The Effects and Value of a Resistant Perennial Variety: An Application to Pudrición del Cogollo Disease

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This article develops a forestry model to obtain the optimal control strategy and optimal rotation length after a disease attacks in a perennial variety. Three cases are considered: a benchmark consisting of a disease-free field, an identical field with the disease present but no resistant variety with which to replant, and an identical field with the disease present and a resistant variety with which to replant. We determine general decision rules and then apply the model to the case of Pudrición del Cogollo, a major disease threat to the Colombian oil palm industry. In the application, we compare the optimal rotation length between the three scenarios and determine the optimal level of control in each period for the disease scenarios. The singular solution involves complete control of the disease, and in the absence of a resistant variety, the presence of the disease increases the rotation length. With these solutions, we then determine the value of developing a resistant variety. This value depends heavily on the age distribution of the current trees and decreases as the average tree age decreases. The value further declines when the resistance variety has negative attributes such as higher replanting and maintenance costs than the original variety.

JEL codes: C61, Q12, Q16, Q23.

Although much work has explored crop pests and diseases in annual crops, less attention has been given to diseases in perennial crops. Unlike annual crops, perennials involve a long-term investment, usually require a number of years before reaching maturity, and, once established, are costly to remove. Most important, pests and diseases can become established in perennial crops and affect the crop for many years (Spreen, Zansler, and Muraro 2003). Crop rotation, an important pest control strategy for annual crops, is not a short-term option for perennial crops, and the development of a resistant variety will not benefit the producers of perennial crops until the stand is replanted, which may not occur for many years.

Understanding optimal disease management in perennial crops is particularly important because of the value of perennial crop production. In 2012, the United States produced \$25.9 billion worth of fruit and nut crops, more than double the value of its vegetable production and approximately 13.2% of total crop value (U.S. Department of Agriculture 2014). In the global market for vegetable oils and animal fats, perennial crop sources of fats and oils, such as oil palm, coconuts, and olives, contribute to 35% of global consumption (Fedepalma 2013). Additionally, many perennial crops are grown in tropical regions, where the number of crop diseases tends to be ten times as high as in temperate regions, putting production at greater risk (Ploetz 2007).

This article develops a forestry model to obtain the optimal control strategy and optimal rotation lengths when a disease is present. Three cases are considered: a benchmark consisting of a disease-free field, a field with the disease but without a resistant variety with which to replant, and a field with the disease and with a resistant variety with

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which to replant. We compare the optimal rotation lengths between the three scenarios and determine the optimal level of control in each period for the disease cases. With these solutions, we then determine the value of developing a resistant variety. As will be shown, this value depends heavily on the age distribution of the current trees, a key feature of perennial crops. To illustrate the model, this article analyzes Pudrición del Cogollo (PC), a disease affecting the Colombian oil palm industry.

To the best of our knowledge, this is the first time that both optimal rotation length and optimal per-period disease control have been considered for a perennial crop disease or pest with infinite rotations. It is also the first time that the value of a resistant variety has been considered for a perennial crop when timing of adoption is considered. As we will demonstrate, the perennial nature of a crop could decrease the value of developing a resistant variety substantially, relative to a similar annual variety. We also use a method not used previously in the literature to deal with the nonuniformity of rotations, which occurs when the disease enters the field midrotation and persists for all subsequent rotations.

This article proceeds as follows: We first present a summary of previous work and discuss how this work contributes to the literature. We then discuss the theoretical model and general results. We next provide the background information for our application, our data sources, and empirical specifications. We then present the application results and discuss the value of a resistant variety. Finally, we present conclusions and policy implications.

Previous Work

Previous work pertaining to the analysis that follows falls into four categories: optimal pest control in general, optimal forest rotation, optimal pest control in perennial crops, and resistant variety valuation. Extensive work has considered the optimal control of crop pests in the presence of uncertainty, pesticide resistance, intra- and inter-seasonal insect dynamics, and pesticide externalities (Feder 1979; Feder and Regev 1975; Plant, Mangel, and Flynn 1985; Regev, Shalit, and Gutierrez 1983; Lichtenberg and Zilberman 1986; Saha, Shumway, and Havenner 1997; Regev, Gutierrez, and Feder 1976). Much of this work considers pests afflicting annual crops, which is an inherently different problem than pests and diseases affecting perennial crops because pest and disease damage affecting a perennial crop in one season can potentially affect yields for many seasons, unlike in the case of annual crops.

Less work has considered pest control in perennial crops. Several articles undertake empirical analysis of pest control decisions, damage functions, or production as a function of pest control (Hubbell and Carlson 1998; Goodhue, Klonsky, and Mohapatra 2010; Babcock, Lichtenberg, and Zilberman 1992; Cobourn et al. 2011). However, none of this work determines optimal pest control decisions.

Three articles consider some component of optimal pest control in perennial crops or forests. Carlson (1970) analyzes optimal pesticide use for peaches but uses a static model. Herrick (1981) considers optimal area of treatment for gypsy moth in forests in Pennsylvania but does not consider the possibility of rotation. Roosen and Hennessy (2001) model the effects of an antibiotics ban on apple production. They consider optimal rotation length, but in the no-ban scenario, they consider a fixed level of antibiotic use instead of optimizing over use. We contribute to this body of literature by using a dynamic model to analyze both the optimal level of disease control and the optimal rotation length within an infinite rotation framework, which to the best of our knowledge, has not yet been done.

Within the forest rotation literature, several articles consider optimal rotation of trees that provide annual income or benefits instead of just income at the end of the rotation, but these models do not consider an optimization problem in each season as we do (Monkkonen et al. 2014; Johnson 1998; Liao and Zhang 2008; Purnamasari, Cacho, Simmons 2002; Guo et al. 2006). Other work considers optimal rotation length when the forest faces some probability of damage due to fires or invasive species but does not consider within rotation control efforts (Sims 2011; Kuboyama and Oka 2000). Amacher, Malik, and Haight (2005) advance the fire control literature by considering optimal rotation length as well as stand density and a fire prevention method. However, the model assumes that the landowner utilizes the fire prevention method in only one period instead of determining an optimal level of prevention in each period. We contribute to the forestry rotation literature by considering control in every period as well as the optimal rotation length. Although our model is an agricultural application, it is applicable to any forest issue that involves control within the rotation (e.g., invasive species, fire prevention).

Within the pest-/disease-resistant variety valuation literature, most analysis has only considered annual crops. Moyo et al. (2007) conducted a survey to assess rates of technology adoption. Using these estimates, they modeled the value of developing a variety of peanut that is resistant to Rosette virus. Because wealthier households were more likely to indicate that they would adopt the new technology, the predicted benefits of a resistant variety were distributed regressively. Marasas, Smale, and Singh (2003) model the value of resistance to leaf rust in spring bread wheat varieties. Unlike Moyo et al., they assume full and immediate adoption of the resistant variety and find substantial returns to investment.

To the best of our knowledge, only one article has considered the value of resistant varieties for perennial crops. Alston et al. (2014) consider the value of developing a grapevine variety that is resistant to Pierce's disease, but they assume immediate adoption of the variety to replace diseased vines. Our model shows that immediate adoption may not be optimal and that this delay in adoption can dramatically reduce the value of developing a resistant variety, especially in situations where the affected trees are young and/or when the resistant variety has other less desirable traits.

