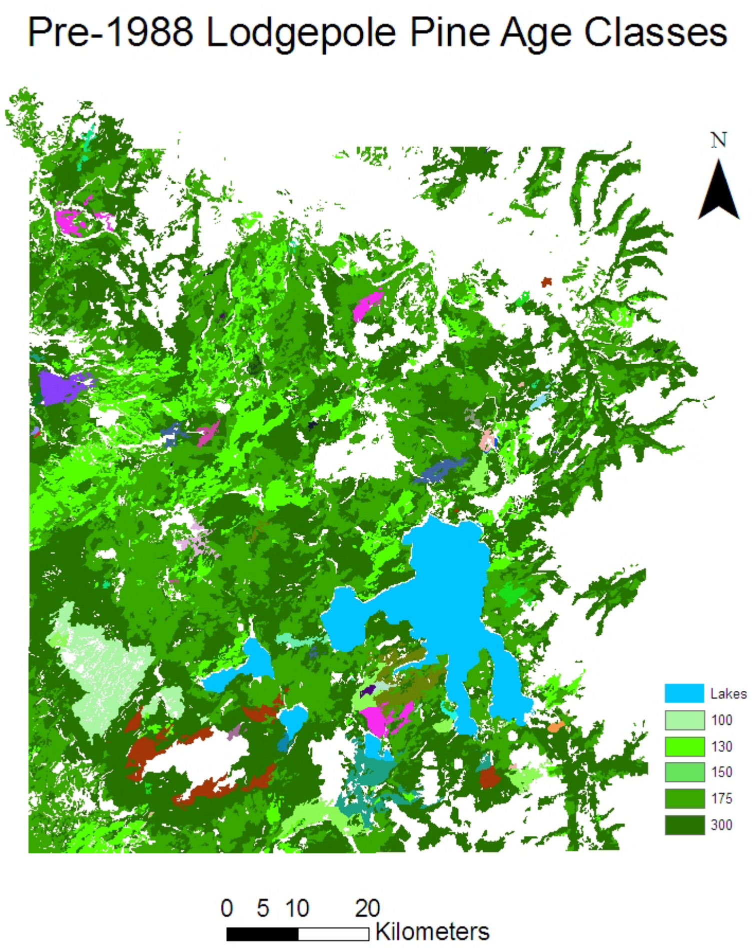
Pre-1988 Lodgepole Pine Age Classes

Figure 10. Pre-1988-fire stand age class map derived from Landsat remote sensing. White areas are either non-forested or not forested with lodgepole pine.

We used a chronosequence approach with 77 independent sites to measure how all components of carbon storage varied with stand age and tree density. All sites originated from stand-replacing wildfire (see pre-fire stand age classification map, Figure 10). However, since local disturbance histories are difficult to determine, the stands older than the ones originating after the 1988 fires may have experienced different levels of insect attacks, canopy gaps, and low-intensity surface fires during the interval between stand-replacing fires. The stands were selected to span the range in age and tree density currently present across the park. Stands were grouped by age class (<25, 40-70, 80-130, 170-230, >250), by tree density for the stands 130 years and younger, and by visible evidence of beetle outbreak or not for stands 170 years and older. Because tree density declines with age, the actual tree density varied by age class (Table 1). Each age and density or beetle outbreak class had 4-7 replicates.

At each site, we estimated NEP as the sum of the annual change in C stored in aboveground live biomass (C_W), belowground live biomass (C_R), dead aboveground wood, standing and down (C_{DW}), dead coarse roots (C_{CR}), forest floor (C_L) and soil (C_S):

$$\mathrm{NEP} = \Delta[C_W + C_R + C_{DW} + C_{CR} + C_L + C_S] / \Delta t \qquad [1]$$

In each stand, we directly measured all C stocks in Eq. 1 using three plots as subsamples (transect width will vary with stem density). We estimated the annual change in C stocks by directly measuring annual changes in aboveground live vegetation (foliage and wood of trees, shrubs, and herbs), live roots (coarse and fine), and litter. We used our chronosequence to develop simple models of annual changes through time of the slowly-changing components of the C cycle—soil C (litter layer and mineral soil), dead coarse woody roots, and CWD.

