Influencing natural forest disturbance through timber harvesting: Tradeoffs among disturbance processes, forest values, and timber condition

**Abstract:** Governments provide technical, political, and financial incentives to encourage timber harvesting for the purpose of mitigating natural forest disturbance. This paper dynamically integrates forest management and a natural disturbance regime to estimate live and salvage timber harvest subsidies needed to incorporate these disturbance-mitigating benefits before and after three types of natural disturbance. Results indicate that the degree of forest mortality may be a poor metric for gauging management response to large disturbance events. The live timber harvesting subsidy is substantial but quickly falls after a disturbance event. In contrast, salvage subsidies increase following a disturbance event but remain modest.

**Keywords:** Forest disturbance; Forest management; Harvest subsidies; Insect outbreak; Salvage harvesting; Storm event; Wildfire

**JEL Codes:** Q23, D62, Q54, Q57

**Running head:** Influencing forest disturbance

**Funding Statement:** This research was supported by the Utah Agricultural Experiment Station, Utah State University, and approved as journal paper number 8517.

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Depending on one’s perspective, natural forest disturbances such as wildfires, insect outbreaks, and storm damage are critical drivers of ecosystem function, challenges to natural resource policy, or sources of economic loss. While the average rate of natural disturbance in temperate forests ranges from 0.5% to 2% per year (Runkle 1985), occasional large disturbance events create vast amounts of forest mortality with ecological benefits ranging from species diversity (Connell 1978), nutrient cycling (Bormann and Likens 1994), and ecosystem productivity (Sprugel 1991). Large disturbance events also represent a shock to timber markets leading to shortened timber rotations (Reed 1984), an overall dampening of timber investments (Yin and Newman 1996), and millions of dollars in economic losses (Butry, et al. 2001; Holmes 1991). Losses are expected to increase as climate change (Dale, et al. 2001; Logan and Powell 2009; Overpeck, Rind and Goldberg 1990) and historic patterns of forest management (Sims, et al. 2013) amplify the rate of natural forest disturbance.

Timber harvesting can mitigate this increase in natural disturbance when disturbance events are endogenously determined by forest structure (Holmes, Prestemon and Abt 2008). Preemptive harvest of live trees may lessen the severity of future wildfires and insect outbreaks providing benefits beyond timber market values. Following a large disturbance event, forest managers may temporarily switch from harvesting live to killed and mortally damaged trees that remain commercially viable (salvage harvesting). This transition may mitigate or exacerbate future disturbances depending on the characteristics of the disturbance process (Amman and Ryan 1991; Brown, Reinhardt and Kramer 2003; Foster and Orwig 2006; McIver and Starr 2000; Saab and Dudley 1998; Stephens 1998). Forest managers often ignore the impact of their
harvest decisions on the disturbances they face due to the complexity of the interactions (Long 2009) and stock externalities created as disturbances spread beyond management boundaries (Sims, Aadland and Finnoff 2010).

To capture these disturbance-mitigating benefits, governments intervene to encourage both live and salvage harvesting. Despite large federal subsidies, little guidance exists concerning the disturbance-mitigating benefit of live and salvage harvesting. Economic factors such as preferences for timber versus nontimber benefits, the reduction in harvestable live timber inventory, and the market substitutability of live and salvage timber all influence harvesting in response to disturbance (Holmes 1991; Prestemon and Holmes 2004; Prestemon and Holmes 2000). However, the ability of harvesting to influence natural disturbance depends on the degree of disturbance endogeneity and synergisms among different types of disturbance (Paine, Tegner and Johnson 1998) requiring the dynamic integration of multiple disturbance processes within a decision-making framework (Seidl, et al. 2011; Turner 2010). Unfortunately, much of the economic literature either treats disturbance events as exogenous (e.g., Reed and Errico 1987) or looks at forest management in response to a single endogenously determined disturbance process (Daigneault, Miranda and Sohngen 2010; Konoshima, et al. 2008; Sims, Aadland and Finnoff 2010; Thorsen and Helles 1998; Yoder 2004).

This paper extends the existing literature by modeling the live and salvage harvest decision in response to a natural forest disturbance regime which, unlike a single disturbance event or process, accounts for the temporal dynamics of interactions between forest disturbance processes (White and Pickett 1985). By considering the dynamics of these disturbance processes, forest growth and mortality, and incentives facing forest
managers, the model isolates the timber and nontimber considerations shaping a manager’s anticipation of and response to large natural disturbance events. The analysis combines traditional multiple-use management and more recent calls by ecologists for “disturbance-based management” (Long 2009).³

This more extensive modeling approach produces three results. First, the type of disturbance event can lead to differences in the optimal response even when controlling for the severity of the disturbance. This implies the degree of forest mortality alone may be a poor metric for gauging management response to large disturbance events and cautions against relying on timber markets to determine harvest levels following natural forest disturbance. Second, the disturbance-mitigating subsidy for live timber harvesting is substantial but falls sharply after a major disturbance event. In contrast, subsidies to encourage salvage harvesting increase after a major disturbance event but remain modest because salvage timber is an imperfect substitute for live timber. Due to this substitutability, efforts to encourage salvage harvesting 1) leave more live trees in the forest which exacerbates the rate of other disturbances and 2) must be accompanied by a decrease in adult harvest subsidies. Lastly, recent trends in public forest management may result in more or less salvage harvests depending on the type of disturbance that creates the salvage.

Forest Management in a Natural Forest Disturbance Regime

The integrated model involves a resource-based economy where society derives welfare $U$ from timber $T$, a composite commodity $Q$, and nontimber ecosystem services proxied by the stock of living adult trees $A_H$.⁴,⁵ The model is dynamic and time set in discrete
annual increments \( t = 1, \ldots, \infty \) to match the seasonal nature of disturbance processes. For instance, insect outbreaks and wildfires generally occur in the summer whereas hurricane season is in the fall.

**Economic Behavior**

For simplicity, assume a log-linear utility specification:

\[
U(Q_t, T_t, A^H_t) = \ln(Q_t) + (1 - \alpha) \ln(T_t) + \alpha \ln(A^H_t),
\]

where \( \alpha \) determines society’s relative preference for timber and nontimber benefits.\(^5\)

Timber products \( T \) can be produced through harvests of live adult trees \( h^A \) or harvests of dead (salvage) trees \( h^S \). Society is willing to substitute adult harvests for salvage harvests at a constant rate of \( \eta < 1 \):

\[
T_t = h^A_t + \eta h^S_t,
\]

to reflect the lower quality of salvage timber. Such an approach implies 1) the resource rents earned from salvage are a constant mark-down of the resource rents earned from adult harvests and 2) the demand function for timber products is a function of the adult timber price only (Holmes 1991).

Harvesting adult and salvage timber requires labor and depends on harvestable stock according to Schaeffer harvesting functions \( h^A_t = \rho L^A_t A^H_t \) and \( h^S_t = \rho L^S_t S^H_t \) where \( \rho \) is a scale parameter measuring harvest efficiency. The inclusion of stocks in the harvest functions is a simple way of accounting for complex spatial considerations inherent in timber harvesting. For instance, fewer trees will result in longer distances to transport logging equipment into the forest and drag felled trees back to logging roads.
Labor endowments are fixed over time and normalized so that \( L = L_t^Q + L_t^A + L_t^S \). 1 units of labor are annually allocated between the production of the composite commodity \( L_t^Q \) and the harvest of live adult \( L_t^A \) and salvage \( L_t^S \) trees. The composite commodity is treated as the numeraire good with labor the only input in production: \( Q_t = L_t^Q \).

