Journal of Agricultural and Resource Economics 48(2):376–397
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ISSN: 1068-5502 (Print); 2327-8285 (Online)
doi: 10.22004/ag.econ.320670

Carbon and Timber Management in Western Oregon under Tax-Financed Investments in Wildfire Risk Mitigation

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We examine how forest taxation should be designed when tax revenues are used to finance expenditures on wildfire risk mitigation and when forest carbon storage has value. A model is solved sequentially in two stages by a forest tax planner and a representative private landowner. Our results show that neither an acre-based fee nor a unit-based harvest tax is able to incentivize the same levels of sequestration as a carbon price. However, a neutral tax like the acre-based fee is preferred when the external benefits of carbon sequestration are captured by the private landowner.

Key words: distortionary taxes, forest carbon offsets, neutral taxes, optimal forest taxation, Ramsey rule, rotation age, suppression expenditures

Introduction

Forests in the Pacific Northwest are highly productive both as sources of timber supply and for their potential to capture and store carbon (Kline et al., 2016; Diaz et al., 2018). Some of the most productive areas are privately owned, either by industry or family owners. Emerging markets for carbon offset credits are one mechanism that landowners in this region can utilize to receive compensation for carbon storage (Kline, Mazzotta, and Patterson, 2009; Latta et al., 2016). For example, landowners in Oregon are currently eligible to sell offset credits as part of California's regional cap-and-trade program. Several projects have recently been approved, including Green Diamond's carbon offset project, which covers 600,000 acres across southern Oregon (Green Diamond, 2022). Offset projects in the state are currently underway in Clatsop, Multnomah, Jefferson, and Klamath counties (Burtaw et al., 2019).

There is growing interest in enrolling more forests in the Pacific Northwest into a carbon offset credit program (Latta et al., 2016). Landowners can enroll their land into an offset program through "improved forest management" actions, which can entail a commitment to increase forest rotation ages beyond the length they would have planned in the absence of an offset program (California Air Resources Board, 2015, *ORS 526.786*). In return, landowners are eligible to sell

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The authors thank Jeff Kline of the US Forest Service, David Lewis of the Department of Applied Economics at Oregon State University, and an anonymous reviewer for helpful comments on this manuscript. This work was partially funded through the support of the USDA Forest Service, Pacific Northwest Research Station, under Joint Venture Agreement 20-JV-11261955-064. The authors gratefully acknowledge additional support from the US Department of Agriculture McIntire-Stennis program under project 1009830 and from Justin Baker of the Department of Forestry and Environmental Resources at North Carolina State University.

Review coordinated by Timothy Park.

offset credits to regulated entities in a regional offset auction, such as the California–Quebec joint auction administered by the California Air Resources Board.

However, these same forests are also subject to a risk of wildfire disturbances that may lead to unintentional releases of carbon and losses in carbon storage (Law and Waring, 2015). From 1980 to 2019, approximately 17% of total burned area across Oregon and Washington has affected private forestland, compared to 28% in 2020 alone (Campbell Global, 2020). The Labor Day Fires of 2020 impacted over 1 million acres of forestland in Western Oregon, of which about 40% was estimated to be private timberland. Such disturbances and the increasing risk of disturbances may also jeopardize the effectiveness of carbon offset programs that demand longer rotations (Kuusela and Lintunen, 2020).

To mitigate wildfire risk exposure, both federal and state forestry agencies manage wildfire ignitions and spread patterns at the landscape scale through annual investments in wildfire suppression programs and projects that remove hazardous fuels (Crowley et al., 2009; Lueck and Yoder, 2015). Both suppression and prefire hazardous fuels management undertaken by public agencies have been modeled as inputs that serve to reduce parcel-level burn probability (Rideout et al., 2008). Also, fuels management activities undertaken by private landowners at the stand level act as fire prevention measures that can decrease the frequency of disturbances experienced by the stand and neighboring stands (Amacher, Malik, and Haight, 2005a; Konoshima et al., 2008). Research has also found that increases in suppression program budgets can significantly reduce parcel-level fire frequency by improving initial attack response and the successful containment of large fires (Lee et al., 2013). Higher initial attack success rates can lower parcel-level burn probability estimates via reductions in crew response times (Rideout et al., 2016; Reimer, Thompson, and Povak, 2019).[1] Therefore, effective risk mitigation efforts on private lands encompass both public suppression investments and private or public fuels management, both of which serve to decrease the frequency of disturbances experienced by an acre of private forestland.

Federal land management programs actively fund both suppression and hazardous fuels management programs on federal lands (Gebert et al., 2008). However, at the state level, the main focus of wildfire management programs has traditionally been the suppression and containment of fires on private forestlands (Oregon Department of Forestry, 2021). For example, the Oregon Department of Forestry is responsible for suppressing wildfires on private lands in Oregon. Its expenditures on fire suppression activities are financed in part through forest taxes which include both unit taxes on harvest volume and acre-based assessments. Additional appropriations come from Oregon's General Fund. In the 2021–2023 biennial budget, $191 million was appropriated toward the agency's fire protection program, 47.6% of which was allocated from the state's General Fund and 9.7% of which was provided through federal funding (Oregon Department of Revenue, 2021). The remaining 42.3% of the biennial allocation was raised through forest-based taxes, including emergency sources provided by the Oregon Forest Land Protection Fund and Landowner Assessed Fees (Oregon Department of Revenue, 2021).

This funding of fire protection through forest-based taxes is not unique to Oregon. Other western states rely on forest taxes to finance state government provision of forest fire protection services, including California's Timber Yield Tax, Washington's Timber Tax, and Idaho's per acre fire protection fee. In California and Washington, forest tax receipts are raised for those states' general funds, which are used in part by state forestry agencies to fund fire suppression on state and private forestlands (Cook and Becker, 2017). However, in Washington, the majority of Washington's state-funded fire suppression responsibilities are financed through a separate landowner assessment levied on a per acre basis for landowners with more than 50 acres and a flat fee for landowners with

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[1] Maintaining an "initial attack success" rate above 98% is a stated federal policy objective (US Forest Service, 2007). In fiscal year 2018, 97% of forest fires on US Forest Service land were contained before reaching 300 acres in size (US Forest Service, 2019). Initial attack success is also a stated policy objective of state forestry agencies. In 2017, the Oregon Department of Forestry extinguished 94% of wildfires before they reached 10 acres in size (Oregon Department of Forestry, 2017).

less than 50 acres (Cook and Becker, 2017). Revenues for Idaho's Forest Protection Fund are raised through a separate fee assessed annually on a per acre basis; any suppression funding needed beyond the amount available in this account is drawn from the state's General Fund (Cook and Becker, 2017). Given this funding structure, wildfire risk on private lands depends partly on the level of taxes collected from private forestland owners since the tax receipts are used to fund fire preparedness and initial- and extended-attack suppression response. However, it is not well understood how such tax schemes that fund risk mitigation programs should be designed, especially when there is potential for forest carbon offset markets to incentivize longer rotations.

The purpose of our research is to analyze the optimal design of a state-level tax program that funds risk mitigation activities on private lands when the carbon stored in both forests and wood products has value. Following the literature on the design of forest tax policy, we use a stand-level model of an even-aged forest to investigate the effects of taxation (e.g., Koskela and Ollikainen, 2003; Amacher, Ollikainen, and Koskela, 2009, ch. 5). We restrict our attention to two tax instruments utilized in Oregon to raise revenue at the state level: (i) a unit tax on harvest (yield tax) and (ii) an annual acre-based assessment.[2] In our model, the social planner (a state forestry agency) is modeled as a Stackelberg leader that commits to a time-invariant tax policy when deciding both tax rates and annual expenditures on fire risk mitigation.[3] In the second stage of the model, a private forestland owner responds with their choice of the optimal harvest rotation age. Following Koskela and Ollikainen (2003), we assume the existence of a steady state, and so transitional dynamics of the optimal policy rule are ignored. A quantitative assessment of the optimal tax policy is conducted using a parameterized timber yield function for Western Oregon Douglas-fir (*Pseudotsuga menziesii*) and a production function that describes the transformation of risk mitigation expenditures into reductions in the fire arrival rate.

Prior research on stand-level carbon and timber management under disturbance risk has used the framework of a representative timberland owner to understand the interactions between fire risk management and carbon sequestration capacity (Daigneault, Miranda, and Sohngen, 2010; Ekholm, 2020). Daigneault, Miranda, and Sohngen (2010) use a numerical model to show that the introduction of a carbon market can induce more frequent management of hazardous fuels on the forest stand in order to better secure older-growth carbon revenues. By combining the optimal rotation models analyzed by Reed (1984) and Van Kooten, Binkley, and Delcourt (1995), Ekholm (2020) examines the impact wildfire risk on rotation choice when forest carbon has value. This leads to a model of multiple-use stand management subject to fire risk that is similar to the models analyzed by Englin et al. (2000).

In our study, we also use the optimal rotation framework that is based on the Faustmann approach to forest valuation (Samuelson, 1976). However, we add the additional complication that the fire arrival rate is dependent on public investment in suppression and this investment is explicitly financed through forest taxation. This linkage between forest taxation and public investment in suppression occurs through an intertemporal public budget constraint but has not yet been considered in the forest taxation literature. In contrast to the model presented by Crowley et al. (2009), we model the planner's suppression expenditures as having an influence on the arrival rate of an acre of forestland rather than on the stand's salvage possibilities. This allows us to capture the effects of a reduction in fire spread probability that accompanies an annually active suppression program, effectively lowering the fire arrival rate on an acre of forestland.

The impacts of different tax instruments on management choices have been studied in several papers using the optimal rotation framework (e.g., Klemperer, 1976; Chang, 1982, 1983; Amacher,

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[2] Other forest taxes levied in Oregon include property taxes on timberland and severance taxes paid by timberland holders with less than 5,000 acres who are eligible to defer property tax expenses. However, these tax revenues are raised for county governments and do not directly fund fire protection programs provided at the state level.

