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Research article

Comprehensive comparative economic evaluation of woody biomass energy from silvicultural fuel treatments

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ABSTRACT

Fuel treatments are used in overstocked, fire-prone forests to alter wildfire behavior and reduce fire risk. Some of the benefits they provide are not captured in markets, and therefore represent unaccounted environmental externalities that can lead to inefficient decision making. This study uses a replicable method to integrate market and nonmarket economic values into a comprehensive economic evaluation of fuel treatment and bioenergy production using a case study of ponderosa pine and mixed-conifer forests in Colorado's wildland-urban interface. Treatment costs and people's willingness to pay for better forest health, lower likelihood of wildfire, improved air quality, and expanded renewable energy production are incorporated into techno-economic analysis of biopower production. Results show that fuel treatments are likely to be undervalued when evaluated strictly on a financial basis. Under the standard practice of disposing of treatment residues through pile-burning, net present value (NPV) of fuel treatment on 138,034 ha over 20 years is -$275 million, without consideration of nonmarket benefits. If nonmarket benefits associated with forest health, wildfire likelihood and air quality are included, NPV improves to -$116 million. Without the consideration of nonmarket benefits, when treatment resides are used for biopower production, NPV is -$178 million, with net cost savings compared to pile burning attributable to reduced biomass disposal costs and electricity revenue. Accounting for additional air quality benefits and nonmarket value associated with renewable energy, the bioenergy scenario improves NPV to -$25 million, with 27.7% of outcomes having positive NPV. The impact of additional nonmarket values and potential revenues from timber harvest are discussed, and are likely to make mean NPV positive for this scenario.

1. Introduction

Many of the forests in the western United States (U.S.) are adapted to periodic low-to-mixed severity wildfire. Across this region, many forests have become overstocked as a result of past land management practices, especially wildfire exclusion since European settlement (Ryan et al., 2013). Forests in this condition are less resilient to disturbances like drought, disease, and insect outbreaks, and are more likely to experience uncharacteristically large, intense and severe wildfire (Fule et al., 2012). In addition, climate change is increasing the length and severity of the wildfire season (Westerling et al., 2006; Rocca et al., 2014). Although fire serves an important ecological function in these forests (Keane et al., 2008), it poses risks to human health, safety, and property (O'Donnell et al., 2014), and unnaturally severe fires can damage ecosystems (Agee, 1997).

Fuel treatments that are planned and implemented as part of a silvicultural system can reduce the likelihood and severity of wildfire and improve conditions for the control of fire when it occurs (Helms, 1998). Treatments typically include thinning, prescribed fire, or a combination of the two, and can be used to reduce surface fuels, increase height to live crown, or decrease crown density, depending on management objectives (Agee and Skinner, 2005). However, fuel treatment can be very costly for landowners and forest managers. For example, in its 2017 budget justification, the United States Forest Service (USFS) identified $384 million in funding for hazardous fuels management to focus on fuel treatments in the wildland urban interface (WUI) and other high priority areas. For comparison, the 10-year average annual expenditure on wildfire suppression was calculated as $1.248 billion (USFS, 2016). Wildfire suppression costs now make up more than 50% of the USFS annual budget, and the ability to conduct fuel treatments at the landscape scale is constrained by funding limitations and tradeoffs (USFS, 2015).

Revenues from timber harvested during fuel treatment can lower net costs, but often fail to cover the full cost of implementation because

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the treatments may not produce sufficient quality or quantity of merchantable logs that can be sold as pulpwood, sawlogs and other timber products, or because markets for these products are prohibitively distant from treatment sites. Thinning produces large amounts of unmerchantable small trees and tops, limbs, foliage, and cull logs, commonly referred to as "treatment residues". This biomass is typically disposed of through piling and burning (i.e. "pile-burning"), broadcast burning, or mastication (Agee and Skinner, 2005). When economic conditions are favorable, residues may be collected, processed, and delivered to power plants and industrial facilities to be used as fuel or feedstock rather than burned for disposal, but the financial viability of biomass utilization is highly dependent on market prices and proximity to end users (Keefe et al., 2014).

The primary purpose of fuel treatments is to alter wildfire behavior and reduce fire risk, especially to property and human lives, but they are also associated with improved forest health and less smoke from wildfire, which reduces risks to human health. Fuel treatments are often coordinated with restoration treatments prescribed primarily to move the forest toward some ecological reference condition with a structure and species composition considered more appropriate for the site. Often this means an ecosystem that is more resistant and resilient to disturbances, including wildfire, drought, insects, and disease. Because the values of these environmental effects are not captured in markets, they represent unaccounted environmental externalities, which can lead to inefficient decision making.

To account for these values in decision making and resource allocation, nonmarket valuation techniques can be used to quantify such externalities. Indeed, several studies have been conducted using stated preference methods to quantify nonmarket values associated with biomass energy. Generally, they have found positive willingness to pay (WTP) for the potential benefits associated with bioenergy production and fuel treatments. For example, in a choice modeling study conducted in the southeastern U.S., Susaeta et al. (2010) found positive but statistically insignificant WTP for improved forest health, reductions in carbon dioxide emissions, and improvement of forest habitat from reduced wildfire risk. In Spain, positive WTP was found for reduced greenhouse gas emissions, lower risk of forest fire, and reduced pressure on natural resources associated with biopower production (Solino et al., 2012).

Previous studies have generally focused either on nonmarket values or financial analysis, with few attempts to include both in a comprehensive socioeconomic valuation of fuel treatments and bioenergy production using forest biomass. Notable exceptions include a pair of studies that quantified the environmental and health benefits of using residues from thinning treatments for electricity generation (Huang and Bagdon, 2018) and the net benefits associated with fuel treatments (Huang et al., 2013). Both of these studies were conducted in the U.S. state of Arizona. Huang and Bagdon (2018) found that using residues from thinning to offset coal with a 1 MW biopower plant reduced damage costs by over $900,000 compared to not thinning. However, thinning and disposing of residues with pile-burning had the highest damage costs of all options, at $1.7 million. In the most comprehensive study to date, Huang et al. (2013) quantified avoided future wildfire suppression costs, fatalities, facility and timber losses, regeneration and rehabilitation costs, and benefits associated with regional economic activity, fire risk reduction, forest heath, water supply protection, and the value of carbon storage and carbon releases associated with alternative management scenarios. The study found net benefits ranging from -$3458 ha^{-1} up to $5030 ha^{-1} (-$1399 acre^{-1} to $2036 acre^{-1}), depending on assumptions about prescribed fire, wildfire return-interval, avoided losses, regional economics, and the value of fire risk reduction.

In this study, a detailed techno-economic analysis (TEA) of biopower production from a firm's point of view is combined with accounting of treatment costs incurred by land management agencies and household WTP for potential nonmarket benefits, in order to assess social welfare outcomes in a comprehensive comparative cost-benefit analysis. Nonmarket values for forest health, wildfire risk, air quality and renewable energy are quantified using WTP estimates from a choice modeling nonmarket valuation study. The hypothesis is that the true socioeconomic value of fuel treatment is significantly higher than the market values it encompasses. Findings are relevant to effective policy making and public lands management, and to setting efficient levels for renewable energy incentives. This study also demonstrates a replicable method to make future TEA more comprehensive in their approach by effectively incorporating nonmarket values and facilitating deeper insight into the socioeconomic outcomes associated with energy production using biomass from fuel treatments and forest restoration.

