Carbon stock conditions and how climate and disturbance may influence carbon dynamics on the Shoshone National Forest, Wyoming

Janine Rice[1,2]

1 University of Colorado, CIRES, Western Water Assessment, 216 UCB, Boulder, CO 80309-0216
2 USDA Forest Service, Rocky Mountain Research Station, 240 W. Prospect St., Fort Collins, CO 80526

Executive Summary

This report for the Shoshone National Forest Plan revision synthesizes regional scientific information about carbon (C) and how past and future trends in climate, disturbance and land use may affect C stocks in the Shoshone National Forest. Over the last century, forests in the Greater Yellowstone Ecosystem (GYE), of which the Shoshone is a part, have functioned as a C sink. Fire disturbance plays a large role in affecting regional C balance. The regional fire regime has generally been characterized by long fire return intervals with severe fires, which has allowed forests to regrow and maintain a C sink. Future fire is expected to be more frequent and could shift forests to function as a C source. Over the last decade, bark beetle outbreaks have caused mortality in the Shoshone's forests, typically in mature trees. These outbreaks may have reduced above ground forest C storage in the short term, however the long term effects on C are unknown. Continued outbreaks are expected to move higher in elevation as climate warms. Carbon storage potential may also be further reduced by future human population growth causing more frequent fires and thereby influencing the fire regime. Although the effects of complex interactions between climate, fire, insect outbreaks, and human population activity are not well understood at this point, evidence from studies suggest that there could be reductions of forest C storage and sequestration potential owing to intensifying disturbance regimes, such as increased fire. It is possible that the GYE may become a C source or a net emitter of C under future climate. Mitigation options can help reduce climate change impacts on forest C balance by increasing forest capacity to store C, decrease C loss potential from disturbance, and utilizing biomass for energy. However, some mitigation options come with significant tradeoffs and risks that should be considered.

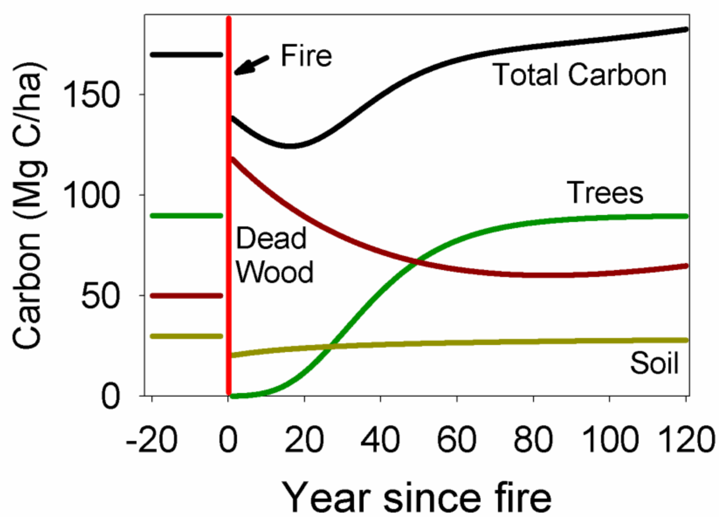
Introduction

The flow of carbon (C) in its many forms through the atmosphere, oceans, soils, rocks, and forests is an important cycle that serves, in part, to regulate global temperature. The atmosphere currently stores over 390 ppm CO_2, a level that has increased from about 280 ppm over the last 150 years. Increases in atmospheric CO_2 concentration and other greenhouse gases (GHGs) have contributed to a rise in global temperatures by approximately 0.74 ^oC (1.3 ^oF) since the late 1800s (IPCC 2007). Future global temperature is likely to increase another 1.1 – 5.5 °C (2 – 10 °F) (IPCC 2007). Forests store C in biomass and soil, remove CO_2 from the atmosphere and release oxygen (O_2) during photosynthesis, and release CO_2 during respiration and with decay of plant material. U. S. forests store about 12 - 19% of U.S. fossil fuel emissions each year (Ryan and others 2010).

Forests and atmospheric C fluxes are interdependent; changes in the flow of C from one can affect the other. Increased atmospheric CO_2 can cause higher productivity of trees and C sequestration potential through increased efficiency of photosynthesis (Norby and others 2005, Norby and Zak 2011), where water (Linares and Camararo 2012) and soil nitrogen are not strongly limiting (Luo 2004; Norby and Zak 2011). However, disturbances such as fire and insect outbreaks can cause forested areas to shift from a C sink (net C sequestration), to a C source (net release of C) (Kashian and others 2006; Kurz and others 2008). Land uses also alter C flows and sink-source dynamics. Deforestation for agricultural purposes, harvesting for wood, and land development reduces C stocks, while afforestation increases C stocks (Birdsey and others 2006; McKinley and others 2011).