The application of the model developed in this article builds off of that of Mosquera et al. (2013) in which the optimal rotation of a diseased oil palm stand is considered for the case where the grower abandons oil palm production after rotation and sells the land for the market price. Market imperfections in Colombia prevent the market price from reflecting the potential value of the land from future oil palm production. When the disease first arrived, control strategies were uncertain, so abandonment was common. Most land that was abandoned has been or will soon be replanted with oil palm. Only approximately 6% of land has been converted to other crops (Torres 2014). Given that growers no longer need to abandon oil palm production, the application that follows improves upon this by modeling growers who will continue to produce oil palm after the first rotation. Additionally, it considers the possibility and value of a resistant variety and contributes a better understanding of important features of resistant variety valuation with regards to perennial crops.

Theoretical Model

The analysis considers three cases: an orchard with no disease present (ND), an identical orchard with the disease present but with no resistant variety with which to replant (DNR), and an orchard with the disease present with a resistant variety with which to replant (DR). The model is a classic optimal control model containing one state variable and one control variable nested within a modified Faustmann forestry model to jointly address the choice of level of disease control and rotation length. The grower maximizes the net present value for an infinite stream of rotations.

No Disease Case

First, consider the optimal rotation length for a field with no disease risk. The net present value (NPV) of perpetual rotations is given by:

$$(1) \qquad NPV = p\int_0^T Y(t)e^{-rt}dt - Re^{-rT} + \left(p\int_0^T Y(t)e^{-rt}dt\right)e^{-rT} - Re^{-r2T} + \cdots$$

where p is net price defined as the output price minus the average cost of production, $Y(t)$ is the per-hectare output in time t, T is the rotation length, r is the discount rate, and R is the replanting cost. We restrict the analysis to those perennial crops for which the value of timber from removed trees does not exceed the transportation costs required to process it and the grower only experiences a net cost of removal. This includes crops such as bananas (which provide no timber), oil palm in Colombia, avocadoes, citrus, and so on (Bender and Takele 2010; Mosquera et al. 2009; Stelinski et al. 2013). The revenue received in each time period, $pY(t)$, distinguishes this model from the classic Faustmann rotation model. The time variable, t, is measured in months, and for this case, t is also the age of the trees. Using a geometric series to consolidate the infinite stream of rotations, the optimization problem becomes:

$$(2) \quad Max_T NPV = p\int_0^T Y(t)e^{-rt}dt + \left[p\int_0^T Y(t)e^{-rt}dt - R\right] \times \frac{1}{(e^{rT}-1)}.$$

The first order condition is:

$$(3) \quad \frac{\partial NPV}{\partial T} = pY(T)e^{-rT} + \frac{pY(T)e^{-rT}}{e^{rT}-1} - \left[p\int_0^T Y(t)e^{-rt}dt - R\right] \times \frac{re^{rT}}{(e^{rT}-1)^2} = 0$$

which can be rearranged to yield:

$$(4) \quad pY(T) = r\left[p\int_0^T Y(t)e^{-rt}dt - R\right] + \left[p\int_0^T Y(t)e^{-rt}dt - R\right] \times \frac{r}{(e^{rT}-1)}.$$

The left-hand side of equation (4) represents the marginal benefit of waiting one more period to harvest, which is the revenue from selling the harvested fruit in that period instead of removing the trees. The right-hand side of equation (4) represents the marginal cost of waiting an additional year to replant. The first term on the right-hand side represents the interest on the whole stream of profits, which would be delayed for an extra year, and the second term represents the "site rent" or the value at which the bare ground could be sold under perfect land market conditions. At the optimal rotation length, the grower is indifferent between replanting and waiting one more period.

This case, although less interesting than cases with the introduction of a disease, enters into the optimal control problem when the grower has a resistant variety with which to replant. It also serves as a reference point for considering how a new disease's presence affects the status quo optimal rotation length.

Diseased Cases

For the cases that consider the disease, we assume that once the disease arrives on the grower's field, the grower faces disease pressure forever in the absence of a resistant variety. This would be the case for diseases where the agent remains in the soil or on equipment after removal of the trees, such as Panama disease, afflicting bananas, which remains in the soil for up to thirty years after removal of the diseased plants (Ploetz 2006). Citrus greening disease, a major threat to citrus worldwide, could also be represented by the model. Once the disease arrives in a region, the disease vector, the Asian citrus psyllid, serves as a reservoir of the disease, and movement of the vector between fields makes it unlikely that replanting a field would eliminate the disease (Halbert and Manjunath 2004).

The grower faces a disease incidence, D_t (the number of diseased trees), in each period and chooses the number of diseased trees to treat, H_t. We assume that a tree-level treatment exists, which represents diseases such as avocado root rot and black knot (plums and cherries) (Faber, Eskalen, and Bender 2008; Moorman 2014). Yield, $Y(D_t, a_t)$, is now a function of both disease incidence and the age of the trees. Additionally, growers face a control cost, $C(H_t)$, which is a function of the number of trees treated and could also include scouting and detection costs.

The problem begins when the disease enters the field. We denote the age of the trees when the disease first appears as a_0 and will refer to this as the age at initial incidence. This deviates from some of the forest fire literature that applies a stochastic model to determine the optimal rotation length when there is some constant probability of catastrophic losses from fire. For these models, growers receive no revenue until they harvest the trees for timber. When a forest fire strikes, the losses are catastrophic because the grower loses his or her investment immediately. The landowner then faces the same threat in the next rotation. As a result, determining an optimal rotation length that can be applied to all rotations and that considers this risk is informative. In such a scenario, uniformly shortening rotation lengths would be optimal relative to the no-risk case.

However, the process that underlies the disease model presented here differs substantially from a forest fire. First, losses are only catastrophic if left untreated, so a grower would not necessarily want to uniformly shorten the rotation length to avoid possible catastrophic risk. The reduced yields from young trees could result in lower revenue than experiencing yield losses or increased control costs when mature trees become diseased. Second, unlike in the case of a forest fire, where each rotation faces fire risk and uncertainty as to whether and when a fire might strike, with the diseases considered here, once the disease is present, it is always present in the field and known with certainty (assuming away the possibility of additional diseases, catastrophic events, etc.). As such, determining a fixed rotation length to be applied to any rotation in which the disease first appears would not yield the maximum possible net present value. Instead, we solve for the optimal rotation length, T_1, of the first rotation in which the disease appears (figure 1). This length will depend on a_0. Additionally, we solve for the optimal rotation length for the rest of the rotations, T. Another key parameter will be the length of time between initial incidence and the end of the first rotation; this will be denoted as T_a. This parameter will appear in the models, but our reported results will only discuss T_1 because this has a more natural interpretation. The relationship between T_a, T_1, and a_0 is such that $T_1 = a_0 + T_a$.

As mentioned previously, two possibilities for the future rotations are considered: planting with a resistant variety or planting with the current nonresistant variety. For either case, the optimization contains a scrap value function that will equal the net present value of the future infinite stream of rotations from the second rotation onward (all rotations of length T in figure 1), given the resistant or nonresistant variety. For variety type i, the scrap value is:

$$(5)\qquad \phi(T_{a_i}, T_i, D_{T_i}) = (PV_i - R)e^{-rT_{a_i}} + \frac{PV_i - R}{e^{rT_i} - 1} e^{-rT_{a_i}}, \quad i = DNR, DR,$$

where T_i is the optimal complete rotation length for variety i from the second rotation onward, PV_i denotes the present discounted value of one complete rotation of length T_i excluding replanting costs, and R is the replanting cost (see supplementary online appendix for the calculation). Because the analysis is restricted to those perennial crops for which no timber value exists, growers must pay for removal of both healthy trees and diseased trees.

PV_i equals:

$$(6)\qquad \int_0^{T_i} [pY(D_t, a_t) - C(H_t)]e^{-rt} dt.$$

For case DR, $\frac{\partial Y(D_t,a_t)}{\partial D_t} = 0$ in equation (6), and the length of future rotations, T_R, could be the same as case ND if the resistant variety is identical to the current variety in all respects except resistance. These assumptions will be relaxed in the application of the model. For case DNR, the value of T_{NR} must also be chosen optimally.