2. Methods

2.1. Economic methods

Two different forest management scenarios are considered: fuel treatment without biomass utilization (Pile-burn Scenario) and fuel treatment with biomass utilization for bioenergy (Bioenergy Scenario). Scenarios are evaluated on a net present value (NPV) basis, determined by appropriately discounting market and nonmarket costs and benefits in a cost-benefit analysis (CBA). The NPV of each scenario in the CBA is calculated for a 20-year project time period using the following formulas:

$$\textit{Net Present Value Bioenergy} = \sum_{t=1}^{20} \frac{([Z + L + K + J + H]_t - [A + S + D + F]_t)}{(1 + r)^t}.$$

$$\textit{Net Present Value Pile-burn} = \sum_{t=1}^{20} \frac{([K + J + H]_t - [A + S + G]_t)}{(1 + r)^t}.$$

where r is the discount rate and t is the year. Table 1 defines each of the variables used in the calculation, with variables described in detail in

Table 1
Variables used in calculating NPV of the two scenarios.

Variable	Name	Definition
A	Thinning Cost	Mechanized thinning: felling, skidding, piling
S	Broadcast Burning Cost	Post-thinning prescribed burn of the treated area
D	Biomass Logistics Cost	Chipping, loading and transportation
F	Biopower Production Cost	Capex, Opex, Financing
G	Pile-Burning Cost	Post-thinning burning of piled treatment residues
H	Forest Health Benefit	$MWTP_{forest\ health}$ * Change in percent of healthy forest
J	Wildfire Likelihood Benefit	$MWTP_{wildfire}$ * Change in number of large wildfires
K	Air Quality Benefit	$MWTP_{air\ quality}$ * Change in unhealthy air days
L	Renewable Energy Benefit	$MWTP_{renewable\ energy}$ * Homes powered with biomass electricity
Z	Electricity Revenue	Megawatt hours (MWh) produced * $ MWh^{-1}
t	Accounting Year	20-year project period with annual accounting
r	Discount Rate	Rate used to calculate present value of future costs and benefits

subsequent sections.

CBA is a systematic approach to evaluating actions, such as policy changes or proposed projects, in which all positive and negative impacts (i.e. benefits and costs) are monetized and compared to assess the net benefits of the action from the viewpoint of society as a whole (Boardman et al., 2018). The values of costs and benefits are derived from people's WTP for more of something desirable, or conversely, willingness to accept (WTA) compensation for tolerating something undesirable (Hanley and Barbier, 2009). The concept of utility or satisfaction that individuals receive from consuming goods is the foundation of WTP and WTA. Often, these values are revealed by market prices, determined by the interaction of supply and demand for a consumable product (e.g. lumber, electricity). In some cases however, markets do not exist, and nonmarket valuation methods must be used to estimate WTP based on underlying welfare measures, like consumer surplus.

In theory, prices determined by markets and WTP values represent comparable metrics of value that can be aggregated at the project scale. In practice, there may be differences in the metrics that make them less than perfectly compatible, and also case and context dependent. Because market prices are determined by the interaction of supply and demand, they do not necessarily represent the maximum WTP for a product. Values elicited using nonmarket valuation techniques on the other hand, seek to elicit maximum WTP. However, in order to conduct CBA that considers both nonmarket and market values together, there is currently no preferable alternative to using estimates from nonmarket valuation techniques. This study uses stated preference methods to estimate WTP, where values are inferred thorough carefully designed questions in a choice modeling survey that elicits preferences for specific non-market attributes. Because maximum WTP values from nonmarket valuation may overstate value relative to market prices revealed by supply and demand, extra effort is made to ensure conservative WTP estimates and to consider the effects of uncertainty using Monte Carlo simulation. Furthermore, to minimize the potential effects of uncertainty and assumptions, the study relies on relative comparison of specific, well-defined scenario pathways that have clear system boundaries.

2.2. Scenario pathways

The Bioenergy and Pile-burn scenarios are shown in Fig. 1. Both scenarios include fuel treatment in which mechanized thinning is conducted first to reduce fuel loads, and then followed by prescribed fire in the form of broadcast burning throughout the treatment unit. Broadcast burning is included in the treatment because mechanized thinning alone has been shown to be less effective at reducing fire severity than mechanical thinning followed by burning (Prichard et al., 2010). Though it is generally accepted as the least costly fuel treatment option, prescribed fire alone is not considered in this analysis because of the risks of escaped fire, heavy smoke and unintended site impacts, which can be socially unacceptable in the WUI, especially in the western U.S. (Brunson and Evans, 2005; Weisshaupt et al., 2005). The combination of the two also represents the most costly option for fuel treatment, therefore representing the high end of treatment costs associated with the market and non-market benefits included in this study.

Both scenarios use whole-tree ground-based harvesting methods, employing a feller-buncher to fell trees and a skidder to move and pile trees and residues on the unit. In order to accomplish the objectives of the treatment and reduce post-treatment fire risk, as well as the risk of insect outbreak, the treatment residues from mechanized thinning must be handled in both scenarios, and cannot be left on site to decompose over time. This is a common regulation or policy associated with fuel treatments and timber harvest in the region. In the Pile-burn Scenario, the biomass piles are burned on site for disposal. In the Bioenergy Scenario, the piled biomass is processed through chipping or grinding, loaded onto a chip van, and transported to a power plant where it is combusted in a boiler system to produce electricity for residents of Colorado.

The costs incurred and benefits generated by each scenario vary depending on the method used to dispose of the treatment residues. Both scenarios incur the same costs associated with mechanized felling, skidding, piling, and broadcast burning (Fig. 1). The Bioenergy Scenario incurs additional costs associated with biomass feedstock logistics (including processing and transportation) and downstream biopower production. The Pile-burn Scenario incurs additional costs associated with burning the biomass piles for disposal.