[3] The two-stage game-theoretic framework of the forest taxation problem in this paper further avoids "time inconsistency" problems that may be associated with a discretionary tax policy developed using optimal control theory (Kydland and Prescott, 1977).

Brazee, and Thomson, 1991). The findings from these studies have made a general distinction between two categories of taxes: distortionary and neutral taxes. Neutral taxes (e.g., acre-based assessments) have no impact on the optimal decision made by the private landowner at the intensive margin, whereas distortionary taxes (e.g., yield taxes) cause landowners to change management choices compared to the no-tax scenario. While knowing the responses in management choices (e.g., rotation age) induced by taxes is useful, state agencies still need to know what instruments are best on efficiency grounds and what tax rates should be set to achieve this efficiency. Some of the important determinants of this problem are whether the government faces binding revenue constraints and whether private landowners generate public goods valued by society (Amacher, Ollikainen, and Koskela, 2009, ch. 5).[4] In the absence of externalities, a government seeking to raise revenue from forest taxes should only use neutral taxes as suggested by the Ramsey rule of optimal taxation (Gamponia and Mendelsohn, 1987). However, when externalities are present together with government revenue constraints, the government may also need to resort to the use of distortionary taxes (Koskela and Ollikainen, 2003). In cases where both unit and *ad valorem* taxes on timber revenues are available, a combination of these two distortionary taxes can be neutral or used to achieve the socially optimal equilibrium in cases where private landowners do not internalize the social benefits of forest amenities (Amacher, Ollikainen, and Koskela, 2009, ch. 5).

Despite these well-established results on optimal forest taxation, there have been few attempts in the literature to understand the properties of first- and second-best taxation schemes on landowner management decisions and forestland values when disturbance risk is present. One exception is the work of Alvarez and Koskela (2007), who examine the effects of yield taxes and lump-sum taxation schemes on rotation length when landowners are risk neutral or risk averse in the presence of stochastic forest values. They find that these taxes raise the optimal harvesting threshold, leading to longer rotations regardless of risk preferences. However, their research has left unaddressed the influence of a planner's provision of risk reduction and its impact on a private landowner's disturbance risk. Our results demonstrate that the presence of endogenous risk in the optimal forest tax problem has implications for the choice of the tax instrument. Namely, an endogenous fire risk can alter the optimal second-best tax policy depending on whether the benefits of carbon sequestration are internalized by private landowners.

We find that acre-based assessments are still neutral from the perspective of the landowner. However, when receipts from acre-based assessments are raised for the purpose of funding risk mitigation, they will indirectly influence rotation lengths. We also show that the landowner's inability to internalize the social benefits of carbon sequestration can lead the planner to instead prescribe harvest taxes in lieu of the acre-based assessment. However, the capacity for the harvest tax to serve as a corrective (Pigouvian) instrument is limited by its small impact on net stumpage value. When fire risk is present but carbon sequestration benefits are internalized by the landowner, the acre-based assessment remains the preferred instrument and harvest taxes should be set to zero from a purely efficiency perspective. The optimal size of these taxes is sensitive to the carbon price, carbon storage parameters, and the effectiveness of the planner's expenditures on risk mitigation in terms of its ability to reduce the frequency of fire disturbances experienced by a private landowner.

Model

Landowner's Problem

A representative landowner manages an even-aged stand of trees. The per volume unit stumpage value is the delivered log price (p) net of harvesting costs (c_h) and the per volume unit harvest tax

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[4] Taxation schemes are said to be first-best if they are used align the decisions of the landowners with the socially optimal decisions. Additionally, if neutral taxes can be used to satisfy potential revenue constraints, the scheme is first-best. If neutral taxes are not available and distortionary taxes must be levied to meet an exogenous public revenue constraint, the tax scheme is said to be second-best.

(τ). The function $F(T)$ defines the volume of merchantable timber available for harvest at any given age T. The timber yield function takes the standard sigmoid shape.[5] The net revenue from harvest at age T is defined as

$$R(T) = (p - c_h - \tau) F(T). \tag{1}$$

The real discount rate is defined as r and the stand establishment cost by c_0.

The stand is subject to a wildfire risk. The average annual arrival rate is denoted by λ. Following Reed (1984), the fire arrival is modeled using a homogeneous Poisson process. We furthermore assume that the average arrival rate is a strictly decreasing function of the annual level of investment in risk mitigation, $\lambda'(y) < 0$ (Reed, 1989). Mitigation expenditures, y, are broadly defined as investment expenditures on fire preparedness, "initial attack" or "extended attack" wildfire suppression response, that serve to reduce fire spread rates. Let the random variable X denote the time between each forest growth cycle either due to a clearcut harvest or a wildfire disturbance. The probability of a fire disturbance occurring before age T is defined as $\Pr[X < T] = 1 - e^{-T\lambda(y)}$, while the probability of the stand reaching age T before a disturbance occurs is $\Pr[X = T] = e^{-T\lambda(y)}$. To simplify the model, we assume that there is no salvage harvesting.[6]

We follow the approach taken by Van Kooten, Binkley, and Delcourt (1995) to define the payments for carbon released and stored during the rotation. Let p_c denote the price of carbon, k be the carbon dioxide sequestered per unit volume of timber, and η represent the portion of the stand's carbon content released during a fire.[7] When a fire occurs before the chosen harvest age, T, the net future revenue of the nth rotation is given by

$$P_1 = e^{rX} p_c k \int_0^X F'(x) e^{-rx} dx - p_c k \eta F(X) - c_0 e^{rX}, \tag{2}$$

where the first term represents the compounded carbon payments up to age X; the second term, $p_c k \eta F(X)$, represents the cost of carbon released from a fire disturbance; and $c_0 e^{rX}$ gives the compounded cost of stand establishment. When the harvest age arrives before a fire destroys the standing timber stock, the net future revenues are given by

$$P_2 = R(T) + e^{rT} p_c k \int_0^T F'(t) e^{-rt} dt - p_c k (1 - \theta) F(T) - c_0 e^{rT}. \tag{3}$$

At the clearcut age, a fraction θ of the carbon content on the stand is sequestered in long-lived wood products.[8] The rest of the carbon is released at the time of the clearcut. If the landowner does not internalize the social benefits of carbon sequestration, then $p_c = 0$ so that $P_1 = -c_0 e^{rX}$ and $P_2 = R(T) - c_0 e^{rT}$.

To summarize the random payoffs, for the nth rotation we have

$$P_n = \begin{cases} P_1 \text{ if } X_n < T \\ P_2 \text{ if } X_n = T \end{cases}. \tag{4}$$

As shown by Reed (1984), a risk neutral landowner's objective function can be written as the expected present value of an infinite stream of n random future cash flows:

$$V = \mathrm{E}\left\{ \sum_{n=1}^{\infty} e^{-r(X_1 + X_2 + \cdots + X_n)} P_n \right\}. \tag{5}$$

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[5] The yield function is assumed to have the standard sigmoid shape, with $F'(T) > 0$, $F''(T) > 0$ before an inflection point and $F'(T) > 0$, $F''(T) < 0$ after an inflection point.

[6] Salvage harvesting can be incorporated as in Reed (1984) by decreasing the cost of a destructive event. Including the possibility of salvage harvesting will not qualitatively change our results.

[7] Below-ground carbon can be retained in soil following a fire disturbance, and some above-ground carbon may be retained following a low- to mid-severity fire.

[8] Long-lived wood products are those that do not decay before long-term use in construction (e.g., framing lumber, plywood, or structural wood panels manufactured from softwood timber).

We can also write the landowner's objective as a function of an endogenous choice T, so that the optimizing landowner may select a constant harvest age for all future rotations:

$$\max_{T\geq 0} V(T) = \frac{\mathrm{E}\left[e^{-rX}P\right]}{\mathrm{E}\left[1-e^{-rX}\right]} - \frac{\omega}{r}, \tag{6}$$

where the last term with parameter ω represents the present value of annual per acre tax expenses. For a given choice of T, equation (6) gives the expected value of the bare land conditional on the set of parameters that are exogenous from the perspective of the landowner, $\mathbf{\Omega} = (p, p_c, c_h, r, y, \tau, \omega, c_0, k, \theta, \eta)$. A risk-neutral landowner's objective is to maximize the expression in function (6) by choosing the optimal rotation age.[9] The first-order condition of the objective function (6) defines the optimal rotation age as a function of exogenous parameters $T^*(\mathbf{\Omega})$. The second-order condition for the maximum is assumed to hold.

We will note here, without proof, the expected signs of the optimal solution based on prior literature. Most of the comparative statics of the optimal solution to a forest rotation problem have been established by others (e.g., Chang, 1982; Amacher, Ollikainen, and Koskela, 2009). For example, a higher harvest tax will lengthen the rotation ($\frac{\partial T^*}{\partial \tau} > 0$), but acre-based site value taxes are neutral ($\frac{\partial T^*}{\partial \omega} = 0$). Higher timber prices (or, equivalently, a lower cost of harvest, c_h) will shorten the rotation age ($\frac{\partial T^*}{\partial p} < 0$), while higher establishment costs will lengthen it ($\frac{\partial T^*}{\partial c_0} > 0$). Higher discount rates will shorten forest rotation ages as the greater present value of timber revenues under a higher discount rate will raise the opportunity cost of delaying harvest (Gaffney, 1960). This effect holds when amenity values are present (Koskela and Ollikainen, 2001). Risk has the effect raising the *effective* or "risk-adjusted" discount rate (Reed, 1984; Insley and Lei, 2007) and so shortens the rotation length. Therefore, greater investment in risk mitigation will raise the rotation age ($\frac{\partial T^*}{\partial y} > 0$) since, by assumption, risk is reduced as fire protection expenditures increase (see Reed, 1989). Previous numerical models have shown that a larger fraction of carbon stored in wood products will shorten the rotation age ($\frac{\partial T^*}{\partial \theta} < 0$) (Van Kooten, Binkley, and Delcourt, 1995). Further, numerical modeling has shown that a larger carbon price and a larger quantity of carbon sequestered per unit of merchantable volume will raise the landowner's rotation age ($\frac{\partial T^*}{\partial p_c} > 0$, $\frac{\partial T^*}{\partial k} < 0$), whereas a greater percentage of carbon released from a fire will shorten the rotation age ($\frac{\partial T^*}{\partial \eta} < 0$), as long as these carbon stores and losses are priced as we have specified here. Ekholm (2020) use a numerical model to show that that higher carbon prices have a greater impact than a reduction in disturbance risk on an extended rotation age, although this result may depend on the ranges chosen for other parameters in the model.

