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# Modeling climate and fuel reduction impacts on mixed-conifer forest carbon stocks in the Sierra Nevada, California

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ABSTRACT

Quantifying the impacts of changing climatic conditions on forest growth is integral to estimating future forest carbon balance. We used a growth-and-yield model, modified for climate sensitivity, to quantify the effects of altered climate on mixed-conifer forest growth in the Lake Tahoe Basin, California. Estimates of forest growth and live tree carbon stocks were made for low and high emission scenarios using four downscaled general circulation model (GCM) projections. The climate scenarios were coupled with a range of commonly-used fuels reduction treatments to quantify the combined effects of these factors on live tree carbon stocks. We compared mid- (2020–2049) and late-21st (2070–2099) century carbon stock estimates with a baseline period of 1970–1999 using common input data across time periods. Recursive partitioning analysis indicates that GCM, forest composition, and simulation period most influence live tree carbon stock changes. Comparison with the late 20th century baseline period shows mixed carbon stock responses across scenarios. Growth varied by species, often with compensatory responses among dominant species that limited changes in total live tree carbon. The influence of wildfire mitigation treatments was relatively consistent with each GCM by emission scenario combination. Treatments that included prescribed fire had greater live tree carbon gains relative to baseline under the scenarios that had overall live tree carbon gains. However, across GCMs the influence of treatments varied considerably among GCM projections, indicating that further refinement of regional climate projections will be required to improve model estimates of fuel manipulations on forest carbon stocks. Additionally, had out simulations included the effects of projected climate changes on increasing wildfire probability, the effects of management treatments on carbon stocks may have been more pronounced because of the influence of treatment on fire severity.



## 1. Introduction

Management of forest-based carbon sequestration represents part of the portfolio of current technologies that can be implemented to mitigate changing climatic conditions (Pacala and Socolow, 2004). This can take the form of reducing deforestation, increasing carbon density, afforestation/reforestation, or replacing fossil-based energy sources with sustainably-harvested forest biomass (Canadell and Raupach, 2008). While forest-based climate change mitigation does offer promise, especially with regards to reducing tropical deforestation (Gullison et al., 2007), it is not without risk (Galik and Jackson, 2009).

Risk is commonly defined as the product of the probability of an event occurring and the consequence of that event. In the case of forest carbon loss due to wildfire, the consequence is a function of fire effects on the forest (Hurteau et al., 2013). High-severity fire causes greater carbon loss than low-severity fire, resulting in a larger consequence (Hurteau and Brooks, 2011). Fire effects on the forest can be managed by altering forest structure and fuel loads, thereby reducing the risk of carbon loss due to wildfire (Hurteau et al., 2009). However, this risk reduction measure carries a carbon stock reduction cost and the carbon balance of a specific treatment is dependent upon a wildfire burning in the treated area, the end-use of the trees harvested during treatment, among other factors (Mitchell et al., 2009; North et al., 2009; Stephens et al., 2009b; Hurteau et al., 2011; Campbell et al., 2012; Winford and Gaither, 2012). Generally, the probability of a fire event occurring at most

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forest locations in any given year is quite low (Dickson et al., 2006). However, warming temperatures are increasing the frequency of large wildfires (Westerling and Bryant, 2008; Pechony and Shindell, 2010; Westerling et al., 2011) and may also increase fire severity. Based on two general circulation model projections under a doubling of atmospheric $CO_2$, Flannigan et al. (2000) projected that mean fire severity in California (measured by difficulty of control) would increase by about 10% averaged across the state by mid-century. Results from Lenihan et al. (2003, 2008) suggest that large proportions of the Sierra Nevada landscape may experience an increase in mean fire intensity over current conditions by the end of the century, depending on future precipitation patterns. Therefore, the risk of carbon loss due to wildfire is likely to increase as a function of the increasing probability and severity of wildfire.

The carbon carrying capacity of a system has been defined as the amount of carbon that can be sustained under prevailing climatic conditions and natural disturbance regimes (Keith et al., 2009). Human intervention in the form of fire exclusion has resulted in a carbon density that exceeds the carrying capacity in some systems, with the result being a proportionately greater carbon loss when wildfire occurs (Dore et al., 2008; Hurteau et al., 2011). In addition to altering forest structure, fire exclusion has also impacted forest composition. In the mixed-conifer forests of the Sierra Nevada of California, fire-exclusion has resulted in increased tree density, decreased mean diameter, and a greater proportion of the basal area being comprised of fire-sensitive species (North et al., 2007). The pulse of post-fire-exclusion recruitment of these species (e.g. *Abies concolor* and *Calocedrus decurrens*) coincided with a climatic shift to warmer and wetter conditions (North et al., 2005; Beaty and Taylor, 2008). While it is difficult to discern the exact cause of this change in species composition, it raises the question of how a shift to even warmer conditions, with increased fire frequency and altered precipitation, will influence the carbon carrying capacity of forests.

