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Toward full economic valuation of forest fuels-reduction treatments

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Our goal was to move toward full economic valuation of fuels-reduction treatments applied to ponderosa pine (*Pinus ponderosa*) forests. For each of five fuels-reduction projects in northern Arizona, we calculated the economic value of carbon storage and carbon releases over one century produced by two fuels-reduction treatments of thinning following by prescribed burning every one (Rx10) or two (Rx20) decades and for no treatment followed by intense wildfire once in the first 50 years (HF50) or once in the first 100 years (HF100). Our estimates include two uses of harvested wood, the current use as pallets, and multiproduct use as paper, pallets, and construction materials. Additionally, we included the economic value of damage and loss from wildfire. Results indicate that treatments increase carbon stock in live trees over time; however, the inclusion of carbon emissions from treatments reduces net carbon storage and thereby carbon credits and revenue. The economic valuation shows that the highest net benefit of \$5029.74 ha^{-1} occurs for the Rx20 treatment with the HF50 baseline and the high estimated treatment benefits of avoided losses, regional economic benefits, and community value of fire risk reduction. The lowest net benefit of −\$3458.02 ha^{-1} occurs for the Rx10 treatment with the HF100 baseline and the low estimated treatment benefits. We conclude that current nonmarket values such as avoided wildfire damage should be included with values of traditional wood products and emerging values of carbon storage to more appropriately estimate long-term benefits and costs of forest fuels-reduction treatments.

1. Introduction

Historically, low-severity fires burned frequently in southwestern ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws) forests and maintained open, fire-resilient stands (Covington and Moore, 1994; Swetnam and Baisan, 1996). However, fire exclusion over the last century has resulted in an overstocking of pole-sized trees, creating forests that now contain on average 2.3 times more live tree carbon than pre-fire exclusion forests (Covington and Moore, 1994; Hurteau et al., 2011). Current dense forests are at high risk of intense burning that releases large pulses of CO_2 into the atmosphere (Fulé et al., 2004; Wiedinmyer and Neff, 2007) and often causes biome shifts from forest to low-biomass non-forest for decades or longer (Roccaforte et al., 2012; Ross et al., 2012; Bowman et al., 2013). Fuels-reduction treatments such as mechanical thinning and low-intensity prescribed burning extract small-diameter trees and reduce fuel mass, fuel continuity, and subsequent fire intensity and tree mortality (Agee and Skinner, 2005; Finney et al., 2005; Fulé et al., 2012). Whether the decrease in fire intensity and reduction of deforestation caused by fuels-reduction treatments helps offset long-term anthropogenic carbon emissions is controversial because the offset is weakened or perhaps reversed when carbon emissions from harvesting, wood production and use, and prescribed burning are considered (Sorensen et al., 2011; Campbell et al., 2012).

The potential for carbon storage and release resulting from fuels-reduction treatments extends beyond the biological carbon cycle of forest ecosystems. Harvested wood products store carbon until discarded, after which the carbon is emitted rapidly through combustion or slowly through decay (Skog et al., 2004). The amount of carbon sequestered in wood products depends on the amount of timber harvested, its use in primary wood products, and the longevity of wood in end-use products (Row and Phelps, 1996; Skog et al., 2004). While wood products can constitute a carbon sink, associated emissions produced during harvesting, transportation of logs, manufacturing, and product distribution affect net carbon sequestration (Pingoud and Lehtilä, 2002). Therefore, full accounting of the impacts of fuels-reduction treatments on long-term carbon storage should include carbon stock in forest, carbon emissions from treatments, wildfires and production of wood products, and carbon storage in wood products.

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The costs of wildfires to society include direct costs (i.e., suppression costs, property losses, timber losses, aid to evacuated residents, damages to utility lines and recreation facilities), rehabilitation costs, indirect costs (i.e., tax and business revenue losses), and special value losses (i.e., human life losses, ecosystem service losses) (Lynch, 2004; Dale, 2009; Impact DataSource, 2013). Previous studies that have estimated wildfire impacts on societal and ecological services such as wildlife habitat, vegetation resilience, carbon sequestration, watersheds, tourism, public health and transportation suggest undervaluation of fuels-reduction treatments by failure to include broader wildfire impacts (Morton et al., 2003; Mason et al., 2006; Mercer et al., 2007; Richardson et al., 2012; Vegh et al., 2013; Impact DataSource, 2013). Few studies have combined economic valuation of treatment costs, forest carbon sequestration, wildfire and prescribed fire carbon releases, and damages/losses avoided via wildfire reduction to evaluate the economic benefits of fuels-reduction treatments. In this study, we used well-documented operational fuels-reduction treatments applied to five ponderosa pine forests in northern Arizona (Sorensen et al., 2011) to broaden economic valuation of treatments to include numerous current market and nonmarket benefits and costs. Our goal is to advance forest economics and policy toward full economic valuation of fuels-reduction treatments. Specifically, the objectives are to compare 1) forest net carbon storage between two wildfire scenarios and two management scenarios, 2) carbon credits and carbon revenue between scenarios with two carbon accounting approaches and two baseline approaches, and 3) net present value (NPV) among scenarios using a variety of treatment benefits including avoided loss.

