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Methodological and Ideological Options

Climate Change Constrains the Efficiency Frontier When Managing Forests to Reduce Fire Severity and Maximize Carbon Storage

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ABSTRACT

Pareto efficiency frontiers are ideal analytical tools for evaluating likely shifts in the production of forest ecosystem services under climate change. In the context of multi-objective forest management, these frontiers, or the set of non-dominated solutions for a set of objectives at varying levels of output, provide quantitative measures of trade-offs between competing ecosystem services and changes in the best-possible management outcomes for different climate change scenarios. We used outputs from a forest growth-and-yield model that simulated wildfire and management to examine three types of Pareto frontier analyses: 1) carbon storage maximization under changing budgetary constraints with and without wildfire effects, 2) minimization of undesirable wildfire effects under changing budgetary constraints, and 3) minimization of undesirable wildfire effects at varying constrained carbon storage levels. We found that over 45 years climate change reduced the average amount of carbon stored, whether or not we simulated a wildfire on the 23,204 ha study area despite our best management efforts. Climate change also adversely affected the trade-off rate, or slope of the frontiers, between carbon storage and wildfire effects. We illustrate how the application of a methodology typically used in economics can reveal insights in forest ecosystem management otherwise hidden to decision-makers.

1. Introduction

As climate continues to shift towards a more arid norm in the southwestern US ([SW US], Williams et al., 2010; Kunkel et al., 2013; Garfin et al., 2014), forested ecosystems in this region are projected to undergo large contractions and transitions to woodland and/or grassland ecosystems (Allen and Breshears, 1998; Laughlin et al., 2011; Bagdon and Huang, 2014; Stoddard et al., 2015). Research has shown that the observed increases in frequency and severity of drought and wildfire are directly attributable to climate change (Grissino-Mayer and Swetnam, 2000; Westerling et al., 2006; Allen et al., 2010; Williams et al. 2010, Williams et al., 2014a; Williams et al., 2014b). Furthermore, as climate alters site productivity and suitability of forests affected by wildfire or drought, regeneration rates are likely to decrease to levels that cannot sustain forest cover (Rehfeldt et al., 2006; Bagdon and Huang, 2014; Stoddard et al., 2015). Forests are a key pool in the global carbon cycle, providing a net carbon sink up to 1.9 Pg C year^{-1}, that are increasingly at risk of becoming an emission source due to observed and projected increases in widespread mortality and wildfire events (Allen and Breshears, 1998; Pan et al., 2011; Williams et al., 2014a; Wiechmann et al., 2015). Surprisingly, there is a dearth of research exploring how well optimized management efforts could mitigate these forecasted negative outcomes at a tactical level.

The restoration of ponderosa pine forests has become the principal management objective in the SW US (Covington and Moore, 1994; Covington et al., 1997; Fule et al., 1997; Reynolds et al., 2013), as current conditions in these forests are characterized by an abnormal overabundance of non-merchantable, small-diameter trees, which act as ladder fuels that perpetuate uncharacteristic wildfires. In addition to improving ecological structure, function, and service provisioning (Reynolds et al., 2013; Roccaforte et al., 2015; Bagdon et al., 2016a), restoration of ponderosa pine forests provide numerous economic benefits such as job creation and avoided suppression costs (Sitko and Hurteau, 2010; Huang et al., 2013; Bagdon and Huang, 2016b). These dense forests also contain vast amounts of carbon, which would otherwise reside in the atmosphere, yet they are vulnerable to large carbon releases resulting from wildfire (Huang et al., 2013). Studies have predicted that the capacity of ponderosa pine forests to sequester and store carbon will decline sharply due to climate change, uncharacteristic wildfires, and drought (Allen et al., 2010; Hurteau et al., 2011; Huang et al., 2013; Bagdon and Huang, 2014).

Whether forest management can increase net carbon storage, therefore providing an effective climate mitigation strategy, while accounting for wildfire effects has been debated in the literature (Hurteau et al., 2008; Campbell et al., 2012; Dore et al., 2012; Huang et al., 2013). The

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outcome seems to depend on factors such as the time-span of analysis, the severity and intensity of wildfire observed or simulated, and the species composition of the forest, among other factors. Reductions in fire severity, or the effect of a fire(s) on a wildland system, are typically accomplished through management of the fuel complex, i.e. type, volume, arrangement (Agee and Skinner, 2005; Hardy, 2005), yet a large portion of forest carbon is stored in these fuels. Still, there is no debate that climate change is already affecting wildfire and drought severity (Allen et al., 2010; Williams et al., 2014a; Williams et al., 2014b), two factors that adversely affect carbon storage over the short- and long-term. Thus, the practical issue is how to manage forests under climate change to maximize carbon storage and minimize the severity of potential wildfires. While various stakeholders value the importance of carbon- and wildfire-management differently, all would benefit from a better understanding of the trade-offs between the best-possible outcomes to maximize carbon storage and minimize negative wildfire effects.