The grower's optimization problem is

$$(7)\qquad Max_{H_t, T_{a_i}, T_i} NPV = \int_0^{T_{a_i}} [pY(D_t, a_t) - C(H_t)]e^{-rt} dt + \phi(T_{a_i}, T_i, D_T).$$

Subject to

$$(8)\qquad \dot{D}(D_t, H_t) = f(D_t) - H_t$$

$$(9)\qquad 0 \le H_t \le D_t$$

$$(10)\qquad H_t, D_t \ge 0$$

$$(11)\qquad D_T T_{a_i}, T_i \text{ free}$$

where $a_t = a_0 + t$. Again, both age and time are measured in months.

Equation (8) displays the disease dynamics. The disease grows as a function of the current level of disease, and treatment is the only way to reduce disease incidence. Constraint (9) indicates that the number of treated trees must be between 0 and the total number of diseased trees present in period t. Equation (10) implies that both control and disease incidence must be nonnegative. Because negative control implies infecting trees, this constraint should not bind. Negative disease incidence could mathematically

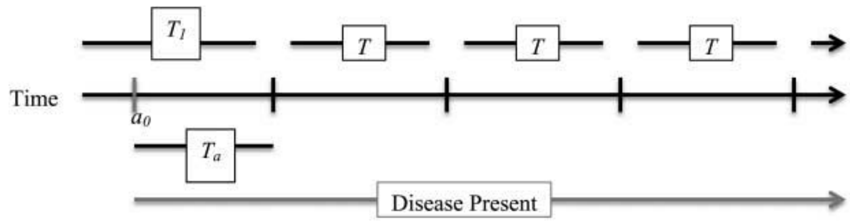

Figure 1. Length of the first rotation, T_1, length between initial incidence and the end of the first rotation, T_a, and the optimal rotation length of all subsequent rotations, T

increase yield despite being physically impossible, so this constraint must be enforced. Finally, equation (11) provides endpoint conditions.

The Lagrangian corresponding to equation (7) is given by:

$$(12)\quad L = pY(D_t, a_t) - C(H_t) + \lambda_t(f(D_t) - H_t) + \varphi_t D_t$$

where λ_t is the costate variable and φ_t is the Lagrange multiplier for the nonnegativity constraint for disease incidence. This yields the following first-order conditions:

$$(13)\quad \frac{\partial L}{\partial H_t} = -\frac{\partial C(H_t)}{\partial H_t} - \lambda_t = 0 \text{ if the cost function is nonlinear in } H_t.$$

$$(14)\quad H_t = \begin{cases} H_t = 0 & if \; -\dfrac{\partial C(H_t)}{\partial H_t} < \lambda_t \\ H_t = H^S(a_t) & if \; -\dfrac{\partial C(H_t)}{\partial H_t} = \lambda_t \\ H_t = H_{Max} = D_t & if \; -\dfrac{\partial C(H_t)}{\partial H_t} > \lambda_t \end{cases} \text{ if the cost function is linear in } H_t.$$

$$(15)\quad -\frac{\partial L}{\partial D_t} = -\left[p\frac{\partial Y(D_t, a_t)}{\partial D_t} + \lambda_t \frac{\partial f(D_t)}{\partial D_t} + \varphi_t\right] = \dot{\lambda}_t - r\lambda_t.$$

$$(16)\quad \frac{\partial L}{\partial \lambda_t} = \dot{D} = f(D_t) - H_t.$$

on the relative magnitude of the terms in equation (17) and the sign of the last term for any particular application. Control could be increasing or decreasing over time. The rate of change of control will be constant and equal to the interest rate when $\frac{\partial^2 Y(D_t, a_t)}{\partial D_t^2} = 0$ and $\frac{\partial^2 f(D_t)}{\partial D_t^2} = 0$. For the case of a linear cost function, $\dot{H}_t$ will either be zero if at a corner solution or will be a function of tree age if there is an interior solution.

Regardless of the functional forms assumed, yield will be a function of tree age. Consequently, the age at initial incidence affects how much of the rotation experiences unhindered profits prior to disease.[1] As a result, all solutions will be a function of tree age at initial incidence.

From the first-order conditions, assuming an interior solution and a nonlinear cost function, optimal control of the disease will evolve over time according to

$$(17)\quad \dot{H}_t = r + p\left(\frac{\frac{\partial Y(D_t, a_t)}{\partial D_t}}{\frac{\partial C(H_t)}{\partial H_t}}\right) - \frac{\partial f(D_t)}{\partial D_t}.$$

It must be true that $\frac{\partial Y(D_t, a_t)}{\partial D_t} \leq 0$, but the sign of $\frac{\partial f(D_t)}{\partial D_t}$ could be positive or negative or the term could equal zero. The evolution of disease control over time is then dependent

To determine T_{a_i}, the following transversality condition applies:

$$(18)\quad H(T_{a_i}) + \frac{\partial \phi}{\partial T_{a_i}} = 0.$$

[1] We assume that the grower does not have within-rotation measures to prevent the disease's arrival. This assumption holds for diseases such as PC disease in oil palm.

Plugging in from the first-order conditions, this can be re-written as

$$(19)\quad pY(D_T,a_T) - C(H_T) - \frac{\partial C(H_T)}{\partial H_T}(f(D_T) - H_T) + \frac{\partial \phi(T_{a_i},T_i,D_T)}{\partial T_{a_i}} = 0$$

where $a_T = a_0 + T_{a_i} = T_{1_i}$. Using the Implicit Function Theorem, equation (19) could be used to determine the effects of parameters for any given disease on optimal initial rotation length.

To determine the level of disease incidence at the end of each rotation, we must consider the two cases separately. For case DR, the end of the rotation is also the end of the effects of the disease, so the following transversality condition applies:

$$(20)\quad \lambda_T = \frac{\partial \phi(T_{a_R},T_R,D_T)}{\partial D_T}.$$

If there is a negative value associated with diseased trees at rotation, for example if diseased trees need to be handled differently (e.g., burned and disposed of), this would determine the optimal level of disease incidence at the end of the rotation. For case DNR, even though a finite time horizon exists for the trees in the rotation, the disease has an infinite time horizon because it remains in the field in some manner after replanting. Because of this infinite time horizon, for linear cost functions, the grower will remain on the singular path forever (Clark 2005). The only variation will occur when the singular path is a function of tree age and the path at a_0 differs from a_{T_a}, in which case a transition would occur during a blocked interval (Arrow 1968). Similarly, for nonlinear cost functions, an adjustment would occur between optimal within-rotation disease incidence paths, but with a more gradual adjustment.

To determine the value of a resistant variety, the net present values of cases DR and DNR can be compared. It is important to note that when $T_1 > a_0$ or $T_a > 0$ for case DR, the grower does not immediately replant with the resistant variety, even though it is available and the disease is present. This is an important element of resistant variety valuation for perennial crops. Unlike annual crops, which are removed and replanted in-between each season, there is the potential for a long time span between first disease infection and the adoption of the resistant variety. This will be illustrated with the PC case study.

Colombian Oil Palm Industry and PC

To illustrate the theoretical model, we apply it to the case of PC disease in Colombian oil palm. During the past three decades, Colombian oil palm production has averaged an annual increase of 7.2% (Gomez, Mosquera, and Castilla 2005). Further production increases are expected due to an increase in global demand for fat and oils and an increase in demand for biofuels derived from oil palm (Carter et al. 2007).