Forest dynamics

Because of the importance of forest structure in determining disturbance events (Holmes, Prestemon and Abt 2008), the forest resource is divided into three size classes: seed base \( X \), young trees with diameter at breast height (DBH) less than 8 inches \( Y \), and adult trees with DBH 8 inches and larger \( A \). Each size class is measured in trees (or seeds) per acre. The laws of motion for the beginning-of-period density in each size class are given by:

\[
X_{t+1} = (1 - \delta_X)X_t + b_Y Y_t + b_A A_t
\]

\[
Y_{t+1} = (1 - \delta_Y - \lambda)Y_t + \delta_X X_t
\]

\[
A_{t+1} = (1 - \epsilon - \pi_t - \lambda \gamma_t)A_t + \delta_Y Y_t - h_t^A.
\]

Each period, a proportion (\( \delta_X \) and \( \delta_Y \)) of the seed base and young trees mature to the successive size class. Contributions to the seed base are made by the young and adult size class at rates \( b_Y \) and \( b_A \). Only adult trees are considered viable for commercial harvest \( h_t^A \). Adult trees are also subject to storm damage (at rate \( \epsilon \)) and an endogenously determined rate of insect damage \( \pi_t \). Wildfire disturbance affects both young and adult trees and occurs through a combination of an exogenous rate of ignition \( \lambda = 1/I \) and an endogenous rate of severity \( \gamma_t \). The probability of a fire occurring depends on the average
number of years between fire events (fire return interval, I) which differs by forest type and region. Fire occurrence is assumed to immediately result in a ground fire that kills all young trees. The ability of a ground fire to transition to a crown fire that may kill adult trees is endogenously determined by the amount of combustible fuel in the forest (Van Wagner 1977). While these natural forest disturbances may be viewed as probabilistic events from the perspective of an individual landowner (Reed 1984; Yoder 2004), history indicates that at least one large natural disturbance occurs within a national forest in most years. As a result public land managers are more likely to view natural forest disturbance as a rate.

The final two forest categories dictate the amount of standing dead trees (salvage) and downed woody debris. Timber is commercially viable after being killed by natural disturbance, but recovery volumes typically decay over time. The decline in recoverable volume depends on moisture, oxygen, temperature, and the amount of damage (Fahey et al., 1986). Like the young tree stock, salvage and downed woody debris are completely consumed when a fire takes place. The evolution of salvage timber is approximated by a geometric declining function that depends on recoverable volume decay (θ), disturbance-induced mortality from the adult stock, and salvage harvesting (h^S_t):

\[ S_{t+1} = (1 - \theta - \lambda)S_t + (\epsilon + \pi_t + \lambda Y_{t+1})A_t - h^S_t. \]

Once timber is no longer commercially viable it becomes downed woody debris which experiences natural decay at rate ω: \[ D_{t+1} = (1 - \omega - \lambda)D_t + \theta S_t. \]

The structure of equations (5) and (6) imply that growth and mortality occur prior to harvesting. Thus the tree density responsible for growth, mortality, and decay will
differ from the density available for harvesting. A fraction of the adult stock at $t$ succumbs to storm-, insect-, and fire-induced mortality $(\varepsilon + \pi_t + \lambda y_t)A_t$ and moves to the salvage stock. The remaining fraction survives and combines with new growth $\delta Y Y_t$ to provide harvestable adult stock: $A_t^H = (1 - \varepsilon - \pi_t - \lambda y_t)A_t + \delta Y Y_t$. Likewise, the fraction of the salvage stock that does not decay or burn $(1 - \theta - \lambda)S_t$ combines with storm- and insect-induced mortality to create harvestable salvage stock: $S_t^H = (1 - \theta - \lambda)S_t + (\varepsilon + \pi_t + \lambda y_t)A_t$. A portion of the harvestable stock may be harvested and the remainder forms the adult and salvage stock at the beginning of period $t+1$.

*Disturbance regime*

In terms of areal extent and economic impact, insect outbreaks and storm events (hurricanes, wind and ice storms) are the most damaging natural forest disturbance processes in the U.S. (Dale, et al. 2001). These disturbances fall into two general categories differentiated by the influence of forest structure (Holmes, Prestemon and Abt 2008; Taylor and Carroll 2004). Abiotic disturbance processes like storm events are characterized by an exogenous rate of disturbance: all forest stands have an equal probability of experiencing disturbance irrespective of forest structure (tree size and density). In contrast, biotic disturbances such as insect outbreaks are characterized by an endogenous rate of disturbance that is typically increasing in tree size. Wildfire is the third most damaging disturbance process (Dale, et al. 2001) and is unique in that it possesses both abiotic and biotic properties (Holmes, Prestemon and Abt 2008). For instance, the probability of ignition is determined by lightning strikes and arson which is largely independent of forest structure. However, tree size and forest density impact the severity of fire once ignition occurs (Van Wagner 1977).
Of all biotic disturbances, bark beetles are the most obvious in their impact due to the fact they must kill host trees in order to reproduce (Heavilin, Powell and Logan 2007). Given their potential for damage and availability of information on their dynamics, bark beetles are selected as the biotic disturbance process. The probability a tree will die from bark beetle attack is determined by the interaction between the number of beetles attacking the tree and the level of tree resistance (Raffa 2008). Following Heavilin and Powell (2008), the rate of successful attack is

\[ \pi_t = \frac{B_t^2}{B_t^2 + a^2}, \]

where \( B_t \) is the number of beetles per acre and \( a \) reflects the resistance of susceptible trees to beetle attack in year \( t \). Larger resistance implies more beetles required for a successful attack. This parameter varies from year to year as trees become drought-stressed or as the emergence distribution of beetles become more synchronized in time, making the population of attacking beetles more effective in attacking new hosts. Equation (7) is characteristic of the type III functional response in predator-prey interactions (Holling 1959) and captures threshold dynamics characteristic of bark beetle (Berryman, et al. 1985; Raffa and Berryman 1983).

The relationship between bark beetle populations and forest density involves a one-year lag as adult beetles typically emerge from the tree a year after initial infestation (Logan and Bentz 1999). Beetle density at time \( t \) is therefore a function of the density of successfully attacked trees at \( t-1 \) and the number of newly emerged beetles per successfully attacked tree, \( \varphi \):

\[ B_t = \varphi (\pi_{t-1} A_{t-1})^\nu, \]
where $\nu$ is a curvature parameter, modeling proportional decrease in successful brood production when large beetle populations begin to over-utilize available host resources. Together, (7) and (8) capture the endogenous nature of the biotic disturbance process.

The amount of fuel in the forest determines the proportion of adult trees that burn and die by regulating how badly adult trees are scorched and the likelihood that a ground fire becomes a crown fire (Van Wagner 1977). Fuel load is defined as the sum of young, adult, and salvage trees and downed woody debris in the forest:

\begin{equation}
F_t = Y_t + A_t + S_t + D_t.
\end{equation}

Following Daigneault et al. (2010) the proportion of adult trees that die if a wildfire occurs is increasing in the fuel load at a decreasing rate:

\begin{equation}
\gamma_t = \frac{zF_t}{1 + zF_t},
\end{equation}

where $0 < z < 1$ determines the relationship between fuel load and fire severity.

**Forest management**

Adult and salvage harvest levels are chosen to solve the following problem

\begin{equation}
\max \{h_t^A, h_t^S\} \sum_{t=1}^{\infty} \beta^{t-1} U(Q_t, T_t, A_t^H),
\end{equation}

where $0 \leq \beta \leq 1$ is the discount factor. The objective function in (11) is solved subject to the timber preference condition in (2), forest dynamics, the disturbance regime, non-negativity constraints ($h_t^A \geq 0$ and $h_t^S \geq 0$), and the labor constraint:

\begin{equation}
\frac{h_t^A}{\rho A_t^H} + \frac{h_t^S}{\rho S_t^H} + Q_t = 1.
\end{equation}
Each year a benevolent social planner decides how many adult and salvage trees to harvest given preferences, the stock of trees, the beetle population, and the amount of fuel in the forest.\textsuperscript{7} There are economic tradeoffs between harvesting live and salvage trees given the rate of substitution between adult and salvage $\eta$ and preferences for timber products and nontimber benefits $\alpha$. There are also ecological tradeoffs due to the relative influence of adult and salvage on disturbance processes and interactions between disturbances. For example, salvage harvesting reduces the fuel load but leaves more beetle-susceptible trees in the forest.