Any forest management plan requires decisions about when, where, and what kind of treatments should be implemented, usually in the context of pursuing multiple objectives (e.g. Field, 1973; Bettinger et al., 2002; Diaz-Balteiro and Romero, 2003; Bettinger et al., 2003; Tóth and McDill, 2009). For over 40 years, researchers and land managers have used mathematical programming methods to identify and develop optimized forest management plans for a variety of objectives (e.g. Haimes et al., 1971, see Diaz-Balteiro and Romero, 2008 for a review of objectives). Systematic use of mathematical programming can identify the Pareto efficiency frontier, or trade-off curve, for a variety of forestry problems. For instance, trade-off curves have been calculated for carbon storage versus net present value ([NPV], Hoen and Solberg, 1994), acres in wildlife preserve versus NPV (Cox and Sullivan, 1995), or carbon storage versus cork production at different minimum harvest volume constraints (Borges et al., 2014). A renewed interest in identifying the Pareto efficiency frontier in natural resource planning problems has coincided with the rise of ecological economics (Tóth et al., 2006; Bekele et al., 2013; Borges et al., 2014).

A Pareto efficiency frontier is the set of non-dominated solutions depicting the best-possible outcomes for a set of objectives at varying levels of output for each objective (Tóth et al., 2006; Bekele et al., 2013). In the context of forest management, a management plan is said to be Pareto efficient with respect to two objectives if no action could be taken to improve one of the objectives without detracting from the other objective(s), i.e. a non-dominated solution. Thus, the trade-off curve represents the set of optimal management plans at different levels of objective achievement. Methods exist for identifying Pareto efficiency frontiers in multi-criteria (i.e. more than two objectives) forest management problems (e.g. Tóth and McDill, 2009; Borges et al., 2014), or for identifying Pareto frontiers in a bi-criterion problem (e.g. Haimes et al., 1971; Chalmet et al., 1986; Tóth et al., 2006; Kline and Mazzotta, 2012). Bekele et al. (2013) and Kline and Mazzotta (2012) provide excellent discussions of the microeconomic theory underlying trade-off analysis.

This study makes use of recent developments in forest simulation modeling to examine the ways that optimal management regimes for wildfire and carbon storage are likely to shift under different climate and wildfire scenarios. We simulated three climate scenarios with increasing radiative forcing intensities and a constant climate in addition to two wildfire scenarios, i.e. no-wildfire and wildfire during the midpoint of the analysis. For each climate/wildfire scenario, we simulated three fuel treatment intensities and a no-treatment option on each stand during four periods, forming the set of possible treatments for selection in a management plan. These treatment simulations for each climate/wildfire scenario resulted in eight datasets, each representing the decision space for a linear-programming (LP) model to identify the Pareto efficient management plan at a unique constraint level. By systematically changing the constraint values for each climate and wildfire LP optimization model, akin to the method developed by Haimes et al. (1971), trade-off curves were developed and compared to determine how climate change might affect the best-possible management options. We quantified shifts in these curves under various climate change scenarios to evaluate changes in the outcome of forest management objectives. Specifically, our objectives were to:

1) Identify the Pareto efficiency frontiers for wildfire effects reduction and increased carbon storage under climate change given different budgetary constraints,
2) Create a trade-off curve between wildfire severity and carbon storage for each climate change scenario,
3) Identify trade-off rates, or the amount of one good that must be sacrificed to attain one more unit of the other, between objectives at each solution point along each frontier, (a.k.a shadow prices or shadow costs),
4) Quantify shifts in the efficiency frontiers for each climate change scenario.

This research adds to the body of literature by using Pareto frontier analysis to examine the trade-offs between carbon storage maximization and fire severity minimization under climate change. To our knowledge, this study is the first of its kind to use Pareto frontier analysis to quantitatively identify trade-offs between carbon storage and wildfire severity in a managed forest system while incorporating climate change effects.

2. Methodology

2.1. Study Area

The study took place in northern Arizona, USA, on a 23,204 ha (ha) ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.) forest south of Flagstaff, Arizona (Fig. 1). During the 1985 to 2015 climate window, Flagstaff had an average annual temperature of 6.49 °C and received an average

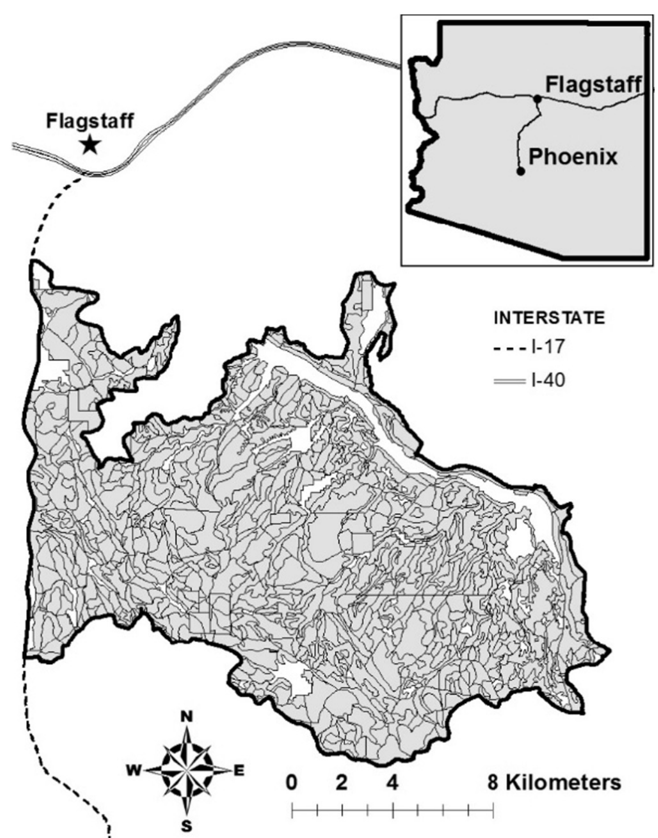

Fig. 1. Map of study area and stand delineations.