Three Essays on Forest Economics and Management

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ABSTRACT

Forest management strategies directly affect landowner welfare, and factors ranging from natural disturbances to institutional environments play important roles in influencing the outcomes for both landowners and society. This dissertation, consisting of three essays, delves into the forest sectors in both developed and developing countries with an aim of uncovering the impacts of various factors in forest management, as well as resulting welfare changes felt by landowners and society.

The first essay extends previous literature on natural disturbances and forest management, where a single disturbance and immediate clearcut after it are always assumed, through the introduction of multiple disturbances and flexible harvest timing. A Faustmann-type rotation model is developed and used to guide simulations of loblolly pine management in the southern United States. We show that failure to consider the possibility of multiple disturbances and the oversimplification of harvest rules after a single disturbance leads to suboptimal harvest decisions.

The second essay further extends the natural disturbance literature by considering the amenity value of unharvested forests in addition to timber value. As before, multiple types of disturbances as well as flexible harvest timing are incorporated into a Hartmann-type framework. Alternative amenity functions are employed in the simulations in which socially optimal harvest strategies are derived. We further examine the discrepancies between optimal harvest decisions of the landowner and those of the social planner, and

compute social costs of ignoring amenity value. Our results show that ignoring amenity value can generate social costs and render harvest decisions socially suboptimal.

Forest production in developing countries also suffers from institutional weaknesses that distorts household decision making. The third essay therefore investigates impacts of village democracy on rural household welfare in China through changes in production efficiency in forestry and agriculture sectors using data collected from a household survey. A theoretical framework is first established, and based upon that framework stochastic production frontier models are estimated where democracy is incorporated as a potential factor affecting the variation of technical efficiency. We find that higher levels of village democracy significantly increase production efficiency. A first study on how village democracy affects rural household welfare, we provide policy lessons for other developing countries undergoing democratization.

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Chapter 1: Introduction

Forest management has long been an important and practical topic all over the world, which directly affects landowner and society welfare. It is a complicated process the outcome of which are affected by many factors, including natural disturbances and social and institutional environments. The roles of these factors differ across countries and receive diverse attention worldwide. This dissertation, consisting of three essays, delves into the forest sectors in both developed and developing countries with an aim of uncovering the impacts of various factors affecting forest management, as well as the resulting welfare changes felt by landowners and society.

Most developed countries rely on intensively managed forest plantations to meet timber demands, where adaptation of harvesting strategies in the presence of natural disturbances is a major component in forest management decision making. However, almost all previous studies consider only one specific type of disturbance (e.g. fire, windstorm, pests, etc.) and assume immediate harvesting after the occurrence of the destructive event. These assumptions are rather restrictive and thus less realistic than allowing consideration of multiple disturbance within one rotation, because the landowner may choose not to harvest the forest immediately following the event but continue holding it, especially when the damage is small. Recognizing these limitations, the first essay relaxes these assumptions by introducing multiple disturbances and flexible harvest timing that recognize the possibility of ending the rotation either at the occurrence of destructive events, or at the planned rotation age. A Faustmann-type rotation model is developed and used as a basis for simulations of loblolly pine management in southern United States. We show that failure to consider the complexities discussed above leads to suboptimal harvest decisions. The arrival rates of disturbances and key parameters such as the salvage proportion and changed growth rate after each disturbance are also found to affect optimal harvest decisions.

Based on the modeling framework of the first essay, the second essay further takes into consideration the amenity value of unharvested forests in addition to the timber value. Multiple disturbances as well as flexible harvest timing are incorporated into a Hartmann-type framework. Using loblolly pine management in Southern United States as an example, alterative amenity functions are employed to simulate a variety of amenity services that unharvested forests provide to society, and socially optimal harvest strategies are derived. We further examine the discrepancies between optimal harvest decisions of the private landowner and those of the social planner. Social costs of forest management decisions that ignore amenity value, as well as the value loss due to the consideration of only a single disturbance with an immediate clearcut following that disturbance are then evaluated. Our results show that ignoring amenity value can generate positive social costs and render harvest decisions socially suboptimal. Key parameters such as arrival rates of disturbances and the timber growth response after disturbances are also found to affect the socially optimal harvest decisions.

In addition to natural disturbances, forest production in developing countries also faces challenges from institutional weaknesses, which can substantially distort forest management decisions at the household level. Using data collected in a recent and unique household survey, the third essay addresses the impacts of village democracy on rural household welfare in China from a production efficiency perspective, jointly considering agriculture and forest production. A theoretical framework is first established that links democracy to household welfare through changes in production efficiency. Stochastic production frontier models are estimated that incorporate various considerations of household-level heterogeneity, while allowing for the identification of multiple factors that drive production inefficiency through a decomposition procedure. We find that higher levels of village democracy significantly increase farmer production efficiency and reduce variation in inefficiency errors when farmers are inefficient and located inside the production frontier. As a first study on how village democracy affects rural household welfare, we contribute to the literature of decentralized governance in weakly institutionalized polities by suggesting that meaningful analyses of reforms cannot ignore democratization effects.

Chapter 2: Optimal Forest Management with Sequential Disturbances

2.1 Introduction

Disturbances play a major role in determining forest composition and structure. Events such as fire, drought, ice storm, windstorm, insect and pathogen outbreaks, often lead to considerable damages and result in tremendous losses to forest landowners. In the United States, insects and pathogens cost landowners more than $2 billion and loss of $20.4 million ha per year respectively (USDA, 1997). Wildfire has regularly consumed millions of acres per year in the Western U.S. with over 6 million acres in burned in Alaska alone during recent years (EPA website). Drought occurs in almost all regions of United States with varying frequency and intensity (Hanson and Weltzin, 2000), and pine beetles and other invasive species are common problems in the Southern pine region.

The risk of arrival of such disturbances is a major factor in the management of forests, and the economics literature has established the importance of these risks to the length of the rotation age (Martell, 1980; Routledge, 1980; Reed, 1984, 1987; Reed and Apaloo, 1991; Yin and Newman, 1996; Englin et al., 2000; Stainback and Alavalapati, 2004; Yoder, 2004; Amacher, Malik and Haight, 2005). Most studies employ the Faustmann rotation framework and consider the effect of a certain type of catastrophic risk on the optimal rotation age choice. Reed (1984), one of the most highly cited papers in forest economics, investigates the relationship between risk of fire arrival during a rotation and the optimal cutting age, assuming that the arrival rate of fire follows a time-independent Poisson process and that the forest is totally destroyed upon the occurrence of fire, hence beginning a new rotation in either the case of a fire or the case that the rotation age is reached. Some later studies relax the assumption of total damage upon arrival of a catastrophic event and consider potential salvage of stands. The salvage in most of these studies is defined as the percent of trees in the forest surviving a disturbance, and we consistently use it with the same definition in our paper. In this work, it is possible that the landowner can employ costly protection effort during a rotation in order to reduce forest damage should an event arrive before the rotation age is reached, thereby not always leading to rotations as short as Reed-based models predict, but still shorter than a Faustmann rotation age that omits any risk of future damaging events.

Two assumptions are pervasive in this literature. First, only one event is assumed to arrive in any future rotation, and second, the stand is either harvested when the rotation is reached in the absence of a disturbance, or it is harvested immediately after a disturbance arrives before the planned end of the rotation. There are only two exceptions we are aware of where the stand is not necessarily harvested after an event arrives (Goodnow et al. 2008; Suseta et al. 2013), however, both of these studies continue to use the other assumption and only allow one disturbance during any future rotation. As a result of these assumptions, the literature universally shows that rotation ages remain shorter under risk of stand damage than without incorporating such risks.

We relax these two assumptions to find that the rotation age results in the literature do not hold in a more general framework. Further, in order to aid comparison, we retain other assumptions that not only make sense in practice but facilitate such comparison. For example, it is assumed that the damage once an event arrives, and not the probability of arrival, is dependent on forest condition (see for example, Reed (1987) and Reed and Apaloo (1991), who consider thinning and fire salvage, and Yoder (2004) and Amacher et al. (2005), who consider fuel reduction during a rotation in advance of any possible fire event, and Goodnow et al. (2008) consider ice storm). This assumption is reasonable considering that most catastrophic events arrive independent of landowner decisions, i.e. through fire fronts affecting a region, lightning strikes, or windstorms and pest arrival. What is dependent on stand condition is the damage that occurs once any event arrives. In fact pine beetles in the southern pine region often live dormant in soil or trees for years without causing problems given that healthy trees can pitch out insects without affecting the quality or quantity of saleable wood at harvest time; however, should the stand be stressed through an event such as an ice storm or fire, this reduces the possibilities of keeping beetles contained and leads to beetle damage in the stand. Stand damage at any event can also depend on the timing of that event with any previous event that occurred when a landowner chooses not to immediately harvest. Certainly, the damage from a lightning strike is higher if the stand previously was ice damaged and fuel loadings have increased.

All previous studies in this line of literature focus on one specific type of disturbance that may arrive during a rotation. However, in practice many disturbances are likely to occur in a forest stand before a landowner decides to harvest: one prior catastrophic event early in a rotation can mean that the arrival of another event causes more damage to the stand later in its life. For example, stems damaged by ice storm are more vulnerable to damage should insects and disease arrive later (USDA Forest Service, 1998; Smith, 2000). Two-way interactions between fire and insects can also be dramatic (McCullough, Werner and Neumann, 1998). A forest weakened by drought early in a rotation will lose more trees should fire or insects arrive later – the fire implication is due to increases in fuel loadings on the ground and in the crown (Dale et al., 2001). Clearly, the damage interaction between the arrival of a previous event and the arrival of another one must be considered yet is still an open problem in forest economics.

The assumption of immediate harvest and commencement of a new rotation upon the occurrence of a single disturbance is restrictive and not representative of silvicultural practice, as immediate harvesting may not be the best solution economically or environmentally in a stand after damage. For example, harvest may not be the optimal practice if damage is not extensive from a given event (i.e., survival is above some level), or if trees in a stand have not reached an optimal market size or are too small to harvest (Parker et al., 1999, Alexander, 1986). Further, the long-term impacts on soil and residual trees (e.g. root injury) need to be carefully considered and sometimes render harvest suboptimal after a damaging event (USDA Forest Service, 1998; Dale et al., 2001). To consider rotation age choices under risk and under these complexities, a model is needed that allows for flexible continuance of a rotation even when the possibility of more than one disturbance exists.

For this paper and consistent with our continuance assumptions, a modified Faustmann framework is developed where probabilities of two sequential disturbances are jointly considered, and importantly, damages and survival of trees due to future disturbances depend on the timing of this disturbance relative to previous disturbances that may have occurred. The arrival of more than one event is possible given that forest rotation will not necessarily ended (unless it is optimal to do so) when the first event arrives. Like the literature, disturbances are assumed to arrive via a Markov process consistent with arrival rates distributed according to a Poisson distribution. The potential sequence of occurrence of more than one event in any rotation therefore is a function of both the independence of events and the conditional probabilities governing event arrival and rotation age.

In this new model, it may be optimal to harvest at the first disturbance, at the second one, or at a planned rotation age. Partial forest stand damage and tree survival, as well as forest growth changes after an event or a sequence of events, are considered in deriving the optimality of these decisions. Survival and forest growth depend on the timing of an event in a given rotation as well as timing relative to previous events. The optimal rotation age is found as the solution of an expected net present value maximization for forest rents, and as such our work is a direct modification of Reed (1984) to allow for more general forest management decisions and more general arrival of catastrophic events. We show that there are important cases of arrival rates and damage links between disturbances that render the rotation age solved under Reed (1984) and other models using the standard assumptions as non-optimal, and further, we show that rotation ages can approach and even be longer than a Faustmann rotation age even though we do not require costly protection effort on the part of the landowner.

2.2 **Model**

In our model, more than one stochastic damaging event can arrive in each rotation, and unlike previous literature we assume that the forest stand is not always harvested and a new rotation started after the arrival of any event. Further, we allow the salvage possibilities (or tree survival) and subsequent growth of the stand once an event arrives to reflect prior damage and arrival of earlier events. The landowner chooses rotation age and a strategy concerning harvesting or continuation of the stand. We consider the decision to harvest and continue a rotation under these cases in an open loop problem like Reed (1984), solving the problem to arrive at an optimal rotation age that accounts for these new considerations. We also show how our model applies generally to any number of events, and also to events where one is expected to arrive more often than another, or when there are possibilities of repeated events of the same type (such as two fires or ice storms during the life of a forest). The basic unit of analysis will be a land unit growing an even aged forest that is planted and harvested for ongoing rotations. Thus, the basic underlying assumptions of Faustmann's problem concerning some parameters and land rents will continue to hold (e.g., see Amacher et al. 2009, chapter 2).

The fact that a stand may not be harvested after a damaging event, and that it is therefore possible to have more than one event before a rotation age is reached, is a common situation in forest management. Damaged stands are sometimes continued through a rotation if there is a lack of salvage possibilities, or if damage is not extensive, and in fact there is a subfield of silviculture specifically devoted to the management of previously damaged stands (Straka and Baker, 1991; USDA Forest Service, 1998; Bragg, Shelton and Zeide, 2003). For example, ice storms are rarely devastating, and rehabilitating storm damaged timber is possible and may be less costly than harvesting and starting a new rotation (Straka and Baker, 1991; Shepard, 1978; Guldin, 2002). Moreover, Alexander (1986) finds that wind risk, and some outbreaks such as red turpentine, pine engraver beetle, and tip moth, do not often cause widespread losses to certain forests and therefore are not important considerations for harvest, even though from an economic standpoint some potential rent is lost. A failure to consider these possibilities may result in oversimplification of the rotation age solution, rendering it non-rent maximizing.

We present a case with up to two possible events that may arrive in any future rotation. This situation is a likely one for planted softwood stands that are normally harvested within a window of 20-80 years. However, the model we present and our approach applies to any number of m damaging events that may happen during a stand's rotation. We show that our model collapses to Reed's (1984) model (Reed model hereafter) if the stand is assumed to be harvested at the arrival of the first event, should an event arrive before the rotation age is reached. Adherence to this assumption is the only case where our rotation age choice is equivalent to Reed's, despite that we also employ a simple open loop approach to solving for the rotation age. We will show that our model also collapses to Faustmann's problem if risk is assumed away, i.e., there is a zero probability of a future catastrophic event in any rotation.

We begin with the assumption that there are two possible natural disturbances to a forest stand once it is established, for illustration purposes. The arrival of these disturbances is stochastic, but the landowner is assumed to know the arrival probability in any year for each event. The first disturbance in the n^{th} $(n = 1,2, \ldots)$ rotation can be defined as A_n, and the second disturbance defined as B_n, with the arrival of A_n and B_n events assumed to follow a homogeneous Poisson process – this simply implies that the arrival rate does not change over time, although such a modification to relax this would be straightforward and not change the nature of our analysis. This assumption has been used in a number of studies (Yin and Newman, 1996; Boxall and Hauer, 2000; Stainback and Alavalapati, 2004; Amacher, Malik and Haight, 2005), and is part of all of the extensions of the optimal rotation age under risk of natural losses that follow Reed (1984). Let $X_n (n = 1,2, \ldots)$denote the times between planting a stand and the arrival of the first disturbance A_n in any future rotation, and let Y_n be the times between planting the stand and arrival of the second disturbance B_n in the n^{th} rotation ($n = 1,2, \ldots$). Under the Poisson assumptions, X_n and Y_n follow an exponential distribution and $(Y_n - X_n)$ denotes the time interval between events A_n and B_n if both occur during the same rotation and the landowner decides to continue the rotation after event A_n (Figure 2.1).

We assume that the arrival rate of event A_n is uncorrelated with event B_n in the n^{th} rotation, that is, the events are independent from an arrival rate probability point of view. This uncorrelated event timing is by far the most likely case with forest stands in temperate and tropical zones. For example, a windstorm can strike a stand early in its life causing some stand damage, and yet the stand is kept standing and continues growing, only to have a fire front arrive (or lightning strike) causing damage at a later time. The arrival of the second event is not dependent on whether the first event arrived (i.e. on stand conditions). However, the extent of damage that the second event causes certainly depends on current stand conditions and therefore on whether a previous disturbance has occurred and how long ago such a disturbance occurred. For example, fire damage from a lightning strike largely depends on stand attributes like tree density and size structure. If a windstorm arrives as the first event, it affects the size structure by producing canopy disruptions and changing tree densities (Dale et al., 2001; Turner et al., 1998). This in turn changes fuel loadings which are then the main factor in the intensity of fire if it occurs as the second event.

The assumption that the probability of fire and other large weather events arriving in a stand does not depend on stand conditions is consistent with the fact that these weather events arrive in fronts independent of a given landowner's management, as much of the literature has noted (see Amacher et al. 2005); for example, lightning strikes are random, windstorms are weather dependent, and insect infestations either spread from adjacent land as insects are blown into a stand from winds, or they are already present in the soil. Other work that assumes this but considers only one event includes Reed and Errico 1987; Martell, 1980; Routledge, 1980; Reed, 1984, 1987; Yin and Newman, 1996; Englin et al., 2000; Stainback and Alavalapati, 2004; Amacher, Malik and Haight, 2005; and Boxall and Hauer, 2000.

While stochastic events are independent, the sequencing of events matters to stand survival after an event arrives, stand growth after these events should the rotation be continued, and the decision to harvest the stand. Thus, the rotation age should be similarly affected when solved as an open loop Faustmann-type problem. In terms of the notation to illustrate our model, by definition event A_n occurs before B_n during the n^{th} rotation, thus $X_n < Y_n$. Let all potential events of type A_n occur at the rate

λ_A, while all potential events of type B_n occur at rate λ_B. Figure 2.1 illustrates a possible arrival sequence during the nth rotation.

There are three scenarios that may happen during each rotation. In the first scenario, neither A_n nor B_n occurs before the rotation age T is reached. That is, $Y_n \geq X_n \geq T_n$, which without loss can be denoted as $Y_n = X_n = T$. In the second scenario, only event A_n occurs before T; so we have $X_n < T < Y_n$, which is written as $X_n < T = Y_n$. In the third scenario, both A_n and B_n occur before the rotation age T, or $X_n < Y_n < T$.

Once any disturbance occurs, the landowner can either harvest the forest or continue the rotation. We represent this decision using binary indicator variables d_A and d_B: d_A equals 1 if the landowner harvests the forest after the first event A_n and equals 0 otherwise. Similarly, d_B equals 1 if the forest is harvested after the second event B_n and 0 otherwise. There are thus three harvest strategies that the landowner can choose to maximize present value of net rent over an infinite time horizon. The first strategy is that the landowner always harvests at the first event A_n if it ever occurs, so that $d_A = 1$. The second strategy is that the landowner does not harvest until the second event B_n occurs, denoted by $d_A = 0, d_B = 1$. The third strategy is that the landowner does not harvest at the either event and waits until the rotation age to harvest, denoted by $d_A = 0, d_B = 0$. Regardless of d_A and d_B, the landowner always waits and harvests at the rotation age if no event arrives during a rotation. Thus, no matter what strategy is used, the waiting time to harvest from the date of planting is equal to either: Y_n, X_n or T. As we discuss below and investigate in the simulation, the best strategy will depend on the relative arrival rates of the events as well as the timing of events and their interaction through the damage function of the forest.