2. Methods

2.1. Study sites

Our study was based on data from five stands on federal and state lands in northern Arizona that were thinned to reduce fire risk: a) Government Hill (GH, 35°19′N and 111°58′W) located on the Kaibab National Forest; b) Horse-Pine (HP, 35°13′N and 111°59′W) located on the Kaibab National Forest; c) Mountainaire (MT, 35°07′N and 111°39′W) located on the Coconino National Forest; d) Rogers North (RN, 35°09′N and 111°56′W); and e) a restoration thinning site (RT, 35°09′N and 111°43′W), both located on Northern Arizona University's Centennial Forest. All sites were located near Flagstaff, Arizona, where the mean annual temperature from 2003 to 2009 was 8.3 °C, with a mean July temperature of 20.0 °C and a mean December temperature of −1.9 °C (WRCC, 2010). Annual precipitation ranges between 271 and 882 mm with an annual mean of 452 mm (WRCC, 2010). The driest months in this region typically occur in the late-spring/early-summer followed by monsoonal rainfall in the later summer months and snowfall in the winter (Sheppard et al., 2002). All sites were dominated by ponderosa pine with small amounts of the following species: quaking aspen (*Populus tremuloides* (Michx.)), Douglas-fir (*Pseudotsuga menziesii* Mirb.), white fir (*Abies concolor* (Gord. & Glend.)), southwestern white pine (*Pinus strobiformis* Engelm.), Gambel oak (*Quercus gambelii* Nutt.), alligator juniper (*Juniperus deppeana* Steud.), Arizona cypress (*Cupressus arizonica* Greene), and piñon pine (*Pinus edulis* Engelm.).

The silvicultural prescriptions for all five sites had the primary objective of reducing the risk of high-intensity fire. The treatments are best described as low and crown thinnings of varying intensities, which are commonly used in this region to reduce stand density, canopy continuity, and ladder fuels (Covington et al., 1997; Fulé et al., 1997; Finkral and Evans, 2008). Mostly smaller diameter ponderosa pine trees (<40 cm diameter at breast height (DBH)) were harvested along with some larger trees to open up the canopy. In general, older trees (approximately 135 years old), standing dead trees, and all non-pine tree species were retained unless they presented safety hazards. Sorensen et al. (2011) presents detailed information on the effect of thinning on vegetation at each site.

2.2. Wildfire and management scenarios

Fuels-reduction treatments in ponderosa pine stands reduce standing carbon stocks while releasing carbon through the combustion of fuel in logging machinery, burning slash, and the decay of logging slash and wood products. Any activity that removes biomass from a forest carbon project site, including a thinning treatment or prescribed burning, removes carbon that would otherwise be sequestered until it is released by decay or burning. Therefore, these reductions and releases of stored carbon must be examined in detail to more fully understand the total carbon stock and net carbon storage. We used pre-treatment and one-year post-treatment empirical field measurements of overstory conditions and surface fuels to project future site growth and carbon stocks and releases under different wildfire and management scenarios for each site. The projections were made using the Central Rockies variant of the Forest Vegetation Simulator (Dixon, 2008) with the Fire and Fuels Extension (Reinhardt and Crookston, 2003; Reinhardt et al., 2008) parameterized for the study sites (Sorensen et al., 2011). The Fire and Fuels Extension uses weather, fuels, and stand characteristics to predict fire behavior, which in turn allows predictions of tree growth and mortality, fuel consumption, and carbon emissions (Reinhardt and Holsinger, 2010).

We chose a 100-year timeframe for this project as this represents the crediting period for which baseline onsite carbon stocks must be maintained under the Forest Project Protocol of the Climate Action Reserve (Version 3.2). We included two wildfire scenarios (HF50 and HF100) and two management scenarios (Rx10 and Rx20) in the projections at each site. Both HF (high-intensity fire) scenarios are based on the occurrence of a high-intensity fire in untreated stands under hazardous fire conditions (wind speed 22 m s^{-1}, air temperature 29 °C, very dry fuels) that consequently kills all trees, followed by ponderosa pine regeneration 20 years after burning. The HF50 (high fire risk) scenario assumes that one high-intensity fire occurs within the next 50 years and no fire occurs the following 50 years. For the HF50 scenario, six 100-year simulations were run on the pre-treatment stands based on the occurrence of one high-intensity fire in each of years 2010, 2020, 2030, 2040, 2050, and 2060. Average century-scale carbon stocks (above- and below-ground live and dead trees and surface fuels) and releases over these six simulations were used for the HF50 scenario. Likewise, the HF100 (moderate fire risk) scenario assumes that one high-intensity fire occurs within the next 100 years; 11 simulations were run for high-intensity fire occurring each decade between 2010 and 2110 and averaged per century. Both Rx (prescribed fire) scenarios, occurring after thinning, were based on prescribed surface fires applied to post-treatment stand conditions under low hazard fire conditions (wind speed 2.4 m s^{-1}, air temperature 10.0 °C, moist fuel conditions). The Rx10 scenario assumes the application of prescribed fire every decade between 2010 and 2110, and the Rx20 scenario assumes the application of prescribed fire every two decades. Both Rx scenarios included impacts of prescribed fire on mortality of mature trees and seedlings (see Sorensen et al., 2011). As for the HF scenarios, carbon stocks and releases for the Rx scenarios were calculated per century.

2.3. Total carbon stock and net carbon storage

We estimated carbon biomass in the stands, carbon releases associated with the management and wildfire scenarios, and long-