Both scenarios generate nonmarket benefits associated with WTP

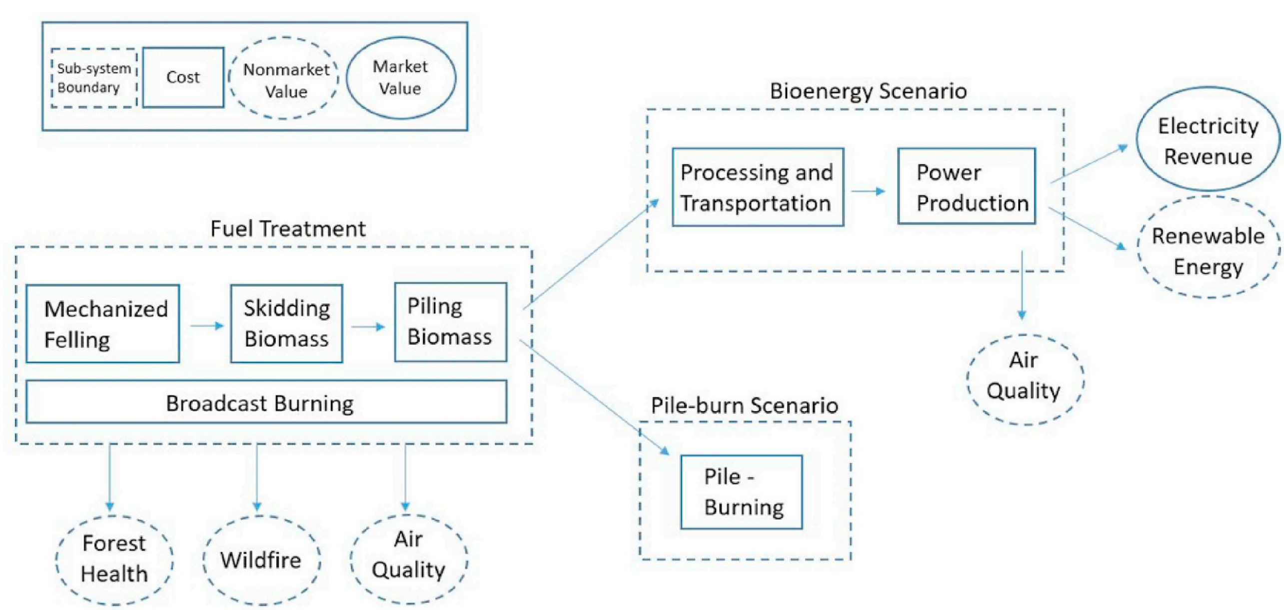

Fig. 1. Schematic of the nonmarket values and market values associated with two alternative fuel treatment scenarios, one burning biomass for disposal and the other using biomass for bioenergy.

for improved forest health, air quality, and wildfire risk reduction, which are tied to fuel treatment. In addition, the Bioenergy Scenario generates additional nonmarket air quality benefits, market benefits associated with electricity revenue, and non-market benefits associated with WTP for renewable energy. The Pile-burn Scenario does have negative air quality effects, but this scenario is assumed to provide marginal air quality benefits compared to large wildfires because emissions from pile burning: 1) do not include the combustion of large green trees in the stand that can occur during the most intense wildfires, and 2) emissions from burning are controlled and spread out in time to control extreme negative effects on local air quality. Additional air quality benefits over the Pile-burn Scenario are attributed to the Bioenergy Scenario because the biomass is collected and combusted in a controlled combustion environment with modern emissions controls to reduce point source pollution, reducing some emissions by 80% relative to open pile-burning (Loeffler and Anderson, 2014). Negative local air quality effects from bioenergy are accounted, but marginal benefits accrue compared to wildfire and the Pile-burn Scenario.

2.3. Fuel treatment and biomass production

The state of Colorado, located in the central Rocky Mountains of the U.S., is the study region for this analysis. Fuel treatments are assumed to occur in Ponderosa pine (*Pinus ponderosa*) and mixed conifer forests located in the WUI, which has been identified by government agencies and others as a priority for treatment. Forest characteristics, including stand structure and species composition, and the specific silvicultural prescription determine what costs and benefits are associated with fuel treatment. The WTP values that are applied in this study were quantified in the context of benefits associated with fuel treatments in overstocked ponderosa pine and mixed conifer forests in the WUI in Colorado. Other forest types and prescriptions are not considered. The ability of fuel treatment to reduce the severity of wildfire in these forest types is well established, especially when mechanical thinning is combined with prescribed fire (Graham et al., 1999; Agee and Skinner, 2005), and conducting such treatments in the WUI to maximize fire protection benefits is a clearly stated policy goal of many public land managers, including the USFS.

In order to reduce negative wildfire impacts at the landscape level, fuel treatments need to be conducted on large portions of the landscape, potentially on the order of hundreds of thousands of acres (ac) in total area (Finney et al., 2006). Rather than examine aggregate costs and benefits at this scale, with biomass demand spread across many different facilities, this study uses a project scale tied to the operation and fueling of a single 11 MW (MW) biomass power plant, with a treated area scaled to the amount of biomass required to meet its fuel demand over a 20-year project period. Working at this scale is justified because it provides a well-defined treatment area, quantifiable biomass harvest, well understood and widely deployed bioenergy conversion pathway, and defined beneficiaries of nonmarket benefits. Detailed TEA has been conducted recently on facilities like this operating in the U.S. (e.g. Campbell et al., 2018b), such facilities already exist in Colorado (Eagle Valley Clean Energy, 2019) and other western states (Novo Biopower, 2019), and power plants have been proposed by industry and policy makers in the region to meet both forest management and renewable energy goals (Arizona Corporation Commission, 2018). The treatment area needed to fuel such a plant can be calculated relatively accurately and, if targeted in the WUI, can reduce fire risk to communities (Ager et al., 2010). In addition, such facilities can provide power to a known number of residents within a clearly defined service area, such as the customers of an electric cooperative or a specific municipality.

Spatially-explicit case studies can be conducted to estimate the amount of biomass available for a specific project (e.g. Wells et al., 2016; Hogland et al., 2018). However, to stay congruent with the approach used in the nonmarket valuation survey (described below), this study does not make a spatially explicit assumption about the specific location of the power plant or the fuel treatments that provide it with biomass. A generalized estimate of biomass produced by fuel treatment in Colorado is used to represent the range of treatment outputs that exist in the state. In 2005, USFS estimated that the 2.4 million hectares (ha; 5.9 million ac) of non-reserved forest in Colorado (e.g. timberland and other lands not administratively restricted from treatment) held 90.6 million dry tonnes (99.9 million dry tons) of removable biomass. Assuming 70% of the removable volume is suitable for merchantable timber products such as sawlogs, pulpwood, and post and pole logs (U.S. Department of Energy, 2016), and therefore not available as biomass for energy applications, the remaining 30% of the removable volume, or approximately 11.2 tonnes ha^{-1} (5.0 tons $acre^{-1}$) are residues that are available for uses such as power production. The 11 MW biopower facility consumes 77,263 dry tonnes (85,185 dry tons) of biomass per year (Campbell et al., 2018a,b,c,d). If 11.2 tonnes ha^{-1} is the average treatment yield, the 77,263 dry tonne annual feedstock consumption of the facility would be supplied by a treatment area of 6,902 ha (17,054 ac) annually. The area treated to fuel the power plant is the basis of the magnitude of the costs and benefits accrued from the two scenarios.

It is common that merchantable timber products are produced by fuel treatments, and timber products account for 70% of the removable volume in the calculations. However, revenue from timber products is not included as a benefit in this analysis – the cost of biomass harvest is in no way reduced by marginal product costing linked to higher value timber products. Excluding timber revenue provides a conservative low-end threshold for economic justification of fuel treatments, and allows the results of this study to be used for treatments that generate biomass revenue only. If treatments that produce only biomass are found to be economically justified based on their combined market and nonmarket values, then treatments that produce merchantable timber products in addition to biomass are likely to be economically justified as well.

The costs of mechanized thinning (including felling, skidding, and piling), broadcast burning, and pile burning are based on the average of values for these activities that were measured or estimated in previous studies (see Supplemental Material). Not all of the referenced studies evaluated the same activities, so adjustments were made where necessary to make sure cost estimates appropriately characterize the operational components defined and included in the scenarios. All values were adjusted to 2017 USD ($) using pertinent inflation factors. Average values used for thinning, broadcast burning and pile burning are $2,110 ha^{-1}, $692 ha^{-1}, and $405 ha^{-1}, respectively.