Carbon exchange between the atmosphere and terrestrial ecosystem is complex and can be influenced indirectly by processes that vary spatially and temporally. The amount of C stored in a forest varies over its life cycle. Forested areas can shift from a C source after fire or insect disturbances, to a C sink as a forest recovers (Figure 1) (McKinley and others 2011). Over longer time periods and larger spatial scales, C stocks remain relatively stable. However, changes in climate, disturbance regimes, or human activities can increase or decrease average forest C stocks over time (McKinley and others 2011). Atmospheric carbon concentrations can also affect forest carbon dynamics. For example, an increased amount of CO_2 and other GHGs in the atmosphere raises global temperatures, which can in turn cause an increase in fire regimes that can result in an overall reduced amount of C stored in biomass and soils (Smithwick and others 2011). However, increased amounts of atmospheric CO_2 can also increase forest productivity for some period of time, resulting in greater amounts of biomass in some forests, which in turn can increase the rate of atmospheric CO_2 absorption and possibly C storage.

Figure 1. Post-fire forest C recovery over time showing Total Carbon that includes the decomposition of trees killed by fire (Dead Wood), tree regeneration (Trees), and soil (Soil). If a forest regenerates after a fire and the recovery is long enough, the forest will recover the carbon lost in the fire and in the decomposition of trees killed by the fire. Model output is from an analysis published in Kashian et al. (2006). Graph available at: http://www.firescience.gov/projects/briefs/03-1-1-06_FSBrief86.pdf



Current Shoshone National Forest Vegetation and Carbon Stocks

Shoshone Vegetation

On the Shoshone National Forest (NF), Wyoming (Figure 2), coniferous forests dominate the landscape covering approximately 600,000 ha (1,482,632 acres) of the total ~971,000 ha (2,400,000). Shoshone forests contain mixed conifer species; with subalpine forests (9,000 – 10,500 ft) supporting whitebark pine (*Pinus albicaulis*), Englemann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) and less common occurrences of aspen. The montane zone (6,000 – 9000 ft) supports lodgepole pine (*Pinus contorta*), Douglas-fir (*Psuedotsuga menziesii*), limber pine (*Pinus flexilis*), and less common aspen (*Populus tremuloides*) occurrences down to ~7,000 ft. Mature stands age > 100 years dominated Shoshone forests according to measurements taken during 1990 – 2005 (Table 1). However, bark beetle outbreaks, which primarily attack older trees (Shore and others 2006) began during the early 2000s and may have reduced the dominance of mature stands (Table 1).

Figure 2. Shoshone National Forest

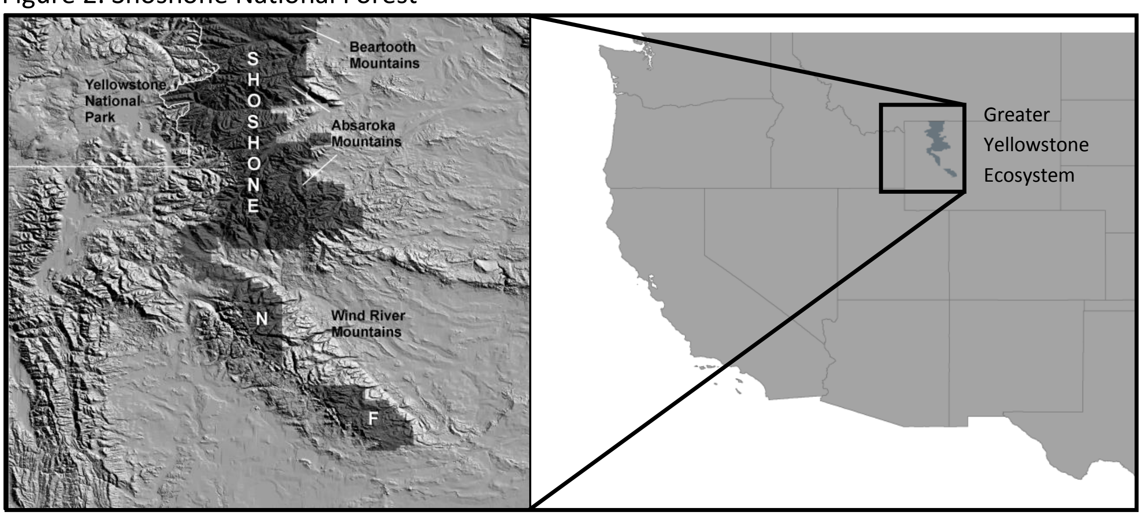


Table 1. Shoshone National Forest Number of Common Stand Exam (CSI) (1990 – 2005) and Forest Inventory Analysis (FIA) (1998-2000) plots and Average Stand Age by Habitat Structural Stage (Keyser 2006). Note: Bark beetle outbreaks began in the early 2000s and may have reduced stand density.