Annual changes in C stocks in live vegetation: stands <25 yr old: We sampled aboveground biomass in live trees by measuring basal diameter and height of all saplings in three 50m belt transects in each stand, and used allometric equations (Litton et al. 2003) to compute biomass and change in biomass of foliage, branch, stem, and coarse roots. The annual change in live tree biomass in the young stands was estimated by measuring the height and diameter of each stem for the current and prior year, applying the allometric equations, and subtracting biomass in year 1 from that in year 2. Fine-root biomass was estimated from 15 cores (6 cm diameter) per stand (3 per transect) to 30 cm. We estimated biomass of shrubs and herbs from visual estimates of percent cover in subplots of each transect using relationships developed under previous studies. Subsamples of each component were analyzed for C and N content.

Annual changes in C stocks in live vegetation: stands >40 yr old: We developed YNP allometrics (Tinker et al. Submitted) for aboveground wood, foliage, and roots > 2 mm and used these to estimate biomass and change in biomass for different tree components. The annual change in live tree biomass was estimated from the 5-year mean radial increment measured on 30 trees that span the size range in the stand and applied to the population using double sampling (Cochran 1977). Fine root, herb, and shrub biomass and annual increment were estimated with the same techniques described above for stands < 25 yr old.

Annual changes in C stocks in CWD: In each stand, CWD was estimated separately for standing-dead trees, downed trees not yet touching the ground, and downed wood in contact with the ground, with diameter measured for all samples. The mass of CWD in standing-dead trees and in fallen trees not yet touching the ground was estimated by measuring the diameter at 1.4 m and applying Pearson et al.'s (1984) allometric equations. Biomass of CWD in fallen trees in contact with the ground was estimated by decay class using the planar intercept method (Brown 1974). Annual changes in CWD C were estimated by measuring CWD biomass in each decay class throughout our chronosequence and estimating the annual rate of change from change in biomass over time.

Annual change in C stocks in litter: For each transect of each stand, we measured the mass of each component of the litter layer (fine litter, charcoal, and woody material <7.5 cm) by removing all material down to mineral soil within three randomly located 50 x 50 cm plots (15 plots/stand). These three samples were composited, and then a subsample of the composite was separated into litter components, weighed, and dried. A subsample of fine litter was measured for ash content to correct for any contamination by mineral soil. The annual change in C stocks in litter was estimated by measuring litter mass for our replicated chronosequence, and estimating the annual rate of change from change in biomass over time.

Annual change in C stocks in soil: We sampled mineral soil from 0-10 cm and 10-30 cm depth at 5 locations per transect in each stand (15 sample locations per stand). Cores from a stand were composited, sieved to pass 2 mm screen, mixed, and three subsamples dried, weighed, and analyzed for C. Bulk density was estimated as soil dry weight (root and rock free)/volume. We estimated the annual change in soil C by modeling soil C change along our chronosequence.

C loss in fire: We estimated the C lost from the ecosystem in the 1988 fires for each of the stands in the youngest age class. Biomass is lost through combustion from five compartments within lodgepole pine stands: live trees, standing-dead trees, down wood, fine woody debris (twigs and branches <7.5 cm diameter plus forest floor litter), and herbaceous and shrubby biomass. We estimated biomass in the trees that were alive in 1988 by measuring dbh for each dead tree in each transect, correcting for loss of bark, and then estimating the biomass using allometric equations developed at YMP. Down and standing dead wood that existed prior to 1988 was identified in sampling. Litter and herb and shrub biomass was estimated from values in stands in our chronosequences of the same age as the burned stand. Depending on fire intensity, all or a portion of each of these compartments is consumed or converted in a fire. Based on field measurements in stands that burned in 1988, Tinker and Knight (2000) and Tinker (unpublished data) developed equations for predicting C loss from each of these sources. We used these equations and our biomass estimates in each stand to estimate the C loss associated with the stand-replacing fire.

ANPP and additional data needed for modeling. To facilitate calibration of the Century model, we collected litterfall (needed to estimate ANPP from biomass increment + litterfall) and N availability for each stand. We collected litterfall using three 50 x 50 cm litter traps for each of the 3 transects in each plot. N availability was assessed using resin bags inserted between mineral soil and the O horizon for a year (5/transect). We also sampled canopy foliar N content for a subset of stands in the chronosequence by sampling branches from the top, middle, and lower canopy thirds. Additionally, a composite soil sample from each stand was analyzed for general soils characteristics (Midwest Laboratories, Omaha, NE) at both 0-15cm and >15-30cm soil depth. Variables analyzed included weak Bray P (extraction with dilute acid and ammonium fluoride), strong Bray P (extraction with 4 times the acid concentration), Potassium (K), Magnesium (Mg), Calcium (Ca), Cation Exchange Capacity (CEC), Base Saturation (BS), and Buffer Index. Soil methods can be found online (https://www.midwestlabs.com/).