PC, a disease caused by the microorganism *Phytophthora palmivora* Butler, is one of the most detrimental diseases faced by Colombian oil palm growers. The disease disrupts the creation and maturation of new leaves and allows other organisms such as insects, fungi, and bacteria to attack the tree. The disease reduces yields, and if left untreated, the infected tree eventually dies (Martinez et al. 2009). The disease can be devastating if not treated; in the Tumaco area, the disease forced the removal of 70,000 acres of oil palm (Mosquera 2007).[2]

Currently, the spread of the disease is imperfectly understood. Evidence suggests that the causal agent exists in the soil and can be spread to healthy trees through irrigation water. Tools and equipment can also spread the disease between trees (Martinez et al. 2009). These two vectors imply that simply removing a diseased tree or diseased tissue does not entirely remove the presence of the disease from the field once the disease has arrived.

In the long run, the most efficient way to control PC will likely be the development of varieties that are resistant to the disease. Although no resistant variety has been developed yet, researchers have developed a quasi-resistant prevariety.[3] This analysis will inform growers of the optimal rotation

[2] The majority of this acreage has been replanted with oil palm now that growers are aware of how to scout for and control the disease (Torres 2014).

[3] A prevariety has some genetic differences from the original variety but is not a named new variety (Schrumpf and Pfeifer 1993).

length when such a fully resistant variety is developed, and it will also determine the value of developing a resistant variety. To manage PC in the absence of a resistant variety, the Colombian Oil Palm Research Center (Cenipalma) suggests monitoring for PC at the tree level on a regular basis and immediately treating diseased tissue upon detection. Treatment involves removing all diseased tissue and covering the wound with pesticides. When treated in early stages, the tree fully recovers (Torres, Sarria, and Martinez 2010). This PC management strategy has been tested with successful results, but its cost-effectiveness depends on early detection because trees are unlikely to recover from later stages of the disease.

The model that follows assumes that growers constantly scout for the disease, and these scouting costs are included in the grower's costs. In the case of PC, where continual harvest occurs, implying regular movement throughout the fields even in the absence of the disease, scouting costs are small relative to the benefits of early detection (Rubio 2010). There could be cases where the cost of scouting and detection exceed the benefits of doing so regularly or at all (Epanchin-Niell et al. 2012; Homans and Horie 2011). In these cases, there would be two choice variables: level of scouting effort and level of control of detected disease. This could be an interesting extension for future work. Additionally, the model assumes that if growers treat, they will do so while treatment is still effective. As will be shown, this latter assumption does not change results because immediate treatment of any observed diseased tissue is optimal when the grower undertakes control.

Data

An overview of data sources is provided here, whereas the supplementary online appendix contains the empirical estimation of parameter values. The combination of output price and input costs yield net price. Production cost data to calculate the costs per kilogram of oil palm fresh fruit bunches were available from Cenipalma's Research Station, Campo Experimental el Palmar de La Vizcaina (CEPLV). These same data provided an estimate of replanting costs. Replanting costs are the same for both diseased and healthy trees. In both cases, growers remove the trees, chip the leaves and trunks, apply pesticides, wait two months for the residues to decompose, and then till the material back into the soil (Mosquera, Botero, and Villegas 2009). Because of a lack of infrastructure to transport trees to timber-processing plants, there is no timber value for the trees.

Monthly price data in Colombian pesos (denoted by \$) ranging from January 2000 to December 2010 for the international palm oil market were available from the Colombian Federation of Oil Palm Growers (Fedepalma) and were used to estimate market prices of a kilogram of oil palm fruit (Fedepalma 2007; Fedepalma 2011). The international price received is largely independent of PC disease because of three factors: (*a*) oil palm is produced in many countries with varying degrees of PC incidence and susceptibility; (*b*) expansion of oil palm production is occurring in many locations, which mitigates disease impacts on global supply; and (*c*) close substitutes for palm oil, such as soybean oil, exist and stabilize price (McFerron 2013).

Monthly yield per hectare as a function of age was calculated based on Fedepalma's yearly cost survey, which includes monthly yield data obtained from fields with no PC incidence (Duarte and Gutterman 2007). The tree goes through a developing stage when yields increase over time. Yields reach a maximum after about 17 years, at which point they begin to decline. Older palms tend to produce bunches with a higher proportion of woody material, decreasing the amount of oil in the bunch, and older palms bear fewer bunches. Additionally, harvesting tall oil palms implies greater harvest losses due to fruit losses when the bunch impacts the ground at harvest, and harvesters have a more difficult time determining whether the bunch has ripened or not when the bunches are high. This concave quadratic yield function is the potential yield in the absence of disease (Lichtenberg and Zilberman 1986). Data pertaining to the effect of disease incidence on yield were available for 2007 from more than 730 plots (approximately 15,000 acres) in the Tumaco area of Colombia.

The control strategy proposed by Cenipalma was tested under actual PC pressure at CEPLV. The strategy of immediate removal of diseased tissue kept total disease incidence low, although new cases were continuously found. CEPLV researchers kept records of the costs of activities, inputs, and labor for PC control. The control costs per treated palm result from these data. Disease control exhibits constant returns to scale, making control costs a linear function of diseased palms. Cenipalma recommends that growers frequently monitor their fields for new cases of disease, and growers appear to be following these recommendations. This requires inspecting each tree individually, with a single scout capable of covering approximately 25 acres per day, regardless of disease incidence (Fontanilla et al. 2014). Consequently, monitoring is set as a fixed cost in the control cost function.

As mentioned above, data and grower experiences indicate that PC spreads from two sources. First there is an environmental PC infestation pressure. Even when control is implemented perfectly such that all diseased tissue is removed, new cases still appear each time period. This exogenous pest pressure was estimated with data from CEPLV where strict treatment of the disease was implemented. The second PC source consists of the diseased palms themselves, that if untreated serve as a pathogen reservoir; this value was estimated from the data available from the Tumaco PC outbreak (2005–2007).[4]

The annual discount rate was assumed to be 10%, corresponding to the safest interest rate for investments in Colombia, received for deposits at a fixed term plus inflation rate. This rate (equivalent to 0.8% monthly) was chosen because oil palm is a relatively low-risk crop in terms of yield and price fluctuations.

Empirical Specifications

Using these data, appropriate functional forms and parameter value estimates were determined for each function and parameter in equations (1), (7), and (8) (table 1). The supplementary online appendix contains the empirical estimation results.

[4] In this outbreak, no control was implemented, allowing us to determine how the disease spreads from infections within the field. At CEPLV, the strict control program only allows estimation of the environmental pressure. Estimating both terms using the data from fields under no disease control results in essentially no change in the estimate for g and only a modest decrease in the estimate of b (equation (24)). As will be shown, strict control is optimal. Reducing b to the value estimated using data from the no control fields still results in the optimality of strict control. Because control is estimated prior to the rest of the analysis and because strict control is found to be optimal under all spread conditions, we chose to utilize the parameter estimates from the fields under strict control for the rest of the analysis.