	Habitat Structural Stage		
Forest Cover Type	**Seedling # of CSI/FIA plots (Age in years)**	**Sapling/Pole # of CSI/FIA plots (Age in years for (Low/Med/High Stand Density Index Category))**	**Mature # of CSI/FIA plots (Age in years for (Low/Med/High Stand Density Index Category))**
Aspen	5 (2)	9 (46)	7 (66)
Douglas-fir	6 (4)	8 (79)	120 (113/118/124)
Limber pine	5 (1)	--	28 (67/90/118)
Lodgepole Pine	25 (2)	112 (43/69/81)	120 (98/118/135)
Subalpine Fir	12 (8)	53 (49/67/75)	120 (114/134/133)
Whitebark Pine	4 (4)	12 (50)	74 (111/116/132)

Shoshone C

The Shoshone NF stores a small portion of the U.S. Forest Service Rocky Mountain Region 2 forest carbon, 94 Tg C[1] or 9.5% of the Region 2 total C (Heath and others 2011). Total C stores in the Rocky Mountain Region 2 are estimated at 993 Tg C, which is about 8.5% of total C stores in U.S. National Forests (11,604 Tg C) (Table 2). The annual CO_2 sequestration potential for the Shoshone based on calculations derived using the Rocky Mountain Regional average from Heath and others (2011) would be approximately 2.2 Tg CO_2/yr[2]. The National Forests in Rocky Mountain Region 2 sequester on average 22.8 Tg CO_2/yr, and the U.S. National Forest average is about 150 Tg C/yr. Rocky Mountain Region 2 above ground C is approximately 115 Mg C/ha, and below ground C is around 40 Mg C/ha. These estimates may not reflect current carbon stock and sequestration amounts as this calculation was done before extensive bark beetle outbreaks occurred on the Shoshone NF over the last decade. Mortality in many lodgepole pine, whitebark pine, and Douglas-fir stands occurred on the Shoshone NF since the early 2000s. Over 368,264 ha (910,000 acres) or about 50% of forested acres on the Shoshone NF have been affected by bark beetle outbreaks from 2002 to 2011 (Bryan Armel, personal communication). It is

[1] Teragram (Tg) = 1 million Megagrams (Mg) = 1 million tonnes
1 tonne C = 3.67 tonnes CO_2
[2] The Shoshone NF covers about 9.6% of the Rocky Mountain Region 2 total area. Region 2 sequestered on average 22.8 Tg CO_2/year. The Shoshone NF percentage of this Region 2 total is about 2.2 Tg CO_2/yr.

currently unknown if the tree mortality from these insect outbreaks has caused these stands to become C sources. Simulations for the Shoshone NF that incorporate beetle outbreaks show that lodgepole pine stands have been reduced from mature stands to pole stands, and Douglas-fir stands have become less dense (FVS, 2012, unpublished data).

Table 2. Total National Forest C stocks and annual sequestration potential for the U.S., Rocky Mountain Region 2, and Shoshone (Heath and others 2011)
Note: Shoshone average measurement year is 1999. Bark beetle outbreaks began in the early 2000s and it is unknown how beetle outbreaks have affected C stocks.

	U.S. National Forests	Rocky Mountain Region 2	Shoshone National Forest
Total C stock (Tg C)	11,604	993	94
Annual $C0_2$ sequestration potential (Tg $C0_2$/yr)	150	22	2.2

Forest Products

Stockmann and others 2012 found that the U.S. Forest Service Region 1 of Idaho and Montana that borders the Shoshone to the north had C storage in harvested wood products below 0.5 Tg C before mid-century. C stored in wood products increased to 2.5 Tg C during the 1960s, and has dropped below 0.5 Tg C since the 1990s (Stockmann and others 2012).

Over the last decade, the Shoshone NF has sold an average of 11,289 MBF (Thousand Board Feet) annually, Wyoming National Forests averaged over 37,249 MBF/year, and Region 2 National Forests averaged 194,936 MBF/year (USDA FS, 2002-2011). Using Smith and others (2005) calculation method to estimate carbon stocks in harvested wood products, the Shoshone NF may have sequestered over 5,500 Mg C/year into harvested wood products since 2002. National Forests in the state of Wyoming may have sequestered over 18,400 Mg C/yr, and Rocky Mountain Region 2 National Forests may have sequestered over 96,000 Mg C/yr over the last 10 years. The Shoshone NF harvested C total is about 30% of Wyoming National Forest total C in harvested wood products and about 6% of U.S. Forest Service Rocky Mountain Region 2 total harvested wood products

Trends in Forest Carbon

Global Change

Global change may affect forest C stores and fluxes in several complex ways, resulting in drivers that could both increase and decrease C storage capacity. Increased atmospheric CO_2 allows for greater water use efficiency by trees (Eamus 1991). Water losses during transpiration (evaporation of water from plant leaves) are reduced because stomata do not need to be as open – reducing water loss – to fix the requisite amount of CO_2 for metabolism and growth. This may result in higher forest productivity.

Additionally, Smithwick and others (2011) modeling study found that lodgepole pine forest productivity in the Greater Yellowstone Ecosystem (GYE) (Figure 2) increased as a result of longer growing seasons under climate change when water was not strongly limiting. However, warmer temperatures may cause slower tree regeneration or make some areas unable to support current tree populations (Ryan and others 2010). However, warmer temperatures may increase the length of the growing seasons and increase productivity (Smithwick and others 2011). Forest productivity could also be lower owing to decreased late season water availability caused by higher air temperatures. Current projections of precipitation for the GYE show increasing winter precipitation and decreasing summer precipitation (Littell and others 2011).