Planner's Problem

The planner uses either a harvest tax or an area-based assessment to fund risk mitigation expenditures (or both). For a given rotation age T, the planner's intertemporal budget constraint can be written as

$$\frac{(r+\lambda(y))e^{-(r+\lambda(y))T}\tau F(T)}{r\left(1-e^{-(r+\lambda(y))T}\right)} + \frac{\omega}{r} = \frac{y}{r} + G, \tag{7}$$

where the first term on the lefthand side represents the present value of expected harvest tax receipts (see the online supplement). It is an expected value since the arrival of a fire event during any rotation also means that there are no harvest tax receipts from that rotation. Additionally, it is worth pointing out that larger harvest volumes, and hence longer rotations, translate to greater tax receipts. The second term on the lefthand side is the present value of area-based assessments. The right

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[9] Using the expressions in equations (2) and (3) and the Poisson process probabilities, the full expression for the objective function in equation (6) is derived in the online supplement (see www.jareonline.org).

hand side expresses all expenditures, including the present value of annual per acre risk mitigation expenditures (y/r) plus the present value of all other annual per acre revenue requirements minus per acre risk mitigation funding from nonforest tax sources (G) (see the online supplement). The sum of these expected present value revenues (lefthand side of equation 7) must equal the present value of annual expenditures (righthand side of equation 7.

The planner chooses the values of (ω,τ,y) with knowledge of the landowner's optimal response function, $T^*(\mathbf{\Omega})$. In other words, the planner acts as a Stackelberg leader. We assume that the planner's objective function is aligned with the landowner's objective but with the addition of the budget constraint. In its general form, the planner's problem can be written as

$$\max_{\tau\geq 0,\omega\geq 0,y\geq 0} V\left(T^*(\mathbf{\Omega})\right) \text{ subject to equation (7).} \tag{8}$$

Additionally, the expected bare land value must be nonnegative. Otherwise, forest ownership would be abandoned.

Given the parameter values, the solutions to the planner's problem provide information on the equilibrium productivity of the stand. One such measure is the expected long-run timber supply under stochastic production, as defined by Reed (1984), which is given by

$$\frac{\mathrm{E}[F]}{\mathrm{E}[X]} = \frac{\lambda F\left(T^*(\mathbf{\Omega})\right)}{\left(1 - e^{-\lambda T^*(\mathbf{\Omega})}\right)}. \tag{9}$$

Similarly, we can define the expected long-run carbon uptake under stochastic production as

$$\frac{\mathrm{E}[B]}{\mathrm{E}[X]} = \frac{\lambda k\left(F\left(T^*(\Omega)\right) + \lambda\int_0^{T^*(\Omega)} e^{-\lambda x}dx + F'\left(T^*(\Omega)\right)e^{-\lambda T^*(\Omega)}\right)}{\left(1 - e^{-\lambda T^*(\Omega)}\right)}. \tag{10}$$

These measures of stand productivity can be solved under different combinations of the exogenous parameters $\mathbf{\Omega}$ to determine the effects of different parameters on timber and carbon productivity.

Characterization of the solution to the planner's problem is analytically difficult and hence we resort to examining numerical solutions. However, it is still worthwhile to examine and compare in detail three potential policy scenarios: (i) only acre-based taxes are available to the planner, (ii) only yield taxes are available to the planner, and (iii) both taxes are available.

Case 1: Acre-Based Assessment

Suppose that only an area-based assessment is levied and there is no harvest tax $(\omega \geq 0, \tau = 0)$. Constraint (7) then defines the area assessment as a function of risk mitigation expenditures:

$$\omega = y + rG. \tag{11}$$

Using this relationship and the landowner's response function T^*, the planner's problem becomes

$$\begin{aligned}\max_{y\geq 0}\Bigg\{&\frac{r+\lambda(y)}{r\left(1-e^{-(r+\lambda(y))T^*}\right)}\Big\{e^{-(r+\lambda(y))T^*}\left[(p-c_h)F\left(T^*\right)+p_c k\theta F\left(T^*\right)\right]-c_0\\ &+rp_c k\left[\lambda(y)\left(\int_0^{T^*}e^{-\lambda(y)x}\left(\int_0^x e^{-rz}F(z)dz\right)dx+\int_0^{T^*}(1-\eta)e^{-(r+\lambda(y))x}F(x)dx\right)\right.\\ &\left.+\ e^{-\lambda(y)T^*}\int_0^{T^*}e^{-rz}F(z)dz\right]\Big\}-\frac{y+rG}{r}\Bigg\}.\end{aligned} \tag{12}$$

The planner's solution to problem (12) is the per acre expenditures on fire risk mitigation: $y^*(p_c,T^*(\mathbf{\Omega}))$. An application of the implicit function theorem on the solution gives an expression for the total effect of carbon prices on the planner's choice of the acre-based assessment:

$$\frac{d\omega^*}{dp_c} = \frac{\partial \omega^*}{\partial y^*}\left[\left(\frac{\partial y^*}{\partial p_c}\right) + \left(\frac{\partial y^*}{\partial T^*}\right)\left(\frac{\partial T^*}{\partial p_c}\right)\right], \tag{13}$$

where the first term is the direct effect on the planner's tax policy from a change in the carbon price, $\frac{\partial \omega^*}{\partial y^*}(\frac{\partial y^*}{\partial p_c})$; and the second term is the indirect effect, arising from the planner's reaction to the landowner's best response to the price change, $\frac{\partial \omega^*}{\partial y^*}(\frac{\partial y^*}{\partial T^*})(\frac{\partial T^*}{\partial p_c})$. The acre-based assessment required to finance the optimal expenditures defined by the solution to problem (12) is $\omega^* = y^*(p_c, T^*(\mathbf{\Omega})) + rG$. Therefore, $\frac{\partial \omega^*}{\partial y^*} = 1$. However, since we do not know the signs of $\frac{\partial y^*}{\partial p_c}$ or $\frac{\partial y^*}{\partial T^*}$, the sign of equation (13) is ambiguous. For plausible values of the model parameters, we expect to see the landowner's rotation age induce greater mitigation effort ($\frac{\partial y^*}{\partial T^*} > 0$) since a longer rotation age enhances the value of land at risk of disturbance. Likewise, we expect $\frac{\partial y^*}{\partial p_c} > 0$ so that the total effect will be positive. A positive relationship ($\frac{d\omega^*}{dp_c} > 0$) would suggest that an increase in carbon price would require the planner to raise acre-based assessments in order to finance greater expenditures on fire risk mitigation. Notice that when carbon sequestration benefits are not internalized by the landowner, then the indirect effect is 0.

Case 2: Harvest Tax

Suppose now that only a harvest tax is levied and there is no area-based assessment ($\omega = 0, \tau \geq 0$). Constraint (7) then implicitly defines the harvest tax as a function of risk mitigation expenditures, $\tau^* = \tau(y^*(p_c, T^*(\mathbf{\Omega})))$. Using this constraint, equations (6) and (10), and the landowner's response function $T^*(\mathbf{\Omega})$, the planner's problem becomes

$$\begin{aligned} \max_{y \geq 0} \Bigg\{ & \frac{r + \lambda(y)}{r\left(1 - e^{-(r+\lambda(y))T^*}\right)} \Big\{ e^{-(r+\lambda(y))T^*} \left[(p - \tau(y) - c_h) F(T^*) + p_c k\theta F(T^*)\right] - c_0 \\ & + r p_c k \Bigg[\lambda(y) \left(\int_0^{T^*} e^{-\lambda(y)x} \left(\int_0^x e^{-rz} F(z) dz \right) dx + \int_0^{T^*} (1-\eta) e^{-(r+\lambda(y))x} F(x) dx \right) \\ & + e^{-\lambda(y)T^*} \int_0^{T^*} e^{-rz} F(z) dz \Bigg] \Big\} \Bigg\}. \end{aligned} \tag{14}$$

Again, the planner's policy rule is written as $y^*(p_c, T^*(\mathbf{\Omega}))$ and we seek to investigate the effects of carbon price on this policy. An application of the implicit function theorem on the solution gives an expression for the total effect of carbon prices on the planner's choice of the acre-based assessment:

$$\frac{d\tau^*}{dp_c} = \frac{\partial \tau^*}{\partial y^*}\left[\left(\frac{\partial y^*}{\partial p_c}\right) + \left(\frac{\partial y^*}{\partial T^*}\right)\left(\frac{\partial T^*}{\partial p_c}\right)\right]. \tag{15}$$

The direct effect, $\frac{\partial \tau^*}{\partial y^*}(\frac{\partial y^*}{\partial p_c})$, may be positive or negative, particularly since τ may be increasing or decreasing over different domains of y (see the online supplement). The sign of the indirect effect is then also ambiguous, $\frac{\partial \tau^*}{\partial y^*}(\frac{\partial y^*}{\partial T^*})(\frac{\partial T^*}{\partial p_c}) \lesseqgtr 0$. This tells us that the planner's choice of the harvest tax may be larger or smaller with an increase in carbon prices. Hence, if carbon prices increase annual expenditures, then the planner may increase or decrease harvest tax rates ($\frac{d\tau^*}{dp_c} \gtreqless 0$). Again, note that when carbon sequestration benefits are not internalized by the landowner, then the indirect effect is 0.

