Modeling the Effects of Subsidizing Timber Harvests on Lands Vulnerable to Disturbance[1]

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Abstract

Forest disturbances such as wildfires and pine beetle outbreaks result in large-scale damages on human health, environmental quality, and economic productivity. Although policies are used to reduce the severity and frequency of such disturbances, understanding the effect of these policies is limited by the scope of available models. We construct a spatial partial equilibrium forest sector model that is solved at high resolution across the western United States. We are able to solve this uniquely large-scale high-resolution model using a novel price-search algorithm that considerably decreases the solve time. The forest sector model can be directly integrated into large-scale climate simulators that provide a detailed representation of biological and climate processes on the landscape. Our model captures the feedback between forest disturbance and economic activity in the forest sector and demonstrates how short- and long-term harvest patterns adapt to these disturbance events. We utilize data on disturbance risk to formulate a policy experiment involving subsidies for timber harvest in at-risk areas. We find that when these subsidies are applied on a regional scale, they shift harvests from marginal yet economically viable timberland onto more vulnerable land. Although this changes the harvest pattern, and thus the pattern of fire mortality, on the landscape, the overall amount of fire remains unchanged due to leakage effects. Additionally, we find that producers of softwood lumber and biofuels experience the largest change in production due to the subsidies. Another benefit of our model is the ability to conduct analyses of state-level policies on the entire region's economy. We perform an additional modeling exercise in which a state-level policy is enacted for Oregon. We find that even state-level policies change the pattern of wildfire both within the state itself, and in the outlying area.

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1. Introduction

Forests in the western United States play a large role in the environmental and economic health of the region. In addition to providing considerable economic benefits, including the supply of wood products, forests also sequester significant amounts of carbon from the atmosphere, and provide recreational opportunities for communities and critical habitat for many species. These ecosystems are subject to various disturbances, including harvests, wildfire, and pest outbreaks. In the western United States, forest disturbances such as wildfire can cause substantial damages to property and human health (Westerling & Bryant, 2008). Forest disturbances also impact the economic well-being of industries and communities that rely on forest resources. Due to feedbacks between the forest ecosystem and forest sector, a disturbance in one area can translate to disturbances in other areas through market mechanisms. This means that policies affecting these resources can have effects outside the area in which they are enacted. However, such feedbacks are rarely accounted for in ecological modeling exercises. This limits our understanding the potential impact of policies directed at reducing damages from these disturbances.

Past modeling efforts that focus on the ecological representation of forest growth (e.g. Hudiburg et al., 2013) often lack detailed representations of the forest sector, including a representation of forest product markets. Forest product pools are important because they influence the rate at which CO_2 is released into the atmosphere. Furthermore, economic fluctuations can cause disproportionate impacts to some products, while leaving others relatively unaffected. Shifting demand for wood products is also a crucial determinant of where harvest occurs as well as the intensity of that harvest. However, this feedback is unaccounted for in many models, especially the large-scale climate simulations used regularly to evaluate the impacts of climate change on natural systems.

A forest sector model with the ability to link to large scale climate simulations can improve the representation of forest management within those models. The biological and social systems are coupled through timber harvest and other management activities. Current approaches to modeling forest management within climate simulations, and land system models more generally, consist of downscaling exogenous projections of country-level timber harvests to the grid cell level. The use of national datasets, such as those found in Hurtt et al. (2006), can greatly limit the resolution of the modeling results. This work provides a way to generate finescale estimates of timber harvests that are determined endogenously in the model. This represents an important contribution of market mechanisms to research in ecological and climate modeling.

The goal of this paper is to couple a partial equilibrium model of the forest sector to a large-scale climatic ecology model in order to adequately model both economic and ecological feedbacks. For our climatic ecology model, we select the Community Land Model (CLM) (Oleson et al., 2010) which is part of the Community Earth System Model (CESM), commonly used in climate simulations. The study region within CLM is organized into 16km^2 parcels, which is a high resolution for models of it's type. This high resolution is one of the major benefits of CLM. In order to take advantage of the high resolution of the model, we construct our own partial equilibrium model of the forest sector, which uses a unique method to solve for spatial market equilibrium. Despite the complexity of the solution, our method does not greatly increase the time of the model run. We refer to our forest sector model as the "Timber Harvest Model" (THM) to emphasize its function within CLM.

A major benefit of our forest sector model is that provides the ability to conduct experiments within CLM. Previous policy experiments in CLM often come in the form of exogenously-specified input datasets (e.g. Law et al., 2018) that prescribe land management practices. Our forest sector model, because of its explicit representation of timber and forest products markets, allows for policies, such as taxes or subsidies for timber removal, to be implemented within the model. Establishing a coherent economic framework within the model itself increases the usefulness of CLM to a larger group of researchers.

We are also interested in understanding the effect of forest disturbance and climate change on the pattern of timber harvests. The economics of forest management play a significant role in determining the ecological impacts of harvest (Van Kooten et al., 1995), and the forest sector model presented in this paper allows for the investigation of this relationship. Understanding the roles and effects of natural processes is important, but a major aspect of our model is the ability to conduct detailed and theoretically consistent policy experiments.

Although the economic impact of forest mortality and climate change on the forest sector are addressed through linking our model to CLM, the focus in this paper is on policies that incentivize harvesting in order to reduce the number and severity of future disturbance events. There are several reasons why this policy is an important area of study. Though many disturbances occur on federal lands, private lands are still subject to the same risks. Additionally, there exist many areas in which the harvest of timber is unprofitable, despite the fact that its removal would reduce the risk of disturbance. Using a new dataset of disturbance risk (Buotte et al., 2018), we implement a policy of subsidizing removals in high-risk areas.

Our results show that such policies substantially change the spatial pattern of harvest, as well as that of fire. However, we find that the overall level of fire does not decline substantially across different versions of the policy compared to a no-policy baseline. We find that this is due to leakage effects, as increases in harvest in some areas offset harvests in other areas that are ecologically similar, with only marginally lower fire vulnerability. This highlights the importance of accounting for economic feedbacks when conducting policy experiments within climate and ecological models, as a prescribed approach would not account for such leakage effects.

The impact of climate change on forests and the wood products industry has been a subject of much research (e.g. Sohngen et al., 2001). Land use changes involving forests can have large environmental impacts (Lubowski et al., 2006), and it has been shown that forest management can be influenced by a changing climate (Sohngen and Mendelsohn 1998, Spittlehouse & Stewart 2003). There are large computational costs associated with modeling economic and environmental feedbacks at a very high resolution. Despite the obstacles, there is a significant benefit to performing such an analysis. For instance, it becomes possible to investigate how different future climate patterns affect forestry at a regional scale, as well as adaptive economic behavior. It can also clarify ways in which human activities can manipulate environmental phenomena, such as wildfire frequency and pest outbreaks.

The rest of this paper is organized as follows. The next section discusses the methodology of the THM, the datasets used to parameterize the model, as well as a brief discussion of the linkage to CLM. An expanded discussion of CLM can be found in the appendix. The following section will outline the the simulation scenarios, and then results will be presented. The paper concludes with a discussion of the results.

2. Methodology

2.1 The Forest Sector Model

The goal of the THM is to solve for the equilibrium harvest quantity, which includes the location and intensity of harvests on the landscape. This is similar to other forest sector models (Latta et al., 2013) and represents the level of harvest one would expect to see on the landscape from private forest managers. The THM also accounts for the location of harvests on public lands, and the processing of this timber at forest products facilities. There may be factors that prevent the forest sector from reaching a state of market equilibrium, but market equilibrium provides a useful tool for determining current activities as well as how they might evolve over time given that no other factors change.

One potential method of calculating the equilibrium harvest level is with a search over quantity space. This method includes searching for harvest levels at different locations that balance supply and demand in timber and wood products markets. Such a procedure may be feasible for smaller models, but for a model that covers a wide region at a high resolution, it is infeasible with currently available computational resources and solution methods. Instead, we search over price space, which greatly reduces the number of variables within the optimization algorithm. Thus, the goal of our algorithm is to calculate the set of mill-level timber prices and market-level output prices that result in a balancing of the amount of timber and output demanded with the amount supplied. The model solves on an annual time step to provide a sequence of recursively-updated static equilibria.