Fire

Climate change can modify disturbance regimes that affect the C cycle. Fire is a major control of forest C balance, as more frequent and severe fires above the historical average reduces C storage potential. The number of large fires in subalpine forests of the northern Rocky Mountains and the GYE has increased during the past 25 years, due to warmer temperatures, longer fire seasons, and earlier snowmelt (Westerling and others 2006, Westerling and others 2011). On the Shoshone NF, fire regimes in higher elevations tend to be higher severity and less frequent (~150 - 700 years) while lower elevation fires tend to be lower severity and more frequent (~10 - 300 years) (Meyer and others 2006; Rice et al. 2012).

Carbon stores in the Greater Yellowstone Ecosystem (GYE) over the last 300 years were found to have high variability based on forest structure but have remained a carbon sink (Kashian and others in press). Under the historical fire regime, 150 – 300 yr Fire Return Interval (FRI), forest C was found to recover 80% of pre-fire C within 100 years. Older forests remained a C sink throughout Kashian and others (in press) chronosequence over the last 300 years, but as stands aged and wood growth slowed they were not as strong of a C sink. Potter and others' (2011) remote sensing study of Yellowstone National Park (YNP) forests found that the entire area was a sink of C, but the areas burned in the 1988 fire were sources of C that were being offset by other areas within YNP with higher productivity.

Increasing fire frequency under climate change may reduce the strength of forests C sinks and may turn C sinks into sources (Smithwick and others 2011). Westerling and others (2011) project FRIs in most of the GYE would fall from the current frequency of 100 – 300 yr to < 30 yr by the mid-2100s. These results suggest that the future fire regime would be consistent with a lower montane – non-forested fire regime – shifting from a climate-limited to a fuel-limited system would occur in the GYE by mid-century (Westerling and others 2011). Smithwick and others (2011) study using the CENTURY fire model in the GYE found that FRIs above 90 years would be needed to recover the region's C stocks to within 5% of pre-fire levels. Increased productivity of trees from warmer temperatures and longer growing seasons under climate change helped to lower the estimated C recovery time. With a 5-6 ^{o}C temperature increase, future fire occurrence was projected to be similar to what would be expected in an open montane-ponderosa pine forests by 2100. Although future FRIs are uncertain, if the magnitude of projected changes occurs there could be a massive re-organization of vegetation types that would likely shift regional C sinks to C sources within the GYE (Smithwick and others 2011).

Bark Beetle

Bark beetle outbreaks is another climate change related disturbance affecting C storage in forests. Recent outbreaks have reached unprecedented levels and have caused mortality on over 12 million ha in western North America (Bentz and others 2005; Kurz and others 2010). On the Shoshone NF, bark beetle outbreaks from 2002 to 2011 have caused mortality on about 368,264 ha (910,000 acres) of forested areas (personal communication, Bryan Armel). While the effects of beetle outbreaks on C in the Shoshone have not been measured, a study in the Sawtooth National Recreation Area, Idaho found that the effects of bark beetle outbreaks on forest C varied substantially according to forest structure and the growth response of remaining live trees (Pfeifer and others 2011). Mountain pine beetles (*Dendroctonus pondersae*) killed 52% of trees (usually larger diameter), reduced above ground live tree C stocks in lodgepole pine plots by 31 – 83%, and it took 25 years or less for C stocks to recover to pre-outbreak levels (Pfeifer and others 2011). Plot level C fluxes (growth rates) were reduced 28 – 73%, but increased after the outbreak, however, growth responses of remaining trees did not always replace the productivity of trees killed by the beetle outbreak (Pfeifer and others 2011). Beetle outbreaks were also found to have a large amount of spatial and temporal variability from partial mortality and preference of mature trees (Pfeifer and others 2011). Kurz and others (2008) modeling study for British Columbia projected that C stocks would not recover to pre-outbreak levels until sometime after 2020 (the maximum projection of the study) and do not speculate on the rate of recovery. Additionally, future climate warming may cause bark beetles outbreaks in the GYE to expand upward in elevation and the beetles having highly variable spatial and temporal effects (Bentz and others 2010). The expansion of bark beetle outbreaks under climate change would point to a reduction in C storage and sequestering potential on Shoshone forests if this were to occur, but the magnitude and duration of which is not known.

Land Use and Population Growth

Human population growth in the GYE has expanded urban areas and commercial and industrial development (Gude and others 2006; Hansen 2006). Private lands around the Shoshone NF are primarily in low lying riparian corridors used for agricultural purposes, and rural home sites are in higher elevation forested areas or shrublands. Future population is expected to grow between 28 – 234% by 2020 (Gude and others 2006). Larger populations will likely result in greater fire suppression efforts, but warmer climate has been linked to fire increase even with fire suppression (Flannigan and others 2000). Although it is not known how future land use will affect the fire regime in the Shoshone area, larger populations have been linked to higher fire occurrence (Syphard and others 2007). If future population growth results in more frequent and severe fires over a greater area, C storage and sequestering potential could be reduced. Additionally, increased nitrogen (N) deposition from oil and gas development, or other human activities may continue to occur on Shoshone forests (Rice and others 2012). Increased N input through deposition may result in higher productivity of the Shoshone's coniferous N-limited forests, but the magnitude and longevity of the effect is uncertain (McKinley and others 2011).