Case 3: Both Tax Instruments

With both tax instruments available ($\omega \geq 0, \tau \geq 0$), the planner's problem can be solved using constrained optimization. The Lagrangian function for this problem is

$$
\begin{aligned}
L(y,\omega,\tau,\Lambda) = {} & \frac{r+\lambda(y)}{r\left(1-e^{-(r+\lambda(y))T^*}\right)}\Bigg\{ e^{-(r+\lambda(y))T^*}\left[(p-\tau-c_h)F(T^*)+p_c k\theta F(T^*)\right]-c_0 \\
(16) \qquad & + rp_c k\Bigg[\lambda(y)\Bigg(\int_0^{T^*} e^{-\lambda(y)x}\left(\int_0^{x} e^{-rz}F(z)dz\right)dx + \int_0^{T^*}(1-\eta)e^{-(r+\lambda(y))x}F(x)dx\Bigg) \\
& + e^{-\lambda(y)T^*}\int_0^{T^*} e^{-rz}F(z)dz\Bigg]\Bigg\} - \frac{\omega}{r} - \Lambda\left[G+\frac{y-\omega}{r}-\tau\left(\frac{(r+\lambda(y))e^{-(r+\lambda(y))}F(T^*)}{r\left(1-e^{-(r+\lambda(y))T^*}\right)}\right)\right],
\end{aligned}
$$

with the following first-order conditions:

$$
\frac{\partial L}{\partial y^*}=\frac{\partial L}{\partial \omega^*}=\frac{\partial L}{\partial \tau^*}=\frac{\partial L}{\partial \Lambda^*}=0. \tag{17}
$$

In equation (16), variable Λ is the Lagrange multiplier associated with the constraint from equation (7). At the solution, Λ^* gives the shadow price of an increase in tax revenues. Note that $\Lambda^* = 1$ since the neutral area-based tax is available (Koskela and Ollikainen, 2003).[10] The planner's solution is a time-invariant commitment to a tax and spending program (y^*, ω^*, τ^*).

Numerical Analysis

This section outlines the chosen parameters, functional forms, and the computational approach used to solve a specific case of the two-stage model. We focus on parameters specific to the management of forestlands in Oregon's western Cascade region. Table 1 reports all parameters and functional forms used in the numerical exercise.

Economic Parameters

We use price and cost information for delivered Douglas-fir logs, logging and hauling costs, and stand establishment costs reported by Diaz et al. (2018). The delivered log price is \$796 per thousand board feet (MBF), the cost of harvesting and transportation is \$400/MBF, and the establishment cost is \$200/acre. Recent carbon offset credit prices sold in the California–Quebec joint auction range from \$20 to \$35 per ton of CO_2 equivalent (California Air Resources Board, 2023), although we test the model using prices as high as \$60/ton. We set the annual real discount rate to equal 4%.

In Oregon, a Forest Products Harvest Tax or "FPHT" (*ORS 321.005–321.152*) is levied as a unit tax on timber harvests and has been recently set at a rate of \$5.97/MBF (Oregon Department of Revenue, 2023). Around 18% of FPHT receipts are used to finance wildfire risk reduction programs in the state through the Oregon Forestland Protection Fund (OFLPF) (Oregon Department of Revenue, 2023). The other 82% is used to fund research, forestry education, and the administration of the Oregon Forest Practices Act. Approximately \$12 million is raised annually from the FPHT (State of Oregon Legislative Revenue Office, 2013), so an annual average of \$9.84 million is raised from harvest taxes to fund public works not related to fire suppression. Area-based land taxes called "Fire Patrol Assessments" (*ORS 477.880* and *ORS 477.295*) are also used to fund initial attack fire suppression efforts and the OFLPF. The Fire Patrol Assessments are to be assessed as the

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[10] Additionally, nonnegativity constraints should be included in the Lagrangian equation (10), but they have been excluded here to simplify the notation.

Table 1. Parameters and Functional Forms Used for Numerical Analysis

	Exogenous Parameters	**Values**
k	Tons of CO2 sequestered per MBF of timber volume	10.53
η	Fraction of stand's carbon pool released during fire	$\eta \in \{0.22, 1.00\}$
θ	Fraction of carbon stored long-term in wood products	$\theta \in \{0.02, 0.42\}$
a	First parameter of the timber yield equation	101.4019
b	Second parameter of the timber yield equation	0.0247
c	Third parameter of the timber yield equation	3.0
β	Factor productivity of fire suppression	0.005
ρ	Output elasticity of fire suppression	0.21
p	Douglas-fir sawlog delivered price (\$/MBF)	796
c_h	Cost of clearcut harvest, including hauling (\$/MBF)	400
c_0	Stand establishment costs (\$/acre)	210
r	Real discount rate	0.04
G	Planner's budget constraint (\$)	$-0.17/r$
p_c	Carbon credit price (\$/ton)	[0,60]

	Planner's Policy Instruments	**Domain**
y	Annual expenditures on fire suppression programs (\$/acre/year)	$[0, \infty)$
τ	Unit tax on harvest (\$/MBF)	$[0, \infty)$
ω	Area-based tax used to fund fire suppression (\$/acre/year)	$[0, \infty)$

	Landowner's Decision Variable	**Domain**
T	Harvest rotation age or "period of production" (years)	$[0, \infty)$

	Technological Relationships	**Range**
$F(T) = a(1 - e^{-bT})^C$	Timber yield (MBF/acre)	$[0, \infty)$
$B(T) = k \int_0^T F'(t)dt.$	Carbon Sequestration (tons CO_2/acre)	$[0, \infty)$
$\lambda(y) = \beta y^{-\rho}$	Wildfire Arrival Rate	[0.001,0.03]

maximum of either \$0.6565/acre of a taxable lot per year (Elwood, Miller, and Landgren, 2006) or a fixed amount of \$18.75/year for taxable lots smaller than 28.65 acres (Cook and Becker, 2017; Elwood, Miller, and Landgren, 2006). However, this rate depends on the fire protection district in which the forest parcel is assessed (Cook and Becker, 2017).[11] Of these tax assessments, 100% of tax receipts from Fire Patrol Assessments are allocated toward fire protection and suppression services. Additionally, an average of \$3.61/acre in property taxes is levied on forestlands in western Oregon (Elwood, Miller, and Landgren, 2006). Including the Forest Patrol Assessments, this gives an expected annual land tax rate of \$4.31/acre.

All other suppression expenditures on 16 million acres (Oregon Department of Forestry) protected by the state of Oregon are funded from three other sources besides forest-based taxes: (i) the state's General Fund, (ii) a suppression cost insurance policy, and (iii) federal grants from the Federal Emergency Management Agency (FEMA). From 2006 to 2015, Oregon's General Tax Fund after insurance claims has covered an annual average of \$4.28 million of state suppression expenditures (this excludes contributions from "base layer" funding from Forest Patrol Assessments and Forest Urban Interface Lands Assessments). Insurance claims collected through the state's suppression cost insurance policy with Lloyd's of London have covered an average of \$5.0 million annually, while premiums have averaged \$1.35 million annually (Cook and Becker, 2017). Grants to suppress fires from FEMA have averaged \$8.4 million annually over this same period (Cook and Becker, 2017). In total, fire suppression costs funded through nonforest tax sources (including insurance premiums) have averaged \$0.79 per acre per year. Given that \$0.62 per acre per year is

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[11] An additional \$0.05/acre is charged for fire suppression services in Western Oregon (Cook and Becker, 2017).

raised from harvest taxes to fund nonsuppression-related public works, the revenues raised from harvest taxes are less than suppression expenditures from nonforest tax sources, so we use a revenue requirement of −\$0.17/acre (the present value of this annually occurring cost discounted at a rate of 4% is $G = 04.3$).

Biological Parameters

A sigmoid-shaped "von Bertalanfy" yield function, $F(T)$, is used to express the volume of merchantable Douglas-fir timber on per acre on a high-quality site in Western Oregon (Hashida and Lewis, 2019; Hudiburg et al., 2009). Coefficients provided by Hashida and Lewis (2019) provide the growth and yield parameters for a representative stand, presented in Table 1. With these parameters (a,b,c), the rotation age that maximizes volume (i.e., the "biological rotation age") occurs at age 77, where the mean annual increment (MAI) and the current annual increments (CAI) are equivalent. Following Van Kooten, Binkley, and Delcourt (1995), the total carbon sequestered by the forest from its establishment up to age T (given in tons per acre) is given by a scaled integration of the CAI curve (see Table 1). This form of the sequestration function allows carbon sequestration revenues to accumulate on the stand at a decreasing rate.

The arrival rate of a stand-replacing fire on the Douglas-fir dominated forests of the Western Cascades region is one in every 200+ years ($\lambda < 0.005\%$), while low- to mixed-severity fire occurs between once in every 35 years ($\lambda = 0.0286$) and once in every 200 years ($\lambda = 0.005$), (Wolf et al., 2015). This maximum fire return interval for a stand-replacing fire gives an upper bound that we can use for the factor productivity of suppression ($\beta = 0.005$).

Approximately 223 tons of carbon per acre are stored aboveground by age 100 in the Western Cascades region under minimal disturbance conditions (Hudiburg et al., 2009). Given the yield parameters (a,b,c), this suggests that about 2.87 tons of aboveground carbon are stored per MBF of merchantable timber volume at age 100 , requiring a parameter of $k = 10.53$ in the carbon benefits function.[12] We assume that between 2% (Harmon et al., 1996) and 42.1% (Diaz et al., 2018) of standing carbon is stored long-term in manufactured wood products. We also assume that 100% of stand-level carbon pools are released from fire under a "full destruction" scenario. However, we also test partial destruction by assuming that 22% of stand-level carbon pools are released from fire (based on expectations from mixed-severity fire data; see Law and Waring, 2015).