In order to achieve an equilibrium level of harvest, supply and demand must be matched in all markets. We begin by representing demand for inputs and outputs within the forest sector. Our model represents three types of transactions. The first transaction is between timber plot owners and mills, whereby the mills purchase timber from specific plots. The second is among mills, who trade intermediate goods. Wood chips are a byproduct of production for many wood products (e.g. lumber), and can also be used as an input for other products (e.g. paper products). Thus, mills will purchase chips instead of harvesting timber if it is cheaper. Finally, we represent transactions among mills and output markets. Output markets are specified at a regional level, and have no specific location (unlike the plots and mills). The three types of markets – timber, wood chips, and outputs – are nested within the THM. The algorithm we implement (which will be discussed later in the section) solves each market equilibrium through an iterative search process. The algorithm finds the equilibrium price level in a given market, which in turn depends on equilibrium prices and quantities in other markets.

The available quantity of timber is determined by CLM. The study region – which spans the western United States – is divided into a 4km x 4km (16km^2) grid. The total volume of timber is tracked over time at the grid cell level independent of age structure. This is an important growth and yield difference between CLM and many other forest sector models. There are 14 different species represented in CLM, called Plant Function Types (PFTs). Additionally, we represent private and public landownership within the model, with timber being supplied from both ownerships.

We assume that each grid cell that designated as private land is managed by a profit maximizing agent. The agent obtains revenue from selling timber to mills, and incurs harvest costs. Alternatively, other models of forest management represent stumpage markets, where mills buy rights to harvest timber (Leffler and Rucker, 1991). It is important to note that the net price of timber remains unchanged between these approaches. It is well documented that for a given forest plot, harvesting costs typically decline with the volume of harvest (Kluender et al., 1998). As each16km^2 grid cell in our model has a variety of different parcels from which the agent can harvest we amend this simple harvest cost relationship. Within each of these parcels, the costs of harvest decline with volume, yet the agent is assumed to harvest the most accessible and cheapest parcels first. In this way, the cheapest parcels will be harvested before the most expensive, resulting in an upward sloping timber supply curve. We write the forest manager's profit maximization problem as:

$$\max_{t} \; P_m t - \gamma t^{\beta} \tag{1}$$

where P_m is the per unit price of timber that a given mill, m, is offering, and t is the volume of timber sold from the plot. The positive parameters γ and β determine harvest costs.

The solution to the profit maximization problem yields the supply curve reported below:

$$t^{*} = \left(\frac{P_m}{\gamma\beta}\right)^{\frac{1}{\beta-1}} \tag{2}$$

The supply function in (2) is increasing and convex in price P_m, as long as $2 > \beta > 1$. We assume that forest managers have access to the same harvesting technology and parameterize the supply function such that it recreates historically observed levels of harvest in the region. Using the Timber Products Output (TPO) (USDA Forest Service, 2012), we used a non-linear fit routine to optimize the parameters in (2) such that the study region would produce the highest and lowest harvest levels seen in the TPO reports given a range of prices observed in test runs of the THM. A more detailed description can be found later in the section. Heterogeneity in the timber supply is determined by a plot's distance from any given mill. Thus, the prices in (2) are those that are offered by the mills, adjusted for the cost of transportation between the plot and the mill.

Each mill offers an initial price for timber, and price adjustments are made until the timber supplied at the offer price equals the timber demanded. This requires a representation of mill-level timber demand. We utilize empirically derived timber demand functions from Guerrero Ochoa (2012) to represent the relationship between price and mill level timber demand. To determine mill-level production, we adopt the common approach in the forest sector modeling literature and represent production as a fixed ratio that converts timber into products, with the residual going into byproduct such as chips.

Each mill is constrained in the quantity they can produce by their capacity. Data on capacity is taken from Spelter et al., (2009) for 2009 and from Latta et al. (2018) for 2014. It is common for mills to change capacities in response to economic incentives. Our model incorporates capacity changes as a function of the mill's profitability. At every time step, we assume there a certain percentage of the mill's capacity that decays, as in previous studies (e.g., Latta et al., 2018). Mills with negative profitability cannot pay to recover this loss; however, mills with positive profitability can pay a proportion of their profits to recover it. The cost of recovery is assumed to be proportional to existing capacity. Intuitively, these costs can be thought of costs of maintenance, where larger mills must pay more for maintenance than smaller mills.

After all maintenance costs are paid by the mills, any new capacity is distributed among the profitable mills. The level of new capacity is first calculated on a per-product basis for the whole region based on the increase in GDP from the Shared Socioeconomic Pathway (SSP) data, as well as income elasticities derived from previously estimated market demand curves. This gives us an estimate of how the demand for a given product will change, which we are able to use to calculate the magnitude of capacity change in our region. The new capacity is then distributed across the profitable mills in proportion to the profit level, such that more profitable mills receive a higher proportion of the capacity than less profitable mills.

The output market in the model is represented by a set of national level product demand curves for each product that is represented in the model. The demand curves are parameterized with both price and income elasticities. The price elasticities for the output markets are used in the price search algorithm, discussed later in this section, to estimate changes in price levels with respect to changes in the quantity of a product supplied. The income elasticities are used to shift the demand curves according to the growth in GDP per capita that are obtained from the SSP. The national level demand curves are disaggregated to the study region using a ratio of national product capacity levels and product capacity levels specific to the region (Latta et al., 2018).

We utilize our model of the forest sector in the western United States to solve for the equilibrium level of harvest (and production) using a price search algorithm. The choice of searching over price space instead quantity space was made because the number of price variables corresponds to the number of mills, which is a much smaller number of variables than the number of grid cells. For any given set of prices, we can use our models of harvest costs, mill production, and output markets, to derive the quantity of timber supplied from each grid cell and the mill to which it is supplied.

2.2 Solution Method for Forest Sector Model

The price search algorithm begins with an arbitrary guess of mill-level prices for both timber and chips, and output prices. We must specify all prices initially because input and intermediate goods demands depend on output prices according to theory. We evaluate the quantity of timber supplied to the mills at those prices, and then check it against the amount demanded by the mills. If these do not match, we update the prices by taking a convex combination of the current price level, and the price that is implied by the amount of timber supplied. Because supply is monotonically increasing in price and demand is monotonically declining in price, this iterative process converges to the market equilibrium. One iteration of the price search algorithm is visualized in Figure 1. The initial price guess (P_{guess}) is above the equilibrium price. Because of the functional forms, the supply at this price (S_{guess}) implies a price on the demand curve ($P_{implied}$)

that is below the equilibrium. Thus, the price guess and the implied price bracket the solution and successive iterations converge to the equilibrium price.

[FIGURE 1]

The equilibrium quantity of timber at each mill implies a specific level of chip supply according to our production function. Thus, the same search process is used to find the equilibrium in the intermediate goods market.

Our model of the forest sector is a nested model. Although we know the quantity of forest product demanded at a given price level, we do not know the quantity of product supplied until we have solved for the equilibrium in the input (timber) and intermediate goods (chips) markets. Because the demand for timber and chips is a function of output prices, every time the output price is updated, the equilibrium price levels for timber and chips must be recalculated. In the model, we first solve for the timber and chips price equilibria. Using the level of output produced at that price level, we use the output market demand curves to check whether the supply of a given product matches the amount demanded at the current price level. Should it not, the output price is updated using a convex combination of current and implied price, as with timber prices This process continues until we achieve equilibrium in all markets.

The result of solving the price search algorithm is a spatially explicit map of timber harvest, which contains both the locations of harvests as well as their intensities. Additionally, we obtain mill output, mill profitability, as well as the profitability of the forest land itself. If we have a map of initial biomass, we can solve the model for a single year.

As time progresses in the model, we need a way of representing changes in the macroeconomic conditions. These include variables such as population and GDP, two important drivers of forest product demand (Buongiorno et al., 2003). Our model incorporates national-level GDP and population projections found in SSP5 (Kriegler et al., 2017), which corresponds to a scenario in which there are continued increases in CO_2 emissions tied with steady economic growth.

The methods discussed above are combined with data discussed in the following section to simulate future harvest levels and forest products outputs, and how these outcomes are affected by climate change, forest disturbance, or targeted government policies.