For each strategy, we can derive an expected net present value of the future rent. To keep track of the notation, we refer to J_1, J_2 and J_3, as expected rents that follow from the continuance strategies represented by 1) $d_A = 1$, 2) $d_A = 0, d_B = 1$, and 3) $d_A = d_B = 0$, respectively. These J_i $(i = 1, 2, 3)$ functions each depend on the rotation age choice, T. Thus, the landowner's problem is one of choosing $\{T, d_A, d_B\}$ such that the maximal J_i is selected from $\{J_1, J_2, J_3\}$, and this gives a rotation age choice and harvest strategy that depends on the stochastic nature of the events and the survival possibilities that arise when multiple events arrive in a certain order. Specifically, we show how the rotation age choice is dependent on relative arrival rates of the event A_n and B_n (dictating in probability terms which event is more likely to arrive first in a rotation), the survival functions and how they are related especially after a second event, and the growth of the stand after each event. Further, the rent function can be weighted according to the likelihood that one event precedes the other. For example, if the expected rents we derive below will be done under the condition that A_n is expected to always arrive before B_n. However, other cases, where for example, A_n and B_n are the same event, or A_n arrives first on average according to some probability not equal to one, are easily introduced by weighting the rent functions under each case by the appropriate arrival sequence probabilities. Thus, the rent functions developed below are the basic unit of the model that can be modified to suit individual location or event specific realities concerning both events and tree species.

2.2.1 The Two Event Case

Given the assumptions above, and defining T as the planned rotation age, the probabilities of the arrival of events and the sequence of these events during the n^{th} rotation can be written for each case as:

$$\Pr(X_n = Y_n = T) = \Pr(Y_n = T)\Pr(X_n = T | Y_n = T) = \Pr(Y_n = T)\Pr(X_n = T),$$

which represents the case where the landowner reaches the rotation age without any event arriving,

$$\Pr(X_n < Y_n = T) = \Pr(Y_n = T)\Pr(X_n < T | Y_n = T) = \Pr(Y_n = T)\Pr(X_n < T),$$

which represents the case where only a first event (or single event) arrives, and finally,

$$\Pr(X_n < Y_n < T) = \Pr(Y_n < T)\Pr(X_n < Y_n | Y_n < T) = \Pr(Y_n < T)\Pr(X_n < Y),$$

which defines the case where two events arrive before the planned rotation age. As discussed, the arrival rates of the first and second events are uncorrelated, and thus X_n and Y_n are independent and the probabilities reflect this.

Since each event arrives according to a homogeneous Poisson stochastic process, the specific probabilities that event B_n arrives before or after the rotation age T are given for the four possible cases as: $\Pr(Y_n < T) = 1 - e^{-\lambda_B T}$, $\Pr(Y_n = T) = e^{-\lambda_B T}$,

$\Pr\left(X_n = T \middle| Y_n = T\right) = \Pr(X_n = T) = e^{-\lambda_A T}$, and

$\Pr\left(X_n < T \middle| Y_n = T\right) = \Pr(X_n < T) = 1 - e^{-\lambda_A T}$,

Where again λ_B is the arrival rate of event B_n and λ_A is the arrival rate of event A_n. We can now derive the probabilities for the three cases above as:

$$
\begin{aligned}
&\Pr\left(X_n = Y_n = T\right) = \Pr\left(Y_n = T\right)\Pr\left(X_n = T \middle| Y_n = T\right) = e^{-(\lambda_A + \lambda_B)T} \\
&\Pr\left(X_n < Y_n = T\right) = \Pr\left(Y_n = T\right)\Pr\left(X_n < T \middle| Y_n = T\right) = \left(1 - e^{-\lambda_A T}\right)e^{-\lambda_B T} \\
&\Pr\left(X_n < Y_n < T\right) = \Pr\left(Y_n < T\right)\Pr\left(X_n < Y_n \middle| Y_n < T\right) = 1 - e^{-\lambda_B T}
\end{aligned}
\tag{1}
$$

The rent from harvesting over each rotation is also a random variable from the landowner's perspective when the forest is established at the beginning of each rotation, as it depends on the joint realization of X and Y during the rotation. This expected rent also depends on the landowner's choices. In what follows, we denote the rent from harvesting in the n^{th} rotation for each of the three strategies as R_n^k $(k = 1, 2, 3)$. We now elaborate these strategies as a step in defining the landowner's open loop expected value maximization problem.

The first strategy ($d_A = 1$)

In the first strategy ($d_A = 1$), the landowner harvests at the first event A_n if it ever occurs during a rotation, and if the event does not arrive the landowner harvests when the rotation age T is reached. Such a situation could occur if A_n were an especially damaging type of event, such as a high intensity fire, that leaves the landowner with few surviving trees, or if the arrival rate of the second event that could occur is very high – we will explore this in the simulation. For $d_1 = 1$ the current value of the rent function in the nth rotation R_n^1 is:

$$R_n^1 = \begin{cases} pF(T) - C_1 & \text{if } X_n = Y_n = T \\ k_A(X_n)pF(X_n) - C_2 & \text{if } X_n < T = Y_n \end{cases}, \tag{2}$$

where p is the market stumpage price; X_n denotes the time between start of stand and arrival of event A_n in the n^{th} rotation, and $k_A(X_n)$ is the tree survival function, from now on referred to as a salvage function, which represents the proportion of the stand that survives if A_n occurs. $F(t)$ is the volume function at a stand age that equals either X_n or T, and C_1 and $C_2 (> C_1)$ are the costs to start the new rotation without and with the event's arrival, respectively. Thus, C_1 only includes regeneration effort but C_2 includes both regeneration effort and clearing costs incurred after the damage of the event. In this strategy, the rent R_n^1 can be either increasing or decreasing in X_n; for example, fire damage may be larger for denser forests while ice damage might be lower. The case ($d_A = 1$) is the only case assumed by Reed (1984) and many others who have followed Reed's approach (e.g. Amacher, Malik and Haight, 2005; Stainback and Alavalapati, 2004; Boxall and Hauer, 2000; Englin et al., 2000), in which the landowner is assumed to harvest the stand, ending the rotation right after the first event.

If $X_n = Y_n = T$, then the two events do not occur before the rotation age T is reached. In this case, the landowner harvests and receives the complete harvest value $pF(T)$ at time T and starts the new rotation at cost C_1. If $X_n < T = Y_n$, there is one disturbance occurring during the n^{th} rotation and the landowner harvests. In this case the landowner receives whatever value of the forest can be recovered, $k_A(X_n)pF(X_n)$, and begins a new rotation at a cost of C_2 This cost includes both forest clearing and regeneration effort.

Under this strategy, the waiting time for harvest is X_n in the first case of equation (2), or $X_n = T$ in the second case of equation (2). Thus, the expected net present rent of the stand over an infinite cycle of rotations is represented as:

$$J_1 = E\left[e^{-rX_1}R_1^1 + e^{-r(X_1+X_2)}R_2^1 + e^{-r(X_1+X_2+X_3)} + \ldots\right] = E\left[\sum_{n=1}^{\infty} e^{-r\sum_{i=1}^{n} X_i} R_n^1\right] \tag{3}$$

where r is the real interest rate; e^{-rX_n} is the discount factors. Expected net present rent of stand in the n^{th} rotation is $e^{-rX_n}R_n^1$.

Since the waiting times for harvest in different rotations are independent, the expected values of all rotations are equal, so that $\mathrm{E}[e^{-rX_n}R_n^1]$ is the same for each harvest and can be factored out of the equation. Further, the disturbance or harvest time in each rotation is independent, which implies $E\left(e^{-rX_i}\right) = E\left(e^{-rX}\right)$. Thus, we can rewrite equation (3) as:

$$J_1 = \sum_{n=1}^{\infty}\left[\prod_{i=1}^{n-1} E\left(e^{-rX}\right)E\left(e^{-rX}R_n^1\right)\right] \tag{4}$$

Since the right hand side of (4) is a geometric series, it simplifies to:

$$J_1 = \frac{E\left(e^{-rX}R^1\right)}{1 - E\left(e^{-rX}\right)} \tag{5}$$

Equation (5) represents the expected net present rent of the stand, and thus the landowner maximizes J_1 with respect to T. To calculate the term on the right hand side, we need to work with the cumulative distributions of X_n. The cumulative distribution of the random variable X_n can be derived from the probabilities described in equation (1),

$$F_X(t) = \begin{cases} 1 - e^{-(\lambda_A+\lambda_B)t} & \forall t < T \\ 1 & \forall t \geq T \end{cases} \tag{6}$$

where $F_X(t) = \Pr\{X_n \leq t\}$. If $t < T$, the marginal distribution of X_n is the same as the probability of $X_n < Y_n < T$ and $X_n < Y_n = T$ given in (1). However, if t is greater than the rotation age T, the probability of $X_n \leq t$ is equal to one because X_n cannot be greater than the rotation age T. Therefore, when the waiting time for harvest is X_n, the probability density function of X_n in turn is defined as $f(X)$ which is the same for all the rotations:

$$f(X) = \begin{cases} (\lambda_A + \lambda_B)e^{-(\lambda_A+\lambda_B)t} & \text{for } 0 < X_n < T \\ e^{-(\lambda_A+\lambda_B)T} & \text{for } X_n = T \end{cases} . \tag{7}$$

When $0 < X_n < T$, the probability density function is derived directly from the cumulative distribution function $F_X(t)$. However, if $X_n = T$, $f(X) = p(X_n = T)$. Since there are three scenarios $(X_n < Y_n < T, X_n < Y_n = T$ and $X_n = Y_n = T)$ given in equation (1), only in the third of which has X_n equal to T, we can then write $f(X) = p(X_n = T) = p(X_n = Y_n = T)$, which should be equal to $e^{-(\lambda_A+\lambda_B)T}$ as shown in equation (1).

In equation (5), the expected value $E(e^{-rX})$ is established as the sum of the probabilities of ending the rotation by either harvesting or the arrival of the first event subjective to their possibilities:

$$
\begin{aligned}
E\left(e^{-rX}\right) &= \int_0^{\infty} e^{-rt} f(X)dX \\
&= \int_0^{T} e^{-rt}\lambda_B e^{-\lambda_B t}dt + \int_0^{T} e^{-rt}[(\lambda_A+\lambda_B)e^{-(\lambda_A+\lambda_B)t} - \lambda_B e^{-\lambda_B t}]dt + e^{-(\lambda_A+\lambda_B)T}e^{-rT} \\
&= e^{-(r+\lambda_A+\lambda_B)T} - \frac{\lambda_A+\lambda_B}{r+\lambda_A+\lambda_B}[e^{-(r+\lambda_A+\lambda_B)T}-1]
\end{aligned} \tag{8}
$$

and

$$
\begin{aligned}
E\left(e^{-rX}R^1\right) &= e^{-rT}\left[pF(T)-C_1\right]e^{-(\lambda_A+\lambda_B)T} + \int_0^T\left[k_A(X_n)pF(X_n)-C_2\right]e^{-rt}\lambda_B e^{-\lambda_B t}dt \\
&\quad + \int_0^T\left[k_A(X_n)pF(X_n)-C_2\right]e^{-rt}[(\lambda_A+\lambda_B)e^{-(\lambda_A+\lambda_B)t} - \lambda_B e^{-\lambda_B t}]dt \\
&= \left[pF(T)-C_1\right]e^{-(r+\lambda_A+\lambda_B)T} + \int_0^T\left[k_A(t)pF(t)-C_2\right]e^{-(r+\lambda_A+\lambda_B)t}(\lambda_A+\lambda_B)dt
\end{aligned}
$$

(9)

By substituting the right hand sides of equation (8), (9) into equation (5) ,we obtain:

$$
\begin{aligned}
J_1 &= \frac{(r+\lambda_A+\lambda_B)[pF(T)-C_1]e^{-(r+\lambda_A+\lambda_B)T}}{r[1-e^{-(r+\lambda_A+\lambda_B)T}]} \\
&\quad + \frac{(r+\lambda_A+\lambda_B)\int_0^T\left[k_A(t)pF(t)-C_2\right]e^{-(r+\lambda_A+\lambda_B)t}(\lambda_A+\lambda_B)dt}{r[1-e^{-(r+\lambda_A+\lambda_B)T}]}
\end{aligned} \tag{10}
$$

According to equation (10), if we assume that the stand is totally destroyed when the disturbances occur ($k_A(t)=0$), or there is only one disturbance ($\lambda_B=0$), the expected value of the stand in (10) reduces to that of Reed (1984).

The simulation discussed later investigates various cases for the salvage and forest growth functions. If linear forest growth is assumed, $F(t)=at$, then a relatively intuitive closed form for the first order condition can be obtained with respect to rotation decision T :

$$
\begin{aligned}
J_T &= pF'(T) - \frac{(r+\lambda_A+\lambda_B)\left[pF(T)-C_1\right]}{(1-e^{-(r+\lambda_A+\lambda_B)T})} + Tak_A p(\lambda_A+\lambda_B) \\
&\quad + \frac{akp(\lambda_A+\lambda_B)\left[\dfrac{e^{-(r+\lambda_A+\lambda_B)T}}{r+\lambda_A+\lambda_B} - \dfrac{1}{r+\lambda_A+\lambda_B} + Te^{-(r+\lambda_A+\lambda_B)T}\right]}{(e^{(r+\lambda_A+\lambda_B)}-1)} = 0
\end{aligned} \tag{11}
$$

If the salvage proportion $k_A(t)$ is assumed to be 0, which implies that the stand is totally destroyed, then the first order condition becomes:

$$J_T = pF'(T) - \frac{(r + \lambda_A + \lambda_B)[pF(T) - C_1]}{(1 - e^{-(\lambda_A + \lambda_B + r)T})} = 0 \tag{12}$$

Equation (12) is similar to Reed (1984) but modifies his land value to allow for two events. In our model the effective discount rate is adjusted by the possible risk from two events, $r + \lambda_A + \lambda_B$. Therefore, the opportunity cost of continuing a rotation when the first disturbance occurs is now higher, and the optimal rotation age under the first strategy considering correlated disturbance is clearly shorter than Reed (1984) predicts.

The second strategy ($d_A = 0, d_B = 1$)

We now depart from the literature in these problems for our continuance strategy and for multiple events. In the second strategy $(d_A = 0, d_B = 1)$, the landowner harvests only if the second disturbance B occurs but allows the stand continue to grow if the first disturbance A occurs. This might be the case if lightning causes some damage early in a stand's life, but then after the stand continues growing another large event occurs necessitating harvesting and restarting of the stand. Another example might be an ice or wind storm followed later in the rotation by fire, given that ice storms may increase fuel loadings in a stand by a factor of six times the normal loading (Mississippi Forestry Commission, 1994). If a fire later arrives with a stand in such a state, great damage can occur – insects and fire have a similar relationship as discussed in Dale (2001).

For these types of situations, we can write rent of the n^{th} rotation, now denoted as R_n^2, in the following way:

$$R_n^2 = \begin{cases} k_B(Y_n - X_n, X_n)pF(Y_n \mid X_n < T) - C_2 & \text{if } X_n < Y_n < T \\ pF(T) - C_1 & \text{if } X_n = Y_n = T \\ pk_A(X_n)F(T \mid X_n < T) - C_1 & \text{if } X_n < T = Y_n \end{cases} \tag{13}$$

where $k_B(Y_n - X_n, X_n)$ is now the salvage function (i.e., the percent of trees surviving) for this case. Notice that this salvage function depends not only on the timing of the first event (when it occurs during the rotation), but also on how much time has passed between the first and second events. We assume that $k_B(Y_n - X_n, X_n)$ is increasing in $(Y_n - X_n)$, which makes sense for most disturbances in that the farther two disturbances occur apart, the greater the salvage should be. For example, if beetle infestation and an ice storm occur too close to each other, the damage should be larger and salvage correspondingly smaller. When an ice storm occurs as the first event, the damage is caused by the breakage of twigs, bending stems to the ground, or outright breakage of the trunk (Smith,2000; Cannell and Morgan, 1989; Irland 2000). The woody debris accumulates and therefore increase the fuel loading and lead to severe damage if fire then arrives close to the ice storm. Fire damage is lower however as the period between these two events gets longer because of decomposition of debris and the subsequent reduction in fuel loading. Note that $k_B(Y_n - X_n, X_n)$ can be either increasing or decreasing in X_n. For example, if the first event is ice storm, the damage of ice storm may be smaller as X_n gets larger. In this case, the salvage function is increasing in X_n. On the contrary, if the first event is fire and the second event is pest infestation, the damage of both events may be worse as X_n increases, and the salvage function $k_B(Y_n - X_n, X_n)$ would be decreasing in X_n.

In this second strategy, the waiting time for harvest is Y_n or T, depending on event arrival. Thus, the expected net present rent of the stand over an infinite cycle of rotations is represented as:

$$J_2 = E\left[e^{-rY_1} R_1^2 + e^{-r(Y_1+Y_2)} R_2^2 + \ldots\right] = E\left[\sum_{n=1}^{\infty} e^{-r\sum_{i=1}^{n} Y_i} R_n^2\right] = \sum_{n=1}^{\infty}\left[\prod_{i=1}^{n-1} E\left(e^{-rY}\right) E\left(e^{-rY} R_n^2\right)\right] \qquad (14)$$

Following the derivation of (5), J_2 can be rewritten as:

$$J_2 = \frac{E\left(e^{-rY} R^2\right)}{1 - E\left(e^{-rY}\right)} \qquad (15)$$

Equation (15) represents the expected net present value of rent for the stand, and again we assume that the objective of the landowner is to maximize J_2 with respect to T. To evaluate the right hand side of (15), the cumulative distributions of Y_n, $F_Y(t)$ is again needed:

$$F_Y(t) = \begin{cases} 1 - e^{-\lambda_B t} & \forall t < T \\ 1 & \forall t \geq T \end{cases} \qquad (16)$$

where $F_Y(t) = \Pr\{Y_n \leq t\}$. If $t < T$, the marginal distribution of Y_n is the same as the probability of $X_n < Y_n < T$ which is established in equation (1). However, if t is greater than the rotation age T, the probability of $(Y_n \leq t)$ equals 1 because Y_n cannot be greater than the set rotation age T. Therefore, when the waiting time for harvest is Y_n, the probability density function of Y_n is the same for all rotations, therefore can be defined as:

$$f(Y)=\begin{cases}\lambda_B e^{-\lambda_B X} & \text{for } 0<Y_n<T \text{ when } X_n<Y_n<T\\ (1\text{-}e^{\text{-}\lambda_A T})e^{\text{-}\lambda_B T} & \text{for } Y_n=T \text{ when } X_n<Y_n=T\\ e^{-(\lambda_A+\lambda_B)T} & \text{for } Y_n=T \text{ when } X_n=Y_n=T\end{cases} \tag{17}$$

When $0<Y_n<T$, the probability density function is derived directly from the cumulative distribution function $F_Y(t)$. However, if $Y_n=T$, $f(Y)=p(Y_n=T)$. Y_n is equal to T in scenarios where $X_n<Y_n=T$ and $X_n=Y_n=T$, therefore $f(Y)$ should be equal to probabilities of $X_n<Y_n=T$ and $X_n=Y_n=T$ as discussed in equation (1).