Model Calibration

To investigate the impact of wildfire suppression effectiveness, a relatively flexible production relationship is specified for the fire arrival rate (see Table 1). The parameter ρ is the output elasticity of suppression. Every percentage increase in suppression expenditures will reduce the arrival rate by ρ%. As this effectiveness of suppression expenditures increases, the parameter ρ increases and the fire arrival rate falls at a faster rate for any incremental increase in suppression. If $\rho < 1$, the suppression technology displays decreasing returns to scale. If $\rho > 1$, the suppression technology displays increasing returns to scale. Note that this specification of the arrival function assumes that fire occurrence is independent of the age of the forest. This derives from the assumption of a homogeneous Poisson process for the fire arrival, which means that fire arrival risk does not increase or decrease as the stand matures.

Given current tax rates, the revenue constraint, and typical rotation lengths for working timberlands in the study region (T^o), we calibrate the first-stage model (case 1) to solve for the unknown value of the output elasticity. This calibration is conducted for two alternative climate scenarios: (i) a frequent, low-severity fire regime ($\beta = 0.0286, \eta = 0.22$) and (ii) a low-frequency,

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[12] Since carbon is priced in terms of its carbon dioxide equivalent mass (California Air Resources Board, 2012), we set $k = 2.87 \times 3.67$ in the sequestration function, where 3.67 represents the mass of carbon dioxide equivalent per ton of carbon.

high-severity fire regime ($\beta = 0.005, \eta = 1.0$). This entails a root-finding problem to equate the planner's solution with observed site values (assuming no participation in carbon offset markets):

$$0 = V_s\left(T^o; \beta, \eta\right) - V_s\left(T\left(y^*(\rho; \beta, \eta)\right)\right). \tag{18}$$

Under the frequent, low-severity regime, if we assume that the arrival rate of high-severity fire is one event every 200 years ($\lambda = 0.005$) and the typical rotation age of plantation forests managed solely for timber in this region is between 35 and 40 years, we solve for an implied elasticity of $\rho = 0.61$ if $T = 35$ and $\rho = 0.48$ if $T = 40$. If instead we assume that a high-severity event occurs more frequently at a rate of once in every 100 years ($\lambda = 0.01$), the implied output elasticity for these rotation lengths is $\rho = 0.18$ if $T = 35$ and $\rho = 0.14$ if $T = 40$. The calibration exercise shows that assuming a more frequent fire regime (i.e., a larger λ), would imply less effectiveness of suppression investment under current management conditions.

Under the less frequent, high-severity fire regime, if we assume that the arrival rate of high-severity fire is one event every 333.3 years ($\lambda = 0.0030$) and the typical rotation age of planation forests managed solely for timber in this region is between 35 and 40 years, we solve for an implied elasticity of $\rho = 0.31$ if $T = 35$ and $\rho = 0.27$ if $T = 40$. If instead we assume that a high-severity event occurs more frequently at a rate of once in every 250 years ($\lambda = 0.0040$), the implied output elasticity for these rotation lengths is $\rho = 0.14$ if $T = 35$ and $\rho = 0.11$ if $T = 40$.

Results

Solutions to the model and the three different cases are called Stackelberg equilibrium solutions. These policy outcomes are subgame perfect equilibria. Alternative taxation schemes will shift the expected marginal value of delaying harvest and so will have differing impacts on both timber and carbon productivity. We examine these effects in Table 2, which shows the Stackelberg equilibrium when both taxes are available to the planner (case 3) under the baseline set of parameters ($\theta = 0.42$, $\eta = 1.0$, $\beta = 0.005$) and when the full benefits of carbon sequestration are either internalized or not internalized by the landowner. We see in Table 2 that when carbon benefits are internalized, a higher carbon price raises the optimal tax rates and the associated annual suppression expenditures per acre. This suggests that either the indirect effects in equations (13) and (15) are positive or that the positive direct effects of a higher carbon price dominate any potentially negative indirect effects from a higher carbon price. As a point of comparison, the Faustmann solution (no risk, no carbon benefits) is 36.4 years for the baseline set of parameters given in Table 1.

We also see from Table 2 that when there is no social value from forest carbon storage, the private and social bare land values are the same ($1,980/acre) and the stand is harvested every 34.5 years. When sequestration has value to society but its benefits are not accounted for by the landowner, the harvest tax acts as a Pigouvian instrument and generates a larger land value from society's perspective than what can be achieved with an acre-based land tax or a mix of both harvest taxes and the acre-based land tax. At a carbon price of $20/ton, the planner sets a harvest tax rate equal to $12.3/MBF, which enables annual suppression expenditures of $2.3/acre and an arrival rate of one event every 250 years ($\lambda^* = 0.0040$). This policy generates a response from the landowner to harvest once every 34.7 years and a bare land value of $1,973/acre.

However, with the harvest tax policy, the equilibrium rotation age is no longer able to accommodate society's value for carbon stored in forests, so the social value of the bare land is larger than the private value by $1,346/acre ($V_s^* = \$3{,}993$/acre). This result reflects the ineffectiveness of harvest taxes when used as a Pigouvian instrument. A harvest tax increase from $5/MBF to $15/MBF reflects only a $10 reduction in net stumpage value. We see in Table 2 that a higher carbon price will raise the planner's choice of the harvest tax rate, increase annual per acre suppression expenditures, and lengthen the landowner's rotation age, albeit by only a small margin since the landowner does not consider the value of carbon in their rotation decision and the planner's budget constraint is

Table 2. Solutions to Case 3 under Endogenous Fire Risk (with and without carbon payments)

Carbon Value	Acre-Based Tax (ω^*)	Unit Tax (τ^*)	Suppression Expenditures (y^*)	Arrival Rate (λ^*)	Rotation Age (T^*)	Social Bare Land Value (V_s^*)	Landowner's Bare Land Value (V^*)
$p_c = \$0$/ton (no value of carbon storage)	\$1.8/acre/year	\$0.0/MBF	\$1.2/acre/year	0.0043	34.5 years	\$1,980/acre	\$1,980/acre
$p_c = \$20$/ton (not internalized)	\$0.0/acre/year	\$12.3/MBF	\$2.3/acre/year	0.0040	34.7 years	\$3,319/acre	\$1,973/acre
$p_c = \$20$/ton (internalized)	\$3.1/acre/year	\$0.0/MBF	\$2.5/acre/year	0.0039	45.2 years	\$3,499/acre	\$3,499/acre
$p_c = \$30$/ton (not internalized)	\$0.0/acre/year	\$14.5/MBF	\$2.8/acre/year	0.0038	34.8 years	\$3,993/acre	\$1,967/acre
$p_c = \$30$/ton (internalized)	\$3.9/acre/year	\$0.0/MBF	\$3.3/acre/year	0.0037	51.5 years	\$4,397/acre	\$4,397/acre
$p_c = \$50$/ton (not internalized)	\$0.0/acre/year	\$18.9/MBF	\$3.9/acre/year	0.0036	34.9 years	\$5,348/acre	\$1,951/acre
$p_c = \$50$/ton (internalized)	\$5.8/acre/year	\$0.0/MBF	\$5.2/acre/year	0.0034	67.5 years	\$6,449/acre	\$6,449/acre

binding. The distortionary effect from the harvest tax is not large enough to offset the reduction in the rotation age from the landowner's inability to account for the benefits of carbon sequestration. Given a higher carbon price, the harvest tax policy will also increase the difference between private and social bare land values as the larger harvest tax lowers the net stumpage price.

In the case where carbon is internalized by the landowner, the planner's solution maximizes the land value when area-based land taxes are positive, but harvest taxes are set to zero (see Table 2). Under any given carbon price, the social bare land value is larger when carbon is internalized, reflecting society's loss from not having an effective Pigouvian instrument available to incentivize the socially optimal delay of the harvest age. In other words, the landowner's private management of carbon sequestration yields a longer rotation age (and higher land value) than what the planner can achieve with a distortionary tax if the landowner does not manage for carbon. From society's perspective, this loss is larger under a higher carbon price; there is a \$180 difference in V_s^* when $p_c = \$20$/ton and a \$1,101 difference in V_s^* when $p_c = \$50$/ton. In Table 2, we see that the private and social value of bare land coincide when the external benefits of carbon sequestration are accounted for by the landowner. For a carbon price of \$20/ton, the annual assessment is \$3.1/acre. This enables annual suppression expenditures of \$2.5/acre, which will yield an arrival rate of one event every 256 years ($\lambda^* = 0.0039$), a rotation length of 45.2 years, and a bare land value of \$3,499/acre. Also notice that a larger internalized value of carbon sequestration increases the stand's rotation age. An increase in the carbon price from \$20/ton to \$30/ton will lengthen the landowner's rotation age from 45.2 years to 51.5 years. An increase from \$30/ton to \$50/ton will lengthen the landowner's rotation age from 51.5 years to 67.5 years.

The above results (case 3) carry over to the scenarios where only one of the two tax instruments are available (cases 1 and 2) since in those scenarios the planner's policy exhibits corner solutions. Whether the planner uses an acre-based tax or a harvest tax depends on the landowner's capacity to internalize the social value of carbon sequestration. When the landowner does not consider the social value of carbon sequestration, case 3 is identical to the single tax solution of case 2 (i.e., harvest tax only). When the landowner does consider the social value of sequestration (e.g., via participation in an offset market), then case 3 is identical to the single-tax solution of case 1 (i.e., acre-based land tax only).