Assuming an interior solution, the first-order condition requires adult harvesting to proceed until the current and discounted future marginal benefits and costs are equal. The current and discounted future benefit of harvesting an additional adult tree is:\textsuperscript{8}

$$
\frac{(1 - \alpha)}{T_t} + \sum_{k=2}^{\infty} \beta^k (\psi^A_{t+k} - \psi^S_{t+k}) \frac{\partial A^H_{t+k}}{\partial \pi_{t+k}} \frac{\partial B_{t+k}}{\partial B_{t+k}} \frac{\partial A_{t+1}}{\partial h^A_t} \\
+ \beta (\psi^A_{t+1} - \psi^S_{t+1}) \frac{\partial A^H_{t+1}}{\partial \pi_{t+1}} \frac{\partial A_{t+1}}{\partial h^A_t} + \sum_{k=2}^{\infty} \beta^k (\psi^A_{t+k} - \psi^S_{t+k}) \Delta^A \rightarrow S \rightarrow fire_{t+k} \\
+ \sum_{k=3}^{\infty} \beta^k (\psi^A_{t+k} - \psi^S_{t+k}) \Delta^A \rightarrow D \rightarrow fire_{t+k} + \sum_{k=3}^{\infty} \beta^k (\psi^A_{t+k} - \psi^S_{t+k}) \Delta^seed \rightarrow fire_{t+k},
$$

where

$$
\psi^A_t = \frac{(1 - \alpha)}{T_t} - \frac{T_t}{Q_t \rho (A^H_t)^2} + \frac{\alpha}{A^H_t}
$$

and

\[
\Psi^S_t = \frac{\eta(1 - \alpha)}{T_t} - \frac{S^H_t - h^S_t}{Q_t \rho (S^H_t)^2}
\]

is the marginal net benefit of an adult and salvage tree at time \( t \). Harvesting an adult tree produces a timber benefit in period \( t \) determined by society’s preferences for timber (first term). Equation (13) also reveals the disturbance-mitigating benefits of adult harvesting. Adult harvesting in period \( t \) indirectly reduces insect risk by lowering the insect stock in \( t + 2 \) which recursively lowers insect risk in all future periods. The value of this reduction in insect risk depends on the difference between the net benefit of a live and salvage tree (second term). Adult harvesting in period \( t \) also lowers the severity of fires by reducing the adult stock in \( t + 1 \) (third term). The fourth and fifth terms capture the effect of adult harvesting on the salvage and downed woody debris stocks which in turn lower fire severity. The last term is the present value at \( t + 3 \) of lower fire damage in all future periods working through the seed base. Due to the relatively slow growth of a forest, this effect is negligible.

The current and discounted future cost of harvesting an additional live tree is

\[
\frac{1}{Q_t \rho A^H_t} + \beta \{ \Psi^A_{t+1}(1 - \varepsilon - \pi_{t+1} - \lambda \gamma_{t+1}) + \Psi^S_{t+1}(\varepsilon + \pi_{t+1} + \lambda \gamma_{t+1}) \} + \sum_{k=3}^{\infty} \beta^k \Psi^A_{t+k} A_{t+k}^seed
\]

(14)

The first term represents the labor cost of harvesting in terms of reduced production of the composite commodity. Harvesting an adult tree in \( t \) means that tree is not available to provide timber and nontimber benefits in \( t+1 \) and will increase the cost of harvesting
other trees in future periods through the stock effect. The opportunity cost in \( t+1 \) of harvesting an adult tree in \( t \) is an expected value because the tree may be killed by storm damage (at rate \( \varepsilon \)), bark beetles (at rate \( \pi_t \)), or wildfire (at conditional rate \( \gamma_t \)) before next period’s harvesting decision. The last term is negligible and represents the present value at \( t + 3 \) of the reduction in the future seed base caused by adult harvesting in \( t \).

A similar first-order condition requires salvage harvesting to proceed until:

\[
\frac{\eta(1 - \alpha)}{T_t} + \beta(\psi_{t+1}^A - \psi_{t+1}^S) \frac{\partial A_{t+1}^H}{\partial y_{t+1}} \frac{\partial y_{t+1}}{\partial S_{t+1}} \frac{\partial S_{t+1}}{\partial h_t^S} 
\]

\[
(15) \quad + \sum_{k=2}^{\infty} \beta^k (\psi_{t+k}^A - \psi_{t+k}^S) \frac{\partial A_{t+k}^H}{\partial y_{t+k}} \frac{\partial y_{t+k}}{\partial D_{t+k}} \frac{\partial D_{t+k}}{\partial S_{t+1}} \frac{\partial S_{t+1}}{\partial h_t^S} = \frac{1}{Q_t \rho S_t^H} + \beta(1 - \theta - \lambda)\psi_{t+1}^S.
\]

Equation (15) states that salvage harvesting should occur until the marginal net benefit of salvage timber (the left side) equals its opportunity cost (the right side). The marginal net benefit of salvage harvesting is composed of the current marginal timber value (first term) and the marginal benefit of a reduction in wildfire severity. Harvesting a salvage tree in period \( t \) lowers the severity of fires by reducing the salvage stock in \( t + 1 \) and the stock of downed woody debris in \( t + 2 \). These reductions in fire severity lead to more adult trees (second and third terms). The first term on the right side of (15) represents the labor cost of harvesting in terms of reduced production of the composite commodity. Harvesting a salvage tree in period \( t \) means that tree is not available to provide timber benefits in period \( t+1 \) and will increase the cost of harvesting other trees in future periods through the stock effect. This opportunity cost recognizes that a salvage tree may be worthless for commercial timber harvest in \( t+1 \) due to decay or fire.
Harvest subsidies to capture disturbance-mitigating benefits

Due to ecological complexity and stock externalities (Long 2009; Sims, Aadland and Finnoff 2010), disturbance-mitigating benefits of harvesting may be ignored by individual forest managers. To internalize the disturbance-mitigating benefits in (13) and (15), consider a time-varying subsidy on adult ($\sigma_t^A$) and salvage ($\sigma_t^S$) harvests financed through a lump-sum transfer ($\Sigma_t$). With the addition of the subsidy the budget constraint becomes:

\[
\frac{h_t^A}{\rho A_t^H} + \frac{h_t^S}{\rho S_t^H} + Q_t = 1 + \sigma_t^A h_t^A + \sigma_t^S h_t^S - \Sigma_t. \tag{16}
\]