In equation (15), the expected value $E(e^{-rY})$ is established as the sum of the probabilities of ending the rotation by harvesting or by the second event subjective to their possibilities, or:

$$\begin{aligned}E(e^{-rY})&=\int_0^{\infty}e^{-rt}f(Y)dY=\int_0^{T}e^{-rt}\lambda_B e^{-\lambda_B t}dt+e^{-rT}(1-e^{-\lambda_A T})e^{-\lambda_B T}+e^{-(\lambda_A+\lambda_B)T}e^{-rT}\\&=e^{-(r+\lambda_B)T}+\frac{\lambda_B}{r+\lambda_B}[1-e^{-(r+\lambda_B)T}]\end{aligned} \tag{18}$$

and

$$\begin{aligned}E(e^{-rY}R^2)&=e^{-rT}[pF(T)-C_1]e^{-(\lambda_A+\lambda_B)T}\\&+\int_0^T[k_B(Y_n-X_n,X_n)pF(Y_n)-C_2]e^{-rt}\lambda_B e^{-\lambda_B t}dt\\&+e^{-rT}(1-e^{-\lambda_A T})e^{-\lambda_B T}\{pk_A(X_n)F(T\mid X_n<T)-C_2\}\end{aligned} \tag{19}$$

Substituting the right hand sides of equations (18) and (19) into equation (15):

$$\begin{aligned}J_2&=\frac{(r+\lambda_B)[pF(T)-C_1]e^{-(r+\lambda_A+\lambda_B)T}}{r[1-e^{-(r+\lambda_B)T}]}\\&+\frac{(r+\lambda_B)e^{-(r+\lambda_B)T}\{pk_A(X_n)F(T\mid X_n<T)-C_1\}(1-e^{-\lambda_A T})}{r[1-e^{-(r+\lambda_B)T}]}\\&+\frac{(r+\lambda_B)\int_0^T[k_B(Y_n-X_n,X_n)pF(Y_n\mid X_n<T)-C_2]e^{-rt}\lambda_B e^{-\lambda_B t}dt}{r[1-e^{-(r+\lambda_B)T}]}\end{aligned} \tag{20}$$

According to equation (20), in the restrictive case that the stand is totally destroyed when a catastrophic event occurs ($k_A=0, k_B=0$) and there is only one catastrophic event ($\lambda_A = 0$), the expected value of the stand reduces to Reed (1984) once again.

The third strategy ($d_A = 0, d_B = 0$)

In the third strategy ($d_A = 0, d_B = 0$), the landowner does not harvest after either event should they both occur before the rotation, representing another departure from the literature. Such as case would occur if stand damage from the events is relatively low, or more importantly the salvage function of the second event is expected to be rather large. For example, the damage of trees by ice storms can be light (e.g. only minor branch breakage), and even though pine beetles or other pests attack occur in the wake of ice storm, the damage may not be serious enough to harvest the stand at the first or second event and start the new rotation. The lightly damaged stand might return very quickly to the original levels before storm or forest growth after the event may not be seriously affected (for an empirical example of this see Irland (2000)). Thus, the landowner could choose to wait to harvest until the arrival of the rotation age at a later time T. In this case, the rent of the n^{th} rotation R_n^3 can be written as:

$$R_n^3 = \begin{cases} pk_B(Y_n - X_n, X_n)F(T \mid X_n < Y_n < T) - C_1 & \text{if } X_n < Y_n < T \\ pF(T) - C_1 & \text{if } X_n = Y_n = T \\ pk_A(X_n)F(T \mid X_n < T) - C_1 & \text{if } X_n < T = Y_n \end{cases} \tag{21}$$

For all the event scenarios, the waiting time for harvest is T. Therefore, the expected present rent of future rotation in the third strategy is J_3:

$$J_3 = \frac{E\left(e^{-rT} R^3\right)}{1 - e^{-rT}} \tag{22}$$

In (22), and following our earlier procedures, R is a discrete variable with three cases and we can therefore define $E(e^{-rT}R^3)$ with respect to the probability in equation (1):

$$\begin{aligned} E(e^{-rT}R^3) = e^{-rT}&\left[pk_B(Y_n - X_n, X_n)F(T \mid X_n < Y_n < T) - C_2\right](1 - e^{-\lambda_B T}) \\ &+ \left[pF(T) - C_1\right]e^{-(r+\lambda_A+\lambda_B)T} \\ &+ \left[pk_A(X_n)F(T \mid X_n < T) - C_2\right](1 - e^{-\lambda_A T})e^{-(r+\lambda_B)T} \end{aligned} \tag{23}$$

Therefore the net present value function becomes,

$$\begin{aligned} J_3 &= \frac{\left[pk_B(Y_n - X_n, X_n)F(T|X_n < Y_n < T) - C_1\right]e^{-rT}(1 - e^{-\lambda_B T}) + \left[pF(T) - C_1\right]e^{-(r+\lambda_A+\lambda_B)T}}{1 - e^{-rT}} \\ &+ \frac{\left[pk_A(X_n)F(T|X_n < T) - C_1\right]\left(1 - e^{-\lambda_A T}\right)e^{-(r+\lambda_B)T}}{1 - e^{-rT}} \end{aligned} \tag{24}$$

2.2.2 The Landowner's Problem

With our approach, and given the discussion for each strategy, the landowner's choice is to find $T = \arg\max\{J_1(T), J_2(T), J_3(T)\}$ by choosing both the rotation age and the continuance strategies under possible event arrivals $\{T, d_A, d_B\}$. As we show in the simulation that follows, the best strategy and optimal rotation age changes according to the stochastic nature of the events and the salvage possibilities that arise when multiple events arrive a certain order.

It is worth noting that allowing for multiple events in the landowner's problem will not change our basic approach. The multiple event case is obviously much more complex and is probably less likely in practice given the typically short rotations used in temperate forests. However, for boreal forests that may be grown for more than 70 years, it is conceivable that there could be a third or fourth potential event that would not dictate the automatic harvesting assumed in the literature. In the appendix we show how more than two events is accommodated using our model.

2.3 **Simulation Results**

We now use a simulation of our model to first show the equivalence of the Faustmann version of our model (i.e. without any disturbance risk) and the basic Faustmann model, and then the equivalence of the single-disturbance version of our model and Reed's model. We then investigate parameter value ranges where the landowner would fail to reach an expected land value maximization if a stand is harvested after the first event. We consider different stochastic scenarios determined by the salvage function, arrival rate of events, and forest growth function changes after an event.

We base our simulation on a commonly used species in the south, loblolly pine (pinus taeda), which represents over half of all planted pine stands in the U.S. and can produce sawtimber as early as age 12. We employ Chang's (1984) loblolly sawtimber growth function, which has been widely applied in the Faustmann based literature (e.g., Amacher, Brazee, and Thompson, 1991; Amacher, Malik and Haight, 2005). A base age 25 site index of 80 feet, and a planting density of 300 trees per acre are assumed. Disturbances are assumed to affect the forest by removing stems and decreasing the growth of the trees, such as occurs in ice or wind storms given that cause crown damage and loss of leaf area accompany these events (Table 2.1).

The arrival rate λ_{A}represents the average arrival rate of the first event A and $\lambda_{\mathrm{B}}$is the arrival rate of the second event B. We will view a case where λ_{A} is greater than $\lambda_{\mathrm{B}}$and the first event always comes before the second event, although this is not restrictive as our approach applies to other cases as well. In the simulation, we reveal how the optimal strategy changes as the arrival rate, tree survival, and forest growth are expected to vary. The range of arrival rates we use follow previous disturbance studies for ice, wind and fire events. In the Faustmann-based literature where fire is considered, the arrival rate is assumed to range from 0.02 to 0.1 per year, which is consistent with 2 – 10 fires in every 100 years (e.g. Amacher, Malik and Haight, 2005). However, when ice or wind storms are considered, the frequency can range from 0 events (Gay and Davis, 1993) to one event every 1-2 years, with most areas having an occurrence frequency greater than 5 years (Bragg, Shelton and Zeide, 2003, Goebel and Deitschman, 1967, Wiley and Zeide, 1991, Gay and Davis, 1993 and Irland, 2000). In our simulation, we generally use arrival rates below 0.1, except where the arrival rate needs greater variation to show optimal strategy changes as it varies.

To better see patterns in how the optimal strategy varies across simulation scenarios, we assume a constant salvage percent, representing the proportion of the trees that survive after the damaging events. In the previous literature, the salvage from ice storms varies greatly, from very light to the total breakage of all mature stems (Irland 2000; Bragg, Shelton and Zeide 2003). Therefore, in our paper, the salvage percent is assumed to vary from 0 to 1 to uncover different patterns in optimal strategy as salvage rate changes.

Our stand establishment costs include site preparation via burning and pre-emergent weed control, as well as seedling and planting costs (all in US dollars). As discussed previously, we expect the marginal cost of replanting the damaged forest site (with event) to be higher than the conventional site (without event). Site preparation cost in damaged sites has indeed been found to be 6.4% to 51% higher than for conventional site preparation (Straka et al., 1995), and we therefore use a conservative value of 6.4% for this difference. According to Smidt, Dubois and Folegatti (2005), site preparation for a conventional site is \$105.23, and machine planting cost is \$0.0988 per seedling so that the seedling cost is \$0.053 per tree (South Carolina Forestry Commission, 2014). Assuming that 300 seedlings per acre are planted, the establishment cost for the conventional site is \$150.77 per acre and the cost in the damaged site is \$160.42 per acre. We use a stumpage value of \$175 per thousand board feet of pine sawtimber based on Timber Mart-South (2013) prices.

We begin by assuming that the landowner ignores the second event and therefore applies the first strategy of always harvesting should the first event arrive. When there is no risk (i.e.,$\lambda_A = \lambda_B = 0$), the results obtained from our model (see Row 2 in Table 2.2) are identical to the Faustmann model (see Row 1 in Table 2.2) which is based on the assumption of no uncertainty. The small discrepancy between our model and Faustmann is due to discretization of the integral in the expected present value function. Comparing our model with that of Reed (see Row 3 to Row 8 in Table 2.2), the arrival rate of the first event in our model is assumed to be 0.1, 0.05 or 0.07 respectively, and that of the second event is 0. By comparison using different scenarios, we demonstrate that our results replicate those of Reed model, under cases where $\lambda_{\mathrm{B}} = 0$ (see Row 3 to Row 8 in Table 2.2). The table also demonstrates the standard result in the literature that rotation ages are shorter as the risk of an event increases, with the decrease being proportional to the arrival rate.

Examining cases with more than one event, we find that our model leads to different results compared with existing approaches. Table 2.3 presents the effect of the magnitude of the timber salvage proportion after the second event (k_B) on the optimal management decisions when k_A is large ($k_A = 0.9$) and k_A is small ($k_A = 0.5$). We show there are cases where optimal management regimes are suboptimal if Faustmann or Reed's assumptions are applied to the case of two events. In fact, now we find a new result that rotation age which accounts for multiple events and a continuance decision is not necessary shorter and may in some case be equal to or greater than the Faustmann rotation. What is happening in these cases is that, due to our assumption that the forest is not totally destroyed after the first event, the event in the future can be thought of as natural thinning processes as long as the stand is expected to recover. Therefore, the opportunity cost of not harvesting does not necessarily become larger after the occurrence of events.

Examining the decreasing tree survival case for the second event, k_B we see other patterns that become apparent. First, as the salvageable percent of trees after the second event (k_B) decreases, the opportunity cost for harvesting at the first event is lower, and therefore harvesting at the first event is more likely to be optimal, holding other parameters constant. Second, if the first strategy is optimal, then the salvage function after the second event will not affect expected rents, as it is now optimal to restart the rotation right after the first event.

Based on our results in Table 2.3, a "real event" can be defined as the threshold of salvage probability below which the damage is severe enough for the landowner to harvest the stand right after, as compared to delaying the harvest. Therefore, the threshold of the "real event" is as high as $k_B = 0.8$ when other variables are held constant. More specifically, when the salvage probability of the second event is lower than 0.7, our result coincides with Reed's assumptions where the optimal solution for the landowner is to harvest right after the first event. In contrast, it is not optimal for the landowner to harvest upon the occurrence of the first event if the damage of the second event is relatively small or 80% or more of the stems survive the event.

Also, when the salvage proportion of events is comparatively high, simply assuming the stand should be harvested after the first event leads to a considerably lower land value than using our decision problem(Table 2.3). Land value decreases from a suboptimal strategy can be higher than 10% of the land value attainable in present value terms.

Table 2.4 shows simulation results as k_A changes when $k_B = 0.9$ and $k_B = 0.5$. It shows that the timber salvage after the first event (k_A) also affects the optimal continuance strategy for the landowner. We begin the analysis from scenarios in which k_A decreases when k_B is comparatively small at 0.5 (i.e., only 50% of the stand survives the event). By comparing different models, we find that when k_B is comparatively small, harvesting at the first event is more likely to be selected no matter what the survival event is for the first event, k_A. This is because if k_B is small, the damage in the second event will serve to dominate any future forest stand growth after the first event. Similarly, when scenarios are designed considered in which k_A decreases when k_B is as large as 0.9, the second strategy turns out to be optimal no matter how large k_A is. The reason is if k_B is large, the growth after the first event will outweigh the damage in the second event even if k_A is very small. Finally, once again Table 2.4 shows the decrease in land value by not following our more general model, and this land value decrease is higher when tree survival is higher.

Referring to Table 2.3 and 2.4, we investigate how sensitive is the optimal management strategy $\{T, d_A, d_B\}$ to the salvage proportion after the second event, k_B. The results show that the effects of the salvage proportion after the first event, k_A, on the rotation age is significant, but there is little effect on the timing of harvesting through d_A and d_B. Therefore, it is important to take the second or even more disturbance events into account to reach an optimal management regime, especially for sites where disturbances occurs frequently or damage is likely more severer.

Table 2.5 presents simulation results as the variation of growth rate parameter after the first event is changed. When the growth rate increases after the first event, the second strategy is more likely to be optimal. This makes sense as in this case, the growth of the stand is more likely to outweigh the damage that the second event causes. Therefore, it is more beneficial for the landowner to harvest after the second event. Table 2.5 also indicates that if the first strategy is optimal as b changes, the rotation age and the expected rent will be the same when holding other parameters constant. Further, the optimal management strategy appears to be very sensitive to the growth rate parameter b, which is reflected by the large variation of the rotation age and decision variables $d_A$and d_B with changes in b.

Table 2.5 also shows the effect of the growth rate parameter after the second event, denoted as g, on the optimal management strategy. As g varies from 0.1 to1, the rotation age and optimal strategy does not change, implying the optimal management strategy is not sensitive to the variation of g. In other words, growth and recovery after the first event appears more important forest management practices than recovery after a second event, although both are important in determining rotation ages.

Table 2.6 considers how sensitive management decisions are to changes in the arrival rates of the two events, $\lambda_A$and λ_B. In Table 2.6, λ_A increases from 0.1 to 0.25.

Here, when the salvage proportions of the events are high, the optimal decision changes from harvesting after the second event ($d_A = 0, d_B = 1$) to harvesting at the rotation age ($d_A = 0, d_B = 0$) as the arrival rate of the first event increases. This makes sense because as λ_A increases, that event is more likely to occur when the forest is young and damages are comparatively small, and so the landowner is reluctant to harvest after the event and instead waits. Table 2.6 also shows the effect of λ_B on the optimal management decision; for this parameter, the optimal decision changes from harvesting after the second event ($d_A = 0, d_B = 1$) to harvesting at the rotation age ($d_A = 0, d_B = 0$) as the arrival rate of the second event increases. The results in the table also demonstrate that the optimal management regime is sensitive to the arrival rate of both events, suggesting the important role arrival rates play in forest management practices and in using our more general approach. Given that the frequency of arrival of different events can vary greatly across regions, care must be taken to understand the optimal harvesting and continuance strategy for each specific case.

Finally, in Table 2.7 we investigate for a range of parameters, the loss in land values from a rotation age solution that is consistent with the (suboptimal) strategy of always harvesting after the first event. The table shows that the loss in land value is higher if tree survival is higher regardless of the growth rate and recovery parameters after an event. In many cases, where tree survival ranges from 50-90% of the stand, land values are close to 10 percent lower if it is assumed the landowner follows a rotation age that assumes harvesting after the first event when it arrives.

2.4 **Conclusions**

This paper contributes to the literature in several respects. Rather than assuming just one disturbance within a given future rotation as found in previous studies, we consider multiple events within a rotation, and incorporate this into a simple open loop problem rather than a cumbersome closed loop model that could easily suffer from parameter complexity. Though our model collapses to either a Faustmann model or Reed's seminal extension in certain cases, our model leads to very different implications for optimal management decisions in a large range of reasonable cases concerning arrival rates and tree survival. Most previous studies on risk and forest rotation decisions conclude shorter rotation age in the presence of catastrophic risks such as the ones examined in our paper. However, our results suggest that the rotation age is not necessarily shorter if more than one risk is considered and a more flexible stand continuance strategy is allowed. Finally, we show that failure to consider the complexities we include in our approach will result in suboptimal forest management decisions and substantial losses in land values.

In addition to multiple possible events during a rotation, we also relax the assumption that the forest is either totally destroyed or clearcut right after a disturbance. We allow both a salvage possibility (the stand is partially but not totally destroyed) and flexible harvest timing even upon the occurrence of disturbances. Therefore, the landowner chooses to either harvest or wait after an event to maximize net present value. The real world decision making of forest landowners are much better modeled in this way. Our results show that clearcutting after an event is not always optimal. This is very intuitive as disturbances can be significant but not damaging enough that the landowner is better off harvesting immediately.

We also empirically show that the nature of events (e.g. arrival rates) and forest recovery, which are region and species specific affect optimal management decisions and rotation ages in different and interesting ways. Specifically, the optimal management strategy can be very sensitive to the salvage proportion, growth rates, and the arrival rates of events. The empirical realization of these parameters is key to understanding how forest management should be adjusted accordingly.

This study can serve as a platform for future work in multiple directions. First, we built our model based on the notion of rent maximization, where rents were obtainable only from harvesting. Forest rents could be defined more generally, for example, by assuming the landowner values not only harvesting returns but also the amenity value associated with the standing forest stock. Second, the market price of forest products (e.g. timber, pulpwood) may also be affected if a comparatively large forest area is affected by disturbances. In such a case, the benefit of forest landowners cannot be expressed using a single net present value function as some are affected by the disturbance while others are not. Also, the implications of relative policies, such as taxes and subsidies on forest production, may affect the optimal management strategy, and this dimension could be studied in a relatively simple way given the open loop nature of our problem.

Appendix: Extension of the model to *h* events

As with the two events framework, the number of events during rotation age would be assumed to follow a homogeneous Poisson distribution, with corresponding and independent arrival rates equal to $\lambda_1, \lambda_2, ..., \lambda_h$. As before, the timing of these events would be denoted $X_1, X_2, ..., X_h$ and would continue to be independent.

According to these assumptions, there are $h + 1$ possibilities of the number of disturbances occurs in each rotation. If there is no disturbance occurring in the rotation age T, the probability is as follows,

$$P(X_1 = X_2 = \ldots = T) = P(X_1 = T)P(X_2 = T)\ldots P(X_h = T) = e^{-(\lambda_1+\lambda_2+\ldots\lambda_h)T}$$

Similarly, if one event occurs, the probability becomes

$$P(X_1 < X_2 = \ldots = T) = P(X_1 < T)P(X_2 = T)\ldots P(X_h = T) = (1-e^{-\lambda_1 T})e^{-(\lambda_2+\ldots\lambda_h)T}$$

and if there are two events occurs, the probability is

$$\begin{aligned} P(X_1 < X_2 < X_3 = X_4 \ldots = T) &= P(X_1 < X_2)P(X_2 < T)P(X_3 = T)\ldots P(X_h = T) \\ &= (1-e^{-\lambda_2 T})e^{-(\lambda_3+\ldots\lambda_h)T} \end{aligned}$$

Therefore, in general, if there are $k(1 < k < h)$ events occurs, the probability is $(1-e^{-\lambda_k T})e^{-(\lambda_{k+1}+\ldots\lambda_h)T}$. Since the probability of the events scenarios have been established, and the rent function for each strategy can be similarly defined as we illustrated in two events case. The best strategy would now be defined as $\{d_1, d_2, ..., d_h, T\}$where $d_1, d_2, ..., d_h$ are binary variables for the harvest decisions after each disturbance.