2.3. Data

The THM incorporates data on land ownership, mill location and capacity, and biological data on forest type and initial volumes. In this section we discuss each dataset, as well as those that are needed for running experiments in the model.

The THM has two ways of modeling biomass growth through time, depending on whether the model is coupled to CLM or not. If the model is coupled to CLM, it will receive a new biomass level every time step that has been calculated within CLM. Taking the harvest of the previous year provided by the THM, CLM will grow the biomass in each grid cell conditional on harvests as well as other disturbances and natural factors that influence growth. More about the coupling procedure can be found in a subsequent section. If coupling to CLM is not available, the THM requires an initial condition and a set of growth functions, which are discussed earlier in the methods section. The data used to parameterize the growth functions mostly come from timber growth tables (Smith et al., 2006; Stage et al., 1988) and the initial biomass levels come from a unique dataset developed in Berner at al. (2017) for use in CLM.

[FIGURE 2]

Along with data on the initial state of the biomass (Figure 2) and its associated growth functions, we also utilize data on the distribution of tree species. Within the model, the species group that a given tree belongs to is referred to as a Plant Functional Type (PFT). The set of PFTs in the model were selected due to their economic and ecological significance in the western United States. These include Douglas Fir, Lodgepole Pine, Ponderosa Pine, Pinyon/Juniper, Engleman Sprice/Subalpine Fir, 5-needle Pine, Aspen and Hardwood, Oak, Hemlock/Cedar/Spruce, Western Douglas Fir, Mixed Fir, California Mixed Conifer, Redwood, and Larch. Synchronizing the PFTs in the THM with CLM increases the value of the model output for CLM applications. A PFT-specific ratio of softwood to hardwood is applied at the grid cell level allowing the THM to determine the species composition of the biomass harvested. Knowing the softwood and hardwood prevalence in each grid cell is important for the timber market, as it constrains which mills timber on a given grid cell can go to, and how much of it can be used by a given mill.

Another important determinant of harvest level is ownership of the land. Harvest on private land is determined by different factors than harvest on public land, and ignoring that distinction would be problematic. In order to classify grid cells into either public or private categories, we make use of the protected areas database (US Geological Survey, 2016). Besides distinguishing private and public land, it also allows us to differentiate public land by government agency, as well as at the National Forest level. This is important, as management differs greatly among public owners as well, with harvest allowed in some public forests and not in others

Data on mill locations and capacities are collected from two datasets. These include data from Spelter (2009) and from another forest sector model, LURA (Latta et al., 2018). Both of these datasets provide snapshots of mill locations and capacity levels at different periods of time. The data from Latta et al. (2018) allow us to specify the location, capacity, and product type, of 421 mills across the western United States (Figure 3) and the data from the Spelter (2009) data is used to evaluate our model of capacity growth, discussed in the previous section.

[FIGURE 3]

The spatially explicit nature of the model – both mill locations and the spatial representation of grid cells on the landscape – allow us to determine the transportation cost between the different agents in the model. It is well established that the costs of transportation are an important determinant of timber supply. In order to calculate the cost of transport, we utilize a proprietary software package called PC Miler (ALK Technologies, 2016) that converts the locations of mills and grid cells into transportation distances and driving times. We calculate distances and times between every mill and every grid cell, as well as every mill and every other mill. We assumed a constant per-gallon cost of gasoline, average truck load capacity, and per-hour labor costs.

Additional data is used to characterize the economic conditions of the forest sector in the western United States. This includes information on national-market level demand elasticities for forest products, such as lumber, plywood, newsprint, and other goods (Latta et al., 2016).

Furthermore, as discussed above, we incorporate projections of population and GDP using SSP5 (Kriegler et al., 2017) and use these data to estimate the region-wide expansion of capacity. The initial period market price and quantity for the market level constant elasticity demand curves are calculated from FAO data on apparent consumption[5] as well as an average of prices derived import and export quantities and values (United Nations FAOSTAT, 2017). The parameterization procedure is described in the appendix.

2.4 Coupling the Model to CLM

The community land model is a large-scale model of land processes that can be coupled to other models within the Community Earth System Model (CESM). When the models are fully coupled to one another, CESM provides a climatic ecology model in which many of the natural feedbacks of these systems are well represented. CESM and CLM are used in numerous applications in the earth sciences.

CLM is unique from other models in CESM in the way it organizes the landscape. The landscape is split into discrete grid cells, generally of uniform resolution, which can be scaled up easily better accommodating parallel processing of the overall model solution. For large global runs, this resolution is quite coarse, though for region-level runs such as those presented in this paper, the resolution can be much finer. Each grid cell is then further disaggregated into pieces representing different categories of land cover, such as forested, urban, or crop. During each time-step, CLM uses a vast array of equations to calculate the flow of matter (e.g., carbon, nitrogen, etc.) up and down each column. These flows are generally functions of climatic variables, such as precipitation or temperature. However, these are also factors that are determined by social systems, notably timber harvest, that affect the flow of matter within each grid cell.

Timber harvest in CLM is typically accounted for with input datasets that prescribe removals for each grid cell. In the version of CLM employed in this paper (CLM 4.5), these removals are prescribed in terms of a proportion of the biomass on the grid cell removed. This prevents the biomass from going negative, which would betray the laws of physics. However, it makes it more difficult for modelers looking to conduct alternative harvest scenarios that match

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[5] Apparent consumption is calculated as production plus imports less exports.

specific volume targets. Perhaps for that reason, later versions of CLM have switched to representing harvest in terms of the level of removal. Another drawback of the way harvesting is typically represented is that it is not responsive to disturbance events or changes in productivity occurring in the model. That is, the user prescribes the harvest proportions, and those proportions do not change even if the area targeted for harvesting experiences a stand destroying fire. With the THM, harvest levels are determined endogenously, using a coupling procedure illustrated in Figure 4.

[FIGURE 4]

The major difficulty with coupling the THM to CLM is that the THM requires grid cell to grid cell communication, which is not allowed in CLM. Other models in CESM do feature grid cell to grid cell communication by using a module named the "flux coupler". However, using the flux coupler along with CLM represents a substantial computational hurdle that was determined to be too computationally expensive. Instead, we resort to stopping CLM every year after it has operated on all of the grid cells in our region, and then running the THM to determine the following year's harvests. Once that is calculated, the new map of harvest proportions is passed to CLM. The specific computational procedure of the coupling is general enough to be used in a wide range of applications.

3. Scenario Construction

Our coupled model is used to evaluate the effects of a policy targeting vulnerable forestlands in the western United States. Subsidizing the removal of the biomass is a controversial idea that some argue may aid in reducing the severity of wildfires through additional fuel treatments (Carrol et al., 2007; Agee and Skinner, 2005). Our model allows for these policies to simulated at a large scale, which in our case includes the western United States. Additionally, the detailed representation of environmental processes in the model allows us to track several important variables that provide insight into how these policies impact the environment.

For this current study, we implement three different scenarios. We begin with a baseline scenario in which market equilibrium is determined absent of any government intervention.

These results will then be compared with the scenarios in which harvest subsidies are offered. In each subsidy case, the per-unit timber subsidy is set to $10 per cubic meter of timber.

The second scenario involves setting a subsidy across the study region for harvesting trees in areas that are designated as vulnerable to wildfire. The vulnerability is determined by from climate modeling analysis performed in a previous study (Buotte et al., 2018). It is assumed that this information is internalized by a regional policy maker, who sets a subsidy level equal to their perceived social benefit of tree removal.

[FIGURE 5]

The third scenario involves implementing a subsidy at the state level. For this study, we select the state of Oregon, which has forests in the dry, eastern part of the state that are uneconomical to harvest under most economic conditions (Adams and Latta, 2005). This experiment allows for us to examine economic and ecological spillover effects that state-level policies may have in other regions. A benefit of selecting Oregon as the state implementing the policy is that neighboring Washington is also a large timber producer.

4. Results

This section reports the results of the three scenarios described above. We present the way in which each policy changes harvests throughout the region, and how those changes in harvest translate to changes in the amount of biomass burned. What we find is that even though the subsidy is applied only to vulnerable areas, it changes the amount of biomass lost to wildfire both inside and outside the vulnerability region. Additionally, we find that the policy has very little effect on the overall quantity of wildfire in the study region, indicating that the policy suffers from leakage effects.