This approach conveniently allows $\sigma_t^A \rho A_t^H$ and $\sigma_t^S \rho S_t^H$ to be interpreted as the percent reduction in adult and salvage harvesting costs due to subsidies. Individual forest managers respond by maximizing utility subject to the subsidized budget constraint. This approach yields the alternative conditions for optimal adult and salvage harvesting

\[
\begin{align*}
\frac{1 - \alpha}{T_t} - \frac{1}{Q_t \rho A_t^H} + \frac{\sigma_t^A}{Q_t} = & \sum_{k=3}^{\infty} \beta^k \left( \frac{1 - \alpha}{T_{t+k}^A} - \frac{A_{t+k}^H - h_{t+k}^A}{Q_{t+k}^A \rho (A_{t+k}^H)^2} + \frac{\alpha}{A_{t+k}^H} + \frac{\sigma_{t+k}^A}{Q_{t+k}^A} \right) \Delta_{t+k}^{seed} + \\
& \beta \left\{ \left( \frac{1 - \alpha}{T_{t+1}^A} - \frac{A_{t+1}^H - h_{t+1}^A}{Q_{t+1}^A \rho (A_{t+1}^H)^2} + \frac{\alpha}{A_{t+1}^H} + \frac{\sigma_{t+1}^A}{Q_{t+1}^A} \right) \left( 1 - \pi_{t+1} - \lambda y_{t+1} \right) \\
& + \left( \frac{\eta(1 - \alpha)}{T_{t+1}^S} - \frac{S_{t+1}^H - h_{t+1}^S}{Q_{t+1}^S \rho (S_{t+1}^H)^2} + \frac{\sigma_{t+1}^S}{Q_{t+1}^S} \right) \left( \epsilon + \pi_{t+1} + \lambda y_{t+1} \right) \right\}
\end{align*}
\]

and

\[
\begin{align*}
\frac{\eta(1 - \alpha)}{T_t} - \frac{1}{Q_t \rho S_t^H} + \frac{\sigma_t^S}{Q_t} = & \beta (1 - \theta - \lambda) \left( \frac{\eta(1 - \alpha)}{T_{t+1}^S} - \frac{S_{t+1}^H - h_{t+1}^S}{Q_{t+1}^S \rho (S_{t+1}^H)^2} + \frac{\sigma_{t+1}^S}{Q_{t+1}^S} \right).
\tag{18}
\end{align*}
\]
The optimal time-varying subsidy rate that captures the disturbance-mitigating benefits of adult and salvage harvesting is:

\[ \sigma_t^A = Q_t \beta \left[ \sigma_{t+1}^A (1 - \epsilon - \pi_{t+1} - \lambda \gamma_{t+1}) + \sigma_{t+1}^S (\epsilon + \pi_{t+1} + \lambda \gamma_{t+1}) \right] + \psi_{t+1}^A \frac{\partial A_{t+1}^H}{\partial \gamma_{t+1}} \frac{\partial A_{t+1}}{\partial h_{t}^A} \]

\[ + Q_t \left[ \sum_{k=2}^{\infty} \beta^k (\psi_{t+k}^A - \psi_{t+k}^S) \frac{\partial A_{t+k}^H}{\partial \pi_{t+k}} \frac{\partial B_{t+k}}{\partial \gamma_{t+k}} \frac{\partial A_{t+k}}{\partial h_{t}^A} + \sum_{k=2}^{\infty} \beta^k \psi_{t+k}^A \Delta_{t+k}^{A-S-\text{fire}} \right] \]

\[ + \sum_{k=3}^{\infty} \beta^k \psi_{t+k}^A \Delta_{t+k}^{A-D-\text{fire}} + \sum_{k=3}^{\infty} \beta^k \psi_{t+k}^A \Delta_{t+k}^{\text{seed-\text{fire}}} + \sum_{k=3}^{\infty} \beta^k \psi_{t+k}^A \Delta_{t+k}^{\text{seed}} \]

and

\[ \sigma_t^S = Q_t \beta (1 - \theta - \lambda) \sigma_{t+1}^S \]

\[ + Q_t \left[ \beta \left( \psi_{t+1}^A \frac{\partial A_{t+1}^H}{\partial \gamma_{t+1}} \frac{\partial S_{t+1}}{\partial h_{t}^S} \right) + \sum_{k=2}^{\infty} \beta^k \left( \psi_{t+k}^A \frac{\partial A_{t+k}^H}{\partial \gamma_{t+k}} \frac{\partial D_{t+k}}{\partial S_{t+k}} \frac{\partial S_{t+1}}{\partial h_{t}^S} \right) \right] \]

Solving the forest manager’s problem with subsidy rates in (19) and (20) internalizes all disturbance-mitigating benefits.

**Dynamic Response to Natural Forest Disturbance**

In the absence of a major disturbance event, storm-, fire-, and beetle-induced mortality is at a constant low level allowing the forest to reach a steady-state. To illustrate the long-run effect of each disturbance process on forest structure and management, table 1 provides steady state values as disturbance processes are removed from the disturbance regime. These steady states are selected as initial conditions. The initial condition with insect, fire and storm disturbance is chosen as a benchmark and is obtained by solving
time invariant versions of (2)-(10) and (13)-(15) given model parameters in table 2.

While the model is general enough to be applied to any forest type, forest-growth parameters \( (\delta_X, \delta_Y, b_Y, b_A) \) and decay rates \( (\theta, \omega) \) are selected to provide steady-state values that reflect a lodgepole pine forest type which is common in the western U.S. and also prone to natural forest disturbance. Mature lodgepole pine stands contain anywhere from 350 to 550 trees per acre and hold anywhere from 25,000 to 160,000 viable seeds per acre (Koch 1996). Younger stands may contain up to 8,000 trees per acre and 14,000 to 500,000 viable seeds per acre (Fowells 1965). Stand densities for other pine species and mixed stands are likely to be much lower. These forest-specific parameters also allow the forest to re-establish within 80 to 140 years following a stand-replacing disturbance (Lotan and Critchfield 1990). Decay rates for lodgepole pine are based on Dobie and Wright (1978) and Plank (1984). The discount rate is set to 4% in accordance with USDA Forest Service practice (Row, Kaiser and Sessions 1981). The assumption \( \eta = 0.5 \) is based on de Steiguer et al. (1987) who indicate salvage prices are typically one-half to three-quarters of green timber prices.

Of particular importance are the parameter values that govern the disturbance processes. The assumption of a homogenous forest resource conveniently allows \( \varepsilon \) to be interpreted as the annual proportion of forestland impacted by storm damage. According to Dale et al. (2001), an average of less than 1% of forestland in the U.S. is impacted by hurricanes, tornadoes, and ice storms each year. In the benchmark case \( \varepsilon = 0.006 \) and in each of the two counterfactual scenarios \( \varepsilon = 0 \). Depending on forest type, fire regimes vary from frequent fires of low severity \( (I < 50 \text{ and } \gamma_t < 25\%) \) to less frequent stand-replacing fires \( (I > 200 \text{ and } \gamma_t > 75\%) \) (Romme, et al. 2006). An intermediate fire
return interval \((I = 80)\) and \(z = 0.0004\) is selected for the benchmark case to ensure the effective steady-state rate of adult mortality due to fire and storm are similar \(\left(\frac{I}{I} \gamma = \frac{0.425}{80} = 0.0053\right)\). For the counterfactual scenario with insect disturbance only, \(\lambda = 0\) is imposed. Bentz (2006) indicate \(\varphi = 4500\) beetles per infested tree. Based on Forest Service aerial detection survey data, Heavilin and Powell (2008) estimate the ratio of beetle fecundity to tree resistance as \(\frac{\varphi}{a} = 0.071\) suggesting \(a = 63,800\) beetles per acre.\(^{10}\) Finally Berryman et al. (1985) report a decreasing relationship between beetle offspring and the number of beetle attacks per square meter of tree surface area. This indicates decreasing reproductive returns from increases in adult-tree mortality and implies a degree of curvature in (8). In the absence of any additional quantitative results, let \(\nu = 0.5\). Collectively these parameters result in a 0.6% rate of endemic beetle mortality and a 1.7% rate of total natural disturbance mortality in the benchmark model at steady state.

The optimal disturbance-mitigating subsidy absent a large disturbance event (i.e., at steady state) would reduce the cost of adult and salvage harvesting by 25.12% and 0.01% respectively in the benchmark model. The positive subsidy in the absence of a major disturbance event represents efforts to encourage harvesting that would alleviate future insect outbreaks and wildfires. Major disturbance events are simulated by a one-period change in model parameters that shock variables off steady state. To illustrate the impact of different types of disturbance events and the importance of accounting for multiple interacting disturbances, the analysis proceeds in two directions. First, the response in forest structure and management to each type of disturbance event is simulated for the benchmark model. Changes in model parameters are selected such that
adult tree mortality is equivalent for each type of disturbance. This assumption is made to aid comparisons across different disturbance events and could easily be relaxed for empirical studies on a given forest stand where certain disturbance events may be more damaging than others. Changes in model parameters could be due to environmental shocks such as warm winter temperatures that increase insect survival or drought that weakens tree defenses or increases the flammability of fuel. Selecting the steady state as the initial condition ensures that the dynamic response can be entirely attributed to the disturbance event and not the initial conditions. The paper then considers the response in forest structure and management to an insect outbreak as the other disturbance processes are removed from the benchmark model.