Knowledge Gaps

Precipitation and temperatures are major factors affecting disturbance regimes and forest C balance. Global Circulation Models (GCMs) are used to project precipitation and temperature that is used in models that forecast disturbance regimes. Generally, there is less confidence for projections for future precipitation than temperature projections. Global Circulation Models project both increases and decreases in precipitation in the GYE. According to Littell and others (2010), an ensemble of 10 GCM's that performed the best in the Northern Rocky Mountain region projected that mean annual precipitation will increase, with winter precipitation increasing about 10% and summer precipitation decreasing about 10% (Rice and others 2012). However, there was disagreement among the 10 GCMs as to how much change in precipitation may occur, especially during summer. Temperature increases span 1.1 – 5.5 °C (2 – 10 °F) over the 21st century, but the magnitude and variability of these temperature changes, although expected and important for ecosystem processes, are not yet well characterized. Projections from GCMs projections are in relative agreement about temperature increase magnitude until mid-century, but there is less agreement how much temperatures increase by the end of the century. Climate science is an active area of research. Climate models currently being developed likely will improve the temporal and spatial characterization of climate. The Shoshone will remain a challenging area to project climate dynamics because of the complexity of the landscape, with mountain ranges and valleys closely interconnected.

How future climate will affect fire and insect disturbance, vegetation changes, and productivity is challenging to quantify and poorly understood. While there is emerging scientific consensus that fire frequency and severity will likely increase in the future in some forests, there is no clear scientific consensus on how bark beetle outbreaks affect the fire regime (Rice and others 2012) and forest C balance. Studies have shown both increases and decreases of fire severity and area burned in post-beetle outbreak areas in the Rocky Mountains (Rice and others 2012). However, the overall predicted trends in fire and insect disturbance point to negative effects on forest C storage and sequestering ability if the recent disturbance regimes continue to increase in frequency and severity compared with the historical norm.

Potential Mitigation Options

Forests offer the potential to partially mitigate increased CO_2 emissions. At a national level, an estimated 10 to 20% of current U.S. CO_2 emissions could be offset by implementing mitigation strategies (Ryan and others 2010; McKinley and others 2011). For context of scale, achieving a 10% offset would require afforestation of 1/3 of U.S. crop and agricultural land (equivalent to about 65% of the land area of Texas), harvesting about the equivalent to the total annual net forest productivity in the conterminous U.S., or implementing intensive management to increase forest growth on 1/3 of U.S. forested lands (McKinley and others 2011). Mitigation strategies have associated co-benefits, but some significant tradeoffs and risks, such as lower agricultural production, implementation at an enormous scale – displacing other land uses, the potential to increase disturbance (e.g., increased fuel loads), leakage in programs to promote C offsets (e.g. harvesting moving elsewhere if reduced in an area), negative societal or monetary tradeoffs, negative effects on other ecosystem services (e.g., reduced non-carbon ecosystem services, such as water), and the future impacts of climate change.

Tradeoffs, risks and uncertainties need to be weighed against the benefits offered by implementing C mitigation strategies. Potential C mitigation strategies that can help increase C storage potential and reduce C source emissions that are discussed by Law and Harmon (2011), McKinley and others (2011), Ryan and others (2011), USDA FS (2010) include:

- **Maximize forest C storage capacity and maintain or increase forested area**
  This can be accomplished by extending harvest rotations; however this option needs to take into account any increased risks of high severity fire and other disturbances that may cause C reversal (Galik and Johnson 2009) and how much project leakage[3] and spillover[4] may occur, if any (Murray and others 2004). Another option is accelerating the recovery of disturbed or harvested areas. This can be accomplished by promoting prompt regeneration of climate-resilient, fire-resilient tree species after disturbance or harvest. Another option is to acquire forested areas at risk of being converted to non-forest with land exchanges or restrictions on development (e.g. conservation easements) and retain these areas as forest.

- **Decrease C loss potential from wildfire and insect disturbance**
  Increasing the resilience of forests and promoting diversity in forest structure can also decrease the undesirable effects of high severity fire disturbances (Reinhardt and others 2008) and potential C loss. Heterogeneity in forest structure has been found to offer benefits by reducing tree mortality from bark beetle outbreaks (Kayes and Tinker 2012), reducing subsequent losses in live tree C. In some cases, retaining and growing large fire-resistant trees has been shown to have less tree mortality and reduce C loss during wildfire (Stephens and others 2012). Also, managing forests with fuel treatments that use controlled burns and/or mechanical treatments have been found to reduce fire severity in some forests, thereby protecting carbon in living trees and sustaining some level of C uptake (Reinhardt and Holsinger 2010; Stephens and others 2012). However, not all studies have found a C benefit from fuel treatments because the probability of fire is often too low, particularly for many western forest types (Cathcart and others 2010; Reinhardt and others 2010; Ryan and others 2010). Carbon costs for fuel treatments may be high in some cases (Hurteau and others

[3] Leakage refers to when actions to sequester C in one area are counteracted by activities that take place in another area.
[4] Spillover is the converse of leakage and refers to when C mitigating activities yield greater benefits than intended.