Table 1. Parameter Values

Parameter Groups	Symbol	Value(s) (base value listed first)
Monthly discount rate	r	0.0080
Net price	p	108; 97.2
Yield	α_1	320.4161
	α_2	27.2652
	α_3	0.0668
Replanting costs	R	10,000,000; 10,087,000
Effect of disease	β	0.00322
	δ	0.00002
PC control costs	F	50900.000
	γ	6332.000
PC dynamics	b	0.4500
	g	0.2000

Yield is a quadratic function of tree age:

$$(21) \quad Y(a_t) = \alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2.$$

When the disease is present, a proportion of yield is lost due to the disease. This proportion is quadratic in disease incidence due to a compensation effect that occurs at low disease incidence; trees surrounding an infected tree tend to produce above average yields, likely due to less competition for resources such as water and nutrients with the diseased tree. This compensation effect partially mitigates the effect of the disease (Bastidas et al. 2000; Corley and Tinker 2003). The disease penalty gets increasingly large as incidence increases because the diseased tree is more likely to be surrounded by other diseased trees that will not compensate for the yield loss. Consequently, yield is specified as

$$(22) \quad Y(D_t, a_t) = (\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2) \times (1 - \beta D_t - \delta D_t^2).$$

PC control costs contain fixed costs, F, that represent monitoring costs as well as a per unit cost of treatment, γ:

$$(23) \quad C(D_t, \delta_t) = F + \gamma H_t.$$

The disease equation of motion is specified as

$$(24) \quad \dot{D}(D_t, H_t) = b + g D_t - H_t$$

where b is the environmental disease pressure and g is the disease pressure arising from the number of infected trees in time t.

Three Optimization Problems

Figure 2 outlines the solution methods used for the three problems. Case ND is solved for first by simply solving equation (3) for T. Then the present value of one rotation is calculated. These two values then feed into case DR through the scrap value, when the resistant variety is identical to the current variety, aside from its resistance. For the two diseased cases, the singular path of disease incidence is solved for first and will be the same for both. To solve for the optimal initial rotation length as a function of age at initial incidence, the two disease cases require differing methods. For case DR, the scrap value is simply determined from case ND. For case DNR, the scrap value must be found through an iterative process. Once the scrap values are constructed, the transversality condition (18) is then applied to determine the optimal initial rotation length as a function of age at initial disease incidence.

Case ND

Under our parameters, solving equation (3) for T yields an optimal rotation length of 375.22 months or 31.27 years. The average grower rotates after twenty-five years, primarily because at this age some bunches exceed the reach of the harvester (Consortium CUE

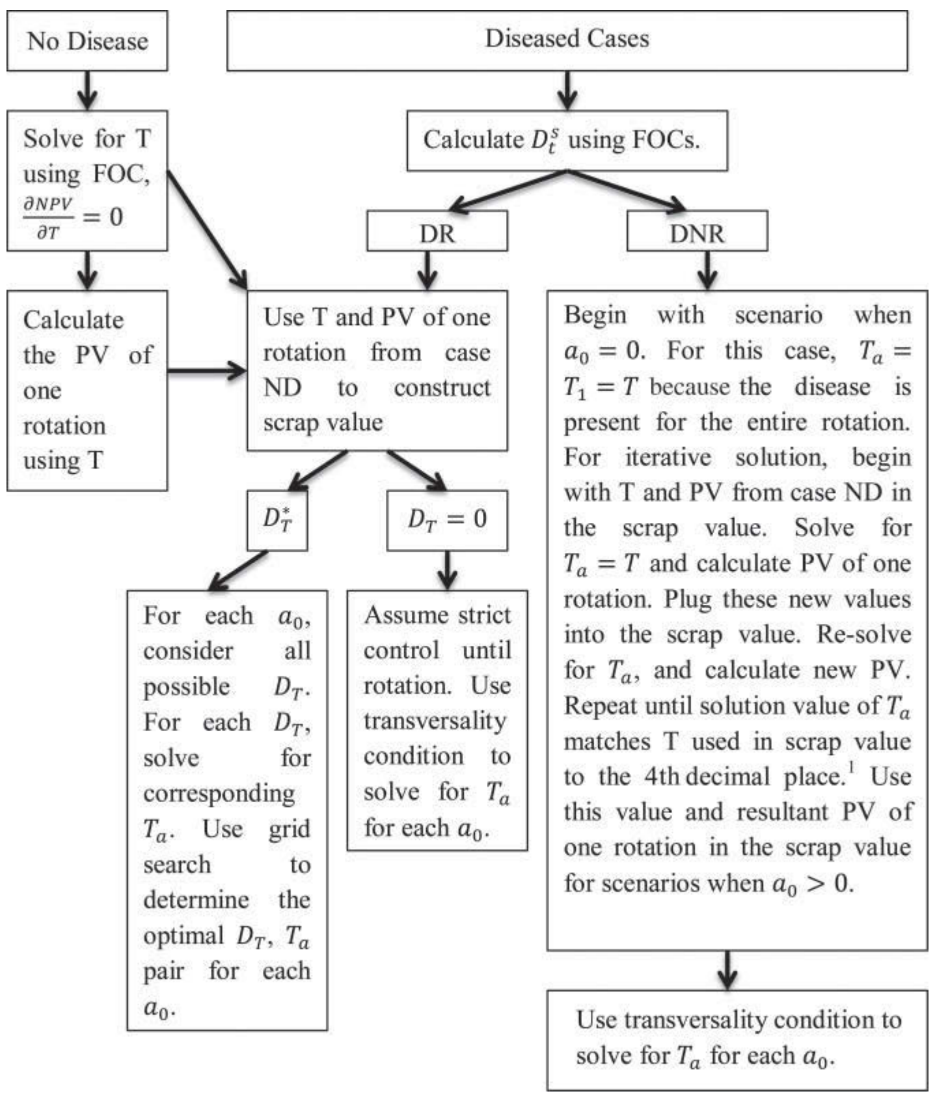

Figure 2. Solution methods for all cases

[1]Note, when $D_t^s = 0 \forall t$, T can be solved from the first-order condition, $\frac{\partial NPV}{\partial T} = 0$, but this is not the case when $D_t^s > 0$.

2012). However, the yield function was estimated with actual harvest data from trees up to age thirty-five and there is no discontinuity at age twenty-five (see figure A.1 in the supplementary online appendix). Growers might be rotating sooner than is optimal due to the perception of wasted yields. The present discounted value of one rotation equals approximately $24,703,600, not including the initial planting costs. This value will be used as in a later subsection. The present discounted value of an infinite stream of rotations is $25,473,000 or $15,473,000, with or without the initial planting costs, respectively.

Case DNR

The Lagrangian is given by

$$(25)\quad L = p(\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2)(1 - \beta D_t - \delta D_t^2) - F - \gamma H_t + \lambda_t(b + gD_t - H_t) + \varphi_t D_t$$

where $a_t = a_0 + t$, λ_t is the costate variable and φ_t is the Lagrange multiplier for the nonnegativity constraint. This yields the following first-order conditions:

$$(26)\quad H_t = \begin{cases} H_t = 0 & if\ -\gamma < \lambda_t \\ H_t = H^S(a_t) & if\ -\gamma = \lambda_t \\ H_t = H_{Max} = D_t & if\ -\gamma > \lambda_t \end{cases}$$

$$(27)\quad -\frac{\partial L}{\partial D_t} = -[p(\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2) \times (-\beta - 2\delta D_t) + \lambda_t g + \varphi_t] = \dot{\lambda}_t - r\lambda_t$$

$$(28)\quad \frac{\partial L}{\partial \lambda_t} = \dot{D} = b + gD_t - H_t.$$

The supplementary online appendix contains the second-order conditions. Because of the linear nature of the optimization, treatment will either be at 0, its maximum value, D_t, or the singular value. Equation (26) implies that control occurs when the marginal cost of control, γ, is less than or equal to the present discounted value of the stream of damage caused by a marginal increase in disease incidence, $-\lambda_t$. When the value of damages prevented exceeds the marginal cost of control, the grower treats all diseased trees.