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Table 2.1 Description of Parameters[1-2]

Type	Function	Assumed Form or value
Growth function without event for sawtimber	$F(t)$	$e^{9.75-\frac{3418.11}{mT}-\frac{740.82}{ET}-\frac{34.01}{T^2}-\frac{1527.67}{E^2}}$ $(m = 300, E = 80)$
Sawtimber growth function after first event A for sawtimber	$F(t\|x < T) = bF(t)$	$be^{9.75-\frac{3418.11}{mT}-\frac{740.82}{ET}-\frac{34.01}{T^2}-\frac{1527.67}{E^2}}$ $(m = 300, E = 80)$
Sawtimber growth function after second event B for sawtimber	$F(t\|X < Y < T)$ $= bgF(t)$	$bge^{9.75-\frac{3418.11}{mT}-\frac{740.82}{ET}-\frac{34.01}{T^2}-\frac{1527.67}{E^2}}$ $(m = 300, E = 80)$
Average arrival rate for first event *A*	λ_A	constant
Average arrival rate for second event *B*	λ_B	constant
Timber salvage after first event *A*	$k_A(X_n)$	constant
Timber salvage after second event *B*	$k_B(Y_n - X_n, X_n)$	constant
Reforestation without event	$C_1(d)$	$c_0 + (c_1 + c_2)d$ $(c_0 = 105.23, c_1 = 0.0988, c_2 = 0.053)$
Reforestation cost with the event	$C_2(d)$	$(1 + \beta)[c_0 + (c_1 + c_2)d]$ $(\beta = 6.4\%, c_0 = 105.23, c_1 = 0.0988, c_2 = 0.053)$

1 b represents the growth rate parameter of the growth function after event A.

2 g represents the growth rate parameter of the growth function after event B.

Table 2.2 Relative Equivalence of Model[1-8]

Model	k_A	k_B	λ_A	λ_B	b	g	m	T	Expected rents Of 1st strategy
Faustmann							300	18.6	942.5
Our model	0	0	0	0	0	0	300	18.6	942.7
Reed			0.1				300	12.7	385.9
Our model	0	0	0.1	0	1	1	300	12.7	385.9
Reed			0.05				300	14.8	588.1
Our model	0	0	0.05	0	1	1	300	14.8	588.1
Reed			0.07				300	13.8	494.5
Our model	0	0	0.07	0	1	1	300	13.8	494.5

[1] k_A represents the proportion of the forest survived after the first event A.

[2] k_B represents the proportion of the forest survived after the second event B.

[3] λ_A represents average arrival rate of the first event A.

[4] λ_B represents average arrival rate of the second event B.

[5] b represents the growth rate parameter of the growth function after event A.

[6] g represents the growth rate parameter of the growth function after event B.

[7] m represents planting density.

[8] T represents rotation age.

Table 2.3 Simulation for Different Survival Proportions after the Second Event[1-8]

k_A	k_B	Best strategy (d_A, d_B)	T	Max $\{J1, J2, J3\}$	k_A	k_B	Best strategy (d_A, d_B)	T	Max $\{J1, J2, J3\}$
Faustmann model								18.6	942.5
Reed model								15.4	643
0.9	1	$d_A = 0, d_B = 1$	19	785.3	0.5	1	$d_A = 0, d_B = 1$	18	656.6
	0.9	$d_A = 0, d_B = 1$	18	768.9		0.9	$d_A = 0, d_B = 1$	17	641.2
	0.8	$d_A = 0, d_B = 1$	18	752.9		0.8	$d_A = 0, d_B = 1$	17	626.7
	0.6	$d_B = 1$	20	744.9		0.6	$d_B = 1$	16	615.1
	0.4	$d_B = 1$	20	744.9		0.4	$d_B = 1$	16	615.1
	0.2	$d_B = 1$	20	744.9		0.2	$d_B = 1$	16	615.1

[1] k_A represents the proportion of the forest survived after the first event A.

[2] k_B represents the proportion of the forest survived after the second event B.

[3] $\lambda_A = 0.04$, which represents average arrival rate of the first event A.

[4] $\lambda_B = 0.03$, which represents average arrival rate of the second event B.

[5] $b = 0.9$, which represents the growth rate parameter of the growth function after event A.

[6] $g = 0.7$, which represents the growth rate parameter of the growth function after event B.

[7] m represents planting density.

[8] T represents rotation age.

Table 2.4 Simulation for Different Survival Proportions after the First Event[1-8]

k_B	k_A	Best strategy (d_A, d_B)	T	Max $\{J1,J2,J3\}$	k_B	k_A	Best strategy (d_A, d_B)	T	Max $\{J1,J2,J3\}$
Faustmann model								18.6	942.5
Reed model								15.4	643
0.9	0.7	$d1$=0,$d2$=1	18	704.8	0.5	0.7	$d1$=1	18	675.3
	0.5	$d1$=0,$d2$=1	17	641.2		0.5	$d1$=1	16	615.1
	0.3	$d1$=0,$d2$=1	17	578.8		0.3	$d1$=1	15	562.6
	0.1	$d1$=0,$d2$=1	16	517.9		0.1	$d1$=1	14	515.7

[1] k_A represents the proportion of the forest survived after the first event A.

[2] k_B represents the proportion of the forest survived after the second event B.

[3] $\lambda_A = 0.04$, which represents average arrival rate of the first event A.

[4] $\lambda_B = 0.03$, which represents average arrival rate of the second event B.

[5] $b = 0.9$, which represents the growth rate parameter of the growth function after event A.

[6] $g = 0.7$, which represents the growth rate parameter of the growth function after event B.

[7] m represents planting density.

[8] T represents rotation age.

Table 2.5 Simulation Results for Different Growth Rate Parameters[1-8]

g	b	Best strategy (d_A, d_B)	T	Max $\{J1,J2,J3\}$	b	g	Best strategy (d_A, d_B)	T	Max $\{J1,J2,J3\}$
Faustmann model								18.6	942.5
Reed model								15.4	643
0.7	0.5	$d_A = 1$	20	744.9	0.8	0.1	$d_A = 1$	20	744.9
	0.7	$d_A = 1$	20	744.9		0.4	$d_A = 1$	20	744.9
	0.9	$d_A = 0, d_B = 1$	18	768.9		0.7	$d_A = 1$	20	744.9
	1	$d_A = 0, d_B = 1$	19	817.9		1	$d_A = 1$	20	744.9

[1] $k_A = 0.9$, which represents the proportion of the forest survived after the first event A.

[2] $k_B = 0.9$, which represents the proportion of the forest survived after the second event B.

[3] $\lambda_A = 0.04$, which represents average arrival rate of the first event A.

[4] $\lambda_B = 0.03$, which represents average arrival rate of the second event B.

[5] b represents the growth rate parameter of the growth function after event A.

[6] $g = 0.7$, which represents the growth rate parameter of the growth function after event B.

[7] $m = 300$, which represents planting density.

[8] T represents rotation age.

Table 2.6 Simulation Result for Different Arrival Rates[1-8]

λ_B	λ_A	T	Max $\{J1, J2, J3\}$	Best strategy (d_A, d_B)	λ_A	λ_B	T	Max $\{J1, J2, J3\}$	Best strategy (d_A, d_B)
0.03	0.1	19	796.3	$d_A = 0, d_B = 1$	0.25	0.01	19	828.7	$d_A = 0, d_B = 1$
	0.15	19	790.0	$d_A = 0, d_B = 1$		0.02	18.9	813.1	$d_A = 0, d_B = 0$
	0.2	19.3	793.9	$d_A = 0, d_B = 0$		0.03	18.8	804.6	$d_A = 0, d_B = 0$
	0.25	18.8	804.6	$d_A = 0, d_B = 0$		0.1	18.5	774.7	$d_A = 0, d_B = 0$

[1] $k_A = 0.5$, which represents the proportion of the forest survived after the first event A.

[2] $k_B = 0.5$, which represents the proportion of the forest survived after the second event B.

[3] $\lambda_A = 0.04$, which represents average arrival rate of the first event A.

[4] $\lambda_B = 0.03$, which represents average arrival rate of the second event B.

[5] $b = 1$, which represents the growth rate parameter of the growth function after event A.

[6] $g = 0.9$, which represents the growth rate parameter of the growth function after event B.

[7] $m = 300$, which represents planting density.

[8] T represents rotation age.

Table 2.7 Simulation Result for Different Scenarios of Mixed Parameters[1-8]

Parameters						Optimal Strategy			Loss
k_A	k_B	λ_A	λ_B	b	g	T	Max $\{J1, J2, J3\}$	(d_A, d_B)	Loss of Reed model
0.9	0.9	0.04	0.03	0.8	0.7	18	752.7	$d_A = 0, d_B = 1$	50.3
0.5	0.9	0.04	0.03	0.8	0.7	18	633.8	$d_A = 0, d_B = 1$	27.6
0.5	0.5	0.04	0.03	0.8	0.7	16	615.1	$d_A = 1$	8.9
0.5	0.5	0.04	0.03	0.9	0.9	16	615.1	$d_A = 1$	8.9
0.9	0.9	0.04	0.03	0.9	0.9	19	785.3	$d_A = 0, d_B = 1$	82.9
0.9	0.9	0.03	0.02	0.9	0.9	18	820.9	$d_A = 0, d_B = 1$	63.8
0.5	0.5	0.03	0.02	0.9	0.9	17	692.8	$d_A = 1$	11.4

[1] k_A represents the proportion of the forest survived after the first event A.

[2] k_B represents the proportion of the forest survived after the second event B.

[3] λ_A represents average arrival rate of the first event A.

[4] λ_B represents average arrival rate of the second event B.

[5] b represents the growth rate parameter of the growth function after event A.

[6] g represents the growth rate parameter of the growth function after event B.

[7] m represents planting density.

[8] T represents rotation age.

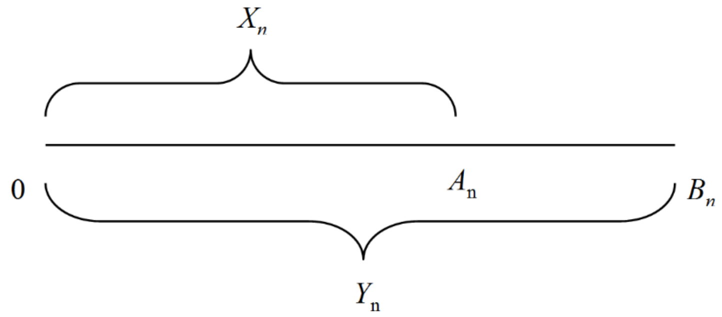

Fig. 2.1 Possible Timeline of Two Disturbances in the n^{th} Rotation

Chapter 3: Socially Optimal Forest Management with Sequential Disturbances

3.1 Introduction

Major disturbances such as fire, drought, ice storm, windstorm, insect and pathogen outbreaks are recognized as major components in forest management decision making, and all have potential to cause tremendous timber loss. Previous literature has examined the effects of a single disturbance on optimal rotation age decisions (Martell, 1980; Routledge, 1980; Reed, 1984, 1987; Reed and Apaloo, 1991; Yin and Newman, 1996; Englin et al., 2000; Stainback and Alavalapati, 2004; Yoder, 2004; Amacher et al., 2005; Goodnow et al., 2008). Among this literature, Martell (1980), Routledge (1980) and Reed (1984) are three pioneering studies that have investigated the impact of fire on forest decision making. Routledge (1980) explores the relationship between timber value of the stand and fire risk in a discrete time framework. Reed (1984) alternatively employs the continuous Faustmann rotation framework and investigates the relationship between fire risk and the optimal rotation decision, assuming that the arrival rates of fire follow a time-independent Poisson process and that the stand is partially or totally destroyed, and that the landowner immediately undertakes a harvest of surviving trees, upon the occurrence of fire. Englin et al. (2000) further extend Reed's model by introducing amenity values to un-harvested forests. Through an empirical application applied to jack pine, they find that the rotation age is shorter in the presence of fire risk, but longer if a certain type amenity is incorporated. These problems remain an active area of forest economics research, but almost all studies consider only one type of disturbance and assume immediate harvesting after that disturbance arrives.

Recognizing these limitations, Xu et al. (2013) extends this literature by incorporating multiple disturbances and flexible harvest timing to examine the optimal harvest strategy for the landowner. Specifically, they consider different disturbances in terms of events with different arrival rates, and allow harvesting at either the occurrence of any disturbance or at a final rotation age. They show that failure to consider various stand continuance options after an event arrives will lead to suboptimal harvesting behavior for the landowner. Based on simulation results applied to loblolly pine, the most important commercial species in the southern US, a "real event" is defined as the threshold above which the damage is severe enough for the landowner to harvest the stand right after a disturbance rather than delaying the harvest. While Xu et al. (2013) reach different conclusions on optimal forest harvesting strategies compared to other previous studies, it is limited by only considering timber value as the component of forest rents. The fact that forests serve as an important source of amenity services and that possible differences may exist between individually and socially optimal forest harvesting decisions are ignored. Maximizing timber value alone from a landowner's perspective can lead to market failures and generate unexpected social costs, and therefore further investigation is needed in this case.

This paper bridges this gap through explicitly modeling the optimal forest harvesting strategies from the social planner's view, through incorporating amenity values of un-harvested forests. We consider multiple disturbances and relax the assumption of immediate harvesting upon either occurrence of disturbances or at predetermined rotation age, considering partial damage and survival value of the stand. We explicitly examine the social costs if amenity value of an un-harvested stand is ignored when making rotation age and stand continuance decisions. We conclude that amenity value plays an important role in ways not expected.

3.2 **Model**

We modify the problem in Hartman (1976) and Englin et al. (2000) to account for generalizations studied in Xu et al. (2013) where multiple disturbances are taken into account and there is flexible harvest timing. In this paper, however, the amenity value is taken into account to investigate socially optimal harvest decisions of forests. Similar to Xu et al. (2013), the model we use is based on the consideration of two possible natural disturbances in a forest stand once it is established. Although disturbances in terms of destructive events are stochastic, the landowner is assumed to know the arrival rate (i.e., probability) of each event. Let A_n denote the first disturbance that may arrive in the n^{th} rotation, and B_n the second disturbance that may arrive in the n^{th} rotation. These two disturbances are assumed to be independent in terms of arrival rates, but the damages each causes are correlated. Figure 2.1 illustrates a potential situation among events.

The arrival rates of both events are assumed to follow a homogeneous Poisson process. The waiting time between any events and the rotation age is a random variable which follows an exponential distribution. Let X_n denote the time interval between planting a stand and the arrival of the first disturbance A_n in any one of these rotations, and Y_n be the time interval between planting the stand and arrival of the other disturbance B_n in any rotation n ($X_n < Y_n$). Using this notation, $Y_n - X_n$ denotes time interval between events A_n and B_n if both occur during the same rotation and the landowner decides to continue the rotation after event A_n (Figure 2.1).

There are three scenarios regarding the sequence of events that may occur during any given future rotation. The forest may grow to a predetermined rotation age without the occurrence of any event ($Y_n = X_n = T$); only one event A_n occurrs before the planned rotation age ($X_n < T = Y_n$); and finally, there can be two events before the rotation age, where under our assumption A_n arrives first ($X_n < Y_n < T$). The binary decision variables d_A and d_B are employed in our model to define the landowner's decisions concerning the timing of harvesting: d_A equals 1 if the landowner harvests the forest immediately upon the arrival of the first event A_n and equals 0 otherwise. Similarly, d_B equals 1 if the forest is harvested after the second event B_n and equals 0 otherwise. Therefore, there are three options for the landowner, and the one that maximizes the expected net present value will be selected: If the landowner harvests immediately after the first event if it occurs than ($d_A = 1$); if the landowner harvests after the second event if it occurs than ($d_A = 0$, $d_B = 1$), and if the landowner foregoes harvesting until the planned rotation age than we have ($d_A = 0, d_B = 0$). Thus, the waiting time to harvest from the date of planting is equal to either: Y_n, X_n or T.

To obtain the socially optimal management decision characterized by the rotation age and the continuance strategies, $\{T, d_A, d_B\}$, we follow a two-step process. We first derive the expected net present values over future rotations for each of the three strategies, J_1, J_2 and J_3. We then solve the problem by choosing the management decision $\{T, d_A, d_B\}$ such that the maximal J_i is selected from $\{J_1, J_2, J_3\}$. We can then compare the socially optimal management decision $\{T, d_A, d_B\}$ with the landowner's private optimal management decision by including amenity values in the social planner's rent maximization problem. We can then use the wedge between these decisions to determine the social cost that results when the private landowner ignores the social amenity value. This social cost is determined using simulation analysis, which also reveals how the socially optimal management decision varies along with changing the stochastic nature of the disturbances and tree survival possibilities.

3.2.1 The Two Event Case

Given the assumptions above, the arrival rates of the first and second events are uncorrelated, and thus X_n and Y_n are independent. Let λ_A and λ_B be Poisson arrival rates for event A_n and B_n respectively, and assume for illustration purpose that $\lambda_A \neq \lambda_B$. The probabilities of the arrival of the events during any n^{th} rotation can be conveniently written for each case as:

$\Pr(X_n = Y_n = T) = \Pr(Y_n = T)\Pr(X_n = T | Y_n = T) = e^{-(\lambda_A + \lambda_B)T}$, which represents the probability of the case where the landowner reaches the rotation age without any event arriving;

$\Pr(X_n < Y_n = T) = \Pr(Y_n = T)\Pr(X_n < T | Y_n = T) = (1 - e^{-\lambda_A T})e^{-\lambda_B T}$, which represents the probability of the case where only one event arrives before arriving at the rotation; and

$\Pr(X_n < Y_n < T) = \Pr(Y_n < T)\Pr(X_n < Y_n | Y_n < T) = 1 - e^{-\lambda_B T}$, which defines the probability of the case where both events arrive before the planned rotation age.

In the following analysis, R_n^k $(k = 1, 2, 3)$ represents the value of the n^{th} rotation for each of the three strategies. For each strategy, we examine the expected present value of the stand over infinite rotations, and we obtain the necessary condition for the optimal rotation age. We will illustrate the social planner's problem below, but it should be recognized that the private landowner's problem omits amenities, and this will be important in the simulation that follows the model section.

The first strategy ($d_A = 1$)

In the first strategy ($d_A = 1$), the landowner harvests at the first event A_n, if it occurs during rotation, and if not the landowner harvests when the rotation age T is reached. Following Xu et al. (2013), as the disturbance or harvest times for each rotation are independent, the expected value of harvest in each future rotation is the same and can be denoted as $E\left(e^{-rX_i}\right) = E\left(e^{-rX}\right)$. The expected present value of harvesting can be written as:

$$J_1 = \frac{E\left(e^{-rX} R^1\right)}{1 - E\left(e^{-rX}\right)} \quad , \tag{1}$$

where E is the expectation operator applied to the random variable X. The probability density function of X_n is then defined as $f(X)$ for each rotation:

$$f(X) = \begin{cases} (\lambda_A + \lambda_B) e^{-(\lambda_A + \lambda_B)t} & \text{for } 0 < X < T \\ e^{-(\lambda_A + \lambda_B)T} & \text{for } X = T \end{cases} \tag{2}$$

The value of the *n*th rotation $\boldsymbol{R}_n^1$, however, is then written as:

$$R_n^1 = \begin{cases} pF(T) + \mathrm{e}^{rT} \int_0^T A(s) e^{-rs} ds - C_1 \mathrm{e}^{rT} & \text{if } X_n = Y_n = T \\ k_A(X_n) pF(X_n) + \mathrm{e}^{rx} \int_0^x A(s) e^{-rs} ds - C_2 \mathrm{e}^{rX_n} & \text{if } X_n < T = Y_n \end{cases} \tag{3}$$

where $F(t)$ is the volume function at a stand age that equals either X_n or Y_n; $k_A(X_n)$ is the survival function at time X_n, which represents the proportion of the stand that survives at the occurrence of the first event A_n; C_1 is the cost to start the new rotation with no event, which only includes regeneration expenses; C_2 is the cost to start a new rotation after a disturbance event, and this includes both regeneration expenses and clearing costs after the damage of the event. Therefore, $C_2 > C_1$. The function $A(s)$ gives the flow of the amenities at time s, and $\mathrm{e}^{rx} \int_0^x A(s) e^{-rs} ds$ sums the discounted amenity values over the time from the birth of the stand at time 0 to time X.