Table 1. Location, age, elevation and tree density of the 77 sites sampled in Yellowstone National Park.

Density or Bark Beetle Class	Age Class	Origin	Age when sampled	Site	UTM Northing	UTM Easting	Elev. (m)	Tree Density
Low	< 25	1988	12	Cascade Meadows Young	4952031	537011	2484	425
	< 25	1988	12	Cygnet Lakes	4949976	533183	2508	742
	< 25	1988	13	Grant Village Housing	4914742	535293	2403	933
	< 25	1988	12	Lewis Canyon North	4896422	527319	2372	533
	< 25	1988	12	Pitchstone Plateau	4900872	528551	2368	758
Moderate	< 25	1988	12	Biscuit Basin	4924817	511695	2223	25250
	< 25	1988	12	Howard Eaton	4920627	514815	2370	39167
	< 25	1988	12	Lewis Canyon South	4893916	527116	2363	8700
	< 25	1988	16	Mallard West	4927735	514525	2323	7133
	< 25	1988	12	Riddle Trailhead	4911737	533160	2429	7000
High	< 25	1988	12	Firehole Loop	4940962	511429	2166	73455
	< 25	1988	16	Fountain West	4943933	499479	2066	523633
	< 25	1988	12	Gibbon Falls Young	4945063	517746	2235	75500
	< 25	1988	12	Riddle High	4909631	532210	2417	50167
	< 25	1988	12	Seven Mile Bridge	4946004	501501	2076	598462
Low	40-70	1932	73	Heart Lake South	4900117	540472	2293	875
	40-70	1946	54	Lewis Canyon	4901119	528718	2382	933
	40-70	1933	72	Moran Bay	4857880	522569	2070	1267
	40-70	1932	73	Sheridan Lake	4899082	539801	2271	1058
Moderate	40-70	1939	65	Arcano	4925875	472606		1350
	40-70	1932	69	Fishing Bridge	4934880	552943	2373	2256
	40-70	1970	35	Moose Creek	4923658	484147		3122
	40-70	1932	73	Basin Creek Junction	4897585	540606		3983
	40-70	1934	66	West Yellowstone	4945784	492711	2033	1308

Density or Bark Beetle Class	Age Class	Origin	Age when sampled	Site	UTM Northing	UTM Easting	Elev. (m)	Tree Density
High	40-70	1923	81	Canyon Campground	4954926	541351	2478	5828
	40-70	1954	46	Cascade Meadows Old	4953827	537607	2486	7850
	40-70	1970	35	Latham Springs	4921005	488333		5700
	40-70	1981	24	Leigh Lake	4851860	522790	2103	7517
Low	80-130	1881	123	Firehole Lake Drive	4931393	514307	2213	1060
	80-130	1900	105	Grant Village	4917155	534343	2374	1320
	80-130	1869	131	Gull Point	4929907	545123	2392	947
	80-130	1869	131	Gull Point Drive	4930089	546410	2362	1117
	80-130	1881	123	Gull Point Fertile	4928366	545956	2379	1093
Moderate	80-130	1932	73	Basin Creek Junction	4897585	540606		3983
	80-130	1875	125	Bluff Point	4922451	534665	2402	1407
	80-130	1884	116	Crawfish Creek	4892563	527053	2283	1520
	80-130	1870	135	Firehole River Picnic Area	4937569	513682	2187	3360
	80-130	1881	119	Midway Geyser Basin	4930649	513253	2214	2400
	80-130	1866	134	Pumice Point	4923168	538511	2370	1667
High	80-130	1875	125	Firehole Cascades	4940475	511574	2174	5525
	80-130	1870	130	Firehole Gulch	4939783	512566	2232	3450
	80-130	1899	104	Gibbon Falls Old	4944342	515451	2131	6150
	80-130	1919	86	Norris Geyser Basin	4952272	523750	2318	3950
	80-130	1900	105	Thumb Creek	4917425	529273	2510	4144
Beetles	170-230	1790	215	Bridge Bay	4931662	542941		1108
	170-230	1764	236	Divide Picnic Area East	4919230	530076	2534	594
	170-230	1806	198	Freaky Bear Road	4941507	514656	2171	2369
	170-230	1824	180	Gull Point Old	4928128	545907	2375	1552