From equations (26) and (27), the singular path of disease incidence is:

$$(29)\quad D_t^S(a_t) = \frac{\gamma(r-g)}{2\delta p(\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2)} - \frac{\beta}{2\delta} + \frac{\varphi}{2\delta p(\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2)}.$$

An interior solution exists when $\varphi = 0$ and $D_t > 0$, and the singular path will be a function of tree age. Given the parameter values in the empirical model, $D_t^S(a_t)$ is at a corner solution at zero for all possible tree ages because the sum of the first two terms in equation (29) is less than zero, implying that $\varphi > 0$. It is optimal for growers to keep PC cases at zero while they remain on the singular path, implying that the optimal level of control, $H(t)$, is constant and equal to b, the outside disease pressure. This corresponds to Cenipalma's instructions to thoroughly scout and immediately treat any detected diseased tissue.

Although the trees in any rotation have a finite time horizon, for case DNR, the disease has an infinite time horizon because it remains in the field even after removal of the trees. Given that this is an infinite time horizon problem, no transversality condition applies to D_T; instead, the grower will remain on the singular path of strict control and no disease incidence for the entire rotation and into the next rotation.

$T_{a_{NR}}$ free implies that equation (18) holds. For this case, the scrap value, $\phi(T_{a_{NR}}, T_{NR}, D_T)$, is unknown *ex ante* because T_{NR} cannot be determined from a single optimal control problem alone. Consequently, the scrap value must be determined through an iterative process. The process begins by assuming that $a_0 = 0$. For this age at initial incidence, $T_{a_{NR}} = T_{1_{NR}} = T_{NR}$ because the disease begins at the start of the initial rotation; all rotations face identical conditions throughout the entire rotation. For starting values, the PV and T from case ND are used in the scrap value function. With this starting scrap value, we found optimal and $T_{a_{NR}}$ calculated the new present discounted value of one complete rotation. These two values were then plugged in for PV_{NR} and T_{NR} in the scrap value for the second iteration. With this new scrap value, a second $T_{a_{NR}}$ was solved for, and a new PV_{NR} was calculated. These values were plugged into the scrap value for the third iteration. This process continued until the optimal $T_{a_{NR}}$ equaled the T_{NR} used in that iteration's scrap value.[5] T_{NR} was determined to equal 402.5741 months, and PV_{NR} equals \$18,362,531. These values were then used for the scrap value for all initial ages at infection, $a_0 > 0$, because the grower's problem after the initial rotation will be identical to the case where infection begins as soon as the trees are planted.

Knowing PV_{NR} and T_{NR}, equation (18) becomes

$$(30)\quad p(\alpha_1 + \alpha_2 a_T - \alpha_3 a_T^2)(1 - \beta D_T - \delta D_T^2) - F - \gamma H_T + \lambda_T(b + gD_T - H_T) - r(PV_{NR} - R)e^{-rT_{a_{NR}}} - r\frac{PV_{NR} - R}{e^{rT_{NR}} - 1}e^{-rT_{a_{NR}}} = 0.$$

If the grower follows the optimal strategy until rotation, $D_T = 0, H_T = b$, and $\lambda_T = -\gamma$, yielding

$$(31)\quad p(\alpha_1 + \alpha_2 a_T - \alpha_3 a_T^2) - F - \gamma b - r(PV_{NR} - R)e^{-rT_{a_{NR}}} - r\frac{PV_{NR} - R}{e^{rT_{NR}} - 1}e^{-rT_{a_{NR}}} = 0.$$

$T_{a_{NR}}$ for any a_0 can be determined from equation (31), knowing that $a_T = a_0 + T_{a_{NR}}$. MATLAB was used to solve equation (31) for $T_{a_{NR}}$. The dashed line in figure 3 displays the optimal rotation length of the first rotation, $T_{1_{NR}}$, as a function of age at initial incidence. For all ages, the optimal rotation length in the first rotation exceeds the optimal rotation length for case ND. The divergence gets smaller as age at initial incidence increases. With the disease present, revenue is reduced, and the incentive to rotate as yields start to wane at older ages lessens because the peak revenues of the next rotation will be lower than they would be without the disease. Additionally, with reduced monthly profit, a longer rotation length is required to offset the large replanting costs; the earlier the disease strikes in the rotation, the more the rotation must be lengthened.

[5] Iterations continued until the optimal T found equaled the T inputted into the scrap value function to the fourth decimal place.

With $T_{a_{NR}}$ now known, the net present value of the entire stream of rotations is

$$(32)\quad PV(a_0) = \int_0^{T_{a_{NR}}} (p(\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2) - F - \gamma b)e^{-rt}dt + (PV_{NR} - R)e^{-rT_{a_{NR}}} + \frac{(PV_{NR} - R)e^{-rT_{a_{NR}}}}{e^{-rT_{NR}} - 1}.$$

Because $T_{a_{NR}}$ is a function of a_0, the present discounted value is a function of age at initial incidence and will be used below to determine the value of developing a resistant variety.

Case DR

This case has the same optimization problem as defined in equations (25)–(28). Just as in case DNR, the singular path of disease is given by equation (29) and is a corner solution. However, the grower may not want to remain on the singular path forever because at rotation the disease is no longer problematic. The following transversality condition theoretically determines the optimal D_T:

$$(33)\quad \lambda_T = \frac{\partial\phi(T_{a_R}, T_R, D_T)}{\partial D_T}.$$

For this case, the scrap value comes from case ND. The grower will replant with a resistant variety, and the removed trees have no value as timber, so the value of all subsequent rotations will not depend on D_T, implying that the derivative in equation (33) will be zero. A zero shadow value implies that the grower cannot lose any more income from a marginal increase in disease. This could occur because the entire field is diseased. However, the shadow value will also equal 0 just before the rotation because adding a diseased tree right before it is going to be removed does not affect costs or revenues. Consequently, the transversality condition provides no information with respect to the optimal D_T.

When $D_T > 0$, the grower will remain on the singular path, controlling the disease perfectly, until period $\hat{t}$, at which point the grower will discontinue control, including scouting. The time between $\hat{t}$ and T_{a_R} can be

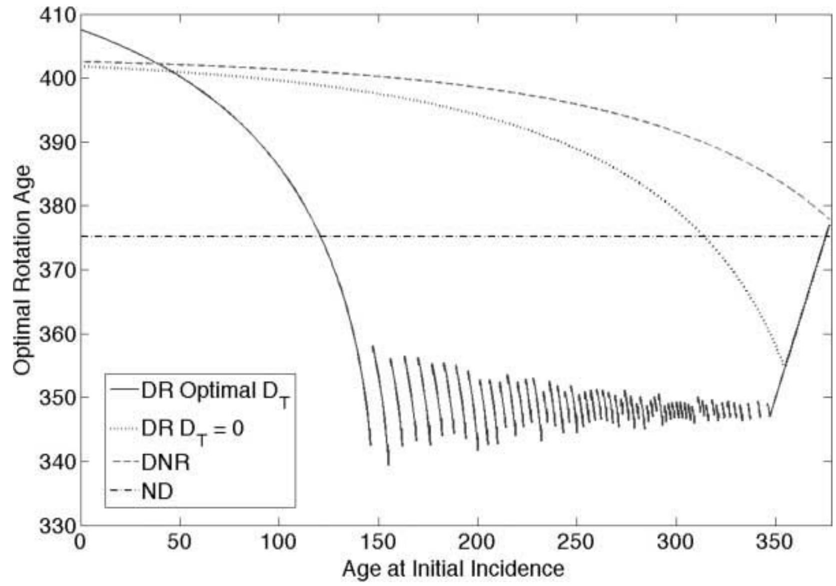

Figure 3. Optimal initial rotation length, T_1, as a function of age at initial incidence for three disease cases with the no disease rotation length as a reference

calculated by

$$(34)\qquad T_{a_R} - \hat{t} = \int_0^{D_T} \frac{1}{b + gD} dD.$$

Just as for case DNR, T_{a_R} free implies that (18) holds. For this case, PV_R and T_R are known *ex ante* from case ND. When $D_T > 0$, $F + \gamma H_T = 0$ because no control is implemented and $\lambda_T = 0$. Plugging these conditions into (18) yields:

$$(35)\qquad p(\alpha_1 + \alpha_2 a_T - \alpha_3 a_T^2)(1 - \beta D_T - \delta D_T^2) - r(PV_R - R)e^{-rT_{a_R}} - r\frac{PV_R - R}{e^{rT_R} - 1}e^{-rT_{a_R}} = 0.$$