**Biotic disturbance: bark beetle outbreak**

A beetle outbreak is introduced in the model through a one-time decrease in host tree resistance \((a)\) that increases \(B_t\) from its respective steady state. An outbreak is assumed to persist until the number of trees per acre killed by beetles falls below the steady state value. In order to trigger a salvage harvest in the benchmark scenario, the beetle outbreak must immediately kill half of the adult tree stock with a total of 150 adult trees per acre killed over the course of the four year outbreak (figure 1). The initial pulse in beetle population leads to a sharp decline in adult trees and a sharp increase in salvage trees. With fewer hosts (adult trees) beetle populations decline, decreasing the severity of the outbreak and allowing for a gradual regeneration of adult trees.

Immediately following the outbreak, the stock of harvestable adult trees is much lower which increases the direct cost of harvesting adult trees through the stock effect
and the opportunity cost of lost nontimber values. In contrast, the direct cost of harvesting salvage trees is lower with more salvage trees in the forest. The opportunity cost of harvesting salvage trees is also reduced as adult tree mortality is higher than decay in the salvage class. In response, forest managers initially reduce adult timber harvesting but do not supplant lower adult harvests with salvage harvests. However, by the next period the salvage stock has sufficiently increased to lower harvesting costs to a level that makes salvage harvesting economically viable. With salvage harvesting costs low and adult harvesting opportunity costs high, managers choose to engage in salvage harvesting and temporarily forgo adult timber harvesting for a single period. Less than 1% of trees killed during the outbreak are salvaged.

Adult and salvage harvest subsidies needed to achieve this level of harvest following natural disturbance are presented in figure 2. Immediately following the start of the beetle outbreak, the adult subsidy rate is cut in half and continues to decline for the next seven years before it begins to return to steady state. During this time adult harvest subsidies only decrease harvest costs by 0.4-6%. In contrast, the salvage subsidy rate immediately doubles. Since salvage harvesting only occurs in one period, a one-time subsidy that reduces salvage harvest cost by 0.08% should be paid following an insect outbreak that kills 150 trees per acre.

The same one-time decrease in $a$ is applied to counterfactual scenario 1 (insect and fire disturbance only) and counterfactual scenario 2 (insect only). As shown in figure 3, accounting for multiple interacting disturbances lowers the total amount of timber harvesting and produces less salvage harvesting in response to a major disturbance event. Just as a forest can only persist with a limited rate of natural disturbance (Runkle 1985),
an interior steady state for the dynamic system will only arise with a bounded rate of disturbance-induce mortality. As disturbance processes are added to the model, the rate of disturbance-induced mortality is divided between more disturbance processes and the rate of steady state insect disturbance must decline. The result is less severe insect outbreaks for the same environmental shock. While the addition of wildfire (Scenario 1) provides an added fuel reduction benefit that triggers an additional period of salvage harvesting, the overall dampening of outbreak severity encourages less salvage harvesting following a major disturbance event.

*Abiotic disturbance: storm events*

A major storm is introduced in the benchmark model by increasing $\varepsilon$ for a single period. Unlike a beetle outbreak, a major storm event focuses mortality on a single period as seen in figure 1. To ensure the total amount of tree mortality is equivalent to the benchmark beetle outbreak simulation, $\varepsilon$ is temporarily increased to produce adult tree mortality of 150 trees per acre in this period. This pulse in mortality also leads to a sharp decline in adult trees and increase in salvage trees.

In contrast to the delayed period of salvage harvesting following a beetle outbreak, salvage harvesting occurs immediately following a storm event and continues for two periods. This discrepancy arises due to differences in the length of the biotic and abiotic disturbance process. While adult tree populations continue to decline for three periods following beetle outbreak, adult populations begin recovering immediately after the storm event. The shortened duration of disturbance mortality has two critical effects on harvesting incentives. First it increases the opportunity cost of adult harvesting
relative to the biotic disturbance case. Following the start of a beetle outbreak there is an incentive to harvest adult trees to avoid losing value due to the imminent threat of beetle-induced mortality. There is no such incentive following a storm event. The shorter duration of mortality also decreases the opportunity cost of harvesting salvage trees. Whereas salvage stocks are being replenished by beetle-induced mortality during an outbreak, there is only a one-time inflow of salvage trees following a storm event. Recognizing that salvage trees will only decline due to decay, managers respond by immediately harvesting 2% of trees killed by the storm.

Compared to the insect outbreak, the adult harvest subsidy exhibits a more drastic decline following a major storm event. Since salvage harvesting occurs for two years, optimal management response calls for a 0.1% reduction in salvage harvest costs in the first year and a 0.09% reduction in the second year following a storm event. The declining subsidy reflects the decreasing stock of salvage trees as time passes.

Mixed disturbance: wildfire

Given its endogenous and exogenous characteristics, a major fire event is created in the benchmark model through a one-time increase in the fire return interval (I) and the fuel flammability parameter (γt). This two-part shock disproportionately impacts the adult tree stock but also recognizes that a more active fire season will impact young tree mortality as well as the stock of salvage trees and downed woody debris. Once again, a fire event that kills 150 trees per acre is simulated for purposes of comparison (figure 1). Like the abiotic storm event, the period of forest mortality is relatively short so salvage harvesting takes place immediately following a major wildfire. However, the stock of
adult trees recovers more slowly since wildfire also decreases the stock of young trees. The less rapid recovery of adult trees triggers a third period of salvage harvesting as managers are reluctant to harvest from the adult stock and further deter its recovery. Due to this prolonged period of salvage harvesting, 2.4% of trees killed by fire are salvaged. The adult and salvage harvest time path can be replicated by immediately decreasing the adult harvest subsidy and making salvage harvest subsidy payments for three years following fire. These payments only reduce the cost of salvage harvesting by 0.1 - 0.2%.

**The Effect of Fire Regime and Management Objectives on Salvage Harvest**

To this point the analysis has assumed a forest that is equally valued for timber and nontimber forest benefits and characterized by a moderate fire regime. However, many public forest lands are managed predominately for nontimber benefits and are characterized by more extreme fire behavior. In addition, two key changes in public forest management have impacted natural disturbance processes over the past century. First, fire suppression activities have increased the fire return interval $I$ in many forest types leading to less frequent but more severe fires (Romme, et al. 2006). Second, timber harvesting on public forests has decreased substantially since 1990 (Smith, et al. 2009) due to increasing public outcry for other nontimber benefits from public forests (Wear and Murray 2004). This shift can be captured by increasing the relative weight society places on nontimber benefits $\alpha$.

Given the environmental shocks described in the previous section, the number of trees killed by each type of disturbance event now varies since changes in $I$ and $\alpha$ produce alternative steady states. To account for these differences in disturbance-induced
mortality, figure 4 shows how different assumptions about fire regime and forest management in the benchmark model alter the percentage of killed trees salvaged. Two results can be gleamed from this analysis. First, forests managed predominately for nontimber benefits will likely experience less salvage harvesting. This suggests that the historic increase in nontimber ecosystem service provision on public forests should cause managers to reduce the amount of salvage harvesting regardless of the type of disturbance that created the salvage timber.