4.1. How do subsidies affect harvest patterns?

One of the most straightforward effects of the policy we consider is that it changes the locations and intensities of timber removals in the study region. In order to compare the effects of the policies, we report the differences in harvest levels between our baseline scenario and our region-wide subsidy and state-specific subsidy, respectively. To represent the results over the time period of the simulation (15 years), we report the average difference.

[FIGURE 6]

There are several interesting effects that a region-wide subsidy has on harvest levels across the West. Initially, the changes in the harvest proportions in each plot are relatively small, typically around 1%, and rarely exceeding 5%. Considering that much of the vulnerable timber resides in areas that are not as productive as other, wetter regions, this means that the amount of timber entering the market is relatively small from these vulnerable regions. Although the vulnerable regions experience increases in harvest, we also see that this is made up for in lower levels of harvest in more productive regions, as the market adjusts harvest levels across the landscape. The state-specific subsidy yields fairly similar results.

[FIGURE 7]

The most noticeable difference between the regional and state-level subsidies is that the magnitude of the difference increases in the border regions of southern Oregon and northern California. This is due to the fact that mills will substitute timber they would have harvested in the baseline scenario with nearby subsidized timber. Given that there is plentiful amounts of subsidized timber in southern Oregon, we see that this results in large changes in harvest between the baseline and regional subsidy scenario. Additionally, the proximity of the northern California timber supply results in changes between the Oregon-wide subsidy and the baseline. Another result is that subsidizing harvests at the state-level have far-flung consequences for the whole region, albeit small ones. The largest changes over the baseline are still concentrated within Oregon. To get a better sense of where these differences are occurring, we've subtracted the harvest levels for the state level subsidy from the regional subsidy in order to compare the differences (Figure 8).

[FIGURE 8]

We see an increase in harvests under the regional subsidy scenario in southern Oregon, and a decrease in harvests in northern California. Although there are other differences within Oregon, these effects are most pronounced in the south. The effects of the state-level policy result in differences between the baseline and two subsidy scenarios in the location of fire induced tree mortality, which is demonstrated in the section below.

4.2 Do harvest subsidies change wildfire patterns?

The benefit of coupling a model like CLM to a forest sector model is that we can simultaneously track ecological changes on the landscape. We have shown that the introduction of harvest subsidies changes harvest patterns; however, we are also interested in the effects on the landscape itself. In particular, we are concerned with how our policy influences the patterns of fire mortality. We can obtain these data from CLM, and compare it to the baseline, as we did with harvest.

The main finding from our simulations is that the policy has large differences in the pattern of wildfire, but very little effect on the overall amount of biomass burned. The spatial difference in biomass burned is localized to Oregon, Washington, and California. As shown, the harvest subsidies shift harvests across the landscape. Similarly, the subsidy levels may lower the amount of fire in one region, but increase it in another. For both the region-wide subsidy and Oregon specific subsidy, the differences in fire-related mortality are concentrated in vulnerable areas (Figure 9).

[FIGURE 9]

Our simulation shows differences in the pattern of fire-induced tree mortality. In particular, we observe declines in the dry regions, especially in those where economically viable harvest may not occur (Figure 9A). Furthermore, we observe a large reduction in northern California and southern Oregon. In fact, across the West we see substantial reductions in fire-induced tree mortality. However, in many of those regions, the mortality is merely shifted spatially. Figure 10B demonstrates that there is an additional increase in fire-induced tree mortality in many regions. The largest swing occurs in the Idaho panhandle and western Montana. Though we observe differences in the location of fire, the magnitude of these changes is not very large. Additionally, there are many regions that receive changes in the pattern of fire that have incredibly small changes in the harvest percentage. These areas tend to have very low levels of biomass to begin with.

It is important to stress that increasing harvests does not necessarily lead to fire reduction in a given region. In some regions, our simulations show that this is the case, but in others, the disturbance is merely shifted elsewhere. The increase in fuel, especially on lands that are on the margin of being classified as vulnerable, can also increase fire risk. Additionally, harvesting a plot does not always decrease the risk of fire. In some regions, it may be the case that harvest actually increases the risk, due to the succession of post-harvest vegetation being more vulnerable. These factors contribute to the results we see in the map.

We also investigate the effect of a state-level subsidies that applies only to forest plots in Oregon. Our results show is that the change in fire patterns spans the whole region, despite the fact that the subsidy is only applied to Oregon. Figure 10 shows the difference between the regional subsidy and the Oregon subsidy. The pattern of changes between the region-wide subsidy and the baseline, and the Oregon-wide subsidy and the baseline have enough similarities to make their respective figures confusing, and so we instead present the difference between the region-wide and Oregon-wide subsidy scenario.

[FIGURE 10]

Despite there being changes across the region, we see that there are relatively larger changes in fire patterns in Oregon and the surrounding states. Although some of these areas are distant from Oregon, they produce similar forest products. Thus, altered levels of production in Oregon translate into changes in disturbance in other states through market mechanisms.

Despite the large differences in the pattern of forest fires, the results suggest that the policy is having offsetting effects on harvest levels. This results in a large difference in the pattern of fire but relatively small changes in the overall amount of biomass burned. Of the two policies, the state-level policy results in less biomass burned. There are several reasons why this is the case. First of all, as harvest is shifted to drier, less productive regions, forgone harvest will tend to occur in slightly more productive but similarly marginal forests. Additionally, the subsidy impacts harvest levels in different ways between the two scenarios. When the subsidy is only applied in Oregon, changes in harvest occur through market mechanisms, while the regional subsidy changes harvests both through market mechanisms and directly through subsidizing removals. Additionally, removals do not always reduce fire risk, as some areas can have regrowth that is more susceptible to fire (Stone et al. 2004).

The fact that the subsides do not reduce the total biomass burned is an important result with implications for future experiments within large scale climate and ecology models. In previous studies using models such as CLM (examples), harvests are prescribed (e.g., Kloster et al., 2010). The risk is that without incorporating economic feedbacks into the modeling, these experiments will overstate the effectiveness of harvest policies. Our findings suggest that simply increasing harvests in vulnerable areas will not necessarily reduce fire damages in forests, as this shifts harvests and fire to other areas.

One question is whether the policies effect areas inside of the subsidized zone differently than those outside the subsidized zone. Our results show that in both regions, we experience decreases in wildfire. In both the region-wide subsidy scenario and the Oregon-wide subsidy scenario, there is a larger reduction of fire within the subsidized region than outside of it. However, the proportion of fire reduction inside and outside of the subsidized region is much closer in the region-wide subsidy. For the region-wide subsidy, 54% of the fire reduction occurs within the subsidized region, while 46% occurs outside of the subsidized region. In the Oregon-wide subsidy, 57% of the fire reduction occurs within the subsidized region, while 43% occurs outside of it.

The fact that there is still fire reduction outside of the subsidized areas is a result of both subsidized scenarios impacting mill capacities. Cheaper timber results in more profitable mills that are capable of investing in better maintaining and in some cases expanding their capacity. This higher capacity results in more harvesting in both subsidized and non-subsidized regions.

5. Conclusion

The goal of this study is to evaluate the effectiveness of subsidized removal of vulnerable timber on fire-induced forest mortality in the western United States. To achieve this, we develop a novel coupling technique that links a forest sector model to a large-scale climate simulator in order to adequately model feedbacks in both the economic and ecological systems. What we find is that the policy does indeed change the pattern of harvest, and thus the pattern of fire-based mortality, but overall does not change the region-wide level of damages. We also find evidence that localized policies have effects on the whole region, as policy-induced changes in a given area affect harvesting incentives throughout the region.

This study makes several contributions. We develop a novel method of coupling economics models with ecological models in a way that provides for nuanced policy experiments within GCMs. Unlike other methods of Integrated Assessment Modeling, our method accounts for feedbacks between the economics and ecology of the system, improving the robustness of policy experiments within CLM and other earth system models. Our results demonstrate how markets shift disturbances across the landscape. We show that policies occurring in one region will affect environmental outcomes in another, in what might be referred to as an economic teleconnection. Our results show that removal subsidies for vulnerable timber do not reduce overall fire mortality, however, they do change the spatial pattern of fires.