If $X_n = Y_n = T$, the landowner harvests at the rotation age and receives the timber value $pF(T)$ and the amenity value $e^{rT}\int_0^T A(s)e^{-rs}ds$ compounded forward to time T, and starts the new rotation at the cost C_1. If $X_n < T = Y_n$, then there is one disturbance during the n^{th} rotation and the landowner receives the survival timber value $k_A(X_n)pF(X_n)$, and an amenity value $e^{rx}\int_0^x A(s)e^{-rs}ds$. Although they incorporate amenity values to the unharvested forest stock similar to A(s), immediate harvesting after the first event is the only case considered by Englin et al. (2000). Thus, the first strategy discussed above coincides with Englin et al. (2000).

In equation (1), the expected value term $E(e^{-rX})$ represents the sum of the probabilities of ending the rotation by either harvesting after the first disturbance or reaching the rotation age and can be written specifically as:

$$\begin{aligned}E\left(e^{-rX}\right) &= \int_0^\infty e^{-rt} f(X)dX \\ &= \int_0^T e^{-rt}\lambda_B e^{-\lambda_B t}dt + \int_0^T e^{-rt}[(\lambda_A+\lambda_B)e^{-(\lambda_A+\lambda_B)t} - \lambda_B e^{-\lambda_B t}]dt + e^{-(\lambda_A+\lambda_B)T}e^{-rT} \\ &= e^{-(r+\lambda_A+\lambda_B)T} - \frac{\lambda_A+\lambda_B}{r+\lambda_A+\lambda_B}[e^{-(r+\lambda_A+\lambda_B)T} - 1]\end{aligned} \tag{4}$$

The term $E\left(e^{-rX}R^1\right)$ is the expected value of the rent discounted to the beginning of the rotation if the first strategy is taken and therefore can be written as:

$$\begin{aligned}E\left(e^{-rX}R^1\right) &= e^{-rT}\left[pF(T) - C_1 e^{rT} + e^{rT}\int_0^T A(s)e^{-rs}ds\right]e^{-(\lambda_A+\lambda_B)T} \\ &\quad + \int_0^T\left[k_A(t)pF(t) + e^{rt}\int_0^t A(s)e^{-rs}ds - C_2 e^{rt}\right]e^{-rt}(\lambda_A+\lambda_B)e^{-(\lambda_A+\lambda_B)t}dt \\ &= \left[pF(T) - C_1 e^{rT} + e^{rT}\int_0^T A(s)e^{-rs}ds\right]e^{-(r+\lambda_A+\lambda_B)T} \\ &\quad + \int_0^T\left[k_A(t)pF(t) + e^{rt}\int_0^t A(s)e^{-rs}ds - C_2 e^{rt}\right]e^{-(r+\lambda_A+\lambda_B)t}(\lambda_A+\lambda_B)dt\end{aligned} \tag{5}$$

By substituting the right hand sides of equation (4), (5) into equation (1) ,we obtain an objective function that modifies Reed (1984) and Englin et al. (2000):

$$J_1 = \frac{(r+\lambda_A+\lambda_B)e^{-(r+\lambda_A+\lambda_B)T}[pF(T)+e^{rT}\int_0^T A(s)e^{-rs}dx - C_1e^{rT}]}{r[1-e^{-(r+\lambda_A+\lambda_B)T}]}$$
$$+\frac{(r+\lambda_A+\lambda_B)\int_0^T\left[k_A(t)pF(t)+e^{rt}\int_0^t A(s)e^{-rs}ds - C_2e^{rt}\right]e^{-(r+\lambda_A+\lambda_B)t}(\lambda_A+\lambda_B)dt}{r[1-e^{-(r+\lambda_A+\lambda_B)T}]}$$

(6)

According to equation (6), if we assume that the stand is totally destroyed when the first disturbance event occurs ($k_A(t) = 0$), and there is only one disturbance ($\lambda_B = 0$), then the expected value of stand in (6) reduces to the expected net present value of Englin's (2000) model with only one disturbance.

If the survival proportion $k_A(t)$ is assumed to be 0, then we can differentiate equation (6) with respect to T to obtain equation (7) (a detailed derivation is provided in the Appendix):

$$pF'(T) + A(T) = (r+\lambda_A+\lambda_B)pF(T) + rJ_1 + (\lambda_A+\lambda_B)e^{rT}[C_2 - C_1] \quad (7)$$

According to equation (7), the first order condition of expected present value of the stand is similar to Englin (2000) in which only one event is considered in the presence of an amenity. When two disturbance events are taken into account, however, the effective discount rate here becomes $r+\lambda_A+\lambda_B$. The left side of equation (7) is the marginal revenue from the next time increment of growth, gained by delaying harvest for one more period of time. It includes a timber value component, $pF'(T)$, and the current benefits associated with amenities. The right side of equation (7) is the opportunity cost of delaying harvest for one period of time. The first term on the right is the value of the forest stand multiplied by the risk-adjusted discount rate. The second term is the land rent term that accounts for both multiple risks and amenity values, which is fundamentally different from Englin (2000). The final term is the difference in site preparation costs associated with the events arriving during the rotation.

The second strategy $(d_A = 0, d_B = 1)$

In the second strategy ($d_A = 0, d_B = 1$), harvest takes place only if the second disturbance B_n occurs but otherwise the landowner allows the stand continue to grow after the first disturbance A_n. In this case, the waiting time for harvest is Y_n or T depending on the event arrival in the nth rotation. If there is only one event in which no harvest occurs, or if no event occurs, then the waiting time is T, or Y_n because $T = Y_n$ as Y_n cannot exceed the rotation age. If there are two disturbance events during the rotation, the waiting time for harvest is Y_n. Therefore, the expected present value of the stand under the second strategy is written as

$$J_2 = E\left[e^{-rY_1}R_1^2 + e^{-r(Y_1+Y_2)}R_2^2 + \ldots\right] = \frac{E\left(e^{-rY}R^2\right)}{1-E\left(e^{-rY}\right)} \tag{8}$$

where J_2 is defined as the expected discounted present value over a series of rotations where the landowner harvests at the second event or at the rotation age if no event arrives. The probability density function of Y_n is the same for all rotations, and can be defined as:

$$f(Y)=\begin{cases}\lambda_B e^{-\lambda_B X} & \text{for } 0<Y_n<T \text{ when } X_n<Y_n<T\\ (1\text{-}e^{\text{-}\lambda_A T})e^{\text{-}\lambda_B T} & \text{for } Y_n=T \text{ when } X_n<Y_n=T\\ e^{-(\lambda_A+\lambda_B)T} & \text{for } Y_n=T \text{ when } X_n=Y_n=T\end{cases} \quad (9)$$

For this case the current rents of the n^{th} rotation R_n^2 can be written as:

$$R_n^2=\begin{cases}k_B(Y_n-X_n,X_n)pF(Y_n\mid X_n<T)+e^{rY_n}\int_0^{Y_n}A(s)e^{-rs}ds-C_2\mathrm{e}^{rY_n} & \text{if } X_n<Y_n<T\\ pF(T)-C_1\mathrm{e}^{rT}+\mathrm{e}^{rT}\int_0^{T}A(s)e^{-rs}dt & \text{if } X_n=Y_n=T\\ pk_A(X_n)F(T\mid X_n<T)+e^{rT}\int_0^{T}A(s)e^{-rs}ds-C_1e^{rT} & \text{if } X_n<T=Y_n\end{cases} \quad (10)$$

where $k_B(Y_n-X_n,X_n)$ is the tree survival function, which depends not only on the timing of the first event, but also on the time interval between the first and second event. The function $k_B(Y_n-X_n,X_n)$ is increasing in (Y_n-X_n) and can be either increasing or decreasing in X_n. For each of the three scenarios of the arrival events, the discounted amenity value is considered as part of the forest value contributing to the society. $F(Y_n|X_n<T)$ is defined as the growth function after the occurrence of the first event, in which volume is smaller than that in the growth function under no event. Therefore, $F(T|X_n<T)$ represents the timber volume when the landowner harvests at time T.

In equation (8), the expected value $E(e^{-rY})$ is the sum of the probabilities of ending the rotation by harvesting or by the second event:

$$\begin{aligned}E(e^{-rY})&=\int_0^{\infty}e^{-rt}f(Y)dY=\int_0^{T}e^{-rt}\lambda_B e^{-\lambda_B t}dt+e^{-rT}(1-e^{-\lambda_A T})e^{-\lambda_B T}+e^{-(\lambda_A+\lambda_B)T}e^{-rT}\\ &=e^{-(r+\lambda_B)T}+\frac{\lambda_B}{r+\lambda_B}[1-e^{-(r+\lambda_B)T}]\end{aligned} \quad (11)$$

The expected discounted value of a single rotation can again be expressed as the sum of the value of harvest either at the rotation age or upon the occurrence of the second event, weighted by probabilities of the three scenarios:

$$
\begin{aligned}
E\left(e^{-rY}R^2\right) = {} & e^{-rT}e^{-(\lambda_A+\lambda_B)T}\left[pF(T) - C_1e^{rT} + e^{rT}\int_0^T A(s)e^{-rs}ds\right] \\
& + \int_0^T \left[k_B(Y_n - X_n, X_n)pF\left(Y_n \mid X_n < T\right) + e^{rt}\int_0^t A(s)e^{-rs}ds - C_2e^{rt}\right]e^{-rt}\lambda_B e^{-\lambda_B t}dt \\
& + e^{-rT}(1-e^{-\lambda_A T})e^{-\lambda_B T}\left\{pk_A(X_n)F(T \mid X_n < T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1e^{rT}\right\}
\end{aligned}
\tag{12}
$$

Substituting equations (11) and (12) into equation (8), we obtain the following present value rent function:

$$
\begin{aligned}
J_2 = {} & \frac{(r+\lambda_B)[pF(T) - C_1e^{rT} + e^{rT}\int_0^T A(s)e^{-rs}ds]e^{-(r+\lambda_A+\lambda_B)T}}{r[1-e^{-(r+\lambda_B)T}]} \\
& + \frac{(r+\lambda_B)e^{-(r+\lambda_B)T}\left\{pk_A(X_n)F(T \mid X_n < T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1e^{rT}\right\}(1-e^{-\lambda_A T})}{r[1-e^{-(r+\lambda_B)T}]} \\
& + \frac{(r+\lambda_B)\int_0^T \left[k_B(Y_n - X_n, X_n)pF\left(Y_n \mid X_n < T\right) + e^{rt}\int_0^t A(s)e^{-rs}ds - C_2e^{rt}\right]e^{-rt}\lambda_B e^{-\lambda_B t}dt}{r[1-e^{-(r+\lambda_B)T}]}
\end{aligned}
\tag{13}
$$

Equation (13) suggests that, if we assume that the stand suffers only one event ($\lambda_A = 0$), and is totally destroyed when it occurs (k_A=0, k_B=0), then the expected value of the stand reduces to Englin's (2000) result.

The third strategy (d_A = 0, d_B = 0)

In the third strategy $(d_A = 0, d_B = 0)$, the landowner does not harvest after either event, but instead always waits to harvest. This strategy might be appropriate if the stand suffers only small losses from both events. Therefore, the expected present value can be expressed as:

$$J_3 = \frac{E\left(e^{-rT} R^3\right)}{1 - e^{-rT}} \tag{14}$$

In this case, the rent of the n^{th} rotation R_n^3 can be written as:

$$R_n^3 = \begin{cases} pk_B(Y_n - X_n, X_n)F(T \mid X_n < Y_n < T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT} & \text{if } X_n < Y_n < T \\ pF(T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT} & \text{if } X_n = Y_n = T \\ pk_A(X_n)F(T \mid X_n < T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT} & \text{if } X_n < T = Y_n \end{cases} \tag{15}$$

where $F(T|X_n < Y_n < T)$ is the timber volume of the stand at rotation age T given the occurrence of first and second events. The expected present value of one rotation $E(e^{-rT}R^3)$ associated with the appropriate conditional probabilities is then:

$$\begin{aligned} E(e^{-rT}R^3) = e^{-rT}&\left[pk_B(Y_n - X_n, X_n)F(T \mid X_n < Y_n < T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT}\right](1 - e^{-\lambda_B T}) \\ &+ \left[pF(T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT}\right]e^{-(r+\lambda_A+\lambda_B)T} \\ &+ \left[pk_A(X_n)F(T \mid X_n < T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT}\right](1 - e^{-\lambda_A T})e^{-(r+\lambda_B)T} \end{aligned} \tag{16}$$

Therefore, the expected present value of harvesting with the third strategy can be expressed as:

$$\begin{aligned} J_3 = &\frac{\left[pk_B(Y_n - X_n, X_n)F(T \mid X_n < Y_n < T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT}\right]e^{-rT}(1 - e^{-\lambda_B T})}{1 - e^{-rT}} \\ &+ \frac{\left[pF(T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT}\right]e^{-(r+\lambda_A+\lambda_B)T}}{1 - e^{-rT}} \\ &+ \frac{\left[pk_A(X_n)F(T \mid X_n < T) + e^{rT}\int_0^T A(s)e^{-rs}ds - C_1 e^{rT}\right]\left(1 - e^{-\lambda_A T}\right)e^{-(r+\lambda_B)T}}{1 - e^{-rT}} \end{aligned} \tag{17}$$

Based on each strategy discussed above, the rotation age is defined as $T \equiv \arg max \{J_1(T), J_2(T), J_3(T)\}$ and the harvest decision variables d_A and d_{B}can be chosen to maximize the expected present value of the stand, by comparing maximums of expected present value of the stand for each of three strategies. This model can also be extended to the case of h possible events using the same method.

3.3 **Simulation Results**

We use simulation methods to illustrate how optimal harvest decisions change under alternative survival proportions (k_A, k_B), and attainable timber volumes after the first and second events, given by b and g respectively. Our primary interest in conducting the simulation is to examine how the best harvest strategy $\{T, d_A, d_B\}$ changes and how social welfare improves when the amenity service of the forest is considered relative to the case where the landowner ignores the amenity value. We use loblolly pine (Pinus taeda) as an example in simulation since it is the most important commercial species in Southern United States (Goodnow et al., 2008). A base age 25 site index of 80 loblolly pine sawtimber plantation with planting density of 300 trees per acre is assumed for all simulations. Because disturbances occurring during the rotation can cause damage which may decrease the growth of the trees, we employ growth parameters to account for such growth changes after adverse events (see Table 3.1).

Since we have assumed that the first event always comes before the second event if both occur, it is makes sense to also assume λ_{A} is greater than λ_{B}. Neither of these two assumptions are restrictive, and the model can be used to allow for any probability that one event follows another. We set arrival rates as 0.04 for the first event and 0.03 for the second event following empirical findings in the literature (Gay and Davis, 1993, Bragg, Shelton and Zeide, 2003, Goebel and Deitschman, 1967, Wiley and Zeide, 1991, Irland, 2000). In addition to arrival rates, we also investigate how the socially optimal strategy changes with regard to various tree survival percentages k_A and k_B, with survival rate varying from 0 to 1, again following previous literature (see Irland 2000; Bragg, Shelton and Zeide 2003 for a few examples).

As discussed previously, the reforestation cost (i.e. the cost for the planting a new rotation) for the damaged forest site (with event) $C_2(d)$ is assumed to be higher than the conventional site (without an event) $C_1(d)$. In the simulation, the reforestation cost in the conventional site is set at $150.77 per acre and the cost for a damaged site is $160.42 per acre. The stumpage price (dollars per thousand board feet of pine sawtimber) is obtained from Timber Mart-South (2013) and equals $174.63 per thousand board feet. A loblolly pine growth function estimated by Chang (1984) is employed and has been used in Xu et al. (2013) to simulate the volume of the sawtimber plantation. To model the changes of the volume after disturbances, we define b as the attainable rate, i.e. the portion remaining harvestable, of volume after the first event and g as the attainable rate of volume after the second event.

Various amenity functions, including those which are increasing, decreasing, and constant over time as well as a concave amenity function following Swallow, Parks, and Wear (1990), are employed to explore impacts of amenity functions on the socially optimal harvest strategy (see table 3.2). The concave amenity function could represent the benefits from a wildlife species best adapted to middle-aged forests. The decreasing function, is suitable to measure water yield benefits. The constant amenity function is more likely to represent the amenity value derived from open space, but not necessarily wild space. Finally, an increasing amenity function is established to model the benefits from a wildlife species (e.g. trout, spotted owl, red-cockaded woodpecker, squirrels) that is more adapted to mature forests, as well as the benefits of scenic views. Parameters of these amenity functions are allowed to vary in the sensitivity analysis to examine how the socially optimal harvest strategy changes with variation of the magnitude of the amenity value.

In our simulation, we first use baseline parameters (b) in Table 3.2 to investigate how the optimal strategy changes due to the amenity value. Additionally, sensitivity analysis is conducted to investigate different optimal harvest strategies under various amenity function forms, and investigate how they change along with changing the relative magnitudes of amenity values. We then determine the social cost of a private rotation age decision by inserting private-based rotation ages into the social rent function that includes an amenity value, and then computing the loss in rents from using the suboptimal rotation age and continuance strategy. Finally, we examine various stochastic scenarios as survival functions, arrival rates of events, and changes in growth function, and discuss patterns found in the results.

The simulation results with multiple amenity functions suggests large discrepancies between our rotation age solution and that of Englin's model (Table 3.3), confirming that only accounting for one possible event leads to suboptimal results and likely lower land values and higher social costs. By comparing different social models, we also find that the optimal management regime is robust over different amenity functions. The rotation age does become shorter as the gradient of the amenity function decreases. This is mainly because the marginal benefit of delaying harvest for one more unit of time decreases as the change over time in the amenity function decreases. This pattern is more apparent in the sensitivity analysis. In contrast to the private model, the socially optimal rotation age seems to extend generally once amenity value is considered, as the marginal benefit of delaying harvest increases.

The discrepancy of the optimal rotation age among models with different amenity functions declines with decreasing the relative size of expected present values of the amenity (Table 3.4). This is because as the relative magnitude of expected present value of the amenity decreases compared to that of the timber value, the timber value becomes dominant over the amenity value in determining the cost of continuing a rotation. Additionally, we can see from Table 3.4 that the optimal rotation age is around 20 years if the relative amenity accounts for less than 1% of the expected present net rent no matter what amenity function is employed. It is longer than the optimal private rotation age for the landowner, which equals 18 years (Table 3.3).

We also derive the social cost of private landowner decisions with regard to various amenity services by assuming the private landowner ignores amenities. Table 3.4 shows the social cost that exists when the landowner makes private harvest decisions without considering the amenity benefit that the forest contributes to society. When the expected present value of the amenity accounts for 1% of total value, the social cost of the landowner's decision is about \$1-\$3 per acre. However, the social cost increases considerably and becomes more than \$40 per acre in present value terms if the expected present value of the amenity accounts for 90%. This shows that as the relative size of the expected present value of the amenity decreases, the social cost of private decisions tend to decrease. This is due to closer similarity between the socially optimal strategy and the privately optimal strategy when the timber value dominates the total expected present value of net rent. Finally, Table 3.4 provides the value loss of the decision from accounting for only one disturbance, and indicates that the social welfare loss is even larger than the social cost of the private strategy with multiple risks given that more than one source of suboptimal decisions is the rule with only one disturbance (rotation age and amenities).