2011), but increased fire resistance benefits with small reductions in C stocks have also been found in dry, coniferous forests with more frequent fire of lower severity (Stephens and others 2012) Fire suppression is more successful under moderate conditions, but extreme weather conditions may become more prominent in the future with climate change. Fire suppression may lead to more area burning with more extreme and unmanageable events (Reinhardt and others 2008, 2010).

- **Utilize forest biomass for energy production**
  Wood biomass from harvest and fuel treatments used for energy production offers a potential benefit of helping to offset C emissions, but recent reports failed to find them in California and Oregon (Pearson and others 2010; Goslee and others 2010). High handling and transportation costs and the need to increase the scope of current forest management over broader areas are some barriers (Reinhardt and others 2008; Ryan and others 2010). Woody biomass energy production on a large scale may not be sustainable nor reduce greenhouse gas emissions in the long term if soil nutrients are depleted and younger forests with lower biomass pools are a result (Schultz and others 2012). The use of bark beetle killed wood biomass may also offer an opportunity, however the high economic costs involved for this wood biomass energy production need to be considered as it may outweigh benefits (Niquidet and others 2012). Additionally, biomass energy production reduces C stocks and initially exceeds avoided some fossil fuel C emissions although total C emissions were greater – falling over time as forests recovered C (McKenchie and others 2012). Modeled longer term reductions of total cumulative emissions were delayed as much as many decades when usingwhole standing trees as compared to using residues to produce biomass energy - as in the case for ethanol production (McKenchie and others 2012).

Conclusions

The global C cycle has experienced an increase of atmospheric CO_2 concentrations and other GHGs over the last century that been attributed to increasing global temperatures. Forests are an important part of the global C cycle as they help slow the rising of atmospheric CO_2 concentration by storing C in forest biomass and soils, as well as in some forest products. Carbon fluxes between the atmosphere and forests are complex and vary spatially and temporally. The Shoshone NF stores and sequesters about 9.5% of the total Rocky Mountain Region C and CO_2. Some evidence suggests that climate, changing disturbance regimes, and land use may cause C stocks in the Shoshone area to shift from regional C sinks to C sources. Fire and bark beetle outbreaks disturbance play a large role in regional C balances. Carbon storage potential may also be further reduced by future human population growth causing more frequent fires and thereby influencing the fire regime and by decreasing forested area with development. How the complex interactions between climate, fire, insect outbreaks, and human population activity will affect the C cycle on the Shoshone NF is challenging to quantify with any certainty because the science is beginning to develop in this area. But from what science is available, the amount and timing of future temperatures increases, expected changes in precipitation regimes, and future fire and insect disturbance regimes suggest the regional C balance could shift to a carbon source. Mitigation options can help reduce climate change impacts on carbon by maximizing forest capacity to store C, decreasing C loss potential from disturbance, or utilizing biomass for energy, but these options need to weigh tradeoffs and risks and must ultimately be coupled with adaptation strategies.

Acknowledgements:

I wish to thank reviewers for their insightful comments and suggestions that contributed to improving the quality of this report: Trey Schille, Policy Analyst, USDA Forest Service, Region 2; James Morrison, USDA Forest Service, Region 1, Linda A. Joyce, Scientist, USDA Forest Service, Rocky Mountain Research Station, and Duncan McKinley, Forest and Grassland Ecologist, Research and Development WO, Washington, D.C.

REFERENCES

Bentz, B. 2005. Bark beetle outbreaks in western North America: causes and consequences. Bark Beetle Symposium. Snowbird, University of Utah Press.

Bentz, B. J., J. Regniere, C. J. Fettig, E. M. Hansen, J. L. Hayes, J. A. Hicke, R. G. Kelsey, J. F. Negron, and S. J. Seybold. 2010. Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects. BioScience 60(8):602-613.

Birdsey, R., K. Pregitzer, and A. Lucier. 2006. Forest carbon management in the United States: 1600–2100. Journal of Environmental Quality 35:1461–1469.

Cathcart, J., A. A. Ager, A. McMahan, M. Finney and B. Watt. 2010. Carbon Benefits from Fuel Treatments. In *Jain, Theresa B.; Graham, Russell T.; and Sandquist, Jonathan, tech. eds. 2010. Integrated management of carbon sequestration and biomass utilization opportunities in a changing climate: Proceedings of the 2009 National Silviculture Workshop; 2009 June 15-18; Boise, ID. Proceedings RMRS-P-61. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 351 p.*

Eamus. D., 1991. The interaction of rising CO2 and temperatures with water use efficiency. Plant, Cell and Environment 14:843-852.

Flannigan, M. D., B. J. Stocks, B. M. Wotton. 2000. Climate change and forest fires. The Science of the Total Environment 262:221-229.

Forest Vegetation Simulator (FVS). 2012. Model runs incorporating beetle outbreak. Rocky Mountain Research Station, Fort Collins, CO.

Galik, C. S. and R. B. Jackson. 2009. Risks to forest carbon offset projects in a changing climate. Forest Ecology and Management 257:2209-2216.