Density or Bark Beetle Class	Age Class	Origin	Age when sampled	Site	UTM Northing	UTM Easting	Elev. (m)	Tree Density
Beetles	170-230	1814	190	Gut Road	4892565	527044	2284	717
	170-230	1814	190	Moose Falls	4888850	525958	2141	1700
	170-230	1833	172	Pumice Point Old	4923779	539054		975
No Beetles	170-230	1806	199	Firehole Gulch Old	4939753	513956		
	170-230	1764	236	Howard Eaton Trail	4921208	529446	2551	1325
	170-230	1785	219	Kepler Scaup 04	4920287	517635	2402	1100
	170-230	1806	194	Kepler South	4919499	516797	2380	933
	170-230	1800	205	Mary Mountain	4935873	517106		1800
	170-230	1795	210	Mystic Falls	4926266	508705	2443	775
	170-230	1833	171	West Thumb Spit	4924499	538067	2367	592
Beetles	>250	1751	252	Arnica Creek	4925128	536068	2373	1080
	>250	1707	297	Carrington Island	4923787	535265	2366	1833
	>250	1736	265	East Loop	4923473	541241	2377	1200
	>250	1698	306	Grave Yard	4940725	513415	2188	2267
	>250	1673	331	Ice Lake	4950463	530302	2451	1013
	>250	1703	297	Kepler Cascades	4920407	516212	2383	2280
	>250	1734	271	Lake Service Yard	4932684	546121	2373	683
	>250	1751	253	Little Thumb Creek	4917986	530570	2518	650
	>250	1735	270	Lower Geyser Basin	4933821	515994	2263	667
	>250	1751	252	West Thumb	4924789	536539	2367	1820
No Beetles	>250	1685	315	Delacy Creek	4920158	524353	2406	960
	>250	1731	269	Delacy Lake Stop	4921507	525710	2490	1060
	>250	1718	282	Divide Picnic Area South	4919869	529180	2545	872
	>250	1737	267	Firehole Lake	4932902	516821	2330	1800

Density or Bark Beetle Class	Age Class	Origin	Age when sampled	Site	UTM Northing	UTM Easting	Elev. (m)	Tree Density
No Beetles	>250	1736	265	Grand Loop Road Pullout	4925120	544381	2390	707
	>250	1714	290	High Bluff	4922568	534383	2466	1117
	>250	1751	252	Howard Eaton Smokey	4919879	530445	2536	867
	>250	1703	297	Scaup Lake	4919651	519064	2416	1442
	>250	1707	297	Shoshone Lake NE	4919968	528162	2570	833
	>250	1707	297	West Thumb Buttonhook	4918721	532386	2477	717

Deliverables

Deliverable Proposed	**Status**
Concept/Overview Article for BioScience	Kashian, D. M., W. H. Romme, D. B. Tinker, M. G. Turner, and M. G. Ryan. 2006. Carbon storage on landscapes with stand-replacing fires. BioScience **56**:598-606.
Journal article: Effects of stand age and stand density on net carbon storage in lodgepole pine ecosystems (RMRS/CSU).	Kashian, D. M., W. H. Romme, and M. G. Ryan. Draft. Changes in lodgepole pine forest carbon stocks over 300 years between stand-replacing fires in Yellowstone National Park, Wyoming, USA. To be submitted to Ecological Monographs Fall 2008.
Journal article: Modeling the effects of changing climate on productivity and carbon storage in lodgepole pine (RMRS/CSU).	Smithwick, E. A. H., M. G. Ryan, D. M. Kashian, W. H. Romme, D. B. Tinker, and M. G. Turner. 2008. Modeling the effects of fire and climate change on carbon and nitrogen storage in lodgepole pine (*Pinus contorta*) stands. Global Change Biology, In Press.
Journal article: Distribution of stand age and tree density in the Yellowstone National Park landscape (UWisc).	Sivanpillai, R., D. M. Kashian, and D. B. Tinker. Draft. Relating lodgepole pine characteristics and Landsat spectral values using logistic regression models. Forest Ecology and Management To be submitted by November, 2008.
Journal article: Current carbon balance of the Yellowstone National Park landscape (UWisc).	Kashian, DM, DB Tinker, and MG Ryan. Effect of the 1988 fires on the carbon balance of the Yellowstone landscape. To be submitted to Landscape Ecology, Fall 2008. Also covered in Kashian et al. (2006) and Smithwick et al. (2008).
Journal article: The effects of stand age and stand density on allometric relationships in lodgepole pine (UWyo).	Tinker, D. B., R. M. Arcano, M. G. Ryan, D. M. Kashian, and W. H. Romme. Submitted. Allometric model development and biomass partitioning in lodgepole pine forests near Yellowstone National Park, WY. Forest Ecology and Management.