The concave amenity function is employed using the parameter assumption (b) in Table 3.2 to explore the changing patterns of the optimal management regime with variation of tree survival $k_{\mathrm{A}}$and k_{B}, and with the variation of attainable rates of volume parameters b and g. We first present the effect of the magnitude of timber survival possibility after the second event (k_B) on the optimal management decision when k_A is held constant large ($k_A = 0.9$) or is relatively small ($k_A = 0.5$) (Table 3.5). Here, we find that instant harvesting after the first event is not always socially optimal as k_B varies. When the survival proportion k_{B} is above 0.7, it is socially optimal to harvest and restart a new rotation right after the second event, no matter whether k_A is small or large. Conversely, when k_{B} is below 0.5, it is socially optimal to harvest right after the first event. Comparatively, in the private model where the amenity value is overlooked by the landowner, the threshold of the "real event" appears to be larger ($k_B = 0.6$). This makes sense as the opportunity cost of the harvest increases as the amenity value is taken into consideration.

We also investigate how the optimal strategy changes along with decreasing of the tree survival proportion after the first event k_{A} (Table 3.5) and find these effects to be significant, but they do not have an effect on the harvest decision d_A and d_B. Such pattern is consistent with that of the private model. Furthermore, Table 3.5 supports the conclusion in Tables 3.3 and 3.4 that the socially optimal rotation age is longer than that of the private landowner, and the maximum present value of future rotations is larger.

In addition, the variation of attainable rate of volume parameter after the first event (b) is examined (Table 3.6). We find that when b becomes higher after the first event, the second strategy is more likely to be optimal. This makes sense because as the attainable rate of volume increases, the growth of the stand is more likely to outweigh the expected damage that the second event might have caused. Therefore, it is more beneficial for the landowner to harvest after the second event.

If the first strategy is optimal as b changes, then the rotation age and the expected rent will be the same when holding other parameters constant (Table 3.6). This is because the growth after the first event does not affect the rotation age and expected present value rent since the stand has already been harvested when the first event occurs. It also reveals that the rotation age of the social planner is longer than that of the private landowner no matter how the attainable rate of volume after the first event b changes, at least when the amenity function is held concave. Finally, we can conclude that the landowner is more reluctant to clearcut the trees after the first event if amenity services are considered.

Finally, we consider the effect of the attainable volume of the stand possible after the second event g on the optimal management strategy (see Table 3.6). As g varies from 0.1 to1, the rotation age and optimal strategy does not change. In other words, the attainable rate of volume after the second event g has no impact on the socially optimal regime and can be ignored in decision making. The pattern that amenity values lengthen the rotation age is also clear when the attainable rate of volume after the second event g changes.

3.4 **Conclusion**

This paper extends the framework of Xu et al. (2013) to incorporate amenity values into forest management decision making when natural damaging events can arrive more than once during a forest rotation. Flexible harvest timing is also considered by jointly modeling a continuance strategy that depends on arrival of events, tree growth and recovery after an event arrives, and the timing of different events. Though equivalent to the single disturbance problem in Englin (2000) in certain cases, different results are found in our more general model for a range of reasonable parameter values. Most previous studies that consider amenity value in landowner decision making show that a decreasing amenity function leads to a shorter rotation age. However, our simulation analysis reveals that the rotation age is not necessarily shorter with a decreasing amenity function if the risk of multiple disturbances is accounted for. When various amenity functions are employed, we also find that amenity services generally lengthen rotation ages through a sensitivity analysis. Moreover, the socially optimal rotation age declines as the slope of the amenity function decreases.

As the private decision made by a landowner who ignores amenities leads to a market failure, governmental intervention may be necessary to eliminate the wedge between social planner and private landowner decisions. Informed policy decisions such as those which aim to increase ecosystem services, need to be made sensitive to the discrepancies we uncover in comparing the profit-maximizing decision made by landowners with the socially optimal solution, and the issues that our more general approach raise. The optimal instruments can be chosen only if the social cost of landowner's decision is greater than the cost of the government intervention. Given there is no previous literature concerning this point to our knowledge, our paper fills this gap by examining different social costs in regard to various amenity services when multiple risks may affect forests. Our model also shows that simply assuming the landowner always harvests at the arrival of the first event can lead to suboptimal land values and therefore a suboptimal flow of amenities if multiple disturbances are possible. Suboptimal decisions lead to significant social welfare losses, and these losses are considerably large when the amenity value dominates timber harvesting rents. Interestingly, we also found that landowners are more likely to harvest the trees after the first event arrives when they do not include the value of amenities in their decision making.

Appendix

We provide detailed derivation from equation (6) to equation (7) in this Appendix.

Differentiating text equation (6) with respect to T, and setting the result equal to zero yields:

$$
\begin{aligned}
J_T = & -r(\lambda_A+\lambda_B+r)^2 e^{-(\lambda_A+\lambda_B+r)T}\left[1-e^{-(\lambda_A+\lambda_B+r)T}\right]\left[pF(T)-C_1e^{rT}\right.\\
& \left.+e^{rT}\int_0^T A(x)e^{-rx}dx\right]\\
& +r(\lambda_A+\lambda_B+r)e^{-(\lambda_A+\lambda_B+r)T}\left[1-e^{-(\lambda_A+\lambda_B+r)T}\right]\left[pF'(T)-rC_1e^{rT}\right.\\
& \left.+A(T)+re^{rT}\int_0^T A(x)e^{-rx}dx\right]\\
& -r(\lambda_A+\lambda_B+r)^2 e^{-2(\lambda_A+\lambda_B+r)T}\left[pF(T)-C_1e^{rT}\right.\\
& \left.+e^{rT}\int_0^T A(x)e^{-rx}dx\right]\\
& +r(\lambda_A+\lambda_B+r)(\lambda_A\\
& +\lambda_B)e^{-(\lambda_A+\lambda_B+r)T}\left[e^{rT}\int_0^T A(x)e^{-rx}dx-C_2e^{rT}\right]\left[1-e^{-(\lambda_A+\lambda_B+r)T}\right]\\
& -r(\lambda_A+\lambda_B+r)^2 e^{-(\lambda_A+\lambda_B+r)T}\int_0^T(\lambda_A\\
& +\lambda_B)e^{-(\lambda_A+\lambda_B+r)t}\left[e^{rt}\int_0^t A(x)e^{-rx}dx-C_2e^{rt}\right]dt=0
\end{aligned}
$$

Divided by $r(\lambda_A+\lambda_B+r)e^{-(\lambda_A+\lambda_B+r)T}$ yields:

$$J_T = -(\lambda_A + \lambda_B + r)\left[1 - e^{-(\lambda_A+\lambda_B+r)T}\right]\left[pF(T) - C_1 e^{rT} + e^{rT}\int_0^T A(x)e^{-rx}dx\right]$$

$$+ \left[1 - e^{-(\lambda_A+\lambda_B+r)T}\right]\left[pF'(T) - rC_1 e^{rT} + A(T) + re^{rT}\int_0^T A(x)e^{-rx}dx\right]$$

$$- (\lambda_A + \lambda_B + r)e^{-(\lambda_A+\lambda_B+r)T}\left[pF(T) - C_1 e^{rT} + e^{rT}\int_0^T A(x)e^{-rx}dx\right]$$

$$+ (\lambda_A + \lambda_B)\left[e^{rT}\int_0^T A(x)e^{-rx}dx - C_2 e^{rT}\right]\left[1 - e^{-(\lambda_A+\lambda_B+r)T}\right]$$

$$- (\lambda_A + \lambda_B + r)\int_0^T (\lambda_A + \lambda_B)e^{-(\lambda_A+\lambda_B+r)t}\left[e^{rt}\int_0^t A(x)e^{-rx}dx - C_2 e^{rt}\right]dt = 0$$

Divided by $1 - e^{-(\lambda_A+\lambda_B+r)T}$, adding $rC_1 e^{rT} - re^{rT}\int_0^T A(x)e^{-rx}dx$, and Isolating $pF'(T) + A(T)$ on the left side of the equation yields:

$$pF'(T) + A(T) = (\lambda_A + \lambda_B)[pF(T) - C_1 e^{rT} + C_2 e^{rT}] + rpF(T)$$

$$+ \frac{\lambda_A + \lambda_B + r}{1 - e^{-(\lambda_A+\lambda_B+r)T}}\int_0^T (\lambda_A + \lambda_B)e^{-(\lambda_A+\lambda_B+r)t}\left[e^{rt}\int_0^t A(x)e^{-rx}dx - C_2 e^{rt}\right]dt$$

$$+ \frac{(\lambda_A + \lambda_B + r)e^{-(\lambda_A+\lambda_B+r)T}}{1 - e^{-(\lambda_A+\lambda_B+r)T}}\left[pF(T) - C_1 e^{rT} + e^{rT}\int_0^T A(x)e^{-rx}dx\right]$$

Collecting the right side of the equation, we can derive equation (11) which is,

$$pF'(T) + A(T) = (r + \lambda_A + \lambda_B)pF(T) + rJ_1 + (\lambda_A + \lambda_B)e^{rT}[C_2 - C_1]$$

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Table 3.1 Description of Parameters

Type	Function	Assumed Form or value
Growth function without event for sawtimber	$F(t)$	$e^{9.75-\frac{3418.11}{mT}-\frac{740.82}{ET}-\frac{34.01}{T^2}}-\frac{1527.67}{E^2}$ $(m=300, E=80)$
Sawtimber growth function after first event A for sawtimber	$F(t\|x<T) = bF(t)$	$be^{9.75-\frac{3418.11}{mT}-\frac{740.82}{ET}-\frac{34.01}{T^2}-\frac{1527.67}{E^2}}$ $(m=300, E=80)$
Sawtimber growth function after second event B for sawtimber	$F(t\|X<Y<T)=$ $bgF(t)$	$bge^{9.75-\frac{3418.11}{mT}-\frac{740.82}{ET}-\frac{34.01}{T^2}-\frac{1527.67}{E^2}}$ $(m=300, E=80)$
9Average arrival rate for first event A	λ_A	$\lambda_A = 0.04$
(Average arrival rate for second event B	λ_B	$\lambda_B = 0.03$
Timber survival possibility after first event A	$k_A(X_n)$	$k_A = 0, \ldots, 1$
Timber survival possibility after second event B	$k_B(Y_n - X_n, X_n)$	$k_B = 0, \ldots, 1$
Reforestation without event	$C_1(d)$	$c_0 + (c_1 + c_2)d$ $(c_0 = 105.23, c_1 = 0.0988, c_2 = 0.053)$
Reforestation cost with the event	$C_2(d)$	$(1+\beta)[c_0 + (c_1 + c_2)d]$ $(\beta = 6.4\%, c_0 = 105.23, c_1 = 0.0988, c_2 = 0.053)$

Table 3.2 Function Forms for the Amenity Service

Type	Annual benefits	Parameters (a)	Parameters (b)	Parameters (c)
Concave amenity function	$A(T) = \beta T e^{-b_1 T} + k$	$\beta = 5000, k = 0, b_1 = \frac{1}{20}$	$\beta = 2000, k = 0, b_1 = 1/20$	$\beta = 12, k = 0, b_1 = \frac{1}{20}$
Decreasing amenity function	$A(T) = a_1 - a_0 T^2$	$a_1 = 30000,\ a_0 = 0.07$	$a_1 = 20000,\ a_0 = 0.07$	$a_1 = 500,\ a_0 = 0.07$
Constant amenity function	$A(T) = a_0$	$a_0 = 30000$	$a_0 = 20000$	$a_0 = 500$
Increasing amenity function	$A(T) = \frac{k}{1 + e^{a-bT}}$	$k = 30000, a = 2, b = 1$	$k = 20000, a = 2, b = 1$	$k = 500, a = 2, b = 1$

Table 3.3 Our Model with Different Amenity Functions and Englin Model[1-9]

Model		Parameters						Optimal strategy			
		K_A	K_B	λ_A	λ_B	b	g	T	Max $\{J1,J2,J3\}$ (\$)	Amenity (\$)	Best strategy
Private Model		0.9	0.9	0.04	0.03	0.8	0.7	18	752.7		$d_A = 0, d_B = 1$
Increasing amenity	Our model	0.9	0.9	0.04	0.03	0.8	0.7	21	1330.0	772.6	$d_A = 1$
	Englin	0		0.04				16	1216.4	744.7	
Constant Amenity	Our model	0.9	0.9	0.04	0.03	0.8	0.7	20	1517.3	772.5	$d_A = 1$
	Englin	0		0.04				15	1389.3	746.9	
Decreasing amenity	Our model	0.9	0.9	0.04	0.03	0.8	0.7	19	1498.2	754.1	$d_A = 1$
	Englin	0		0.04				15	1374.5	732.1	
Concave amenity	Our model	0.9	0.9	0.04	0.03	0.8	0.7	22	1050.9	565.9	$d_A = 1$
	Englin	0		0.04				16	937.3	535.4	

[1] The parameters (b) in Table 3.2 are employed for the amenity functions

[2] k_A represents the proportion of the forest survived after the first event A.

[3] k_B represents the proportion of the forest survived after the second event B.

[4] λ_A represents average arrival rate of the first event A.

[5] λ_B represents average arrival rate of the second event B.

[6] b represents the attainable rate of volume after event A.

[7] g represents the attainable rate of volume after event B.

[8] $m = 300$, which represents planting density.

[9] T represents rotation age.

Table 3.4 Sensitivity Analysis of Optimal Management Strategy1-10

	Rotation age[1]			Social cost of landowner's decision			Loss of Englin model		
Amenity functions	90% relative amenity	60% relative amenity	1% relative amenity	90% relative amenity	60% Relative amenity	1% relative amenity	90% relative amenity	60% Relative amenity	1% relative amenity
Increasing amenity	23	21	20	16.7	11.1	3.9	43.9	34.9	40
Decreasing[2] amenity	19	19	19	1.3	1.4	1.8	25.5	27.1	61.1
Concave amenity	27	22	20	47	15.4	3.8	47	42.7	36.5

1 The parameters (a), (b), (c) in Table 3.2 are employed for the amenity functions

2 The relative amenity means the relative size of expected present amenity value account for the expected net present rent.

3 k_A represents the proportion of the forest survived after the first event A.

4 k_B represents the proportion of the forest survived after the second event B.

5 λ_A represents average arrival rate of the first event A.

6 λ_B represents average arrival rate of the second event B.

7 b represents the attainable rate of volume after event A.

8 g represents the attainable rate of volume after event B.

9 m represents planting density.

10 T represents rotation age.

[1] The rotation age is around 20 years with only small variation when the amenity function is constant.

[2] In the case that the amenity function is decreasing, the changing of first order condition as well as multiple harvest strategies for landowner to choose are two main reasons for the finding that the rotation age is longer than private model.

Table 3.5 Simulation Results for Different Survival Proportions1-9

k_B	k_A	Best strategy (d_A, d_B)		Optimal rotation age T		Maximal present value Max{J1,J2,J3}	
		Social model	Private model	Social model	Private model	Social model	Private model
0.9	0.9	$d_A = 0, d_B = 1$	$d_A = 0, d_B = 1$	20	19	1086.7	785.3
0.7		$d_A = 0, d_B = 1$	$d_A = 0, d_B = 1$	19	18	1051.1	749.4
0.6		$d_A = 1$	$d_A = 1$	22	20	1050.9	744.9
0.5		$d_A = 1$	$d_A = 1$	22	20	1050.9	744.9
0.9	0.5	$d_A = 0, d_B = 1$	$d_A = 0, d_B = 1$	19	18	955.3	656.6
0.7		$d_A = 0, d_B = 1$	$d_A = 0, d_B = 1$	18	17	921.3	623.5
0.6		$d_A = 0, d_B = 1$	$d_A = 1$	18	16	905.4	615.1
0.5		$d_A = 1$	$d_A = 1$	18	16	903.7	615.1
0.9	0.9	$d_A = 0, d_B = 1$	$d_A = 0, d_B = 1$	20	19	1086.7	785.3
	0.5	$d_A = 0, d_B = 1$	$d_A = 0, d_B = 1$	19	18	955.3	656.6
	0.1	$d_A = 0, d_B = 1$	$d_A = 0, d_B = 1$	18	17	825.0	530.9
0.5	0.9	$d_A = 1$	$d_A = 1$	22	20	1050.9	744.9
	0.5	$d_A = 1$	$d_A = 1$	18	16	903.7	615.1
	0.1	$d_A = 1$	$d_A = 1$	15	14	791.5	515.7

1 The parameters (b) in Table 3.2 are employed for the amenity functions

2 k_A represents the proportion of the forest survived after the first event A.

3 k_B represents the proportion of the forest survived after the second event B.

4 $\lambda_A = 0.04$, which represents average arrival rate of the first event A.

5 $\lambda_B = 0.03$, which represents average arrival rate of the second event B.

6 $b = 0.9$, which represents the attainable rate of volume after event A.

7 $g = 1$, which represents the attainable rate of volume event B.

8 $m = 300$, which represents planting density.

9 T represents rotation age.

Table 3.6 **Simulation Result for Different Attainable Rates of Volume**[1-9]

b	g	Best strategy (d_A, d_B)		Optimal rotation age T		Maximal present value Max{$J1$,$J2$,$J3$}	
		Social model	Private model	Social model	Private model	Social model	Private model
0.5	0.7	$d_A = 1$	$d_A = 1$	18	16	903.7	615.1
0.7		$d_A = 1$	$d_A = 1$	18	16	903.7	615.1
0.9		$d_A = 1$	$d_A = 1$	18	16	903.7	615.1
1		$d_A = 0, d_B = 1$	$d_A = 1$	18	16	916.1	615.1
1	0.1	$d_A = 0, d_B = 1$	$d_A = 1$	18	16	916.1	615.1
	0.5	$d_A = 0, d_B = 1$	$d_A = 1$	18	16	916.1	615.1
	1	$d_A = 0, d_B = 1$	$d_A = 1$	18	16	916.1	615.1

1 The parameters (b) in Table 3.2 are employed for the amenity functions

2 $k_A = 0.5$, which represents the proportion of the forest survived after the first event A.

3 $k_B = 0.5$, which represents the proportion of the forest survived after the second event B.

4 $\lambda_A = 0.04$, which represents average arrival rate of the first event A.

5 $\lambda_B = 0.03$, which represents average arrival rate of the second event B.

6 b represents the attainable rate of volume after event A.

7 g represents the attainable rate of volume after event B.

8 $m = 300$, which represents planting density.

9 T represents rotation age.

Chapter 4: Village Democracy and Household Welfare: Evidence from Rural China

4.1 Introduction

The economic reform of China began in the late 1970s and has been gradually transforming the previous central-planning economy to marketization. An emerging prominence of economic centers in many parts of rural China is now a reality. At the same time, however, agglomeration of resources continues to widen the income gap between urban and rural areas, producing increased social tension and conflicts (Xu and Siikamäki, 2012). To address such disparities, China has initiated a series of economic reforms in rural areas targeting the majority of these populations. An example is the introduction of household responsibility systems for agriculture in the early 1980s that have been argued to have achieved success in stimulating agricultural economic growth (Lin, 1997). The recent tax-for-fee reform and subsequent abolition of agricultural taxes have also captured media spotlights as means to improve rural livelihoods through reduction of the financial burdens of farmers (Mushtaq et al., 2008; Alm and Liu, 2013).

As a key step toward the completion of rural land marketization, a comprehensive forest tenure reform has also been initiated in the last decade with an aim to decollectivize forests and give farmers more control over production decisions (Xu and Siikamäki, 2012). The rationale behind forest reforms is to generate additional revenues for farmers by allowing them more economic freedom in production decision making. Institutional rearrangements practiced in these reforms directly call for better rights among the rural public in political participation and decisions concerning production, along with consequent democracy in electing village leaders who were previously government appointed. The argument for democracy reforms is to better safeguard local village interests in decisions impacting them. The linkages between democracy and rural household welfare are particularly expected in to be important in agriculture and forestry where previous government control was pervasive, and where reforms have specifically been targeted.