Second, the type of disturbance matters when evaluating harvest decisions in forests with different fire regimes. For example, forests with longer fire return intervals should see more salvage harvesting following insect outbreaks (figure 4a). Increasing the length of the fire return interval decreases the rate fire impacts the forest and allows the endemic population of insects to increase. An environmental shock that causes an insect outbreak becomes more damaging because insect outbreaks are the dominant disturbance type in this forest. Similar results are found following a storm event although the increase in salvage harvesting is less pronounced (figure 4b). In contrast, forests with shorter fire return intervals increase the rate fire impacts the forest and decreases the endemic population of insects. An identical environmental shock becomes more damaging and triggers more salvage harvesting in this fire regime because fire is the dominant disturbance (figure 4c). When the fire return interval is 120 years or longer, a larger fire-inducing shock is needed for salvage harvesting to occur.

Conclusions
Management response to natural disturbance must carefully balance economic concerns for recouping lost timber value and preserving nontimber benefits with the ecological realization that disturbance is an important part of forest health and function. As the rate of natural forest disturbance continues to increase, this balance becomes increasingly difficult. This paper represents an initial step towards dynamically integrating multiple disturbance processes with forest management decision-making (Seidl, et al. 2011; Turner 2010).

Findings suggest that the degree of forest mortality alone is a poor metric for gauging management response. For example, forest managers optimally continue to harvest adult trees at the start of an insect outbreak but immediately halt adult harvesting and start salvage harvesting after a storm event or wildfire of equal severity. The initial pulse in salvage harvesting is largest following a storm event but the longest period of salvage harvesting (3 years) follows a wildfire resulting in a larger total amount salvaged. These results suggest that market-driven responses based only on changes in live timber inventory will be unable to guide timber harvesting following disturbance events.

In light of likely market failures, the disturbance-mitigating subsidy associated with harvesting live adult trees is shown to be substantial, but falls sharply after a large disturbance event. This suggests that while government incentives to encourage preemptive harvesting may be justified, temporal flexibility will be needed to account for changes in disturbance-mitigating benefits before and after a major disturbance event. In contrast, salvage harvest subsidies critically depend on the type of disturbance that created the salvage but will only reduce the cost of salvage harvesting by 0.1 - 0.2% at most. There are two reasons for this modest response. First, substitutability in the timber
market suggests that efforts to increase salvage initiate further declines in adult harvesting. Due to tradeoffs among disturbance types, increasing salvage limits one type of disturbance but may actually increase the overall rate of forest disturbance. Figure 5 shows the long-run tradeoff between wildfire and insect outbreaks. When salvage and adult timber are not substitutes in the timber market, adult harvests remain constant as salvage harvests increase. In this case, it is possible to lower the rate of fire-induced mortality by increasing salvage harvests. But with salvage timber acting as a substitute for adult timber, increases in salvage harvesting are accompanied by decreases in adult harvesting. Here, attempts to encourage salvage harvesting will eventually result in an increase in both disturbance types. Second, since salvage is an imperfect substitute for adult timber, achieving an optimal level of salvage harvesting will require both increasing incentives for salvage harvesting and decreasing incentives for adult harvesting.

Results also suggest that current trends in public forest management may lead to more or less salvage harvesting. While it appears that a shift from timber to nontimber benefits from public forests will likely necessitate less salvage harvesting, results concerning the effect of historic fire suppression efforts are mixed and depend on the characteristics of the disturbance which created the salvage.

There are many potential directions for future work. First, there is a need for empirical studies that consider multiple disturbance processes. While the results presented herein provide a general overview, it is reasonable to assume that the nature and severity of forest disturbance interactions will vary in specific forest types and the impact of these interactions on harvest activities will depend on local management objectives. Second, natural forest disturbance often creates and mosaic of age classes,
species, and densities within the forest. This suggests the need to move toward more spatially-explicit multi-stand models. There is also a need to extend the definition of management beyond timber harvesting. Natural forest disturbance regimes are affected by and respond to a variety of management activities including pre-commercial thinning, fire suppression, and infrastructure (e.g., road, campground) development.

Appendix

Derivation of Euler equation

A social planner chooses harvesting levels to maximize

\[
\sum_{t=1}^{\infty} \beta^{t-1} \left\{ \ln(Q_t) + (1 - \alpha) \ln(T_t) + \alpha \ln(A_t^H) \right\}
\]

subject to (2), (3)-(10) and (13)-(15) from the main body of the paper. Since the purpose of the paper is to determine how forest management reacts to multiple interacting disturbances, one must isolate opportunity costs of harvesting that are related to natural disturbance from those that are not. Relying on Lagrangian multipliers to reflect shadow values for each stock would lump these opportunity costs together. As all constraints are given by equalities a method of substitution is followed instead. First, as labor endowments are normalized \( L = L_t^Q + L_t^A + L_t^S = 1 \) or \( L_t^Q = 1 - L_t^A - L_t^S \). Noting that

\[
A_t^H = (1 - d - \pi_t - \lambda y_t)A_t + \delta_y Y_t = A_{t+1} + h_t \quad \text{and} \quad S_t^H = (1 - \theta - \lambda)S_t + \]

\[
(d + \pi_t + \lambda y_t)A_t = S_{t+1} + h_t^S \quad \text{and substituting (2) and (12) one can rewrite (A.1) as:}
\]

\[
\sum_{t=1}^{\infty} \beta^{t-1} \left\{ \ln \left( 1 - \frac{h_t^A}{\rho(A_{t+1} + h_t^A)} - \frac{h_t^S}{\rho(S_{t+1} + h_t^S)} \right) + (1 - \alpha) \ln(h_t^A + \eta h_t^S) + \alpha \ln(A_{t+1} + h_t^A) \right\}
\]

To account for the ecological components (3)-(10), equation (5)

\[
A_{t+1} = (1 - d - \pi_t - \lambda y_t)A_t + \delta_y Y_t - h_t^A
\]
\[ h_t^A = (1 - d - \pi_t - \lambda \gamma_t) A_t + \delta_Y Y_t - A_{t+1} \]

and (6)

\[ S_{t+1} = (1 - \theta - \lambda) S_t + (d + \pi_t + \lambda \gamma_t) A_t - h_t^S \]

\[ h_t^S = (1 - \theta - \lambda) S_t + (d + \pi_t + \lambda \gamma_t) A_t - S_{t+1} \]

were rewritten and substituting for \( \gamma_t = \frac{z F_t}{1 + z F_t} \) and \( F_t = Y_t + A_t + S_t + D_t \) from (9) and (10) as well as \( \pi_t = \frac{b_t^2}{B_t^2 + a^2} \) from equation (7):

(A.3) \[ h_t^A = \left( 1 - d - \frac{B_t^2}{B_t^2 + a^2} - \lambda \frac{z(Y_t + A_t + S_t + D_t)}{1 + z(Y_t + A_t + S_t + D_t)} \right) A_t + \delta_Y Y_t - A_{t+1}, \]

(A.4) \[ h_t^S = (1 - \theta) S_t + \left( d + \frac{B_t^2}{B_t^2 + a^2} + \lambda \frac{z(Y_t + A_t + S_t + D_t)}{1 + z(Y_t + A_t + S_t + D_t)} \right) A_t - S_{t+1}. \]

Substituting for \( B_t = \varphi(\pi_{t-1}A_{t-1})^\nu \) from (8) and from (4):

\[ Y_{t+1} = (1 - \delta_Y - \lambda) Y_t + \delta_X X_t \]

\[ Y_t = (1 - \delta_Y - \lambda) Y_{t-1} + \delta_X X_{t-1} \]

yields:

(A.5) \[ h_t^A = \left( 1 - d - \frac{(\varphi(\pi_{t-1}A_{t-1})^\nu)^2}{(\varphi(\pi_{t-1}A_{t-1})^\nu)^2 + a^2} \right) A_t \]

\[ + \delta_Y (1 - \delta_Y - \lambda) Y_{t-1} + \delta_Y \delta_X X_{t-1} - A_{t+1}, \]
\( h_t^S = \left( \frac{d + \frac{(\varphi(\pi_{t-1}A_{t-1})\gamma)^2}{(\varphi(\pi_{t-1}A_{t-1})\gamma)^2 + a^2}}{+\lambda \frac{z[(1 - \delta_Y - \lambda)Y_{t-1} + \delta_X X_{t-1}] + zA_t + zS_t + zD_t}{1 + z[(1 - \delta_Y - \lambda)Y_{t-1} + \delta_X X_{t-1}] + zA_t + zS_t + zD_t}} A_t \right) 

+ (1 - \theta - \lambda)S_t - S_{t+1}. \)

Substituting for \( X_{t-1} \) from (3) and \( D_t \) into (A.5) and (A.6) yields two rather complicated expressions for \( h_t^A \) and \( h_t^S \). Due to the recursive nature of the insect and fire dynamics and the forest stocks one must continually substitute \( \pi, B, \gamma, X, S, D \) and \( Y \) into these expression to fully account for the shadow value of \( B, X, S, D \) and \( Y \). The result can then be substituted into (A.3) to fully account for all constraints.

This substitution procedure also changes the choice variables from harvests to stocks of adult and salvage trees. A similar solution procedure is described in Azariadis (1993). Following the series of substitutions outlined above and taking derivatives with respect to \( A_{t+1} \) yields the first-order condition for welfare maximizing levels of adult tree harvest found by equating (13) and (14) and where

\[
\Delta_{t+k}^{A \rightarrow S \rightarrow fire} = \frac{\partial A_{t+k}^H}{\partial Y_{t+k}} \frac{\partial Y_{t+k}}{\partial S_{t+k}} \frac{\partial S_{t+k}}{\partial A_{t+1}} \frac{\partial A_{t+1}}{\partial h_t^A}
\]

\[
\Delta_{t+k}^{A \rightarrow D \rightarrow fire} = \frac{\partial A_{t+k}^H}{\partial Y_{t+k}} \frac{\partial Y_{t+k}}{\partial D_{t+k}} \frac{\partial D_{t+k}}{\partial S_{t+k-1}} \frac{\partial S_{t+k-1}}{\partial A_{t+1}} \frac{\partial A_{t+1}}{\partial h_t^A}
\]

\[
\Delta_{t+k}^{seed \rightarrow fire} = \frac{\partial A_{t+k}^H}{\partial Y_{t+k}} \frac{\partial Y_{t+k}}{\partial X_{t+k-1}} \frac{\partial X_{t+k-1}}{\partial A_{t+1}} \frac{\partial A_{t+1}}{\partial h_t^A}
\]

\[
\Delta_{t+k}^{seed} = \frac{\partial A_{t+k}^H}{\partial Y_{t+k}} \frac{\partial Y_{t+k}}{\partial X_{t+k-1}} \frac{\partial X_{t+k-1}}{\partial A_{t+1}} \frac{\partial A_{t+1}}{\partial h_t^A}
\]
This provides an indication of the complexity of the “seed effect” terms succinctly presented as $\Delta_{t+k}^{\text{seed} \rightarrow \text{fire}}$ and $\Delta_{t+k}^{\text{seed}}$ in the text and the “fire effect” terms presented as $\Delta_{t+k}^{A \rightarrow S \rightarrow \text{fire}}$ and $\Delta_{t+k}^{A \rightarrow D \rightarrow \text{fire}}$. Taking derivatives with respect to $S_{t+1}$ yields the first-order condition for welfare maximizing levels of salvage harvest found in (15).

**Derivation of time-varying subsidy rate**

A similar sequence of substitutions is followed to find the subsidized Euler equations (17) and (18) with the exception of the subsidized budget constraint $Q_t = 1 - \frac{h_t^A}{\rho A_t^H}$

$$\frac{h_t^S}{\rho S_t^H} + \sigma_t^A h_t^A + \sigma_t^S h_t^S - \Sigma_t$$ which is substituted into the objective function. Rearranging to group all subsidy-related terms on the left hand side

$$1 - \alpha \frac{1}{T_t} - \frac{1}{Q_t \rho A_t^H} + \left[ \frac{\sigma_t^A}{Q_t} - \sum_{k=3}^{\infty} \beta^k \frac{\sigma_{t+k}^A}{Q_{t+k}} \Delta_{t+k}^{\text{seed}} - \beta \left\{ \frac{\sigma_{t+1}^A (1 - \varepsilon - \pi_{t+1} - \lambda \gamma_{t+1})}{Q_{t+1}} + \frac{\sigma_{t+1}^S (\varepsilon + \pi_{t+1} + \lambda \gamma_{t+1})}{Q_{t+1}} \right\} \right]$$

(A.7)

$$= \sum_{k=3}^{\infty} \beta^k \left( \frac{1 - \alpha}{T_{t+k}} - \frac{A_{t+k}^H - h_{t+k}^A}{Q_{t+k} \rho (A_{t+k}^H)^2} + \frac{A_{t+k}^H}{A_{t+k}^H} \right) \Delta_{t+k}^{\text{seed}} +$$

$$\beta \left\{ \left( \frac{1 - \alpha}{T_{t+1}} - \frac{A_{t+1}^H - h_{t+1}^A}{Q_{t+1} \rho (A_{t+1}^H)^2} + \frac{A_{t+1}^H}{A_{t+1}^H} \right) (1 - \varepsilon - \pi_{t+1} - \lambda \gamma_{t+1}) \right\}$$

and

$$\frac{\eta(1 - \alpha)}{T_t} - \frac{1}{Q_t \rho S_t^H} + \left[ \frac{\sigma_t^S}{Q_t} - \beta \left\{ (1 - \theta - \lambda) \frac{\sigma_{t+1}^S}{Q_{t+1}} \right\} \right]$$
(A.8) \[ = \beta \left( (1 - \theta - \lambda) \left( \frac{\eta(1 - \alpha)}{T_{t+1}} - \frac{S_{t+1}^H - h_{t+1}^S}{Q_{t+1} \rho(S_{t+1}^H)^2} \right) \right). \]

To ensure the subsidies fully internalize the stock externality

\[
\sigma^A_t - \sum_{k=3}^{\infty} \beta^k \sigma^A_{t+k} \Delta_{t+k}^{seeds} - \beta \left( \frac{\sigma^A_{t+1}(1 - \varepsilon - \pi_{t+1} - \lambda y_{t+1})}{Q_{t+1}} + \frac{\sigma^S_{t+1}}{Q_{t+1}}(\varepsilon + \pi_{t+1} + \lambda y_{t+1}) \right)
\]

(A.9) \[
\begin{bmatrix}
\beta \left( \psi^A_{t+1} \frac{\partial A^H_{t+1}}{\partial y_{t+1}} \frac{\partial A_{t+1}}{\partial h^A_t} \right) \\
+ \sum_{k=2}^{\infty} \beta^k \left( \psi^A_{t+k} \frac{\partial A^H_{t+k}}{\partial y_{t+k}} \frac{\partial A_{t+k}}{\partial h^A_t} \right)
\end{bmatrix}
\]

and

\[
\left[ \frac{\sigma^S_t}{Q_t} - \beta \left( (1 - \theta - \lambda) \frac{\sigma^S_{t+1}}{Q_{t+1}} \right) \right]
\]

(A.10) \[
\begin{bmatrix}
\beta \left( \psi^A_{t+1} \frac{\partial A^H_{t+1}}{\partial y_{t+1}} \frac{\partial S_{t+1}}{\partial h^S_t} \right) \\
+ \sum_{k=2}^{\infty} \beta^k \left( \psi^A_{t+k} \frac{\partial A^H_{t+k}}{\partial y_{t+k}} \frac{\partial D_{t+k}}{\partial h^S_t} \right)
\end{bmatrix}
\]

Solving (A.9) for $\sigma^A_t$ and (A.10) for $\sigma^S_t$ produces the time-varying subsidy rates in (19) and (20).