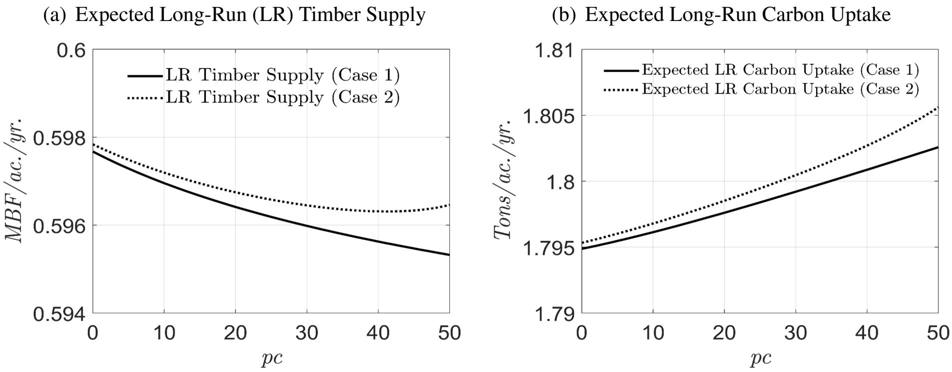
(a) Expected Long-Run (LR) Timber Supply
(b) Expected Long-Run Carbon Uptake

Figure 1. Equilibrium Long-Run Productivity with External Benefits of Carbon Sequestration

Notes: Expected long-run (LR) timber supply (Figure 1a) and expected long-run carbon uptake (Figure 1b) increase when taxes are raised to fund reductions in the fire arrival rate. Stand productivity is larger when a harvest tax is used in lieu of a per acre assessment.

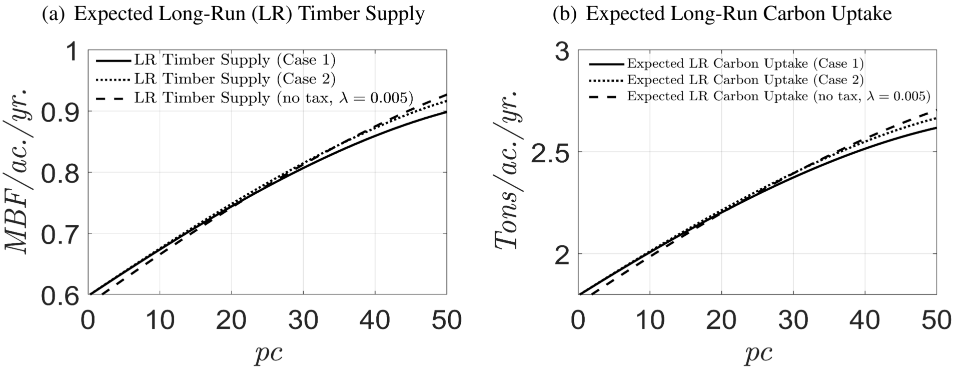
(a) Expected Long-Run (LR) Timber Supply
(b) Expected Long-Run Carbon Uptake

Figure 2. Equilibrium Long-Run Productivity with Internalized Benefits of Carbon Sequestration

Notes: Expected long-run (LR) timber supply (Figure 2a) and expected long-run carbon uptake (Figure 2b) increase when taxes are raised to fund reductions in the fire arrival rate. Stand productivity is larger when a harvest tax is used in lieu of a per acre assessment.

Equilibrium Timber and Carbon Productivity

To compare the impacts of the planner's tax and expenditure policy on equilibrium forest productivity, we show how expected long-run timber supply (equation 9) and expected long-run carbon uptake (equation 10) may change under different carbon prices when carbon benefits are not internalized (Figure 1) and when they are (Figure 2). These result shows that harvest taxes impact the rotation age through two separate channels, generating a larger overall impact on the stand's timber productivity when carbon benefits are internalized. First, there is a distortionary effect of higher harvest tax rates via a reduction in the fire arrival rate. Second, there is an additional distortionary effect of a harvest tax through its reduction in net stumpage value, which further lengthens the rotation age and increases the expected long-run average timber supply and carbon uptake.

Figure 1 compares the expected long-run timber supply and the expected long-run carbon uptake of the forest growing stock under the two single tax solutions (cases 1 and 2). Under cases 1 and 2, the expected long-run timber supply is lower under the planner's tax policy when carbon prices are higher. Under case 2, timber supply can increase under carbon prices higher than $43/ton

(Figure 1(a)). However, these changes in timber supply are small since the carbon price is not accounted for by the landowner and the harvest tax is ineffective at creating the desired Pigouvian response. There is also a monotonically decreasing relationship between expected long-run timber supply and the carbon price under for case 1 because the per acre land tax is neutral from the perspective of the landowner. Therefore, when carbon prices are higher, expected timber yield (equation 9) increases at a slower rate than the expected time between disturbances. Figure 1(b) shows the long-run equilibrium carbon productivity of the forest stand under various carbon prices. For both cases 1 and 2, a higher carbon price increases the planner's optimal tax rate, thereby raising suppression expenditures and lengthening the rotation age such that the expected carbon uptake (equation 10) increases at a slower rate than the expected time between disturbances.

However, we again note only a small change in the expected long-run carbon uptake when the social benefits of sequestration are not internalized. This is because reductions in the arrival rate via investment in risk reduction are not effective Pigouvian instruments since a removal of all risk would limit the rotation length to the Faustmann solution (no risk, no carbon), leaving the full social benefits of carbon still unaccounted for by the landowner. The reason for this low sensitivity of the rotation age to changes in the harvest tax rate is due to the simultaneous effect of the stumpage price (net of the harvest tax) on both the expected marginal benefit of delaying harvest and the expected marginal cost of delaying harvest. When harvest taxes increase, the expected marginal benefit of delaying harvest falls as future harvest revenues become less attractive, but the expected marginal cost of delaying harvest also falls since the landowner cannot reinvest as much in immediate harvest revenues at the risk-free rate of return. The net effect of a larger harvest tax is a slightly longer rotation age since it is identical to the effect of a lower stumpage price (see Samuelson, 1976; Amacher, Ollikainen, and Koskela, 2009).

The solutions are also plotted in Figure 2 for different carbon prices when the social value of carbon sequestration is internalized by the landowner. We see in Figure 2 that long-run equilibrium productivity is much more responsive to the carbon price when sequestration benefits are accounted for by the landowner. When carbon prices are low, the average stand productivity (equations 9 and 10) is larger under the planner's tax policy relative to the no-tax scenario (red curve) with a fixed arrival rate of one event every 200 years. However, the long-run timber supply (equation 9) is larger under a no-tax scenario at higher carbon prices since higher carbon prices and lower risk both work to prolong the time between harvests. We also see that expected annual timber productivity (Figure 2(a)) and carbon productivity (Figure 2(b)) are greater with a harvest tax (case 2) relative to the per acre land tax (case 1) across all carbon prices. In both cases, a higher carbon price raises the optimal tax rate and the associated annual suppression expenditures per acre, leading to greater average annual productivity. This again suggests that the positive direct effects in equations (13) and (15) dominate any potentially negative indirect effects.

Endogenous versus Exogenous Risk with a Carbon Externality

When taxes are raised for the purpose of funding reductions in wildfire risk, then risk is endogenously determined in the planner's problem. This determination of risk in the second-stage model naturally has an impact on the Stackelberg equilibrium rotation length. It is useful to compare the model solutions from such an endogenous risk case to the case where risk is exogenous from the planner's perspective (i.e., risk level is not responsive to suppression expenditures). As discussed above, when both tax instruments are available to the planner and the socially optimal level of carbon sequestration *is not* internalized by the landowner, the optimal policy instead consists of a harvest tax only ($\omega^* = 0, \tau^* > 0$). In Figure 3, where the landowner does not consider the social value of carbon sequestration and risk is exogenously determined by a fixed level of suppression expenditures ($\lambda(g_o = 0.79)$), increases in the carbon price will not affect the rotation length (dashed line). However, when risk is endogenously determined by harvest tax receipts ($\lambda(y^* + g_o)$), the optimal tax rate increases with higher carbon prices, so the resulting reduction in the fire arrival

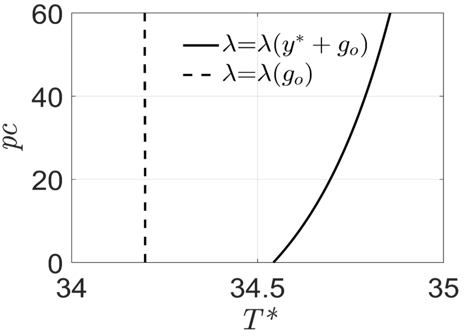

Figure 3. Rotation Length under Exogenous and Endogenous Risk (carbon sequestration benefits not internalized, $\omega^* = 0$, $\tau^* > 0$)

Notes: Responsiveness of the Stackelberg equilibrium rotation age (T^*) to higher carbon prices ()p_c) under the suppression level attainable without forest taxation (g_o, dashed line) and the suppression level attainable with forest taxation ($y^* + g_o$, solid line).

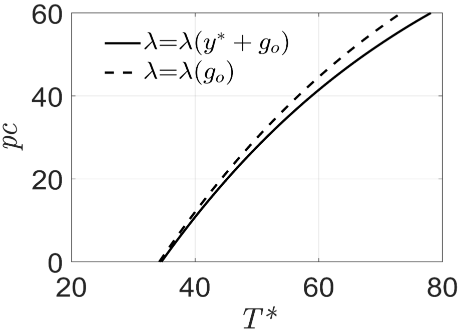

Figure 4. Rotation Length under Exogenous and Endogenous Risk (carbon sequestration amenities internalized, $\omega^* > 0$, $\tau^* = 0$)

Notes: Responsiveness of the Stackelberg equilibrium rotation age (T^*) to higher carbon prices ()p_c) under the suppression level attainable without forest taxation (g_o, dashed line) and the suppression level attainable with forest taxation ($y^* + g_o$, solid line).

rate lengthens the rotation age. The increase in the rotation age from the planner's management of risk is small since the higher carbon price does not have any influence in the second-stage problem. Additionally, the effect of harvest taxes on rotation age is small, especially when the log price is relatively large.