Possible impacts of greater democracy on household welfare may be best observed at a village level, as this is the lowest branch of Chinese government which directly accounts for a large number of farm households - these households are the basic unit of production activities in rural China. Village-level democracy has been steadily introduced through village-level political reforms that have reshaped local governance structure. The 1982 Constitution (Article 111) for the first time defined something called a villagers' committee (VC) as the self-governing body of villagers. The VC consists of three to seven seats that all villagers nominated by others can run for in a formal election (Wang and Yao, 2007). The Organic Law of the Villagers' Committee (OLVC), enacted later in 1987, further authorized the establishment of villagers' representative assemblies (VRA) that manage voting in all village affairs, including production decisions (Chan, 2003).

Despite these fundamental and radical changes, however, village democratization in China has faced several implementation challenges. For example, as the OLVC mandates the VC to work under the leadership of the party committee which is usually appointed by a higher authority (e.g. township) rather than elected, and thus conflicts often emerge between the VC chairperson and the party secretary as both of these individuals have different incentives and goals (Guo and Bernstein, 2004). Although the central government encourages the party secretary to run for the VC chairman as a means to reconcile such conflicts, this substantially recentralizes decision power and implicitly imposes the higher government's opinions into village production decisions, rendering local interests at risk.

The widespread village democratization in China with its institutional complexities and constraints thus provides a very unique setting to study the possible impacts of democracy on rural household welfare. While previous studies have linked village democratization to changes in multiple socioeconomic factors, very few if any have examined whether democracy is important to farmer decision making. As a result, the literature is unclear on whether these reforms have been Pareto improving, although some studies have been clear about the benefits tradeoffs faced among groups with different economic interests (Zhang et al., 2004; Wang and Yao, 2007; Meng and Zhang, 2011). Unintended effects have, for example, been reported with regard to administrative efficiency (Meng and Zhang, 2011), taxation structure (Zhang et al., 2004), income inequality (Shen and Yao, 2008), and public expenditure and fiscal revenue distribution (Wang and Yao, 2007).

In this paper, we examine the link between village democracy and the economic performance of rural households engaged in traditional agricultural and forest production. Our investigation is important to judge whether reforms have generated greater economic opportunities, and our results speak to current arguments that the effects of China's weakly institutionalized reform policies on the rural poor are still not well understood (e.g., see Acemoglu, 2005).

Specifically, we evaluate whether greater democracy empowers farmers to make more efficient income-improving decisions concerning both agricultural and forest production. Agriculture is the foremost sector in rural China, feeding 20% of world's population and covering 8% of its arable land (Brautingam, 2009). Though one may envision agricultural productivity shifts due to democratization, empirical assessments of these effects are extremely rare except for a few cross-country studies that are less informative for domestic policy makers (Lio and Hu, 2009). Even less is known about possible impacts of democracy on forest goods productivity and efficiency. This is an important omission because, unlike agriculture that provides food consumption for Chinese rural households, forest production is more of a cash-generating activity and is perhaps more influenced by institutional factors such as the degree of democracy**.** Also, a large share of household-level forest production has specifically been targeted by China's most recent reforms (Qin et al., 2011). Given that the products derived from forests and agriculture are fundamentally different, it merits comparing the effects of democracy in both sectors.

We investigate the impacts of democracy on rural household welfare in China from a technical efficiency perspective, postulating that democracy as a set of institutional arrangements is more likely to act as a shifter of overall productivity rather than as a direct input, as other studies have suggested but not tested. Efficient households may be able to produce more outputs with the same input levels or produce the same outputs with reduced costs. Thus, higher efficiency nearly always implies greater wealth, which in itself implies greater household welfare. Using a recent household survey that covers both agriculture and forest production, we employ stochastic production frontier techniques as the main strategy in identifying these effects. Using this approach we are able to account for possible heterogeneity in production efficiency as well as stochastic disturbances among producers through error decomposition procedures. We find that higher levels of village democracy significantly increase farmers' production efficiency through reduction of its variation in both agriculture and forestry, confirming the positive impacts of democratization on household welfare in rural China.

Our contribution is threefold. First, we provide for the first time micro-level evidence of a significant link between village democracy and production efficiency, which extends the previous macro-level studies noted earlier. Second, we identify the most important factors to production efficiencies of both agriculture and forestry production. The results of our analysis therefore provide important policy lessons for other agrarian based economies currently struggling with democratization.

The rest of the paper is organized as follows. We first present in the next section a theoretical framework that shows how democracy affects rural household welfare through production efficiency changes. We then discuss in detail our empirical modeling strategies and empirical findings in the next two sections. We conclude with a discussion of important policy implications in the final section.

4.2 **Theoretical Framework**

Most economic theories represent household welfare in rural economies by the maximal utility achievable from optimal choices a household makes while facing a set of constraints on time and cash assets. The decision maker is assumed to be the household head. Unlike pure consumption decisions, rural households face a potentially complex utility maximization problem as their consumption includes not only purchased goods but also own-produced commodities. Household models explaining these issues are well developed for both conventional agricultural and forestry production (e.g., Singh et al. 1986, Amacher et al. 1991), and we will adapt these models to the situation in we study in China.

Following the literature, we assume a household maximizes its utility of the following form:

(1) $U = U(X_a, X_f, X_c, l)$,

where the commodities are agricultural products, X_a, forest products, X_f, purchased goods from markets, X_c, and leisure, l. The household produces agricultural and forest products, where production technologies for both sectors are assumed functions of: 1) variable inputs such as labor (L), capital (K) and land (A); 2) household and other observed characteristics (H); and 3) institutional environments that may shift productivity and are reflected by the degree of democracy (D). Use β_i to denote a set of parameters that empirically link these factors with output and ε_i defined as the error term, we can define the production function as:

(2) $Q_i = Q_i(L_i, K_i, A_i, H, D, \beta_i, \varepsilon_i),\ i = a, f$

The household faces a time constraint and a cash income constraint in the utility maximization problem. The time constraint suggests a maximal allocatable time to household activities that cannot be exceeded by the aggregate time from all specific single activities:

(3) $F_a + F_f + l = T$

The cash income constraint is presented as:

(4) $p_c X_c = \sum_{i=a,f} \{p_i[Q_i(L_i, K_i, A_i, H, D, \beta_i, \varepsilon_i) - X_i] - w_i(L_i - F_i) - K_i\}$

where p_c , p_a and p_f are price vectors for purchased goods, agricultural and forest products; w is the wage for labor; and F_a and F_f are family labor inputs in each sector. Capital cost does not need to be accounted for in this short-run analysis. There is also the assumption, which fits our data discussed later, of using hired labor if total labor exceeds family labor allocatable time in either sector, or off-farm labor supply if the opposite is true. By combining equations (2) - (4) we can write a full income constraint in the following form:

(5) $p_c X_c + \sum_{i=a,f} p_i X_i + wl = wT + \sum_{i=a,f} \left[p_i Q_i (L_i, K_i, A_i, H, D, \beta_i, \varepsilon_i) - wL_i - K_i \right]$

The household's problem then is simplified to maximizing the utility in equation (1) under the full income constraint in equation (5).

The most important issue to be addressed before empirical application is the validity of model recursiveness, or separability in household models like ours. As pointed out by Strauss (1986), if the household maximizes utility subject to its full income and production functions as constraints, then household production and consumption decisions can be modeled as separable, even though they are simultaneously made – separability therefore means that production decisions are made without consideration of consumption needs, and thus income from production is then an independent factor in determining the consumption demands of the household. Separability suitably describes rural China where most farmers are smallholders in both agricultural and forest production, and where labor markets are known to have different properties than in other rural developing countries. Specifically, labor markets are not rendered missing or incomplete as they have been found to be in poor countries. Rather, it has been found and discussed many times in the literature that labor markets are fully developed in rural China due to flexible and accessible labor migration to and from urban areas (Zhao, 1999; 2002).

Therefore, we may reasonably consider the household problem as separable. In this sense, we can solve the demand functions of consumption goods in a simple manner and derive an indirect utility function as:

(6) $V = V(p_c, p_a, p_f, w, T, I^*),\ \ i = a, f$

where I^* is income maximized through application of optimal production decisions indicated on the right-hand side of equation (5) in the utility maximization problem – this is a fundamental separability result.

Using (6), the household welfare implications of village democracy can be revealed through changes productivity associated with democracy. To see this clearly, we take the derivative of (6) with respect to the democracy indicator to obtain:

$$(7)\quad \frac{\partial V(p_c, p_a, p_f, w, T, I^*)}{\partial D} = \sum_{i=a,f} \left[p_i \frac{\partial Q_i(L_i, K_i, A_i, H, D, \beta_i, \varepsilon_i)}{\partial D} \right]$$

Equation (7) establishes the relationship between household welfare and village democracy through changes in the value marginal products of relevant production activities. In our problem and data described below, these production activities are agriculture and forestry. Use of the envelope theorem in deriving (7) suggests changes in input and consumption levels due to village democracy can be ignored at the margin since production is optimized. Therefore, the impact of village democracy on household welfare simply equals the direct contribution of this reform to value marginal productions. The efficiency of production is easily relatable to (7), because, as discussed earlier, anything that increases efficiency will also increase value marginal products for a given set of inputs.

The overall mechanism through which democracy affects productivity is complicated, but a number of perceivable pathways have been proposed. Democracy may generate greater stability (Rodrik, 1999), which in turn encourages greater investments in production over the long run. Democracy can also affect agrarian relations between households, allowing them to have a voting say in policies that could be beneficial for producers (Binswanger and Deininger, 1997). Finally, democracy can facilitate household use of modern technologies and practices in production, all of which one would expect to increase production efficiency (Aghion et al., 2007). Despite these assertions, there are arguments that democracy may not always have beneficial outcomes for farmers. For example, it is suggested that with democracy farmers may have incentives to spent extra and time costly effort in lobbying local (e.g. village) governments at the expense of productivity losses (Rausser, 1982; Harvey, 2004). Even more surprising are some negative associations between democracy and agricultural production efficiency from a cross-country perspective (Lio and Hu, 2009). Thus, one cannot make *a priori* claims on such impacts without formal investigation of the type we make in this paper.

4.3 **Empirical Specification**

Considering the set of possible institutional arrangements, democracy is more likely to shift productivity in more complicated ways than simply affording farmers greater inputs (i.e., in the way that increases in the availability of fertilizer might). In this sense, we implement our empirical analysis using stochastic production frontier techniques which account for productivity shifts in terms of many unobserved aspects of production efficiency. Stochastic production frontier approaches were first developed in Aigner et al. (1977) and Meeusen and van den Broeck (1977) and surveyed relatively recently by Kumbhakar and Lovell (2000). This approach can be used to measure technical inefficiency via testing for a skewed error term in production frontier estimation, because technically inefficient households are always located inside the production possibility frontier; thus, the distribution of households along the frontier when inefficiencies exist is consistent with a half normal distribution of the error. This approach also allows for purely random, rather than efficiency related, shocks that affect a household's position relative to the frontier though specification of a common two-sided error term. Empirical work has employed this type of decomposition in shocks to stochastic frontier estimation in several rural developing country contexts (Sherlund et al., 2002; Binam et al., 2004; Pascual, 2005), but no studies we are aware of have used the procedure to investigate how village democracy possibly alters production efficiency. This is despite that this frontier analysis is precisely the right tool for understanding the likely impacts of democracy on the rural poor.

To formalize our procedure, we start from the production function in equation (2), $Q_i = Q_i(L_i, K_i, A_i, H, D, \beta_i, \varepsilon_i),\ i = a, f$. A decomposition is then assumed for the error term ε_i, in order to separate technical inefficiency errors from purely stochastic random shocks, with technical inefficiency modeled as a percentage reduction of output. Making this assumption, we can rewrite the stochastic production function as:

(8) $Q_i = Q_i(L_i, K_i, A_i, \beta_i, \varepsilon_i) \cdot \exp(v_i) \cdot \lambda_i,\ i = a, f$

where $\varepsilon_i = \exp(v_i) \cdot \lambda_i$, and λ_i is an inefficiency measure that lies between 0 (totally inefficient) and 1 (fully efficient). Any household in a sample with lower production efficiency, or higher inefficiency, therefore generates a lower observed output level whenever λ_i is lower. Conversely, v_i captures pure stochastic disturbances in production that are separate from efficiency shocks. An example could be a weather event that affects production and thus a household's position on or inside the frontier that is not strictly related to efficiency in application of inputs.

To facilitate econometric estimation of (8) we take the natural logarithm and obtain:

(9) $q_i = \ln Q_i(L_i, K_i, A_i, \beta_i, \varepsilon_i) + v_i - u_i,\ i = a, f$

where $u_i = -\ln \lambda_i$ is nonnegative by definition. The deterministic part of the production function (first term on the right-hand side of equation 9) can be specified using any functional form such as a Cobb-Douglas or translog specification. We then need to assume that the error components have some distribution in order to allow maximum likelihood estimation. The common assumption, and the one we use, is that v_i is i.i.d. and standard normal, while u_i is i.i.d. and either half normal or exponentially distributed. The best specification can be chosen through use of the Akaike information criterion.

The impacts of factors affecting production on the error are represented in u_i and v_i as productivity shifters. For our case, these factors include village democracy measures, household demographic variables, and other observed characteristics. We expect that the degree of democracy affects production efficiency, and that we can partition household and other observed characteristics into two subsets, $H = [H_u, H_v]$, where H_u are factors affecting productivity through an efficiency change v_i and H_v are factors that affect productivity through unobserved random disturbances. Also following the literature on these models, we assume an exponential forms for the heteroskedasticity of both error variances that this results through this specification (e.g. Reifschneider and Stevenson, 1991; Hadri et al., 2003; Louriero, 2009).

With $\delta_i = [\delta_{1i}, \delta_{2i}]$ and γ_i denoting coefficients to estimate, these functions are written as

(10) $\sigma_{ui}^2 = \exp(\delta_{1i} H_u + \delta_{2i} D),\ i = a, f$

(11) $\sigma_{vi}^2 = \exp(\gamma_i H_v),\ i = a, f$.

Equations (9) - (11) jointly represent our empirical model. The literature suggests that H_u include farmer's age, gender, and education (Binam et al., 2004; Pascual, 2005), health status, and length of off-farm employment (Louriero, 2009), while H_v includes a set of dummies that capture some systematic differences across time and space such as regions in a sample that may differ in unobserved ways (Hadri et al., 2003; Louriero, 2009).

We also consider other potential explanatory variables for H_u that include household size, gender of the household decision maker, age and education of the household head, a dummy variable that measures if the household head has been suffering from chronicle disease(s), and the length the household head stayed home in the surveyed year (as compared to off-farm employment in urban areas). We only incorporate regional dummies for H_v given the cross-sectional nature of our data. Among all parameter estimates, δ_{ui}^{D} captures possible impacts of village democracy on production efficiency and is of most interest to us. Various measures of village democracy are discussed below and employed in our empirical analysis.

4.4 **Data**

Our data come from a comprehensive field survey in 2011 that covers eight provinces in China, including Anhui, Fujian, Hunan, Jiangxi, Liaoning, Shangdong, Yunnan and Zhejiang. Stratified sampling strategies were employed and information at both village and household levels are included. Among all village characteristics, of our particular interest to our study are possible measures of village democracy, which include the frequency of VRA meetings (Freq_VRA), attendance rates of VRA meetings (Att_VRA), as well as whether the VC chairman and the party secretary is the same person (Same_leader). The variables Freq_VRA and Att_VRA should be positively correlated with the degree of democracy, while such correlation is postulated to be negative for Same_leader due to centralized decision powers discussed earlier.

Details of production activities in agriculture and forestry sectors are collected as recall data in the household survey, following many other studies, where inputs are categorized as labor, capital (the monetary value of all other inputs) and land. Household-level information includes demographics such as household size and characteristics of household head, length of stay on-farm and health conditions. Rather than direct inputs, these human capital variables are likely productivity shifters and can predict technical inefficiency in the stochastic production frontier (Binam et al., 2004; Louriero, 2009).

Due to clear differences between the location that agricultural and forest production is practiced in our sample, we carry out empirical estimation separately for each activity (this also follows from formal tests discussed in detail below). A total of 1,400 households from 207 villages are included in the agricultural production analysis, and 385 households from 106 villages are included in the forest production analysis (some households may participate in both sectors). Fewer households participated in forest production because timber harvesting as the major form of forest production does not occur on an annual basis, though other important forms of forest-related production (e.g. mushroom collection) does take place for all households in the sample. Only those who engaged in forest (timber or non-timber) production in the surveyed year are included.

Table 4.1 summarizes measures of village democracy variables, while Table 4.2 presents detailed information of production and household characteristics. Though simple t-tests are not applicable due to overlapping observations (households who participated in both sectors), the table does show that, as compared to agriculture, forest production takes place on much larger land areas but with smaller magnitudes of labor and capital inputs used. Households in forest production are also more likely headed by younger and less educated males who possess a lower chance of chronic health problems but who spend more time in off-farm employment. Total forest income at the household level averages about two thirds the magnitude of agricultural income in the sample.

4.5 **Results**

Our empirical estimation starts with tests of the OLS residuals of the production function estimation using a Waldman (1982) test. The premise of stochastic frontier analysis is that inefficient households are always located somewhere inside the production possibility frontier, and thus OLS residuals are expected to be negatively skewed. If positive skewness is observed, then this indicates that stochastic frontier analysis does not provide unbiased estimates as it is not supported by the data. Another issue before empirical implementation is to specify the one-sided inefficiency term measuring technical efficiency, or u_i defined above. Options for this include half-normal, exponential, and truncated normal distributions. In our analysis, we select half-normal for the inefficiency term for both sectors based on the Akaike information criterion, and we therefore estimate the half normal-half-normal model proposed in Aigner et al. (1977).

Among all inputs, labor and capital are potentially endogenous as both are associated with the resource allocation decisions of the farmer. We employ formal tests of endogeneity to empirically address this issue. Specifically, we employ a control function approach suggested in Wooldridge (2007) that suitably works for nonlinear models and use it to test whether the control function, which is the residual of the OLS regression of the potentially endogenous variable against all exogenous variables and excluded instruments, results in statistically significant coefficients for potential endogenous variables. Labor is first instrumented using the average (exogenous) wage for hired labor at village level, while capital is instrumented using the asset quintiles of the household. In all cases (agriculture and forestry with multiple village democracy measures), we cannot reject the null hypothesis of exogeneity of these inputs. Thus, treating them as exogenous in the estimation is not likely to lead to biased results.

Concerning whether or not we should implement empirical analysis using a pooled sample of agriculture and forestry sectors, we incorporate a likelihood ratio test following Louriero (2009). Specifically, we compute the following test statistic:

(12) $LR = -2 \times \{\ln(\lambda_{pool}) - [\ln(\lambda_{agricultue}) + \ln(\lambda_{forestry})]\}$,

where $\ln(\lambda_{agricultue})$ is the value of the maximized log-likelihood function using the pooled sample, and $\ln(\lambda_{agricultue})$ and $\ln(\lambda_{forestry})$ are maximized log-likelihood values using respective agriculture and forestry subsamples. Under the null hypothesis that the coefficients are equal across models estimated using subsamples, the test statistic LR follows a chi-square distribution with degrees of freedom that equal the number of coefficients, as our models are specified in the same way for agriculture and forestry subsamples. Our test statistic value shows that the null hypothesis is rejected with the *LR* statistic of 487.3 (with a *p*-value of 0.000). This result is consistent with our intuition that agricultural and forest production are in fact fundamentally different production processes and can be treated separately in our efficiency analysis. Further empirical estimation is therefore implemented separately using subsamples.