Deliverable Proposed	**Status**
Journal article: The effects of stand age and stand density on coarse woody debris and fuels in lodgepole pine (UWyo).	Ryan, M.G. and D.M. Kashian, In preparation. To be submitted by spring 2009.
Journal article: How changing climate will alter fire frequency and landscape carbon storage in lodgepole pine (CSU/UWisc/RMRS/UWyo).	Most of this was covered in two articles already published (Kashian et al. 2006, Smithwick et al. 2008). Given the unlikelihood of climate changing fire frequency enough to alter the age and density distribution enough (Schoennagel et al. 2006) to affect carbon storage on the landscape, we do not think this is sufficiently interesting to pursue.
Workshop: How changing climate will alter fire frequency and landscape carbon storage in lodgepole pine (CSU/UWisc/RMRS/UWyo).	May 2007, Fire and Carbon Storage in Forests, a workshop for Land Managers, Berol Lodge, AMK Ranch, Moran Junction, WY. See presentations below.
RMRS GTR: How changing climate will alter fire frequency and landscape carbon storage in lodgepole pine (CSU/UWisc/RMRS/UWyo).	Included in already published papers.

Other products not included in original proposal:

Journal article: Long-term ecosystem nitrogen storage and soil nitrogen availability in post-fire lodgepole pine ecosystems.	Smithwick, E. A. H., D. M. Kashian, M. G. Ryan, and M. G. Turner. Draft. Long-term ecosystem nitrogen storage and soil nitrogen availability in post-fire lodgepole pine ecosystems. To be submitted shortly to Ecosystems.
Journal article: Comparing age-related trends in carbon isotope composition of wood between a contemporary chronosequence and old trees	Kashian, D.M., and M.G. Ryan. Carbon isotope discrimination and along a 300-year lodgepole pine chronosequence. To be submitted to Tree Physiology, Winter 2008. Data in hand and analyzed.
Journal article: Foliar nitrogen content in a chronosequence of lodgepole pine	Kashian. D.M., and M.G. Ryan. Within-tree and within-stand variability in foliar nitrogen along a chronosequence of lodgepole pine. To be submitted to Oecologia, Winter 2009.

Journal Article: Lessons learned from a chronosequence study	Ryan, M.G. et al. We think that the lessons that we learned in sampling our replicated chronosequence will be valuable for others using chronosequences in the future.

Presentations

Arcano, R. and D.B. Tinker. 2004. Allometric model development, and biomass allocation patterns of lodgepole pine in the Greater Yellowstone Ecosystem. Society of American Foresters Annual Meeting, Vancouver BC, Canada.

Harmon, M. 2007. Forests and carbon cycling. Fire and Carbon Storage in Forests, a workshop for Land Managers, Berol Lodge, AMK Ranch, Moran Junction, WY, May 2007.

Hicke, J.A. 2007. Remote sensing of forest structure and insect outbreaks. Fire and Carbon Storage in Forests, a workshop for Land Managers, Berol Lodge, AMK Ranch, Moran Junction, WY, May 2007.

Kashian, D.M. 2008. Playing with fire: Disturbances shaping Rocky Mountain landscapes and their implications for global change. Department of Biology, University of Windsor, March 2008

Kashian, D.M. 2007. Playing with fire: Implications of climate change for disturbances that shape Rocky Mountain landscapes. School of Natural Resources and Environment, University of Michigan, January 2007.