There are several next steps for this research project. There is substantial space for additional policy experiments, including harvest restrictions, mill-level subsidies, as well as market shocks of various types. Longer simulations to estimate the impacts of climate change on the forest sector could also be done. There are additional models that may be linked to this one, including those that incorporate agricultural management. This paper demonstrates the importance of considering economic feedbacks in integrated assessment models. Future earth system research should consider how to best incorporate these feedbacks. Our study shows that direct coupling of economic and earth system models involves significant challenges, but also rewards.

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Appendix

A.1. Parameterization Procedure for the THM

For many components of the THM, data provided in previous studies is sufficient to capture the relationships among agents in the model. These include data on market demand curves, grid cell level ownership, and transportation costs. For several parameters in the model, the data are insufficient to accurately capture the relationships in the model in a consistent way. This includes the timber harvest cost function, growth functions, and mill production functions. In this section, we will detail the parameterization procedures required for setting up the model.

Our approach includes a generalized representation of timber harvests. The production of timber is dictated by the biological dynamics of the problem. The costs, on the other hand, are a generalized representation of harvests across a grid cell. It is common to characterize within-plot harvest costs as declining in the intensity of the harvest (Kluender et al., 1998). Though we accept that this is certainly true at smaller scales, as it is cheaper per unit to fell large swaths of timber as opposed to selectively harvesting, on the scale of a whole grid cell, this is likely not be the case. A single grid cell contains many different plots of timber land that are more or less accessible, sloped, or otherwise difficult to reach. We assume that the forest manager chooses to harvest the cheapest and easiest-to-get-to timber first, followed by the next cheapest, and so on. Using this assumption, we can generalize a cost function over the harvest of timber on the grid cell that has an increasing per-unit cost. Furthermore, this results in a timber supply curve that slopes upwards. Because our cost function is a generalization, we must parameterize it ourselves.

In order to parameterize the harvest cost function, we first must select an objective with which to optimize the parameter. Through the course of the project, two methods with two different objectives were utilized. The first set the objective as recreating historic harvest levels in the state of Oregon. The second was recreating a realistic range of harvests for a range of prices that the grid cells would observe during the simulation.

The development of the first method was part of another project examining the application of different heuristic algorithms in fitting model parameters. Because models such as the one developed in this project are large and difficult to run many times, heuristic approaches can be used to speed up the parameterization process. The application utilizes simulated annealing (Kirkpatrick et al., 1983) and particle swarm (Kennedy, 2011) in order to create an optimal set of parameters for both harvest costs and mill production. This analysis encountered numerous obstacles, including the fact that the harvest model itself took a very long time to run (this is before many time-saving changes were made to the code). Furthermore, these two algorithms did not generate usable results when optimization of one set of parameters influenced the objective function on a different scale than another set. That is, the algorithm would optimize either the production costs or the harvest costs, but not both. Revisiting this analysis, and including additional meta-modeling are potential areas of expansion.

The second method involves recreating historically observed harvest ranges using a range of prices, and is what we currently employ in the model. Applying the method in the above paragraph would often result in parameters that would recreate realistic harvest levels for a limited set of prices. Any prices beyond that would result in unrealistically high or low harvests. Fitting the parameters to a range of prices alleviates this issue. This method consists of taking state level harvests from the TPO (USDA Forest Service, 2012). This is then used to generate region-wide estimates of harvest for both high and low harvest levels. Next, the harvest model is run and the set of mill level prices is extracted from the model run. This provides the needed information on the price ranges being observed in the model. Using information on average rotation length as well as the number of harvestable grid cells in the region, the average range of per-grid cell harvest is obtained. Finally, Microsoft Excel's non-linear fit algorithm (Fylstra et al., 1998) is used to minimize deviations between the observed range of grid cell harvests and module-generated grid cell harvests across the range of prices observed. Parameters obtained from this procedure are included in the appendix.

The mill level production function is another aspect of the model that required parameterization. Many previous forest sector models represent mill production as an input-output model, with labor, timber, and capital combining to create a unit of product. Initially, we traded this approach for a Cobb-Douglas production function. This allowed us to derive the mill-level demand for timber from solving the mill's profit maximization problem. However, parameterizing these functions became very difficult, and it became clear that accurately representing mill product and timber demand with this approach would require more sophistication. We turned to a representation that matches previous forest sector models (e.g. Latta et al., 2017), wherein every mill has a fixed factor that converts timber into product. This approach is made more attractive by the fact that we have an empirically based representation of timber demand from a previous study (Guerrero Ochoa, 2012).

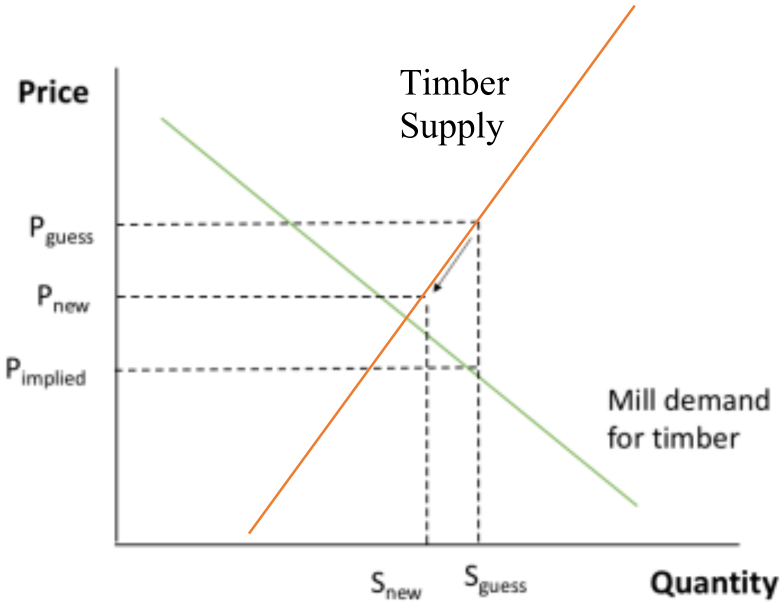


Figure 1: A graphical depiction of the price search algorithm

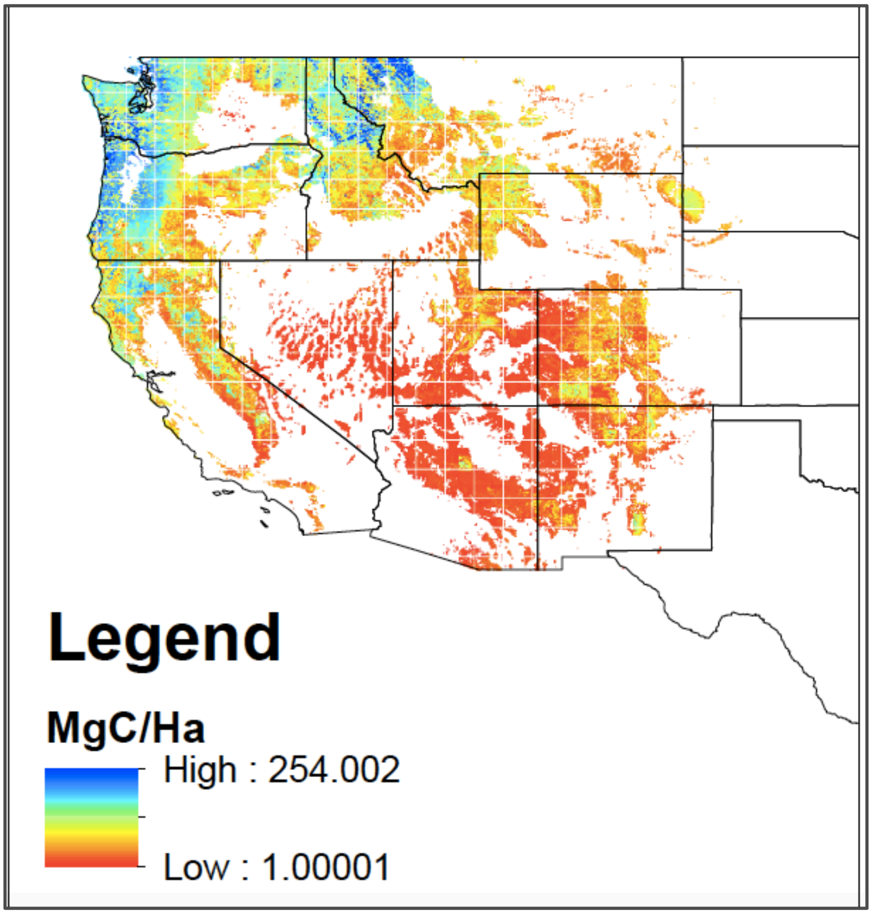


Figure 2: Input data on biomass used for the initial level of timber volume.