Because D_T cannot be determined through its corresponding transversality condition, it is determined manually. For each a_0, equation (35) was solved for as a function of each possible value of D_T. Then for each a_0, the net present discounted value for each D_T and T_{a_R} combination was calculated, and the optimal combination was determined using a grid search method. Figure 4 plots the optimal D_T as a function of age at initial incidence. For ages of initial incidence of 146 months or less, it is optimal for the grower to allow the entire field (143 trees) to become diseased before rotation. When disease begins at ages older than 146, the optimal D_T decreases.

The solid lines in figure 3 display the rotation length for the case where the grower allows disease to increase to its optimal level before rotation. The most obvious unique feature of the solution is its nonlinear and discontinuous nature. This nonlinearity does not occur for the other cases because D_T remains at 0 and only T_{a_i} varies. Choosing both T_{a_R} and D_T simultaneously results in nonlinearities because of the trade-offs between the two variables. The grower can abandon control closer to the end of the rotation, keeping yields higher throughout but incurring control costs. The higher yields for more of the rotation result in a longer T_{a_R}. Alternatively, the grower can abandon control sooner, incur increasingly lower yields, end with a higher D_T, and rotate sooner. Consequently, whenever D_T decreases, we observe an increase in T_{a_R}. The first long continuous section of the function occurs for the ages at initial incidence for which it is optimal for the grower to let the entire field become diseased before removing the trees. The first jump up occurs at the first age at initial incidence for which it is optimal to allow all but one tree to become diseased before replanting. The next jump up occurs when it is optimal to allow all but two trees to become diseased before removing the trees, and so on. Within each optimal D_T range, the optimal T_{a_R} declines with age at initial incidence, paralleling the results for the other scenarios; the later the disease strikes within

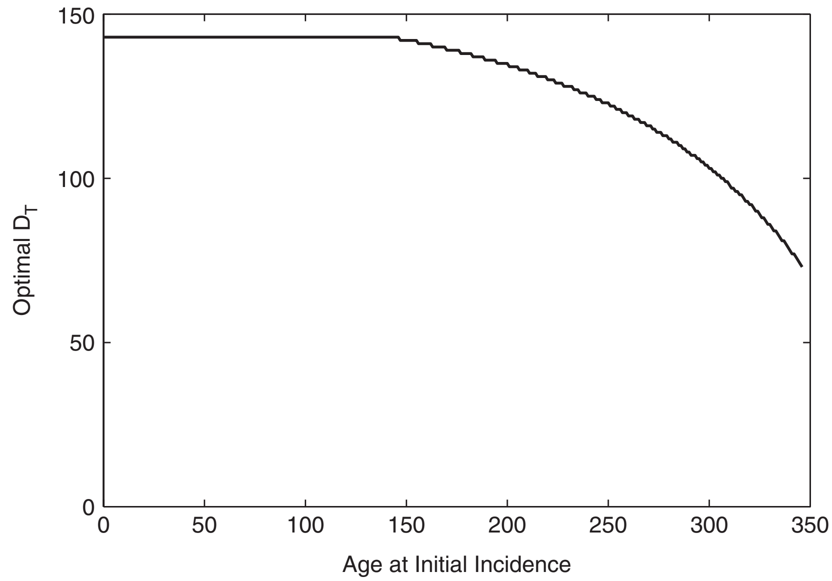

Figure 4. Optimal D_T as a function of age at initial incidence, Case DR

a rotation, the shorter the rotation length for a particular target D_T.

However, growers may not choose the optimal D_T if instructions from Cenipalma tell them to strictly control the disease. Neighboring growers may also pressure each other to maintain strict control to prevent disease spread from one field to another. For either of these reasons, D_T may equal zero, implying that $H_T = b$ and $\lambda_T = -\gamma$. Then (18) becomes[6]

$$(36)\quad p(\alpha_1 + \alpha_2 a_T - \alpha_3 a_T^2) - F - \gamma b - r(PV_R - R)e^{-rT_{a_R}} - r\frac{PV_R - R}{e^{rT_R} - 1}e^{-rT_{a_R}} = 0.$$

From equation (36) the optimal T_{a_R} was determined, knowing that $a_T = a_0 + T_{a_R}$. Again, T_{a_R} is a function of a_0 and was solved for using MATLAB.

The dotted line in figure 3 displays the rotation length for the case where the grower keeps strict control of the disease; the rotation length for case DR with $D_T = 0$ is always less than case DNR. This is intuitive because the grower will want to replace the nonresistant variety with a resistant variety sooner than he would want to replace the nonresistant variety with the same nonresistant variety. Interestingly, the difference in optimal rotation length is small when the disease appears early in the rotation and increases as age at initial incidence increases. When the disease occurs at earlier ages, the grower faces higher costs throughout the rotation and must produce longer to offset the high replanting costs. The benefit of a resistant variety offsets this somewhat but not entirely. For the majority of ages at initial incidence, case DR with $D_T = 0$ has a longer rotation length than case ND, again because of the higher costs incurred throughout the rotation.

When D_T is chosen optimally, there is a small range of ages for which the rotation length exceeds that for case DR with $D_T = 0$ and case ND. For most ages, however, the rotation length when D_T is chosen optimally is well below case DR with $D_T = 0$. When the disease begins beyond age 120 months, the optimal rotation length is less than case ND. With optimal D_T, the grower is essentially letting the field go and starting over more quickly than the other three possibilities. When $D_T = 0$, the grower is still actively managing the disease, keeping production with the disease profitable for a longer period of time but delaying the second rotation that will yield higher profits.

[6] The condition that $\lambda_T = -\gamma$ implies that λ_T embodies a perceived or social cost of disease at rotation because it is known that the physical, private cost of the disease at rotation when a resistant variety exists will equal zero. If Cenipalma's instructions change growers' perceptions of the cost, then λ_T will be greater than zero. If social costs exist, then again, $\lambda_T > 0$.

The increase in optimal rotation length at the highest ages at initial incidence for both case DR scenarios occurs because in this range, if the disease appears, the grower should rotate immediately, so the rotation length equals the age at initial incidence.

With T_{a_R} known, we can calculate the net present value of the entire stream of rotations when following the optimal strategy as

$$(37)\quad NPV(a_0) = \int_0^{\hat{t}} (p(\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2) - F - \gamma b)e^{-rt}dt + \int_{\hat{t}}^{T_{a_R}} p(\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2)(1 - \beta D_t - \delta D_t^2)e^{-rt}dt + (PV_R - R)e^{-rT_{a_R}} + \frac{(PV_R - R)e^{-rT_{a_R}}}{e^{-rT_R} - 1}$$

where $D_t = -b + be^{gt}$, $PV_R = \$24,703,599$, and $T_R = 375.22$. The present discounted value will be a function of age at initial incidence and will be used to determine the value of developing a resistant variety.

If the grower chooses to implement strict control until period T_{a_R}, then the present discounted value will simply be equation (32) with PV_R and T_R substituting for PV_{NR} and T_{NR}.