Goslee, K., T. Pearson, S. Grimland, S. Petrova, J. Walls and S. Brown. 2010. *Final Report on WESTCARB Fuels Management Pilot Activities in Lake County, Oregon.* California Energy Commission, PIER. CEC-500-XXXX-XXX. Available at: http://www.winrock.org/ecosystems/files/WestcarbRPT/WESTCARB%20II_Winrock_LakeCountyReport.pdf.

Gude, P. H., A. J. Hansen, R. Rasker, B. Maxwell. 2006. Rates and drivers of rural residential development in the Greater Yellowstone. Landscape and Urban Planning 77:131-151.

Hansen, A. 2006. Yellowstone bioregional assessment: understanding the ecology and land use of Greater Yellowstone. Technical Report #2, Landscape Biodiversity Lab, Montana State University, Bozeman.

Heath, L. S., J. E. Smith, C. W. Woodall, D. L. Azuma and K. L. Waddell. 2011. Carbon stocks on forestland of the United States, with emphasis on USDA Forest Service ownership. Echosphere 2(1) doi:10.1890/ES10-00126.1.

Hurteau, M. D., M. T. Stoddard and P. Z. Fule. 2011. The carbon costs of mitigating high-severity wildfire in southwestern ponderosa pine. Global Change Biology 17:1516-1521.

Intergovernmental Panel on Climate Change [IPCC]. 2007. Climate Change 2007: Synthesis report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. R. Pachauri and A. Reisinger. Geneva, Switzerland.

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.

Kashian, D. M., W. H. Romme, D. B. Tinker, M. G. Turner, and M. G. Ryan. In press. Post-fire changes in forest carbon storage over a 300-year chronosequence of Pinus contorta-dominated forests. Ecological Monographs.

Kayes,L. J. and D. B. Tinker. 2012. Forest structure and regeneration following a mountain pine beetle epidemic in southeastern Wyoming. Forest Ecology and Management 263:57-66.

Keyser, C. 2006. Shoshone National Forest, Summary of Yield Table Development Report. Shoshone National Forest, 808 Meadow Lane Ave ,Cody, WY 82414.

Kurz, W., C. Dymond, G. Stinson. [and others] 2008. Mountain pine beetle and forest carbon feedback to climate change. Nature 452(7190):987-990.

Law, B. E., M. E. Harmon. 2011. Forest sector carbon management, measurement, and verification, and discussion of policy related to mitigation and adaptation of forests to climate change. Carbon Management (2)1:73-84.

Linares, J. C. and J. J. Camarero. 2012. From pattern to process: linking intrinsic water-use efficiency to drought-induced forest decline. Global Change Biology 18(3):1000-1013.

Littell, J. S., M. M. Elsner, G. S. Mauger, E. Lutz, A. F. Hamlet and E. Salathe. 2011. Regional Climate and Hydrologic Change in the Northern U.S. Rockies and Pacific Northwest: Internally Consistent Projections of Future Climate for Resource Management. Climate Impacts Group. Available online: http://cses.washington.edu/picea/USFS/pub/Littell_etal_2010/Littell_etal._2011_Regional_Climatic_And_Hydrologic_Change_USFS_USFWS_JVA_17Apr11.pdf.

Luo, Y., B. Su, W. Currie. [and others] 2004. Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide. Bioscience 54(8):731-739.

McKinley, D. C., M. G. Ryan, R. A. Birdsey, C. P. Giardina, M. E. Harmon, L. S. Heath, R. A. Houghton, R. B. Jackson, J. F. Morrison, B. C. Murray, D. E. Pataki, and K. E. Skog. 2011. A synthesis of current knowledge on forests and carbon storage in the United States. Ecological Applications 21(6):1902-1924.

McKnechie, J., S. Colombo, J. Chen, W. Mabee and H. l. Maclean. 2012. Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels. Environ. Sci. Technol. 45:789-795.

Meyer, C., D. Knight, G. Dillon. 2006. Historic variability for the upland vegetation of the Shoshone National Forest, Wyoming. U.S. Department of Agriculture, Forest Service, Lakewood, CO. Agreement Number 1102-0003-98-043.

Murray, B. C., B. A. McCarl and H. C. Lee. 2004. Estimating Leadage from Forest Carbon Sequestration Programs. Land Economics 80(1):109-124.

Niquidet, K., B. Stennes and G. C. van Kooten. 2012. Bioenergy from Mountain Pine Beetle Timber and Forest Residuals: A Cost Analysis. Canadian Journal of Agricultural Economics 60:195-210.

Norby, R., E. DeLucia, B. Gielen. [and others] 2005. Forest response to elevated CO_2 is conserved across a broad range of productivity. Proceedings of the National Academy of Sciences 102(50):18052-18056.

Norby, R. J. and D. R. Zak. 2011. Ecological Lessons from Free-Air CO2 Enrichment (FACE) Experiments. Annu. Rev. Ecol. Evol. Syst. 42:181-203.