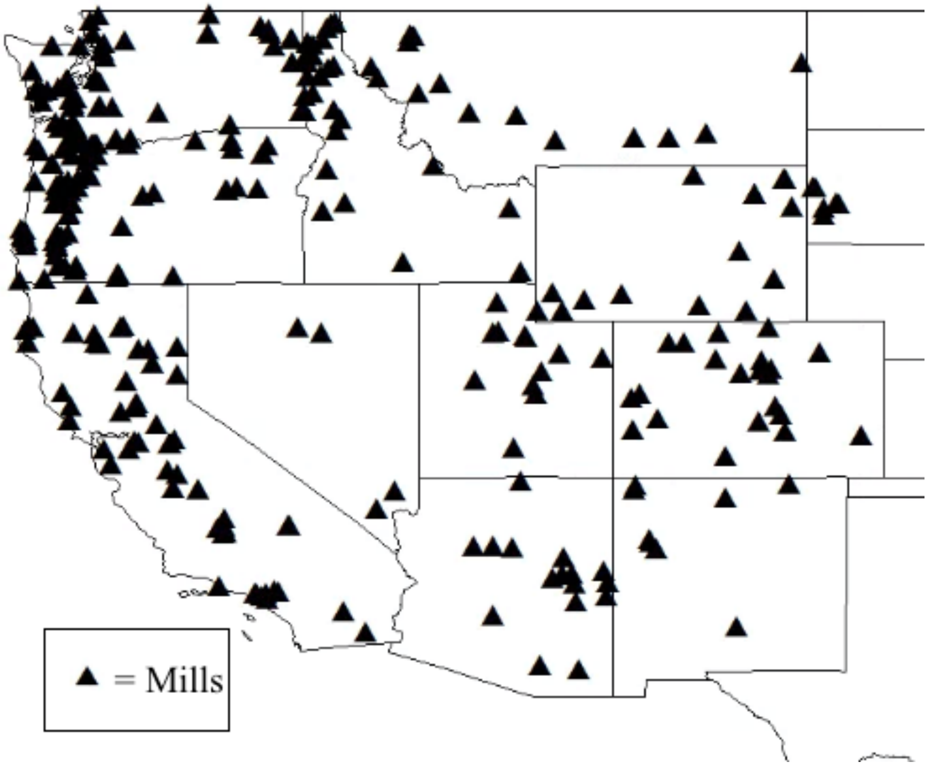


Figure 3: Locations of mills used in the THM

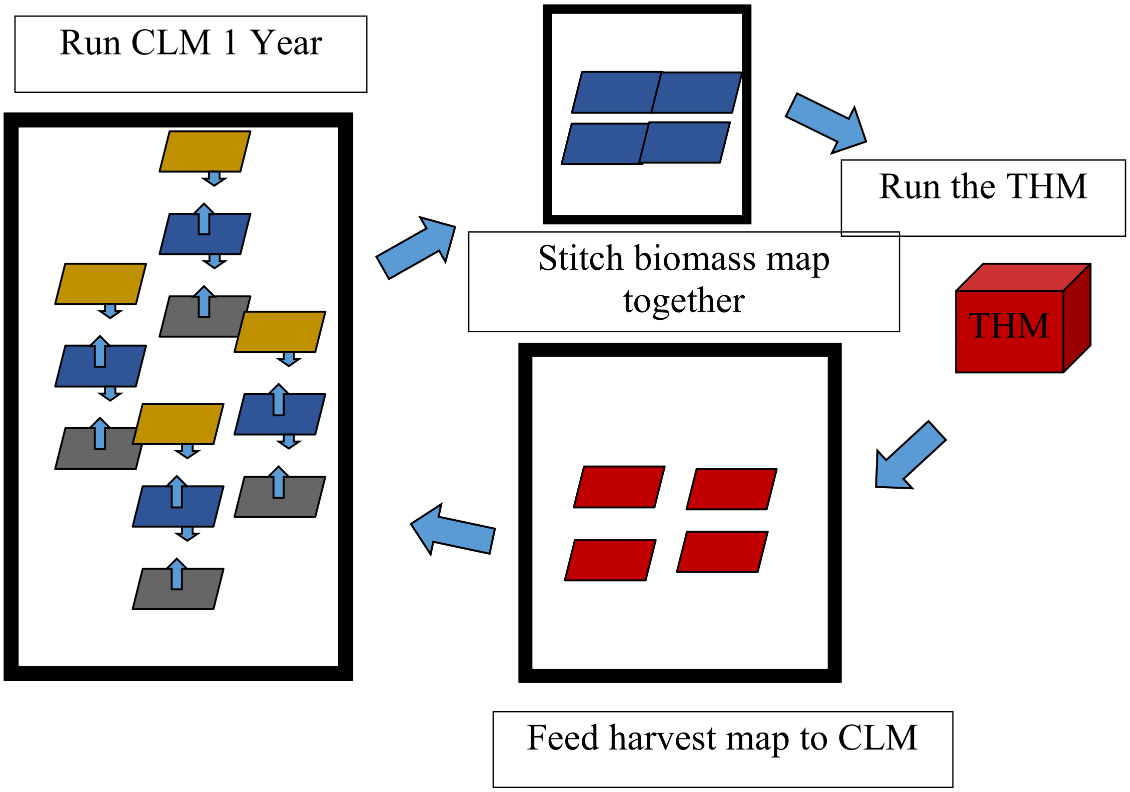


Figure 4: Visualization of the coupling procedure between the THM and CLM

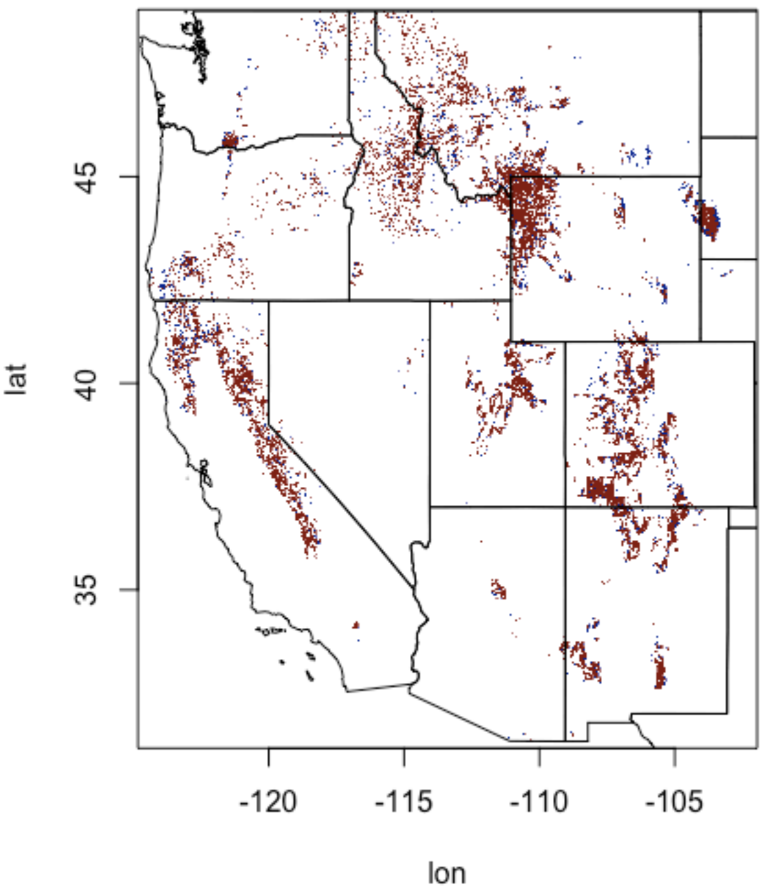


Figure 5: The locations in which the removal subsidy has been applied. These are regions in which prior GCM runs have indicated an increased vulnerability to wildfire.