Processing and transportation costs are included in the Bioenergy Scenario sub-system (Fig. 1). A combined average cost of $24 $tonne^{-1}$ is used for processing and transportation based on published values from previous studies (Anderson et al., 2012; Anderson and Mitchell, 2016; Townsend et al., 2019), with $9 $tonne^{-1}$ allocated to grinding and $15 $tonne^{-1}$ allocated to transportation. The transportation cost of $15 $tonne^{-1}$ is based on values used in recent forest operations studies of sites in Colorado (Wells et al., 2016; Han et al., 2018a, b) and Montana (Hogland et al., 2018). The value of $24 $tonne^{-1}$ should not be interpreted as the total gate cost of biomass feedstock because it does not include felling, skidding and piling, which are included separately in the thinning cost estimate of $2,110 ha^{-1}.

2.4. Bioenergy project accounting

Biomass from fuel treatments can be used to produce bioproducts, liquid biofuels, electricity, heat, or combined heat and electricity (Campbell et al., 2018b). Though other conversion pathways are possible, the Bioenergy Scenario uses only utility-scale electric power production because it is the most widely deployed bioenergy option that is not dependent upon forest product manufacturing, and is therefore a relatively widespread and well-established, stand-alone bioenergy enterprise. Bioenergy project accounting is conducted using

TEA. Commonly used in the evaluation of emerging energy technologies, TEA is a modeling process that combines cost-benefit analysis of a project investment with a detailed technical specification of a specific technology (Zhao et al., 2016). Empirical production information on the quantity of electricity produced and amount of biomass feedstock consumed by the power plant was obtained from the U.S. Energy Information Administration for an existing 11 MW facility in Colorado that supplies power to the electric grid (U.S. EIA, 2014). For an assumed 90% utilization rate (7884 h yr^{-1}), based on the conversion rate of 1.15 MWh t^{-1}, and a feedstock consumption rate of 9.8 t h^{-1}, the modeled facility produces 88,853 MWh yr^{-1} and consumes 77,263 dry tonnes of feedstock (see Campbell et al., 2018b for details).

The total capital investment of the facility is the sum of fixed capital investment and working capital. Fixed capital investment reflects the cost of building and equipping a plant and includes the cost of land, buildings, engineering, construction, and equipment purchase and installation. Fixed capital costs were estimated using the average capital cost per installed capacity from eight published values of plants of a variety of scales and technologies. Based on an average of $3.16 million MW^{-1}, the fixed capital costs of the 11 MW plant are estimated at $35.69 million. Working capital is used to cover components of day-to-day plant operations like accounts receivable, cash on hand, and raw material and product inventory, and is recouped in the last year of the analysis.

Operating costs are incurred continually throughout the life of the plant and are accounted for on an annual basis. Operating costs include feedstock, utilities, maintenance, insurance and taxes, and labor. As is common for such facilities, the plant is assumed to sell all of the electricity it produces and draw the electricity required to run the plant from the grid, with annual electric costs equal to 14% of gross annual revenues and maintenance equal to 7% of gross revenues. Insurance and taxes are equal to 2% of total capital investment, annually (Towler and Sinnott, 2013). Labor requirements were obtained from documents provided by the U.S. Treasury Department related to a biopower plant constructed in Colorado. Wage rates were obtained from the Bureau of Labor Statistics national-level employment statistics for “Biomass Electricity Plants” and “Wood Products Manufacturing” (U.S. BLS, 2017). Overhead equal to 60% of wages is added to account for costs including health insurance, office supplies, and travel expenses (Towler and Sinnott, 2013).

The facility is assumed to be 50% loan financed over a 20-year accounting period (i.e. project life), with a 10-year loan payback period and an 8% annual interest rate on the loan. Depreciation of equipment is calculated using the variable declining balance method and a 7-year time period. An inflation rate of 2.5% is applied to all future costs and revenues in cash flow calculations. The real discount rate is 10%, which is composed of the nominal discount rate of 7.5% and the inflation rate of 2.5%.

2.5. Choice modeling and willingness to pay

Marginal willingness to pay values (MWTP, Table 2) were generated by a choice modeling survey conducted in the fall of 2015. Complete details of the survey methodology are described elsewhere (Campbell et al., 2016, 2018c, 2018d). The survey was distributed to a stratified random sample of households in Montana, Arizona, and Colorado. Survey recipients were asked to complete choice sets containing attributes representing forest health, occurrence of large wildfires, local air quality, biomass energy production, and household energy bill. Among these attributes, household energy bill (including electricity, natural gas, and other fuels used for heat), served as the cost attribute, allowing a dollar value to be associated with the other four nonmarket attributes. Choices were measured against an explicit status quo scenario based on realistic estimates of the current condition of each attribute. Using a combination of mail, internet, and mixed mail-and-internet survey modes with a bilingual English-Spanish option, 1226 complete questionnaires were collected, including 404 from Colorado.

A latent class logit model was used to analyze the data, quantifying preferences toward the attributes, while accounting for preference heterogeneity associated with respondent socioeconomic characteristics and attitudes toward renewable energy and forest management. The latent class model generates results that are split in to multiple separate groups of like preferences, with each group representing an estimated fraction of the total population (i.e. membership probability). In order to estimate average values for the population, mean MWTP values and 95% confidence intervals from each group are multiplied by their respective membership probability and summed to create a weighted average. See Campbell et al. (2018c) for details on model formulation and results for the aggregated three-state study area. The results for Colorado-only, used in this analysis and shown in Table 2, have not been published previously.

In the survey, the amount of biomass energy was defined as electric or thermal energy produced using residues from restoration treatments, including fuel treatments, on public forests. The attribute was presented in terms of the number of homes powered annually to be more easily interpreted by respondents than a standard unit of electric or thermal energy (e.g. MWh). Respondents were informed that the biomass energy would replace fossil fuels and reduce long-term impacts of climate change. However, the survey did not quantify any specific greenhouse gas value independent from the aggregate value of renewable energy compared to fossil fuels, and therefore the non-market value in the Bioenergy Scenario in Fig. 1 should be regarded as encapsulating a broader set of benefits associated with renewable energy in general, not just carbon and climate benefits.

The forest health attribute was presented as the proportion of healthy forests in the state, across all ownership types. The current proportion of healthy forests in Colorado was determined to be approximately 20%, using the Vegetation Condition Class classification system, which categorizes the level of departure of current vegetation conditions from a historic reference condition (Barrett et al., 2010). It is assumed that each hectare of overstocked forest that receives fuel treatment is restored to a healthy condition for at least the duration of the 20-year project period.

Large wildfires were defined in the survey as wildfires that burn at least 1000 ac (405 ha) and threaten homes and structures. The definition provided the average number of homes destroyed annually over the past decade in Colorado, while emphasizing that the majority of homes were destroyed by a small number of very destructive fires. The definition also highlighted that wildfires are an important beneficial natural disturbance present in healthy forest ecosystems in the region.

The air quality attribute was defined as the average number of days annually that are “unhealthy for sensitive groups”, as defined by the

Table 2
Mean MWTP with 95% confidence interval, in native units (2017 $‘s).