Endogenous versus Exogenous Risk with Internalized Value of Carbon Sequestration

When both tax instruments are available to the planner and the socially optimal level of carbon sequestration is internalized by the landowner (case 3), the optimal policy consists of a single tax instrument ($\omega^* > 0, \tau^* = 0$). Notice that, in Figure 4, when fire risk is exogenous (dashed line) and annual per acre suppression expenditures are fixed at a level obtained without forest taxation, (g_o = 0.79), the per acre land tax remains neutral and the only source of an increasing rotation length is a higher carbon price. However, when fire risk reduction is endogenous and afforded by acre-based land tax receipts (solid line), arrival risk falls such that the landowner will further increase their rotation length. When fire risk is endogenous, the Stackelberg equilibrium solution is more responsive to increases in the carbon price than in the case where the risk is exogenous.

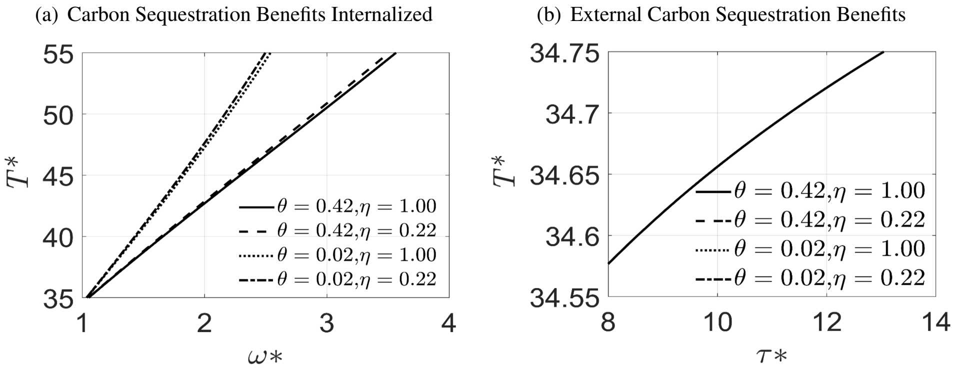

Figure 5. Distortionary Effect of Forest Taxes under Endogenous Risk

Notes: Subgame perfect equilibrium strategies (case 3) given shifts of the carbon storage parameters (η, θ) with carbon sequestration benefits internalized (Figure 5a) and with external carbon sequestration benefits (Figure 5b). Higher carbon prices (p_c) raise the planner's tax rate (ω^*or τ^*), generating the landowner's best response T^*.

Sensitivity to Carbon Storage Parameters under Endogenous Risk

We examine the sensitivity of the above results with respect to two model parameters of interest: (i) the portion of the stand's carbon released after a fire (η) and (ii) the share of carbon stored in long-lived wood products (θ). These parameters are controversial and difficult to estimate, so their sensitivity on equilibrium forest management outcomes is of interest. We focus on a range of values in Figure 4 that have been suggested by others (Harmon et al., 1996; Law and Waring, 2015; Diaz et al., 2018) and that is consistent with a shift in carbon prices from \$1.0/ton to \$30.0/ton. In Figure 5(a), the social value of carbon is internalized so we see the subgame-perfect equilibrium effect of endogenous risk and a larger acre-based land tax on the landowner's rotation age. Higher carbon prices require the planner to select a larger acre-based land tax to afford further reduction in the landowner's fire risk.

When the social benefits of carbon sequestration are not internalized by the private landowner (as in Figure 5(b)), the planner's harvest tax policy has a positive impact on the landowner's rotation length, but the effect is not as large since carbon prices do not matter from the landowner's perspective. Since the carbon storage parameters impact the net current value of sequestration and prices have a limited impact on rotation length when carbon benefits are not privately internalized (see Table 2), the shifts in Figure 5(b) are negligible. In both cases (Figures 5(a) and 5(a)), we see that a larger proportion of carbon retained $(1-\eta)$ following a fire will increase the rotation age (as it lowers the cost of a disturbance event). However, the solution is relatively more sensitive to changes in the percentage of carbon stored long-term in wood products (θ), since long-term storage has a positive impact on the benefit of harvest. Note that whether or not carbon storage is internalized by the landowner, the equilibrium rotation age is shorter when more carbon is stored long-term in wood products. This is because greater levels of long-term carbon storage decrease the social cost of harvesting so that there is a larger net current value of timber harvest, P_2.

Discussion and Conclusions

The main contribution of our research is to formally model and analyze the joint determination of optimal forest taxes and investments in risk reduction activities when carbon benefits are either privately internalized by a forestland owner or not internalized. Our numerical analysis shows that when carbon benefits are internalized by a private forestland owner, the planner's optimal tax policy adheres to the Ramsey rule and uses only the area-based tax, thus minimizing the distortionary effects of taxation on forest rotations. This finding supports the result of Koskela and

Ollikainen (2003). However, we generalize their findings by showing that when the frequency of fires experienced by a private landowner is endogenously determined by the present value of tax receipts and when carbon benefits are privately internalized, land taxes levied on a per acre basis are first-best optimal. This holds even in the presence of an exogenous public revenue target because land tax receipts are raised to fund public expenditures on risk mitigation. A higher acre-based land tax rate raises a landowner's tax liability but also directly benefits the private landowner via a reduction in the risk-adjusted discount rate.

We also learn from our model that when managing for carbon benefits is not internalized by landowners, the use of a yield tax is preferred to a mix of the two tax instruments. However, our results suggest that the yield tax is not an effective Pigouvian instrument and the resulting equilibrium is second-best optimal. This is attributable to the presence of an exogenous public revenue target, the small magnitude of the price effect in the land value problem, and the inability to utilize alternative types of taxes such as *ad valorem* taxes on timber revenues. As a result, the planner is constrained to using a yield tax instead of a mix of tax incentives for lengthening the optimal rotation age. Therefore, in this setting, the planner is unable to achieve as high a land value for society as is possible if the benefits of carbon sequestration are privately internalized by the landowner. A first-best option would be available if the revenue constraint were nonbinding, suggesting that funding for fire risk mitigation would be raised entirely from nonforest tax sources (e.g., federal transfers or general tax revenues). However, this would require the state-level forest tax planner to set tax rates in other areas of the economy or to rely more heavily on federal grants and transfers for covering fire suppression costs. This may burden other sectors within the state or the federal budget. In addition to the regulatory barriers associated with this alternative assumption, it may impose a distortion on other sectors of the economy as tax revenue is drawn away from use for other public services. For these reasons, we have assumed here that the state forest tax planner is subject to a binding revenue constraint, rendering a second-best solution in this case where other distortionary forest tax instruments (besides a unit tax on harvest) are unavailable.

More general policy conclusions relate to the trade-offs between forest carbon offset markets and forest-based taxes as an instrument for producing environmental amenities. A planner seeking a Pigouvian effect on the forest rotation age in carbon-productive, fire-prone regions (such as those in western Oregon) can do so either through an increase in the carbon price or through an increase in the harvest tax rate (such as the FPHT). However, if carbon prices cannot be internalized by landowners via a carbon offset market, our model finds that the capacity for Oregon's FPHT to achieve the socially optimal outcome is limited. State forest planning agencies do not currently regulate the availability of carbon credits and so have no ability to affect the prevailing price of carbon offsets. Therefore, the FPHT rate is an alternative but imperfect mechanism for producing a higher level of carbon sequestration on private forests since it affords risk reduction but does not lengthen a private landowner's rotation age enough to capture the social benefits of carbon sequestration. However, a simultaneous increase in carbon offset prices can reinforce a longer rotation age. Therefore, agency planners may need to consider the effect of high carbon credit prices resulting from the scarcity of tradable permits in carbon offset markets when setting their annual harvest tax rates.

This paper also shows that the optimal tax rates depend on the effectiveness of risk mitigation expenditures in terms of their ability to reduce the frequency of fire disturbances. To reduce our uncertainty about the possible values of this parameter, we conducted a simple model calibration exercise to approximate the output elasticity of risk mitigation implied by current management conditions under two alternative climate scenarios: (i) a high-frequency, low-severity fire regime, and (ii) a low-frequency, high-severity fire regime. We find that under the frequent fire regime, a 10% increase in annual risk mitigation expenditures reduces fire frequency between 1.4% and 6.1%. Under the low-frequency regime, a 10% increase in annual risk mitigation expenditures reduces fire frequency between 1.1% and 3.1 %. These parameters suggest decreasing returns to scale from the tax planner's investments in fire risk mitigation, indicating that there is diminishing marginal productivity of risk mitigation effort. However, we restrict our interpretation of this elasticity to the management conditions specific to Douglas-fir stands subject to wildfire risk in western Oregon where the state's primary method for reducing risk is an aggressive wildfire suppression response. Further research may be needed to develop more general estimates of the output elasticity of risk mitigation at regional or national scales. This parameter may find broader applications for use in public budgeting models or other numerical analyses of endogenous forest fire risk.

The optimization model in this paper makes several simplifications compared to the real-world policy environment. These simplifications should be considered before the model is deemed to be relevant for designing policy or informing policy decisions. First, assumptions can be relaxed about the nature of the fire arrival rate. Future modeling efforts may consider the possibility for the fire arrival rate to increase on the forest stand over time. Second, assumptions can be relaxed to incorporate the possibility for private landowners to explicitly undertake risk mitigation decisions by managing hazardous fuel loads and altering the fire arrival rate of their stand. Third, assumptions can be relaxed about the possibility of salvage harvest. Salvage possibilities are likely to raise land values since a larger expected salvageable portion of the timber stand will lengthen the rotation age (Reed, 1984; Amacher, Malik, and Haight, 2005b). Fourth, we have assumed risk-neutral decision making by both the landowner and the planner. Risk aversion of a landowner can lead to more frequent turnover of forestland (Alvarez and Koskela, 2007). In cases where the planner administering fire suppression is risk averse, there may be additional public spending on risk mitigation beyond the socially optimal level (Rossi and Kuusela, 2020).