Units: Percent
Difference in Harvest

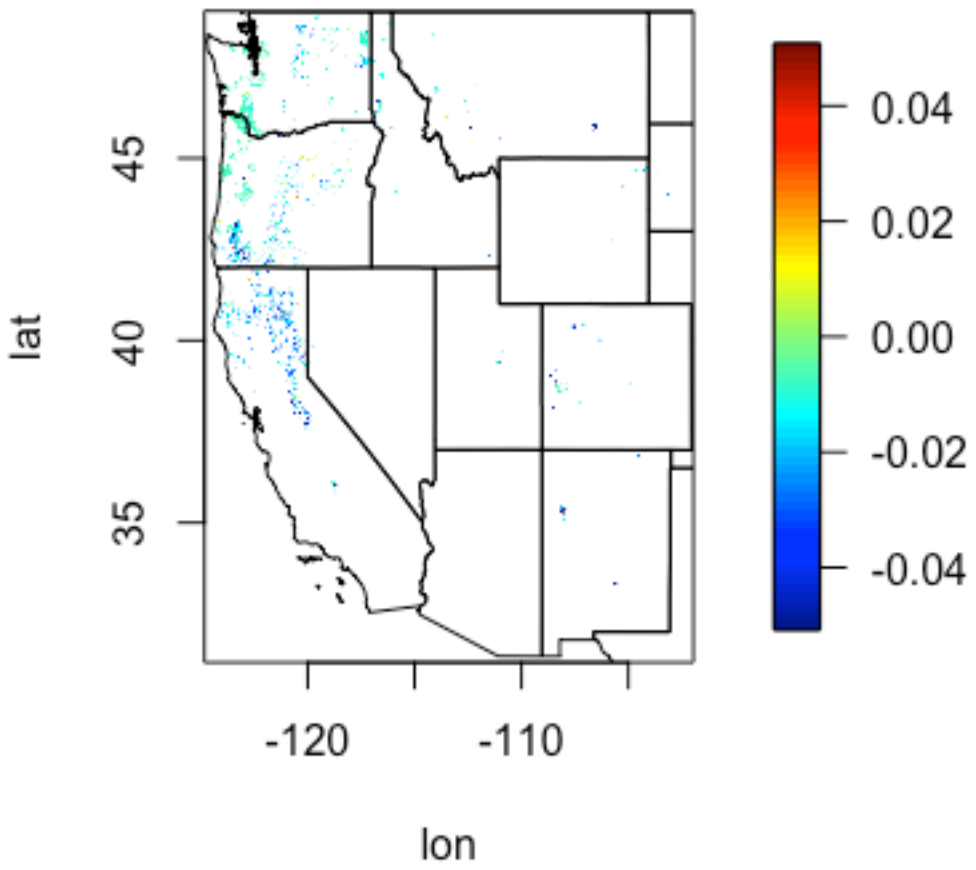


Figure 6: Differences in harvest percentage between region-wide subsidy and baseline subsidy. The baseline is subtracting from the region-wide subsidy scenario. The figure demonstrates that the region-wide subsidy mostly results in lower levels of harvest, with relatively few areas receiving large increases.

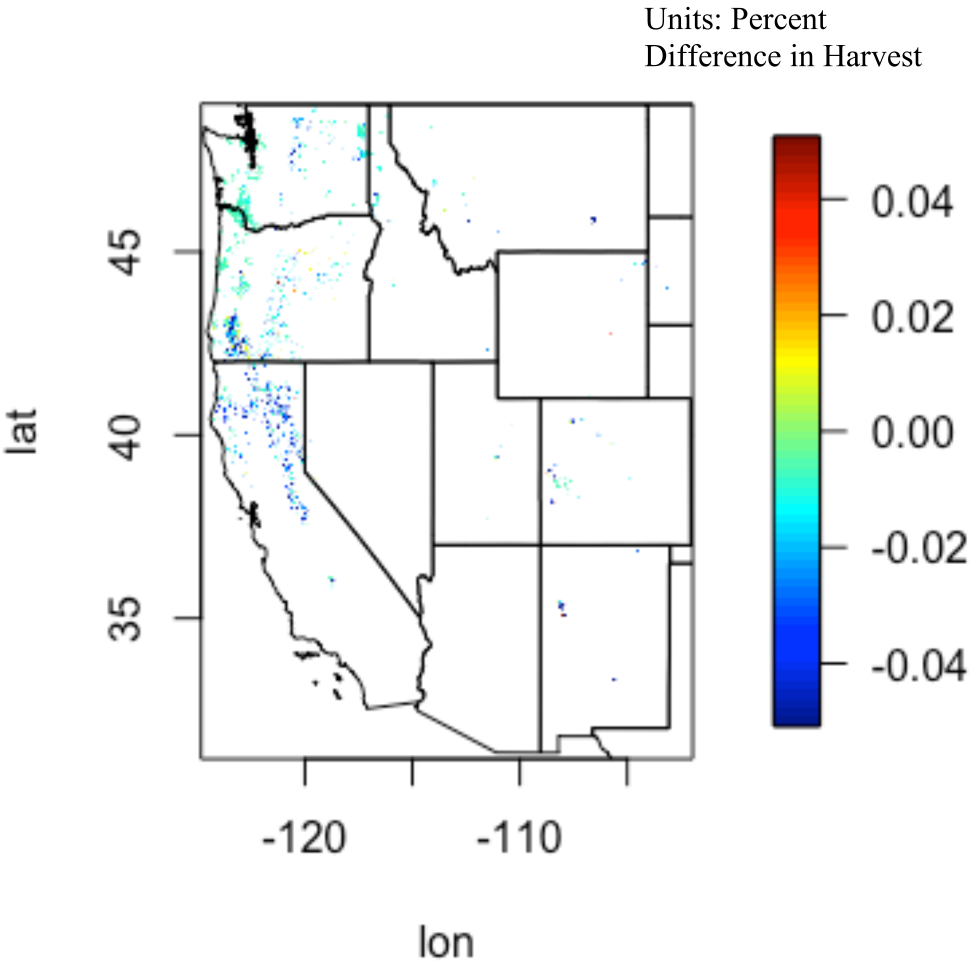


Figure 7: Differences in harvest percentage between Oregon-wide subsidy and baseline subsidy. The baseline is subtracting from the Oregon-wide subsidy scenario. The figure demonstrates that although the Oregon-wide subsidy results in similar differences in harvest, the reductions in northern California and Southern Oregon are greater than in the region-wide subsidy scenario.