Nonmarket Attribute	Metric of Change	2.5th percentile	Mean MWTP	97.5th percentile
Forest Health	Percent of forests in CO	$42.39	$75.75	$109.16
Large Wildfires	Number of large wildfires in CO	-$37.68	$63.57	$164.82
Air Quality	Number Unhealthy Air Days	$68.95	$135.46	$201.97
Biomass Energy	Number of Homes Worth of Power	-$3.33	$19.78	$42.89

Table 3
Magnitude of nonmarket effects and scaling of MWTP values.

Nonmarket Attribute	Original marginal unit of effect	Original mean annual household MWTP	Converted marginal unit of effect	Converted mean annual household MWTP	Magnitude of effect in Pile-burn Scenario	Magnitude of effect in Bioenergy Scenario	Population of aggregation (households)
Forest Health	1% of state forestland	$75.75	1 ha	$0.001	6,902 ha	6,902 ha	1.9 million
Large Wildfires	1 wildfire	$63.53	1% reduction in fire likelihood	$5.27	8.3%	8.3%	10,921
Air Quality	1 day	$135.48	1% reduction in days	$13.55	8.3%	14.9%	10,921
Biomass Energy	1k homes	$19.78	1 home	$0.020	0	10,921 homes	10,921

Note: Mean total household WTP for each nonmarket attribute is = "Magnitude of effect" x "Converted mean household MWTP". Total aggregate WTP = "Mean total household WTP" x "Population of aggregation".

U.S. Environmental Protection Agency, in the respondent's community (simply, "unhealthy" throughout the remainder of the paper). The relationships between fuel treatments, biomass energy production, and air quality are difficult to quantify because of the numerous factors that influence air quality. Wildfire, prescribed burning, pile-burning, biomass logistics, fossil fuel power production, and biopower production all have associated emissions. Wildfires emit significant amounts of particulate emissions that negatively impact air quality, and evidence has been found that prescribed burning may be effective at reducing particulate emissions relative to wildfire (Liu et al., 2017).

Because the survey elicited preferences from a statewide sample of Colorado residents using statewide metrics for bioenergy, forest health and large wildfires, some consideration is needed to align the metrics used to quantify the values elicited in the survey with the magnitude of the effect of a single project that is smaller than statewide in its scope and impact (Table 4). The magnitude of benefits are a function of: 1) estimated value of MWTP, 2) magnitude of the effect, and 3) population over which the benefits are aggregated. MWTP is not influenced by the size of the project under consideration, but assumptions must be made about the magnitude of the effects and the population of aggregation. For the rate of wildfire occurrence and air quality, quantifying the expected effects is difficult and a high degree of uncertainty is assumed. The approach used in this study is intended to provide a conservative estimate of scaled, aggregated nonmarket benefits (Table 4).

To ensure a conservative estimate of the value of benefits associated with increased renewable energy production, benefits for the biomass energy attribute are assumed to only accrue to the households powered by the facility modeled in this study. The total number of households continuously powered with biomass energy is 10,921, which is equal to the amount of energy produced (88,853 MWh) divided by average annual household energy consumption in Colorado (8.14 MWh [U.S. EIA, 2018]).

The status quo level of forest health is 20% of the forestland in the state, so the marginal improvement associated with the mean MWTP of $75.75 per household per year would be an increase from 20% to 21% healthy forests across the state. There are 8.66 million ha (21.4 million ac) of forest in Colorado, 20% of which is 1.73 million ha (4.28 million ac) (the status quo), and 21% of which is 1.82 million ha (4.49 million ac), with a difference between the two levels of 214,000 ac. MWTP is $0.001 ha^{-1} ($0.0004 ac^{-1}) (= $75.75/528,794 ha), which can be used to quantify the benefits associated with any size project. In the survey, forest health was framed in terms of non-use values that are relevant to the whole population of the state, not only people living in forested areas. Because the magnitude of the effect is scaled down to the size of the project by using the per-acre value of MWTP, benefits can be aggregated across all the 1.9 million households in the state for a project size equivalent to the area treated on an annual basis.

The status quo level of the wildfire attribute is 12 large wildfires across the state annually. The marginal change is one fewer large wildfire per year. A reduction from 12 to 11 large wildfires on average represents an 8.33% reduction. Obviously, a single fuel reduction project on the scale of tens of thousands of acres annually is unlikely to significantly reduce the likelihood of large wildfires across the entire state. However, if the treatments were to reduce the likelihood of large wildfires by 8.33% for a smaller area, the benefits could conservatively be aggregated across the population most likely to be affected by the treatment, which provides a means to scale the benefits down to the project scale. In this case, the 10,921 households powered by the biopower plant represent a conservative population to aggregate the nonmarket benefits associated with large wildfire occurrence reduction at the 8.33% level.

The status quo level of the air quality attribute is 10 unhealthy air days annually, and a marginal unit change of 1 day annually, equivalent to a 10% reduction. Air quality effects associated with fuel treatments come from two sources: 1) reduced particulate emissions from reduced likelihood of large wildfires, and 2) reduced emissions from

Table 4
Variables with random probability distributions (2017 dollars).

Variable	Distribution Shape	Min	Mean	Max
Electricity Selling Price	Triangular	$50 MWh^{-1}	$100 MWh^{-1}	$150 MWh^{-1}
Thinning Cost	Triangular	$1,129 ha^{-1}	$2,110 ha^{-1}	$3,361 ha^{-1}
Broadcast-burning Cost	Triangular	$238 ha^{-1}	$692 ha^{-1}	$1,519 ha^{-1}
Pile-burning	Triangular	$160 ha^{-1}	$405 ha^{-1}	$923 ha^{-1}
Feedstock logistics	Triangular	$0 t^{-1}	$24 t^{-1}	$48 t^{-1}
Biopower Capex	Triangular	$26.5 million	$37.8 million	$49.2 million
Nonmarket WTP		2.5th percentile	Mean	97.5th percentile
Forest Health	Normal	$0.0005	$0.0009	$0.0013
Large Wildfires	Normal	-$3.13	$5.27	$13.68
Air Quality	Normal	$20.20	$13.55	$6.90
Biomass Energy	Normal	-$0.0429	$0.0198	$0.0033

combusting biomass in a controlled environment during power production instead of open pile-burning. Air quality benefits in the Pile-burn scenario accrue from the first source only and are assumed to change proportionally with the 8.33% reduction in local likelihood of large wildfires. Air quality benefits in the Bioenergy Scenario accrue from both sources and are 80% larger than in the Pile-burn Scenario attributable to additional benefits of combusting biomass in a controlled environment (Loeffler and Anderson, 2014), resulting in a 14.9% reduction in the number of unhealthy days annually. Because the effect defined in the survey was local in scope (rather than statewide), the same 10,921 households assumed to be affected by the change in probability of wildfire occurrence are also used as the population of aggregation for the air quality attribute.

2.6. Monte Carlo simulation

There is substantial uncertainty associated with the outcomes of fuel treatments and the benefits they generate. Monte Carlo simulation is used to account for this uncertainty, as well as uncertainty in other variables like treatment costs, MWTP and electricity selling price. Rather than being treated as known deterministic inputs, key variables are considered uncertain and random (i.e. stochastic) with defined probability distributions (hereafter called "uncertain variables"). Accordingly, simulations result in a distribution of observed NPV values for many iterations of each scenario, rather than a single NPV value. Uncertain variables and their distributions are shown in Table 4. Monte Carlo simulation was conducted in Excel using @Risk version 7.5 add-in software (Palisade Corporation, Ithaca, NY, USA) with one hundred thousand iterations for each simulation.