Fifth, with the planner's credible commitment to a tax policy, discretionary changes in the tax policy cannot be anticipated by the landowner or internalized into the landowner's valuation problem. The potential for time-varying changes in tax and suppression policy to be internalized into the landowner's decision calculus may render time-varying policy rules ineffective at achieving revenue targets or socially optimal Pigouvian responses. Sixth, we have omitted several information problems that may constrain the planner's decision about optimal tax policy. Specifically, we have omitted the possibility for high- and low-risk landowners and for this information about risk tolerance to be knowledge exclusive to only the landowner. Admitting these information constraints into the first-stage optimization problem may transform the sequential equilibrium outcome. Specifically, incentive-compatibility and policy-participation constraints may induce landowners to reveal their risk type and for the planner to differentiate tax and suppression or fuel reduction policy across landowners of different risks. Seventh, we have ignored in this model the potential for forest carbon offsets to inadequately internalize the social benefits of carbon sequestration if knowledge about rotation lengths is hidden from offset purchasers. These "additionality" concerns may render offset markets incomplete such that our conclusions about optimal taxation in the presence of a positive carbon price may shift. Finally, we have assumed land use change as exogenous and so we have ignored the potentially distortionary effects of land value taxes or acre-based fees as they relate to a landowner's decision to sell land to nonforest uses. The effects of forest taxes on land use change (particularly in this setting where disturbance risk is present and carbon sequestration has value) represents an important area for further research.

[First submitted May 2021; accepted for publication January 2022.]

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Journal of Agricultural and Resource Economics 48(2):S1–S3
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ISSN: 1068-5502 (Print); 2327-8285 (Online)
doi: 10.22004/ag.econ.320670

Online Supplement: Carbon and Timber Management in Western Oregon under Tax-Financed Investments in Wildfire Risk Mitigation

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Formulation of the Forestland Value Equation

This online supplement gives the numerical expression for the landowner's objective function in equation (4). Since stand destruction is a random variable, the effective discount factor is random. Reed (1984) and Englin et al. (2000) show that the expected bare land value can be written as:

$$V(T) = \frac{\mathrm{E}[e^{-rX}P(X,T)]}{1-\mathrm{E}[e^{-rX}]} - \frac{\omega}{r}$$

Recalling that the probability density function for a Poisson distributed random variable X is $f(x) = \lambda(y)e^{-\lambda(y)x}$, the denominator simplifies to:

$$1-\mathrm{E}[e^{-rX}] = 1 - \int_0^\infty e^{-rx} f(x)dx = \frac{r\left(1-e^{-(r+\lambda(y))T}\right)}{r+\lambda(y)}$$

The numerator can be written as follows:

$$\mathrm{E}[e^{-rX}P] = \int_0^\infty e^{-rx}P(x,T)f(x)dx = \int_0^T e^{-rx}P_1(x,T)\,f(x)dx + e^{-rT}P_2(T)\,\mathrm{Pr}(X=T)$$

Recall: $\mathrm{Pr}(X=T) = e^{-\lambda(y)T}$. So, the numerator is written as:

$$\begin{aligned}\mathrm{E}[e^{-rX}P] = {} & \int_0^T e^{-rx}\left(e^{rx}p_c k\int\limits_0^x F'(z)e^{-rz}dz - p_c k\eta F(x) - c_0 e^{rx}\right)\lambda(y)e^{-\lambda(y)x}dx \\ & + e^{-rT}\left[(p-\tau-c_h)F(T) + e^{rT}p_c k\int\limits_0^T F'(t)e^{-rt}dt - p_c k(1-\theta)F(T) \right. \\ & \left. - c_0 e^{rT}\right] e^{-\lambda(y)T}\end{aligned}$$

Applying integration by parts:

The material contained herein is supplementary to the article named in the title and published in the *Journal of Agricultural and Resource Economics* (*JARE*).

$$\begin{aligned}\mathrm{E}[e^{-rX}P] = \int_0^T e^{-rx}\Bigg[&p_c k e^{rx}\left(e^{-r(x)}F(x) + r\int_0^x F(z)e^{-rz}dz\right) - p_c k\eta F(x) \\ &- c_0 e^{rx}\Bigg]\lambda(y)e^{-\lambda(y)x}dx \\ &+ e^{-(r+\lambda(y))T}\Bigg[(p-\tau-c_h)F(T) - c_0 e^{rT} - p_c k(1-\theta)F(T) \\ &+ p_c k e^{rT}\left(e^{-rT}F(T) + r\int_0^T e^{-rt}F(t)dt\right)\Bigg]\end{aligned}$$

We therefore have a full expression for the landowner's objective function in equation (4):

$$\begin{aligned}V(T) = \frac{r+\lambda(y)}{r\left(1-e^{-(r+\lambda(y))T}\right)}\Bigg\{&e^{-(r+\lambda(y))T}[(p-\tau-c_h)F(T) + p_c k\theta F(T)] - c_0 \\ &+ rp_c k\Bigg[\lambda(y)\left(\int_0^T e^{-\lambda(y)x}\left(\int_0^x e^{-rz}F(z)dz\right)dx\right. \\ &\left.+ \int_0^T (1-\eta)e^{-(r+\lambda(y))x}F(x)dx\right) + e^{-\lambda(y)T}\int_0^T e^{-rz}F(z)dz\Bigg]\Bigg\} - \frac{\omega}{r}.\end{aligned}$$

Formulation of the Expected Long-Run Harvest Tax Rate

Find the tax rate required to finance a given annual suppression costs: $\tau = \tau(y, \lambda(y), T^*)$. Following Reed (1984), the long-run expected present value of harvest tax receipts is:

(S1) $$\frac{\mathrm{E}[e^{-rX}\tau F(X)]}{1-\mathrm{E}[e^{-rX}]}.$$

The denominator of (S1) is as in the previous section. Recall: $f(x) = \lambda e^{-\lambda x}$ and $\Pr(X = T) = e^{-\lambda T}$. Then the denominator of (S1) can be written as:

(S2) $$1 - \mathrm{E}[e^{-rX}] = 1 - \int_0^\infty e^{-rx}f(x)dx = \frac{r\left(1-e^{-(r+\lambda(y))T}\right)}{r+\lambda(y)}$$

The numerator of (S1) is:

(S3) $$\mathrm{E}[\tau F(X)] = \tau F(T)\Pr(X = T) = \tau F(T)e^{-(r+\lambda(y))T}.$$

Re-writing (S1) using the expressions in (S2) and (S3), we have:

$$\frac{\mathrm{E}[e^{-rX}\tau F(X)]}{1-\mathrm{E}[e^{-rX}]} = \frac{\left(r+\lambda(y)\right)e^{-(r+\lambda(y))T^*}\tau F(T^*)}{r\left(1-e^{-(r+\lambda(y))T^*}\right)}.$$

Therefore, the present value of forest tax revenues in equation (5) is:

$$\frac{\left(r+\lambda(y)\right)e^{-(r+\lambda(y))T^*}\tau F(T^*)}{r\left(1-e^{-(r+\lambda(y))T^*}\right)} + \frac{\omega}{r}.$$

So, we can rearrange the planner's budget constraint from equation (5) to find the tax rate needed to raise enough funds to cover annual investment in risk mitigation: $\tau = \tau\left(y, \lambda(y), T^*(y)\right)$.

$$\tau\left(y, \lambda(y), T^*(y)\right) = \left(\frac{\left(r+\lambda(y)\right)e^{-(r+\lambda(y))T^*}F\left(T^*(y)\right)}{1-e^{-(r+\lambda(y))T^*(y)}}\right)^{-1}(y - \omega + rG).$$

Formulation of the Planner's Budget Constraint

The budget constraint for fire suppression expenditures is:

(S4) $$\gamma_1 \frac{\mathrm{E}[e^{-rX}\tau F(X)]}{1-\mathrm{E}[e^{-rX}]} + \gamma_2 \frac{\omega}{r} = \frac{y-g_o}{r}$$

The parameter g_o denotes the exogenous funds allocated to fire suppression (i.e., funds raised from a nonforest tax base such as a state's general tax fund). The parameters γ_1 and γ_2 give the fractions of each forest tax raised for the purposes of fire suppression. These parameters make it explicit how much forest tax revenue is flowing to other sources outside of fire suppression or the nonforest sector. An additional constraint expresses how much money is needed from the forest sector to fund an exogenous level of public expenditures unrelated to fire suppression $\overline{N}$:

(S5) $$\overline{N} = (1-\gamma_1)\frac{\mathrm{E}[e^{-rX}\tau F(X)]}{1-\mathrm{E}[e^{-rX}]} + (1-\gamma_2)\frac{\omega}{r}$$

Factor out the terms in the 2nd constraint (S5) and rearrange:

$$\gamma_1 \frac{\mathrm{E}[e^{-rX}\tau F(X)]}{1-\mathrm{E}[e^{-rX}]} + \gamma_2 \frac{\omega}{r} = \frac{\mathrm{E}[e^{-rX}\tau F(X)]}{1-\mathrm{E}[e^{-rX}]} + \frac{\omega}{r} - \overline{N}$$

Notice the left-hand side is the same as constraint (S4), so we can write:

$$\frac{\mathrm{E}[e^{-rX}\tau F(X)]}{1-\mathrm{E}[e^{-rX}]} + \frac{\omega}{r} - \overline{N} = \frac{y}{r} - \frac{g_o}{r}.$$

Define $G = \frac{\overline{N}-g_o}{r}$. This gives the relevant budget constraint presented in equation (5).

$$\frac{\mathrm{E}[e^{-rX}\tau F(X)]}{1-\mathrm{E}[e^{-rX}]} + \frac{\omega}{r} = \frac{y}{r} + G.$$

Therefore, G represents the [exogenous] present value of the sum of all other annual revenue requirements (other expenditures) minus suppression funding collected from other sources. If additional tax revenues are needed to fund nonforest related public expenditures, then $\bar{G}$ goes up. If more funding from nonforest tax sources is collected for suppression (e.g., from the General tax fund or from federal transfers), then $\bar{G}$ goes down.