References


Footnotes

1 Prestemon and Holmes (2004) show that constraints on the mobility of labor and capital may also justify intervention due to the time-dependent nature of salvage harvesting. This paper abstracts from these considerations in order to focus on the dynamic characteristics of disturbance and nontimber values.

2 The U.S. Healthy Forest Restoration Act was passed with the primary goal of expediting the preparation and implementation of fuel reduction projects to mitigate future wildfire damage. The USDA Forest Service has supported an ongoing grant program that provides approximately $4 million annually to encourage the use of the woody biomass removed during fuel reduction projects. As part of the American Recovery and Reinvestment Act of 2009, the Forest Service received over $80 million to remove forest vegetation in response to recent fires, insect outbreaks, ice storms, and hurricanes. Congress has authorized “goods-for-services” timber contracts on public lands through FY2013 which provide commercially valuable timber in exchange for the removal of noncommercial forest vegetation that would improve forest health (Gorte 2003). Federal programs also exist to provide technical and financial assistance for similar harvest activities on private forests (Gorte 2004).

3 Disturbance-based management is one of several conceptualizations (e.g., historical range of variability, emulating natural disturbance regimes) that apply information about past natural disturbances to inform practices such as timber harvest, prescribed burning, and wildfire suppression (Perera and Buse 2004).

4 Since many nontimber ecosystem services are dependent on proximity to live trees and characteristics of forest structure, the standing stock of live trees may proxy some nontimber benefits better than others.

5 Focusing on social welfare provides general results but abstracts from distributional considerations between forest owners and timber consumers that arise following a large disturbance (Holmes, Prestemon and Abt 2008). If forest managers place a greater weight on producer or consumer surplus, it becomes necessary to model the effect of disturbance on timber price. For instance, Holmes (1991) presents a model for assessing timber damage from insect epidemics that includes timber owner and timber consumer behavior. Prestemon and Holmes (2004) extend this work to consider short-run and long-run impacts of Hurricane Hugo on specific product markets.
This specification restricts the elasticity of substitution between goods to 1. Increasing the substitutability between goods causes a more severe drop in adult harvesting and lessens salvage harvesting following disturbance.

There may be many motivations for salvage harvesting such as forest health, aesthetics, and visitor safety. Because these benefits are difficult to quantify, the model focuses on the two most common motivations for salvage harvesting: timber salvage and fuel reduction.

See appendix for details on the derivation of (13) – (15). As all constraints are given by equalities, a method of substitution is followed (Azariadis 1993) as opposed to the more traditional Lagrangian multiplier method. A similar solution procedure was used in Aadland and Bailey (2001) to study the effect of cull rates on the age structure of a cattle stock. While providing identical results (Sims, et al. 2013), the substitution method allows one to highlight the dual role that trees serve. For instance, adult and salvage trees provide timber benefits while also contributing to the fuel load and future fire severity. Shadow values collapse all future values into a single measure which masks the multitude of incentives shaping the decision to leave and harvest trees.

See appendix for details on the derivation of the subsidy rates.

Proportional changes in $a$ and $\varphi$ have little impact on the model. Sims et al. (2013) use a thermal response model to incorporate the impact of climate change on these parameters.
Table 1. Steady State Initial Conditions Absent a Major Disturbance Event

<table>
<thead>
<tr>
<th>Benchmark: Insect, wildfire, and storm</th>
<th>Scenario 1: Insect and wildfire</th>
<th>Scenario 2: Insect only</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>π</strong> Proportion of adult trees killed by insect attack</td>
<td>0.6%</td>
<td>1.2%</td>
</tr>
<tr>
<td><strong>B</strong> Beetles per acre</td>
<td>5,101</td>
<td>7,097</td>
</tr>
<tr>
<td><strong>γ</strong> Proportion of adult trees killed if fire occurs</td>
<td>42.5%</td>
<td>42.6%</td>
</tr>
<tr>
<td><strong>X</strong> Viable seeds per acre</td>
<td>22,707</td>
<td>22,839</td>
</tr>
<tr>
<td><strong>Y</strong> Young trees per acre (&lt; 8 in diameter)</td>
<td>1,376</td>
<td>1,384</td>
</tr>
<tr>
<td><strong>A</strong> Adult trees per acre (≥ 8 in diameter)</td>
<td>202</td>
<td>204</td>
</tr>
<tr>
<td><strong>S</strong> Salvage trees per acre</td>
<td>16.8</td>
<td>16.7</td>
</tr>
<tr>
<td><strong>D</strong> Tons of downed woody debris per acre</td>
<td>249</td>
<td>248</td>
</tr>
<tr>
<td><strong>h^A</strong> Adult harvest per acre</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>h^S</strong> Salvage harvest per acre</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Definition</td>
<td>Value</td>
<td>Source</td>
</tr>
<tr>
<td>------------</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>$\delta_X$ Germination rate in seed base</td>
<td>0.001</td>
<td>Fowells 1965; Lotan and Critchfield 1990; Koch 1996</td>
</tr>
<tr>
<td>$\delta_Y$ Maturation rate of young trees</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>$b_Y$ Seed production rate in young trees</td>
<td>0.0018</td>
<td></td>
</tr>
<tr>
<td>$b_A$ Seed production rate in adult trees</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>$\theta$ Decay rate in dead, salvage trees</td>
<td>0.2</td>
<td>Dobie &amp; Wright 1978;</td>
</tr>
<tr>
<td>$\omega$ Decay rate in downed woody debris</td>
<td>0.001</td>
<td>Plank 1984</td>
</tr>
<tr>
<td>$\varepsilon$ Storm-induced mortality rate</td>
<td>0.006</td>
<td>Dale, et al., 2001</td>
</tr>
<tr>
<td>Insects/acre required for a 50% chance of insect-induced mortality</td>
<td>63,800</td>
<td>Heavilin and Powell 2008</td>
</tr>
<tr>
<td>$\varphi$ Avg. insects per infested tree</td>
<td>4,500</td>
<td>Bentz 2006</td>
</tr>
<tr>
<td>$\nu$ Rate of decrease in MPB reproductive success</td>
<td>0.5</td>
<td>Berryman, et al., 1985</td>
</tr>
<tr>
<td>$z$ Fire severity parameter</td>
<td>0.0004</td>
<td>Romme et al. 2006</td>
</tr>
<tr>
<td>$I$ Fire return interval</td>
<td>80</td>
<td>Romme et al. 2006</td>
</tr>
<tr>
<td>$\alpha$ Forest preference parameter</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>$\eta$ Harvest substitution rate</td>
<td>0.5</td>
<td>de Steiguer, et al., 1987</td>
</tr>
<tr>
<td>$\rho$ Harvest efficiency parameter</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>$r$ Discount rate</td>
<td>0.04</td>
<td>Row, et al, 1981</td>
</tr>
</tbody>
</table>
Figure 1. Forest and harvesting dynamics with benchmark model following biotic (insect), abiotic (storm), and mixed (wildfire) disturbance events that kill 150 adult trees per acre; solid black lines represent adult trees while dashed black lines represent salvage trees.
Figure 2. Adult (solid line) and salvage (dashed line) harvest subsidies with benchmark model following beetle outbreak (a), storm event (b), and wildfire (c)
Figure 3. The impact of multiple interacting disturbance processes on trees per acre killed, forest structure, and management response following insect outbreak.
Figure 4. The impact of forest management and fire regime on salvage harvesting with benchmark model following beetle outbreak (a), storm event (b), and wildfire (c)
Figure 5. The effect of timber market substitutability and increasing salvage harvest on the trees per acre killed by insects and fire.