Thinning, broadcast burning, and pile-burning costs are all included independently and defined with triangular distributions defined by values from the literature (Supplemental Material). Triangular distributions are continuous probability distributions defined by a minimum value, maximum value and mode, and are commonly used in business and finance when limited information is available to describe the true distributions of variables (Sprow, 1967), as is the case with these costs. Biopower capital expenditures are included as an uncertain variable with a triangular distribution and a range of ± 30% of the estimated capital expenditures to account for uncertainty in cost estimation (Peters et al., 2003).

The selling price of electricity is defined across a triangular distribution from $50 MWh^{-1} to $150 MWh^{-1}, with an average value of $100 MWh^{-1}. This average value, which is higher than the average wholesale price of electricity in Colorado, is informed by the actual price received by a similarly sized biomass power plant in the region. Projects that produce electricity from renewable sources often receive price premiums supported by power purchase agreements with utilities, or through mechanisms like renewable energy credits that increase the effective price received by the power producer. With renewable energy credit market values sometimes reaching the realm of $50 MWh-1 (O'Shaughnessy et al., 2015), $150 MWh represents a realistic upper end of electricity price.

Nonmarket WTP values are included as uncertain variables to account for the uncertainty associated with statistical analysis of the choice modeling dataset. WTP values have normal distributions obtained using bootstrapping techniques with a large number of iterations, defined using 95% confidence intervals around mean estimates (Table 3). Intervals that overlap zero for the wildfires and biomass energy attributes represent estimates that are not statistically significant at a 95% confidence level. As a result, some portion of the values drawn in simulation runs for those attributes are negative, and for those iterations with negative values, wildfire reduction and biomass energy generation are accounted for as costs rather than benefits. For the purposes of interpreting negative values for these attributes, this might occur if a respondent values fossil fuels more than renewable energy or believes wildfire is a net positive event, for example. However, the net effect of these attributes on mean NPV outcomes is positive, because mean MWTP is positive for both.

3. Results

A breakdown of the market and nonmarket costs and benefits associated with the Bioenergy and Pile-burn scenarios is shown in Table 5. Fuel treatment effects are the same for both scenarios: each scenario treats 6,902 ha (17,054 ac) annually, resulting in the treatment of 138,034 ha (341,083 ac) over the 20 year project period. The Bioenergy Scenario provides power to 10,921 homes over that period. Fig. 2 shows the range of NPV outcomes for each scenario, with and without consideration of nonmarket benefits.

Under the Pile-burn Scenario without consideration of nonmarket

Table 5
Mean outcomes associated with treatments for Bioenergy and Pile-Burn scenarios.

	Bioenergy Scenario	Pile-burn Scenario
Forest Treated Annually	6,902 ha (17,054 ac)	6,902 ha (17,054 ac)
Electricity Produced Annually	88,853 MWh (10,921 homes powered)	0 MWh
Annual Thinning Costs	$15.3 million	$15.3 million
Annual Broadcast-burning Costs	$5.7 million	$5.7 million
Annual Pile-burning Costs	$0	$3.4 million
Annual Electricity Revenue	$8.9 million	$0
NPV without Nonmarket Values	-$178.32 million	-$274.89 million
Nonmarket Effects WTP		
Annual Forest Health Value	$11.91 million	$11.91 million
Annual Wildfire Value	$694,243	$694,243
Annual Air Quality Value	$2.96 million	$1.48 million
Annual Renewable Energy Value	$2.36 million	$0
NPV with Nonmarket Values	-$25.19 million	-$116.33 million

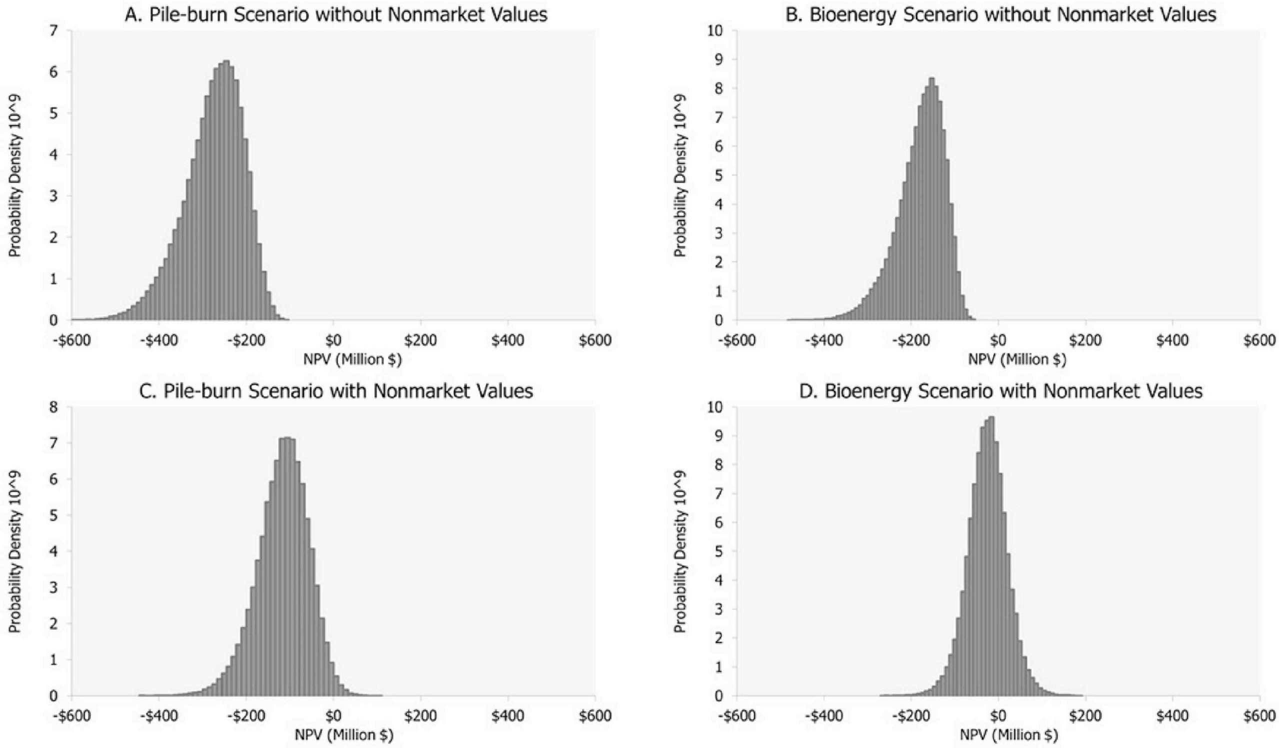

Fig. 2. Net Present Value Simulation Results. Panel A: Pile-burn Scenario with treatment costs only, mean NPV = -$274.89 million (90% CI = -$399 million to -$180 million). Panel B: Bioenergy Scenario without nonmarket benefits, mean NPV = -$178.32 million (90% CI = -$279 million to -$105 million). Panel C: Pile-burn Scenario with nonmarket benefits, mean NPV = -$116.33 million (90% CI = -$219 million to -$28 million). Panel D: Bioenergy Scenario with nonmarket benefits, mean NPV = -$25.19 million (90% CI = -$99 million to $47 million).

values, NPV of fuel treatment on 138,034 ha over 20 years is -$274.89 million (90% CI = -$399 million to -$180 million). If nonmarket benefits associated with forest health, wildfire likelihood and air quality are included, NPV of fuel treatment with pile burning improves to -$116.33 million (90% CI = -$219 million to -$28 million).