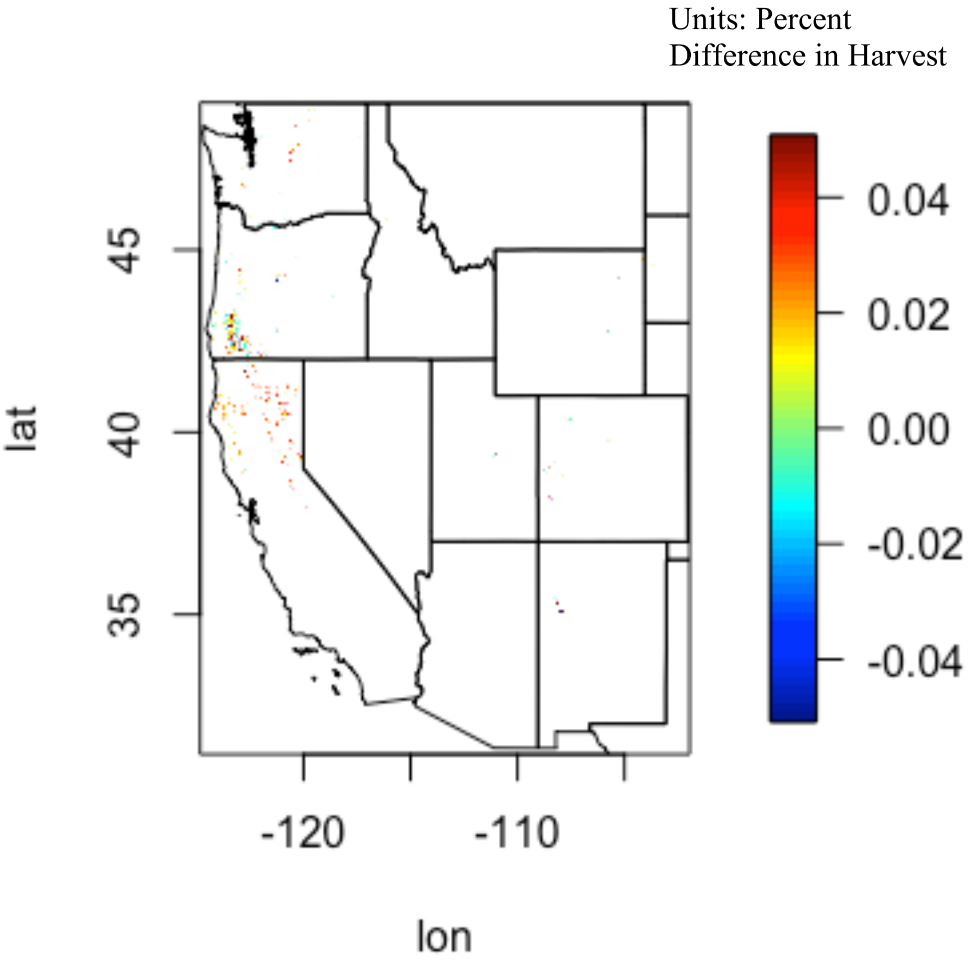
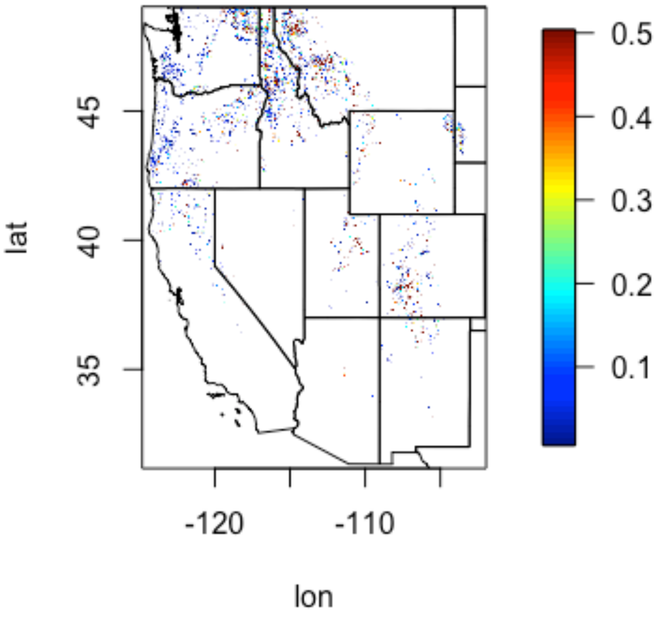
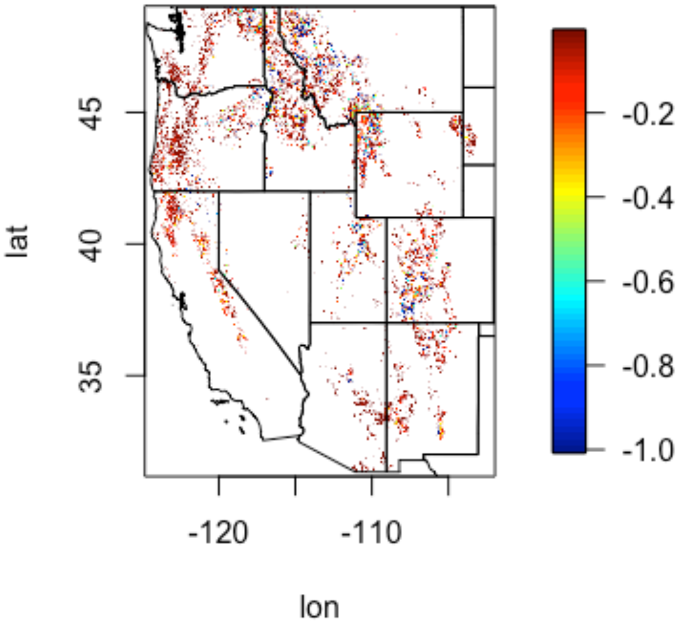


Figure 8: Differences in harvest percentage between Oregon-wide subsidy and region-wide subsidy. The Oregon-wide subsidy scenario is subtracting from the region-wide subsidy scenario. Differences between the two are concentrated in southern Oregon and Northern California, as the Oregon-wide subsidy reduces harvests in those regions to a greater extent.



Units: Megagrams of timber burned per gridcell (16km2)

Figure 9A: Increases in fire-induced forest mortality due to region-wide policy.



Units: Megagrams of timber burned per gridcell (16km2)

Figure 9B: Decreases in fire-induced forest mortality due to region-wide policy.

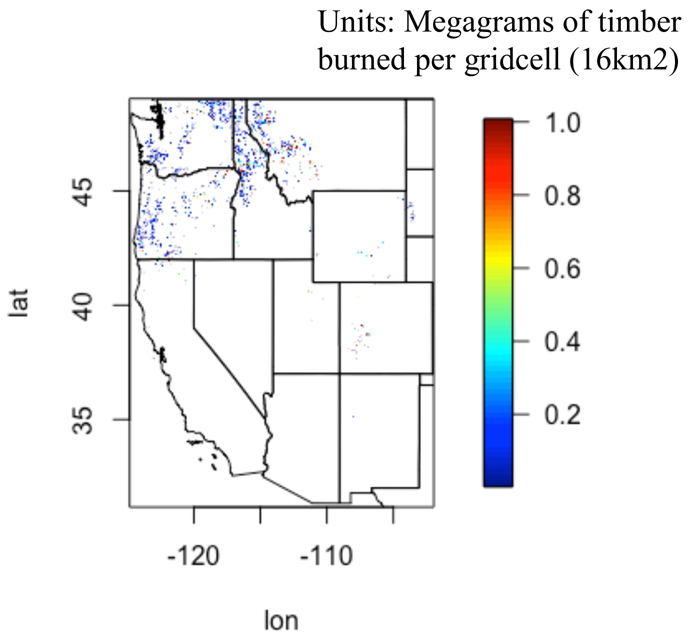

Units: Megagrams of timber burned per gridcell (16km2)

Figure 10A: Increases in fire-induced forest mortality in region-wide subsidy scenario compared to Oregon-wide subsidy scenario

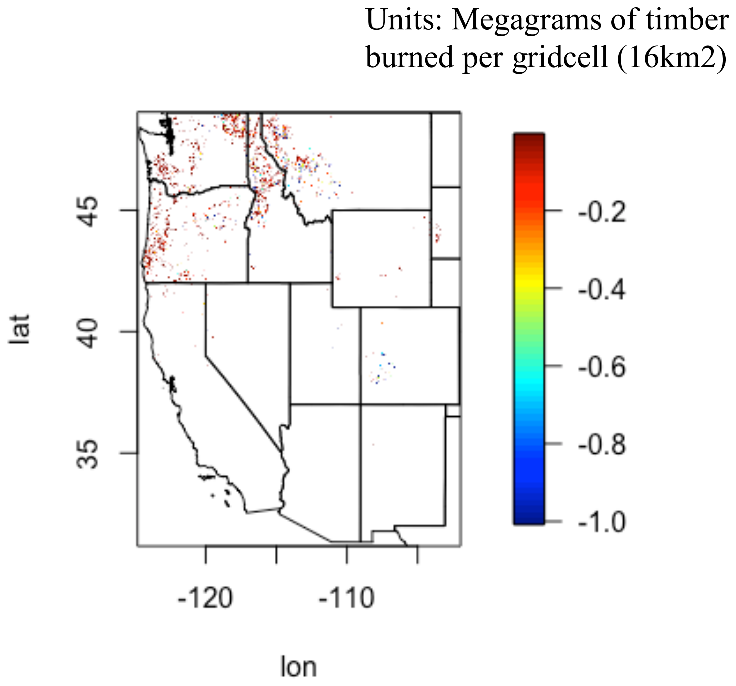

Units: Megagrams of timber burned per gridcell (16km2)

Figure 10B: Decreases in fire-induced forest mortality in region-wide subsidy scenario compared to Oregon-wide subsidy scenario