In each sector, four models are estimated that incorporate village democracy measures of Freq_VRA, Att_VRA, Same_leader and the combination of all of them (Table 4.3 and 4.4). Besides these measures, also included as covariates of the inefficiency variance (in logarithm form) the following variables: household size, gender, age, and education of the household head, months working on farm, and a binary indicator of any chronic disease that he/she suffers from. Provincial dummies are incorporated as explanatory variables for the stochastic variance (in logarithm form) to capture regional household and production conditions which are not observable. We also tried dummy variables in all models that categorize the household's location in either North or South China as the explanatory variable of the stochastic variance, as agro-ecological conditions, major crop and tree types, and institutional environments for forest production are known to vary greatly across these two broad regions (Yin and Newman, 1997). However, such specifications were rejected against those using provincial dummies, and the provincial dummies therefore better capture regional variations in stochastic un-observables – thus we employ provincial dummies in our empirical modeling. In all models, the Cobb-Douglas technology was rejected against the translog through likelihood-ratio tests, and therefore the translog results are presented.

All specifications for agriculture with different measures of village democracy suggest the existence of heteroskedasticity in both error terms, except for model (3) (which uses the variable Same_leader as a village democracy measure) which cannot be rejected for heteroskedasticity in the inefficiency error term. Estimated mean technical efficiency ranges from 0.582 to 0.686. In all agriculture sector models, only the coefficient of capital is found to positively affect production among the inputs. Though insignificant, the linear input of land carries a negative coefficient, intuitively reflecting the nature of smallholder agriculture in most of China which usually is characterized by decreasing returns to land due to the household's limited resources, especially labor. Such a pattern is further suggested by all squared inputs in our regression, which have negative and significant coefficients due to decreasing returns to scale. Substitution might occur between labor and land as reflected in the interaction term between these two inputs, while complementarity might exist between land and capital, and labor and capital.

Models (1) and (2) suggest that higher levels of village democracy tend to reduce the inefficiency variance in agricultural production, with village democracy measured by Freq_VRA and Att_VRA, respectively. These results are intuitive as villages with better democratic participation may better represent farmers' relative comparative advantages, as these farmers are exposed to more opportunities for social learning, which in turn facilitates greater production efficiency and specialization. However, a significant relationship is not found when Same_leader is employed as the village democracy measure, which might be explained by the fact that agricultural production is more stable as an institution given reforms have targeted this sector over a longer period of time, i.e., it is less affected by changes in village leader decisions.

Model (4) incorporates all three measures. In these results, Freq_VRA and Att_VRA, but not Same_leader, are again found to be negative and significant. As we specify here a half-normal distribution for the inefficiency term, where the mean is positively correlated with its variance, these results also suggest that Freq_VRA and Att_VRA can improve farmers' technical efficiency in agricultural production through the reduction of its variance.

Besides the strong relationship between village democracy and technical efficiency, only the age of household head is found to affect technical efficiency with limited impact magnitudes and marginal significance. Most other hypothesized relationships are of expected signs (except for head gender), but none appear to be statistically significant. Also, households in most provinces observe larger stochastic variations as compared to those in Yunnan province (the base group). This makes sense as Yunnan is the only province in Western China included in our survey where agriculture is more traditional and thus modern technologies such as agricultural machinery are less often applied.

Unlike agriculture, forest production appears to be more homogeneous across provinces at least with regards to variances in production, as none of the models can reject the null hypothesis of homoskedacticity in the stochastic error component of the regressions (Table 4.4). However, all models reject homoskedacticity of the inefficiency variance, suggesting a role that village democracy and other covariates play in the determination of technical efficiency and the position of households within the frontier. Technical efficiency in forest production ranges between 0.400 to 0.484, which suggests that households are more inefficient relative to the forest production frontier than they are relative to the agricultural possibilities frontier when they are inefficient. This potentially highlights an important opportunity in democratization if in fact democratization impacts efficiency for forest production.

A closer look at the linear-term input coefficients reveals significance only for labor. Further, significant complementarity between labor and land area is found through the interaction term coefficient. This result, together with the significance of the labor coefficient, jointly implies that forest production at the household level in China is still very much labor-intensive. Increasing returns are found for capital, as inputs such as machinery are not commonly applied for small-scale production at household level. This is further reflected in the substitution effects between labor and capital captured by the interaction term.

Of special interest are the coefficients in the forest production frontier related to village democracy measures, which are found to be statistically very significant in models (1) and (3), individually employing Freq_VRA and Same_leader as village democracy measures respectively, but not in model (2) which uses Att_VRA as the democracy measure. Frequency of VRA meetings reduces inefficiency variances in forest production, but interestingly having the same village leader from households in the village increases it. Model (4) incorporates all three measures but suggests coefficient significance only for the Freq_VRA democracy variable. Under the half-normal distribution for the error component, this can again be interpreted as reductions in inefficiency.

The finding that having the same village leader for the party and the VC jeopardizes technical efficiency in forestry but not agriculture is interesting. This result is likely associated with the fact that forestry is more of a cash-generating sector so that conflicts of economic interests between farmers and village leaders are more severe when those leaders must represent the political interests of the party. Also, a large share of forest production at the household level has only recently been subject to reforms. Thus, villager decisions concerning forests are likely more vulnerable to policy instability if a dictatorship type approach still exists at the village level, as measured with our same leader variable.

Impacts of other covariates on technical efficiency are generally not found to be significant to forest production with the exception of education level of the household head. The results here suggest that a higher education level improves technical efficiency and reduces efficiency based shocks on household production. This is the case in all of the estimated models.

Estimation results clearly suggest the linkage between village democracy and technical efficiency in both agricultural and forest production, as reflected by significant coefficient estimates in most models (Table 4.3 and 4.4). Higher levels of village democracy improves technical efficiency through reduction of its variation in errors, meaning that having democracy results in less errors that make households inefficient when they are in fact inside the frontier. Most other covariates of inefficiency variance equations, though found significant in previous studies, appear to be insignificant in our case once village democracy is properly controlled for. This is a significant finding and suggests that controlling for democracy differences across regions in a reforming economy has implications for not only correct and unbiased estimation of productivity effects, but it is also required for correct interpretation of the importance of rural reforms to household welfare. Given that several countries are currently undergoing policy reforms toward more democratic local decision making, our model suggests the importance of using an econometric model that allows for these complications.

The importance of our efficiency findings can be gleaned through investigating the extent to which democracy alters household disposable income from agricultural and forest production. Income gains follow from productivity gains according to equation (7). As village democracy affects household welfare through the impact of changes in the inefficiency error, we make a direct comparison between the agricultural and forestry income of households living in villages with greater or poorer democracy institutions. We can group households into more democratic and less democratic using ur democracy indicators, taking the highest and lowest one third of the sample with regard to the variables concerning the frequency of VRA meetings, higher VRA meeting attendance rates, and also grouping villages into those with the same party and village leader and those where the leader is different.

Household total agricultural income differs significantly between more democratic and less democratic villages as measured by either Freq_VRA or Att_VRA indicators, with the difference ranging between 1,494 - 1,569 yuan (0.16 Yuan = 1 USD) (Table 4.5). This is nearly 20% of the average annual total income in the sample from Table 4.2. Such a pattern is also observed in the per area (mu) income for agriculture designed to control for any systematic difference in acreages between groups – in this case the difference ranges between 174 - 181 yuan per mu, a significant increase.

The importance of democracy to higher incomes for forest production is even more dramatic. Referring to the table, income differences between more democratic and less democratic villages, using democracy measures Freq_VRA and Att_VRA, range from 1,389 - 2,341 yuan. At the top end this is on the order of nearly 50% of total annual forestry income for our households. If we control for area, income in democratic villages also is significantly higher with democracy to the order of 116 - 148 yuan per mu.

An interesting comparison exists across the results for forestry and agriculture. It appears that the higher end of income differences is dominated by total household income for forestry, but on a per land unit basis the results for income are similar. This can be explained for two reasons. First, agriculture is practiced on higher land qualities and is a higher revenue per hectare crop, and thus we would expect less differences in the ranges once we consider these differences on a per land unit basis. However, our results showed that efficiency gains are greater for forest production, suggesting that the higher total income we observe for the household, and the greater share of total income democracy is responsible for, is indeed an important efficiency effect for this sector. Clearly, democracy is important for both sectors but is critical for forestry related wealth.

4.6 Concluding Remarks

We measure the significance of greater village democracy on rural household welfare in China from a technical efficiency perspective, thereby going beyond existing work on rural reform that has both not addressed forest and agricultural production impacts, or that has not investigated the important role that democratization can have on decision making. Using a unique recent household survey that covers both agriculture and forestry sectors, we provide for the first time micro-level evidence of the linkage between village democracy and technical efficiency.

Our results suggest that democracy and efficiency are strongly positively related across several different democracy measures. Better participation in village democratic affairs can increase technical efficiency, with such impacts also revealed in decentralized decision power at the village level for forestry, which can be more vulnerable to policy instability or economic conflicts. Although there have been many cross country studies of democratic reforms, we have found important effects of decentralized governance in the form of weakly institutionalized politics in rural areas.

The confirmed positive impacts of democratization on household welfare through technical efficiency improvements in both agriculture and forestry directly suggest the need for higher levels of democracy in developing countries like China. For most rural households, enhancements of economic performance in basic sectors that involve the majority of their resources can directly improve their welfare status. The results in our paper suggest that a primary focus for both central and local governments in village democratization should be encouragement through the implementation and public participation of village democratic affairs such as the VRA. Decentralized decision power can also have an important impact in growing sectors such as forestry where political institutions representing the local population are not yet fully developed. Further work should consider the structure of governance across multiple levels of government, and the impacts of democracy in other sectors such as fisheries, horticulture, and off-farm labor markets.

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Table 4.1 Summary Statistics of Village Democracy Measures[1]

	Agriculture (village=207)	Forestry (village=106)
Frequency of VRA meeting	4.612 (5.128)	4.962 (6.127)
Attendance rate of VRA meeting (%)	85.46 (11.76)	85.56 (12.21)
Same leader[2] (yes=1; no=0)	.146 (.332)	.151 (.334)

[1] Standard deviations are reported in parentheses.

[2] It shows whether the VC chairman and the party secretary is the same person.

Table 4.2 Summary Statistics of Production and Household Characteristics[1]

	Agriculture (household=1,400)	Forestry (household=371)
Land (mu)[2]	10.47 (31.65)	52.45 (102.6)
Labor (day)	125.7 (130.4)	112.0 (130.4)
Capital (yuan)	2,365 (5,051)	1,618 (2,731)
Household size	4.471 (1.767)	4.426 (1.480)
Head gender (male=1; female=0)	.950 (.219)	.976 (.154)
Head age (year)	53.24 (10.89)	50.78 (11.26)
Head education (year)	5.730 (3.016)	5.410 (3.115)
Head chronicle sickness (yes=1; no=0)	.184 (.388)	.162 (.369)
Length of off-farm employment (month)	.752 (2.459)	.890 (2.599)
Total income from the sector (yuan)[3]	8,270 (13,465)	5,682 (8,914)

[1] Standard deviations are reported in parentheses.

[2] 1 mu equals 0.067 ha.

[3] 1 yuan equals 0.155 US dollar in 2011 (using daily average exchange rates).

Table 4.3 Stochastic Frontier Estimation for Agriculture (n=1,400)[1]

Alternative Specifications	(1) Freq_VRA	(2) Att_VRA	(3) Same_leader	(4) All
ln(*L*)	.071 (.123)	.052 (.120)	.035 (.123)	.093 (.120)
ln(*K*)	.622 (.116)	.590 (.115)	.588 (.116)	.663 (.116)
ln(*A*)	-.139 (.103)	-.101 (.101)	-.089 (.103)	-.165 (.100)
ln(*L*)×ln(*L*)	-.036 (.009)	-.037 (.010)	-.035 (.010)	-.036 (.009)
ln(*K*)×ln(*K*)	-.052 (.009)	-.052 (.009)	-.051 (.009)	-.054 (.009)
ln(*A*)×ln(*A*)	-.039 (.008)	-.035 (.007)	-.032 (.007)	-.043 (.007)
ln(*L*)×ln(*K*)	.079 (.018)	.083 (.017)	.086 (.018)	.076 (.017)
ln(*L*)×ln(*A*)	-.048 (.021)	-.057 (.020)	-.061 (.021)	-.041 (.020)
ln(*K*)×ln(*A*)	.105 (.016)	.103 (.016)	.102 (.017)	.106 (.015)
Constant	4.60 (.510)	4.82 (.494)	4.85 (.495)	4.36 (.514)
Inefficiency variance equation: $\ln(\sigma_u^2)$				
Freq_VRA	-.099 (.048)			-.183 (.082)
Att_VRA		-.020 (.005)		-.024 (.006)
Same_leader			-.103 (.160)	-.189 (.219)
Household size	.050 (.040)	.038 (.037)	.046 (.036)	.068 (.053)
Head gender	.602 (.367)	.510 (.322)	.523 (.309)	.664 (.478)
Head age	-.010 (.007)	-.012 (.006)	-.011 (.006)	-.014 (.008)
Head education	-.002 (.023)	-.026 (.022)	-.004 (.021)	-.022 (.028)
Head on-farm	-.013 (.027)	.005 (.025)	-.015 (.025)	.005 (.030)
Head sickness	.118 (.174)	.102 (.162)	.096 (.158)	.172 (.209)
Constant	-.548 (.625)	1.11 (.669)	-.478 (.559)	1.45 (.855)
Stochastic variance equation: $\ln(\sigma_v^2)$; base = Yunnan				
Fujian	.531 (.371)	.538 (.374)	.619 (.377)	.387 (.362)
Jiangxi	.229 (.174)	.143 (.178)	.178 (.185)	.193 (.158)
Zhejiang	.915 (.275)	1.07 (.248)	1.07 (.268)	.861 (.241)
Anhui	.985 (.217)	.707 (.235)	.715 (.240)	.966 (.199)
Hunan	.539 (.176)	.461 (.181)	.523 (.183)	.479 (.167)
Liaoning	.657 (.230)	.352 (.220)	.643 (.238)	.462 (.196)
Shandong	.031 (.186)	-.097 (.196)	-.002 (.207)	.020 (.176)
Constant	-1.39 (.129)	-1.35 (.131)	-1.44 (.130)	-1.25 (.130)
Likelihood-ratio specification tests (*p*-value)				
H_0: Cobb-Douglas	120.7 (.000)	130.4 (.000)	110.3 (.000)	142.9 (.000)
H_0: $\delta_i = 0$; $\gamma_i = 0$	48.41 (.000)	58.05 (.000)	37.95 (.000)	70.62 (.000)
H_0: $\delta_i = 0$	19.97 (.006)	29.61 (.000)	9.51 (.218)	42.18 (.000)
H_0: $\gamma_i = 0$	34.36 (.000)	31.65 (.000)	28.89 (.000)	37.48 (.000)
Mean *TE* (s.d.)	.582 (.139)	.604 (.130)	.597 (.131)	.686 (.118)

[1] Standard errors are reported in parentheses.

Table 4.4 Stochastic Frontier Estimation for Forestry (n=371)[1]

Alternative Specifications	(1) Freq_VRA	(2) Att_VRA	(3) Same_leader	(4) All
ln(L)	.195 (.042)	.192 (.135)	.198 (.087)	.195 (.046)
ln(K)	-.025 (.081)	-.057 (.083)	-.015 (.083)	-.017 (.082)
ln(A)	.211 (.238)	.167 (.233)	.202 (.242)	.212 (.237)
ln(L)×ln(L)	.017 (.027)	-.004 (.027)	.007 (.027)	.017 (.027)
ln(K)×ln(K)	.046 (.010)	.047 (.010)	.041 (.010)	.045 (.010)
ln(A)×ln(A)	-.038 (.035)	-.035 (.035)	-.037 (.036)	-.038 (.036)
ln(L)×ln(K)	-.047 (.018)	-.039 (.018)	-.038 (.018)	-.048 (.018)
ln(L)×ln(A)	.087 (.046)	.090 (.048)	.086 (.047)	.087 (.047)
ln(K)×ln(A)	-.022 (.020)	-.019 (.020)	-.020 (.021)	-.048 (.018)
Constant	5.12 (.619)	6.41 (.675)	5.44 (.652)	5.17 (.619)
Inefficiency variance equation: ln(σ_u^2)				
Freq_VRA	-2.24 (.870)			-2.32 (1.01)
Att_VRA		-.000 (.001)		.008 (.005)
Same_leader			1.438 (.700)	.326 (.476)
Household size	-.066 (.238)	.109 (.085)	.165 (.202)	-.084 (.243)
Head gender	2.68 (11.30)	.196 (.746)	-.116 (1.69)	2.98 (2.60)
Head age	-.019 (.032)	-.019 (.011)	-.027 (.032)	-.023 (.036)
Head education	-.387 (.149)	-.155 (.055)	-.420 (.217)	-.378 (.149)
Head on-farm	.040 (.132)	.008 (.043)	.075 (.111)	.063 (.148)
Head sickness	-1.61 (1.64)	.111 (.328)	-.242 (.945)	-1.54 (1.61)
Constant	-2.13 (1.13)	1.67 (1.13)	-.402 (3.16)	-2.52 (2.60)
Stochastic variance equation: ln(σ_v^2); base = Yunnan				
Fujian	.861 (1.02)	1.23 (1.17)	.949 (1.03)	.876 (1.02)
Jiangxi	-.411 (.217)	-.703 (.398)	-.240 (.222)	-.405 (.218)
Zhejiang	.296 (.249)	.216 (.381)	.294 (.261)	.294 (.249)
Anhui	.117 (.244)	.197 (.330)	.067 (.246)	.107 (.244)
Hunan	.295 (.302)	.418 (.428)	.294 (.316)	.297 (.301)
Liaoning	.277 (.512)	.589 (.642)	.343 (.531)	.295 (.511)
Shandong	.000 (.000)	.000 (.000)	.000 (.000)	.000 (.000)
Constant	.540 (.129)	.189 (.304)	.538 (.152)	.540 (.128)
Likelihood-ratio specification tests (p-value)				
H_0: Cobb-Douglas	63.04 (.000)	45.69 (.000)	53.24 (.000)	64.42 (.000)
H_0: $\delta_i = 0$; $\gamma_i = 0$	39.82 (.000)	22.46 (.049)	30.02 (.005)	41.20 (.000)
H_0: $\delta_i = 0$	32.62 (.000)	15.27 (.033)	22.83 (.002)	34.01 (.000)
H_0: $\gamma_i = 0$	9.47 (.149)	8.93 (.178)	5.98 (.425)	9.20 (.162)
Mean *TE* (s.d.)	.484 (.201)	.435 (.168)	.476 (.162)	.400 (.167)

[1] Standard errors are reported in parentheses.

Table 4.5 Agricultural and Forestry Income by Levels of Democracy[1, 2]

Democracy measure	Category	Agriculture		Forestry	
		Total income (yuan)	Income/mu (yuan)	Total income (yuan)	Income/mu (yuan)
Freq_VRA	Above median	9,547 (694.5)	1,686 (85.38)	6,248 (657.9)	353.7 (44.42)
	Below median	8,053 (534.8)*	1,505 (70.53)*	4,859 (608.2)*	238.1 (38.10)*
Att_VRA	Above median	9,899 (682.9)	1,616 (74.41)	6,214 (716.8)	376.3 (54.32)
	Below median	8,330 (500.4)*	1,442 (74.09)*	5,228 (600.9)	247.1 (32.42)**
Same_leader	No	8,796 (554.1)	1,664 (103.8)	6,362 (606.2)	349.8 (40.63)
	Yes	8,472 (642.9)	1,502 (67.71)	4,021 (563.0)**	201.6 (34.49)**

[1] Standard errors are reported in parentheses. *, **, *** indicate the means within each comparison group differ at 10%, 5% and 1% levels, respectively.
[2] yuan equals 0.155 US dollar in 2011 (using daily average exchange rates).