Under the Bioenergy Scenario without considering nonmarket values, fuel treatment with bioenergy production improves NPV to -$178.32 million (90% CI = -$279 million to -$105 million), with cost savings of $96.57 million attributable to reduced biomass disposal costs and electricity revenue. Accounting for additional air quality benefits and nonmarket value associated with renewable energy, the bioenergy scenario improves NPV to -$25.19 million (90% CI = -$99 million to $47 million), with 27.7%% of outcomes having positive NPV. This is an improvement of $153 million over the market-only Bioenergy Scenario and almost $250 million over the market-only Pile-burn Scenario.

Across both scenarios using accounting with and without nonmarket benefits, the full range of NPV outcomes spans a low at the 5th percentile of -$399 million (Fig. 2a) to a high of $47 million at the 95th percentile (Fig. 2d). Fig. 3 displays the effects of uncertainty and volatility in specific variables on NPV outcomes, with the most influential variable at the top of the chart and other variables shown below it in order of decreasing influence. The magnitude of influence of each variable is a function of its quantitative impact on the NPV calculation, its average value, the range of its distribution, which was determined based on the best available data and information as described in the Methods section.

The first and second most influential variables are the same for both the Bioenergy and Pile-burn scenarios, with thinning costs and MWTP for forest health being first and second, respectively. For the Bioenergy Scenario, the rank of influence continues with broadcast burning costs, household MWTP for bioenergy, electricity selling price, MWTP for air quality, and feedstock price, which are 3rd through 7th. Among the variables considered in the sensitivity analysis, MWTP for reduction in large wildfires, capital expenditures for the biopower plant, and the discount rate are not among the seven most-influential variables for the Bioenergy Scenario. For the Pile-burn Scenario, the 3rd through 7th-most influential variables on NPV are discount rate, broadcast burning costs, pile-burning costs, MWTP for wildfire reduction, and MWTP for air quality. Discount rate has a larger influence on outcomes in the Pile-burn Scenario because the annual net benefits being discounted are of larger absolute value than the annual net benefits in the Bioenergy Scenario.

4. Discussion

4.1. Interpretations and implications

These results demonstrate the wide range of economic outcomes that can be expected from fuel treatments, depending on the specific scenario, value of market and nonmarket costs and benefits, and accounting method. Even so, results of the sensitivity analysis illustrate the high degree of influence that thinning costs have on economic outcomes, and highlight the need to reduce the cost of implementing these treatments. Regardless of whether residues are used for energy or some other product, the cost of thinning has the potential to drive economic outcomes, even when nonmarket values are included in accounting. The cost of thinning includes the cost of forest operations, such as felling, skidding, processing and transportation, but also includes administrative costs along the supply chain, which can be significant.

Reducing the cost of forest operations has been the goal of intensive ongoing research to improve the productivity and efficiency of harvesting, processing and transporting biomass for a wide range of uses (Anderson and Mitchell, 2016). Advances have involved both the development of innovative practices using existing equipment (e.g., Anderson et al., 2012) and the development and deployment of new

Fig. 3. Sensitivity tornado for Bioenergy and Pile-burn Scenarios. Bars represent each variable's effect on mean NPV across its distribution (Table 5), with all other variables held at mean values. Dark shaded bars represent an increase in the input value of the variable and light shaded bars represent decrease in input value.

technologies for specific applications (e.g., Woo and Han, 2018). In a recent study comparing five different forest operations, Townsend et al. (2019) highlighted practices that could potentially reduce logistics costs for thinning in Ponderosa pine by nearly 25%. Others have looked to industrial ecology and business clusters to improve efficiency and profitability across the supply chain, including in areas where fuel treatment in ponderosa pine is prevalent (Nicholls, 2014). Despite these improvements, thinning costs continue to be a major challenge to implementing fuel treatments at the landscape scale, and that fact is reflected in these results.

To avoid double counting in this study, federal agency administrative costs are not accounted for independently from aggregate mechanical thinning and burning costs. These costs can include things like project preparation, task order and contract administration, monitoring, project planning and legal and administrative requirements under laws governing public land management, such as the National Environmental Policy Act (NEPA) and National Forest Management Act (NFMA) (Selig et al., 2010). Per-acre administrative and treatment costs have been found to decrease with increases in project size, so benefits from economies of scale can be expected if larger treatment projects are undertaken (Berry and Hesseln, 2004). In fact, reducing transaction costs by conducting landscape scale fuel treatment under large thinning contracts is one of the primary objectives of the U.S. Forest Service Four Forest Restoration Initiative, for example (USFS, 2019a).

The price of electricity exhibits a relatively strong effect on NPV outcomes in the Bioenergy Scenario. Though the Bioenergy Scenario does not lead to a positive mean NPV in this analysis, if higher revenues from electricity sales could be garnered, net benefits of power production could further improve the outcomes of this scenario. The Bioenergy Scenario with nonmarket benefits breaks-even at an electricity selling price of \$146 MWh^{-1}. Stand-alone power production is not necessarily the most profitable conversion pathway for utilization of forest biomass. Analysis indicates that improved NPV outcomes are likely for higher value products like cellulosic liquid biofuels, and for multi-product supply chains like combined heat and power production with coproduction of liquid biofuel and biochar soil amendments (Campbell et al., 2018a, 2018b). However, compared to biopower and large scale CHP pathways, which are widely deployed at industrial scale, these potentially more profitable options have struggled to overcome technical and market barriers to gain significant market share in the liquid fuel and soil amendment markets (Campbell et al., 2018a, 2018b).

Although this is an attempt at a more comprehensive economic evaluation of fuel treatments and biopower production, there are market and nonmarket values that are not included in the calculations. We used MWTP from a choice modeling survey to value nonmarket costs and benefits according to specific attributes, namely those associated with forest health, air quality, reduced wildfire, and renewable energy. Because the attributes of the survey were selected with the help of stakeholders though intensive stakeholder meetings, the values included in this analysis are known to be among the most important effects to residents of Colorado. They provide an appropriate general set of impacts to illustrate what is being overlooked when nonmarket values are not included in economic analysis of fuel treatments. Many values are potentially left out, or may vary by state or region. For example, the effects on recreation, rural job creation, and habitat for specific wildlife species would presumably provide additional nonmarket benefits that are not included here. Regardless of the specific benefits, there is likely to be a tradeoff between higher treatment costs and larger benefits generated when working in the WUI, so projects should be carefully sited to optimize production and provision of nonmarket benefits.