In addition to influencing disturbance, changes in climate can impact forest growth and mortality, contributing uncertainty to the role of forests in climate change mitigation (Battles et al., 2008; vanMantgem et al., 2009). Growth-and-yield models, such as the Forest Vegetation Simulator (FVS), typically project forest growth assuming a static climate (Crookston et al., 2010). Thus, projecting forest growth under changing climatic conditions, using past climate–growth relationships has the potential to yield erroneous results. The bioclimate envelope modeling approach has been widely employed to predict how individual species ranges will change in climate space. A major criticism of this approach has been that it neglects the influence of biotic interactions on species distributions (Pearson and Dawson, 2003). One approach to overcome the short-comings of a purely climate-driven approach to modeling species-specific growth to climate is to incorporate climate sensitivity into the growth and mortality functions of models such as FVS.

The purpose of this study was to quantify the influence of predicted changes in climate on live tree carbon stocks, as a function of species-specific carbon stock changes, in a Sierran mixed-conifer forest by accounting for both biotic and abiotic influences on growth. Additionally, we sought to determine the carbon stock implications of treatments implemented to reduce the risk of high-severity wildfire and their interaction with climate impacts on growth.

## 2. Materials and methods

This study utilized field data to drive a climate-sensitive growth-and-yield model to project species-specific growth as a function of down-scaled climate projections from four different GCMs under two different emissions scenarios. The modeling approach used differs from climate-only approaches by incorporating biotic influences on tree growth, specifically competition. It also differs from the approach of Crookston et al. (2010) by directly incorporating climate projections, as opposed to representing changes in climate through changes in site index.

### *2.1. Study location*

This study was conducted in the mixed-conifer forest of the Lake Tahoe Basin, California (Supplementary Fig. S1). Mixed-conifer forest occupies an elevation range from the lakeshore at 1897 m to approximately 2400 m in elevation, as a function of aspect. The forest is comprised primarily of six tree species; white fir (*A. concolor*), red fir (*A. magnifica*), incense-cedar (*C. decurrens*), Jeffrey pine (*Pinus jeffreyi*), ponderosa pine (*P. ponderosa*), and sugar pine (*P. lambertiana*). The Lake Tahoe Basin has a Mediterranean climate, with a majority of the annual precipitation (mean annual precipitation water equivalent 802 mm, National Climate Data Center, Tahoe City) falling as snow and the summers being dry and warm. The history of human impacts in the Basin includes a significant period of tree harvest during the late 1800s, when a majority of the area was logged to provide timber for Nevada's silver mining operations (Eliott-Fisk et al., 1996). Prior to the late 1800s, frequent fires in the Basin had a mean return interval ranging from 8 to 17 years in the yellow pine and mixed-conifer forest types (Beaty and Taylor, 2008).

### *2.2. Field data*

Two to four plots were established in each of 21 creek drainages and were 1900–2200 m in elevation (Supplementary Fig. S1). Plots used in this study were selected to represent upland conditions and were co-located, approximately 150 m up-slope, with plots in the riparian zone for use in reconstructing riparian fire history (VandeWater and North, 2010). Plots located on the western side of the Basin were fir-dominated, while those located along the eastern shore were pine-dominated. Trees were sampled within plots using a nested design where all trees $\geqslant$5 cm diameter at breast height (dbh) were measured in a 1/50th ha subplot, all trees $\geqslant$50 cm dbh were measured in a 1/10th ha subplot, and all trees $\geqslant$80 cm dbh were measured in a 1/5th ha plot. Fuels were quantified along four modified Brown's transects (Brown, 1974) oriented in the cardinal directions at each plot. To assess regeneration, all trees <5 cm dbh where some portion of the tree intersected the transect were tallied by species along each fuels transect. These plot data were used to initiate model runs for each of three time periods, including a historical baseline (1970–1999), mid-century (2020–2049), and late-century (2070–2099) projections.

### *2.3. Model*

To quantify the effects of climate and management treatment on forest growth and live tree carbon stocks we used a modified version of the Western Sierra Variant of the Forest Vegetation Simulator (Keyser, 2008). The Forest Vegetation Simulator (FVS) is a distance-independent, growth-and-yield model that can simulate a wide range of silvicultural treatments for most major forest tree species (Crookston and Dixon, 2005). The modified Western Sierra Variant of FVS (FVS-WS-CLIM) developed by Robards (2009) uses climate-sensitive, species-specific growth models and downscaled monthly climate data to model tree growth as a function of climate and management. This climate-sensitive model was developed using permanent plot and tree core data from 42,459 trees from 1378 plots on private and public lands across northern California, collected between 1958 and 1998, to calculate annual diameter