Pearson, TRH, K. Goslee, and S. Brown. 2010. Emissions and potential emission reductions from hazardous fuel treatments in the WESTCARB region. California Energy Commission, PIER. CEC-500-XXXX-XXX. Available at: http://www.winrock.org/ecosystems/files/WestcarbRPT/WCHazardousFuelsReport.pdf.

Pfeifer, E. M., J. A. Hicke, and A. J. H. Meddens. 2011. Observations and modeling of aboveground tree carbon stocks and fluxes following a bark beetle outbreak in the western United States. Global Change Biology 17:339-350.

Potter, C., S. Klooster, R. Crabtree, S. Huang, P. Gross, and V. Genovese. 2011. Carbon fluxes in ecosystems of Yellowstone National Park predicted from remote sensing data and simulation modeling. Carbon Balance and Management 6(3) Available online: http://www.cbmjournal.com/content/6/1/3.

Reinhardt, E. D., R. E. Keane, D. E. Calkin, J. D. Cohen. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management 256:1997-2006.

Reinhardt, E. and L. Holsinger. 2010. Effects of fuel treatments on carbon-disturbance relationships in forests of the northern Rocky Mountains. Forest Ecology and Management 259:1427-1435.

Rice, J., A. Tredennick, L. A. Joyce. 2012. Climate change on the Shoshone National Forest, Wyoming: A synthesis of past climate, climate projections, and ecosystem implications. Gen. Tech. Rep. RMRS-GTR-264. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 60 p.

Ryan, M. G., M. E. Harmon, R. A. Birdsey, C. P. Giardina, L. S. Heath, R. A. Houghton, R. B. Jackson, D. C. McKinley, J. F. Morrison, B. C. Murray, D. E. Pataki, and K. E. Skog. 2010. A Synthesis of the Science on Forests and Carbon for U. S. Forests. Issues in Ecology Report 13. Available online: http://www.fs.fed.us/rm/pubs_other/rmrs_2010_ryan_m002.pdf.

Schultz, E.D., C. Korner, B. E. Law, H. Haberl and S. Luyssaert. 2012. Large-scale bioenergy from additional harvest of forest biomass is neighter sustainable nor greenhouse gas neutral. Bioenergy doi: 10.1111/j.1757-1707.2012.01169.x

Shore, T.L., Safranyik, L., Hawkes, B.C., Taylor, S.W., 2006. Effects of the mountain pine beetle on lodgepole pine stand structure and dynamics. In: Safranyik, L., Wilson, B. (Eds.), The Mountain Pine Beetle: A Synthesis of Biology Management and Impacts on Lodgepole Pine. Natural Resources Canada. Canadian Forest Service, Victoria, B.C., pp. 95–114. Available at: http://cfs.nrcan.gc.ca/publications/download-pdf/26041.

Smith, J. E., L. S. Heath, K. E. Skog, R. A. Birdsey. 2005. Method for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States. Gen. Tech. Rep. NE-GTR-343. Newton Square, PA. U.S. Department of Agriculture, Forest Service, Northern Research Station. 218 p.

Smithwick, E.A.H., A. L. Westerling, M. G. Turner, W. H. Romme, and M. G. Ryan. 2011. Climate, fire and carbon: Tipping points and landscape vulnerability in the Greater Yellowstone Ecosystem. Final Report JFSP Project No. 09-3-01-47. Available at: http://www.firescience.gov/projects/09-3-01-47/project/09-3-01-47_smithwick_et_al_jfsp_final_report_09-3-01-47.pdf.

Stephens, S. L., R. E. J. Boerner, J. J. Moghaddas, E. E. Y. Moghaddas, B. M. Collins, C. B. Dow, C. Edminster, C. E. Fiedler, D. L. Fry, B. R. Hartsough, J. E. Keeley, E. E. Knapp, J. D. McIver, C. N. Skinner, and A. Youngblood. 2012. Fuel treatment impacts on estimated wildfire carbon loss from forests in Montana, Oregon, California, and Arizona. Ecosphere 3(5):38. http://dx.doi.org/10.1890/ES11-00289.1.

Stockmann, K. D., N. M. Anderson, K. E. Skog, S. P. Healey, D. R. Loeffler, G. Jones and J. F. Morrison. 2012. Estimates of carbon stored in harvested wood products from the United States forest service northern region, 1906-2010. Carbon Balance and Management 7(1) Available at: http://www.cbmjournal.com/content/7/1/1.

Syphard, A. D., V. C. Radeloff, J. E. Keeley, T. J. Jawbaker, M. K. Clayton, S. I. Stewart, and R. B. Hammer. 2007. Human Influence on California Fire Regimes. Ecological Applications 17(5):1388-1402.

USDA Forest Service. 2010. KIPZ Climate Change Report. Idaho Panhandle National Forest, Kootenai National Forest.

USDA Forest Service. 2002 - 2011. Cut and Sold Report FY2011. http://www.fs.fed.us/forestmanagement/products/sold-harvest/cut-sold.shtml.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam . 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. Science 313 (5789), 940.

Westerling, A. L., M. G. Turner, E. A. H. Smithwick, W. H. Romme, and M. G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. PNAS 108(32):13165-13170.