Some potential market values were purposely excluded to ensure conservative estimates of NPV. Commercial timber harvests, by definition, generate net positive revenue. We recognize that for fuel treatments, the harvest and sale of timber products can drive NPV into positive territory. As discussed in the Methods section, timber revenue was not included in this analysis in order to evaluate fuel treatments independently of timber harvest and establish a baseline valuation that is not dependent upon a viable local timber industry. Without timber sales, the mean NPV of the Bioenergy Scenario is -\$25.19 million over 20 years, treating 138,034 ha (341,083 ac) of forest. This scenario would break-even (NPV = 0) if the fuel treatments over the project period produced average timber revenue of \$426 ha^{-1} (\$172 $acre^{-1}$). This is within the realm of possibility, but is highly dependent upon multiple factors, such as the availability of markets for sawlogs, pulpwood, posts, poles, firewood and other products. For reference, assuming merchantable timber volume of 42–84 $m^3 ha^{-1}$ and a selling price of \$3.96 m^{-3} to \$7.69 m^{-3}, which are reasonable values for this region (Bagdon et al., 2016), timber revenue for these treatments would likely range from \$166 to \$646 ha^{-1}.

At least in theory, the economic value of carbon offset credits associated with fuel treatments can be substantial, depending on the accounting method, price, and discount rate (Huang and Sorensen, 2011). Forest management practices that enhance carbon sequestration, such as lengthening the rotation age of even-aged stands, qualify for such credits under some project-based carbon accounting mechanisms (Foley et al., 2009). However, predicting the carbon effects of treatment to reduce fire risk can be more complicated, and carbon benefits can be positive, uncertain or even negative, depending on baseline assumptions (Malmsheimer et al., 2011; Campbell et al., 2012). In particular, the low likelihood of wildfire interacting with a given fuel treatment during its effective life (e.g. 5–20 years) makes carbon storage benefits from a particular project difficult to estimate (Restaino and Peterson, 2013). There is some evidence that fuel treatments can increase carbon storage in western U.S. forests adapted to frequent low intensity fire by protecting carbon in soils and above ground biomass, and by reducing likelihood of severe wildfire and its carbon emissions (Hurtuea and North, 2008). With regards to bioenergy from fuel treatments, evidence suggests that benefits are positive in the case of residues from forest management activities in disturbance-prone ecosystems (Zanchi et al., 2012; Buchholz et al., 2016), but in general the net greenhouse gas implications of energy from forest biomass are condition-dependent.

Where they exist, the monetization of carbon benefits would obviously improve the bottom line of these treatments, and could be facilitated by project-based carbon offset mechanisms, utility sector regulation, or cross-sector initiatives, such as a tax on carbon emissions (i.e. carbon tax). It is less clear how economically efficient fuel treatment carbon offsets would be compared to other forest carbon options, such as afforestation, reforestation and avoided deforestation projects under both domestic U.S. initiatives (e.g. Climate Action Reserve, 2019) and international programs (e.g. REDD+). Given that much of the forest in need of fuel treatment in the western U.S. is in federal government ownership, monetizing carbon benefits in this context would also hinge on federal lands qualifying for such incentives, which is also uncertain.

Similar to estimating potential forest carbon impacts, the effect of fuel treatments on future fire suppression is difficult to quantify. In theory, treated landscapes require less frequent suppression and less intensive firefighting in the event of a wildfire, which should lead to suppression cost savings to the extent that landscape-scale treatments alter severe fire behavior. For example, using model-based approaches Thompson et al. (2013) projected that fuel treatments across 46% of a 145,000 acre study area would lead to approximately 16% lower overall per-fire suppression costs, but 2.25% higher per-acre costs in treated areas due to smaller fire size. Indirect benefits of fuel treatment from suppression costs savings are the subject of debate (Thompson and Anderson, 2015), and are not included in this study.

4.2. Methodological considerations

Although results of this analysis reveal a gap between the costs of conducting fuel treatments and the market and nonmarket benefits they generate (i.e., a negative mean NPV in all cases), these findings suggest some ways in which NPV could be pushed into positive territory by lower costs and higher benefits. It is also worth noting that projects can obviously be pursued even when NPV is negative. In any evaluation of project performance based on NPV, there is uncertainty in future cost and benefit flows, and such analysis does not effectively capture everything that may influence decision making, such as some qualitative, political and social factors. Even so, comparative analyses like this one provide useful information for decision making, regardless of project profitability in a strictly financial sense.

There is no avoiding the error and uncertainty inherent in multiple key inputs to socioeconomic CBA (e.g., WTP, environmental effects, and markets for products). Therefore it is essential to use Monte Carlo methods to consider and quantify uncertainty. With regards to WTP estimates specifically, there are several known potential sources of error that can influence values. In some cases, respondents to stated preference valuation studies overstate their WTP and the difference between what the respondent would actually pay and the amount they state, known as hypothetical bias, may result in inflated WTP values (Loomis, 2014). Although hypothetical bias may be present in any stated preference valuation data, one of the strengths of the choice modeling method is that by using choice sets of multiple alternatives to quantify tradeoffs between attributes it may reduce the incentive for and ability of respondents to behave strategically compared to questionnaires that ask dichotomous choice willingness to pay questions about a single environmental goods, such as those that are used in contingent valuation (Bennett and Blamey 2001). In addition to hypothetical bias, all survey data is subject to multiple sources of error, including coverage error, sampling error, measurement error, and nonresponse error (Dillman et al., 2014). The amount of these types of error present in the data can be minimized through high-quality survey design, and the potential for these sources of error in the choice modeling dataset used in this study is thoroughly discussed in Campbell et al. (2018d).

Utilizing a cohesive set of WTP estimates from a single choice modeling study conducted in the study region provided high confidence in the validity of findings. However, because conducting a choice modeling study is time consuming and expensive (Campbell et al., 2018d), it is infeasible to conduct a new survey to collect primary data on the value the nonmarket effects of every individual proposed project, and benefit transfer methods (Rosenberger and Loomis, 2003) offer a way to infer value from previous studies with similar characteristics. In conducting benefit transfer, effort should be made to use values that come from studies of comparable environmental goods and of sites with similar characteristics to the site of interest. The more similar the characteristics between the two contexts, the fewer biases will result; however, some amount of additional error compared to conducting an original study is likely, which is one more reason to account for uncertainty with Monte Carlo simulation.

5. Conclusions

This study integrates market and nonmarket economic values into a comprehensive comparative economic evaluation of fuel treatment and bioenergy production using cost-benefit analysis applied to a case study of ponderosa pine and mixed-conifer forests in Colorado's wildland-urban interface. Treatment costs and people's willingness to pay for better forest health, lower likelihood of wildfire, improved air quality, and expanded renewable energy generation are incorporated into techno-economic analysis of biopower production. Fuel treatment with pile burning on 138,034 ha over 20 years results in an NPV of -$275 million, without consideration of nonmarket benefits. NPV improves to -$116 million when nonmarket benefits are included. Using treatment residues for bioenergy production improves NPV to -$25 million through reduced biomass disposal costs, electricity revenue, additional air quality benefits, and nonmarket value associated with renewable energy generation. Results illustrate that fuel treatments are likely to be undervalued when evaluated strictly on a financial basis because the goals and benefits of fuel treatments include nonmarket outcomes like reducing wildfire risk and improving forest health. Incorporating nonmarket values into cost-benefit analysis provides policy makers and managers with information that might otherwise be excluded from the decision making process, potentially resulting in more economically efficient decisions.

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Appendix A. Supplementary data

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