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Kashian, D.M., M.G. Ryan, and W.H. Romme. 2006. Stand-replacing fires and carbon storage: Effects of stand age and density on carbon storage in lodgepole pine ecosystems. Ecological Society of America (ESA) Annual Meeting, August 5-11, Memphis, TN.

Kashian, D.M., M.G. Ryan, W.H. Romme, D.B. Tinker, and M.G. Turner. 2006. Potential effects of altered fire frequency on carbon cycling on coniferous landscapes. US-IALE Annual Meeting, March 28-April 1, San Diego, CA.

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Kashian, D.M., M.G. Ryan, W.H. Romme, D.B. Tinker, and M.G. Turner. 2005. Carbon cycling at the landscape scale: the effect of changes in climate and fire frequency on age distribution, stand structure, and net ecosystem production. Joint Fire Sciences Program Principal Investigator’s Meeting, November 1-3, San Diego, CA.

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Logan, J. 2007. Bark beetles and climate. Manager's Workshop— Fire and Carbon Storage in Forests, A Workshop for Land Managers, Berol Lodge, AMK Ranch, Moran Junction, WY, May 2007.

Romme, W.H. 2007. Historical and future fires in the Greater Yellowstone Ecosystem. Fire and Carbon Storage in Forests, a workshop for Land Managers, Berol Lodge, AMK Ranch, Moran Junction, WY, May 2007.

Ryan, M.G., D.M. Kashian, and W.H. Romme. 2007. Lodgepole pine ecology. Colorado Mitigation and Wildfire Meeting, Pueblo, CO, April 2007 (http://www.wildfirecolorado.org/2007/Mike_Ryan_Lodgepole%20pine%20ecology.ppt).

Kashian, D.M., W.H. Romme, D.B. Tinker, and M.G. Ryan. 2007. Fire and carbon cycling in Yellowstone NP. Fire and Carbon Storage in Forests, a workshop for Land Managers, Berol Lodge, AMK Ranch, Moran Junction, WY, May 2007.

Ryan, M.G., R.A. Birdsey, L.S. Heath, and D.M. Kashian. 2007. Introduction to forests and carbon cycling. Fire and Carbon Storage in Forests, a workshop for Land Managers, Berol Lodge, AMK Ranch, Moran Junction, WY, May 2007.

Ryan, M.G., D.M. Kashian, and W.H. Romme. 2007. Lodgepole pine ecology. Colorado Bark Beetle Cooperative, Lodgepole Pine And Mountain Pine Beetle Workshop, Granby, CO, June and September 2007

Ryan, M.G., R.A. Birdsey, L.S. Heath, and D.M. Kashian. 2008. Fire and forest carbon: the short and the long term view. Society of American Foresters , Northern California and Intermountain Sections Annual Meeting, February 2008.

Ryan, M.G., R.A. Birdsey, L.S. Heath, and D.M. Kashian. 2008. What is the role of fire in the US carbon cycle? USDA Forest Service, Region 2 Renewable Resources Meeting, Fort Collins, CO February 2008.

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Smithwick, E.A.H., D.M. Kashian, M.G. Ryan, and M.G. Turner. 2008. Long-term ecosystem nitrogen storage and soil nitrogen availability in post-fire lodgepole pine ecosystems. ESA Annual Meeting, Milwaukee, WI, August 2008.

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Thesis

Arcano, R. 2005. Allometric model development, biomass allocation patterns, and nitrogen use efficiency of lodgepole pine in the Greater Yellowstone Ecosystem. M.S. Thesis, Department of Botany, University of Wyoming, Laramie, WY.

Publications

Kashian, D. M., W. H. Romme, and M. G. Ryan. Draft. Changes in lodgepole pine forest carbon stocks over 300 years between stand-replacing fires in Yellowstone National Park, Wyoming, USA. For Ecological Monographs, October 2008.

Kashian, D. M., W. H. Romme, D. B. Tinker, M. G. Turner, and M. G. Ryan. 2006. Carbon storage on landscapes with stand-replacing fires. BioScience **56**:598-606.

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Tinker, D. B., R. M. Arcano, M. G. Ryan, D. M. Kashian, and W. H. Romme. Submitted. Allometric model development and biomass partitioning in lodgepole pine forests near Yellowstone National Park, WY. Forest Ecology and Management.

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