The Value of Developing a Resistant Variety

With the present discounted values for case DNR and the two case DR scenarios, the values of the resistant variety can be determined by taking the difference in the present discounted values at each age of initial infection. Figure 5 plots the gains from the resistant variety as a function of a_0 for the two scenarios as well as the present discounted value of the nonresistant variety as a comparison. When the disease begins in young trees, the benefit of the resistant variety is a small fraction of the present discounted value of the nonresistant variety because the grower will not make use of the resistant variety for many years. When the disease strikes in older trees, the value is much higher and almost approaches the present discounted value of the nonresistant variety because the resistant variety is planted shortly after the initial incidence.

These results differ starkly from an annual crop where the grower could use the resistant variety in the next growing season. As demonstrated by Moyo et al. (2007), not all growers of annual crops will adopt the resistant variety immediately, but education and extension efforts could increase rates of adoption. In the case of a perennial, however, efforts to encourage growers to adopt the resistant variety earlier would actually be lessening grower welfare because unless the grower has older trees, it is not optimal to rotate as soon as the resistant variety becomes available. This result has implications for other agricultural crops where scientists are currently working on finding resistant varieties. One prominent example is the pursuit of a resistant variety of citrus to combat citrus greening disease (Gottwald, Graca, and Bassanezi 2007). Although some growers will be able to take advantage of the resistant variety, if one is developed, others will and should wait to replant their trees.

Table 2 contains the 2013 age distribution of oil palm plantings across all of Colombia and the calculated value of the resistant variety per hectare for each age when D_T equals zero and when it is chosen optimal. Unfortunately, the historical date of infection, current rates of infection, and long-distance spread rates are unknown, preventing the calculation of an actual expected value. Instead, we perform a thought experiment to illustrate important features of perennial crops. We assume that no acreage was infected prior to 2013 and that all acreage became infected in 2013. With these assumptions, a_0 is the age of the trees in 2013, and we can calculate a hypothetical gain for each age class as well as the total gain for the entire country under the thought experiment.

Importantly, the age distribution of current plantings is skewed toward younger trees. Because the value of a resistant variety is lower for lower a_0, the value of a resistant variety will be lower than one might expect. The last two columns in the table contain the values if one erroneously assumed that the age distribution was uniform or if one assumed the current age distribution but used the average value per hectare, mathematically the same as the first mistake. Ignoring either feature leads to estimates that are 75% higher than if one uses the correct age distribution or correct value per age. This has important implications for policymakers who consider subsidizing research for resistant

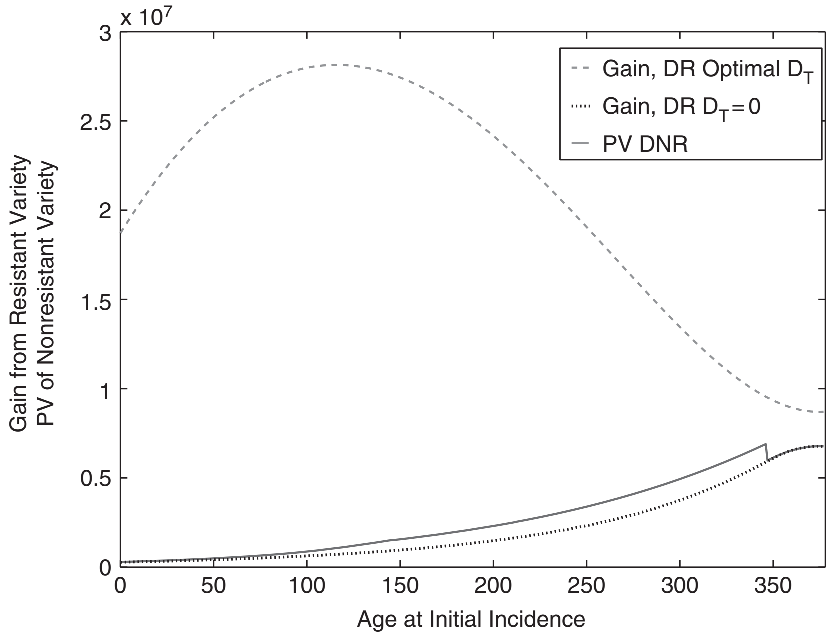

Figure 5. Gain from resistant variety as a function of age at initial incidence with the present discounted value of the nonresistant variety for reference

variety development. Incorrect assumptions can greatly skew results because they are heavily dependent on the age of the trees.

In this thought experiment, the value of a resistant variety would be approximately 25% lower when the grower keeps disease incidence at zero for the entire rotation than when he chooses D_T optimally. The social value of keeping disease incidence at zero may offset these losses, but growers who produce in isolated regions should likely not follow Cenipalma's instructions to maintain strict control if a resistant variety becomes available.

Adding Realism to the Resistant Variety

The results above assume that the resistant variety has the same yields and economic parameters as the current variety. Communication with Cenipalma, however, indicates that this may not be the case. The quasi-resistant prevariety that has been developed and is currently being tested will cost $87,000 more (in Colombian pesos) to replant, only a modest increase above current costs. However, this variety must be pollinated manually, which increases costs considerably. To incorporate these costs, the net price is reduced by 10%. This variety's yields appear to be the same as the current variety, so we will assume that yields remain unchanged.

Figure 6 plots the optimal rotation lengths for the new DR cases as well as the optimal rotation lengths for cases DNR and ND, which have not changed. When $D_T = 0$, case DR is closer to case DNR, although the rotation length for the former case is always lower than for the latter case. With a less advantageous resistant variety, the grower has a smaller benefit of rotating early, so the rotation length is closer to case DNR. When D_T is chosen optimally, the disease reaches 100% disease incidence for a wider age range. Additionally, when the rotation length falls below case ND, it is not as low as under the base parameters; again, with a less advantageous resistant variety, the grower does not rotate as early.

Figure 7 plots the gains from this resistant variety with the present discounted value of the nonresistant variety plotted for reference. The gains are a smaller portion of the present discounted value for all age ranges compared with figure 5. Table 3 presents the value per hectare and total potential value of this resistant variety for the two case DR scenarios. The total potential value under these parameters is only 60% to 65% of the value of the resistant variety that is identical to the current variety in terms of economic parameters. Because the growers are not adopting this variety as early, they are incurring control costs and/or disease losses for

Table 2. Potential Value of the Resistant Variety for Two Disease Incidence Scenarios under the 2013 Age Distribution and an Assumed Uniform Age Distribution

		2013 Age Distribution				Uniform Age Distribution	
		Optimal D_T		$D_T = 0$		Optimal D_T	$D_T = 0$
Age (years)	2013 Area Planted (Ha)	Value/Ha ($\times 10^6$)	Total Gain ($\times 10^6$)	Value/Ha ($\times 10^6$)	Total Gain ($\times 10^6$)	Total Gain	Total Gain ($\times 10^6$)
1	27,243	0.33	8,935.70	0.30	8,227.39	5,212.81	4,799.60
2	31,178	0.37	11,567.04	0.33	10,382.27	5,896.20	5,292.27
3	32,481	0.42	13,706.98	0.37	11,953.01	6,706.73	5,848.52
4	51,387	0.48	24,614.28	0.41	20,863.04	7,612.61	6,452.44
5	37,436	0.55	20,514.93	0.45	16,808.76	8,709.21	7,135.83
6	39,142	0.63	24,581.18	0.50	19,414.43	9,980.63	7,882.79
7	25,476	0.72	18,368.34	0.55	13,960.96	11,458.65	8,709.21
8	22,651	0.83	18,845.63	0.61	13,703.86	13,222.74	9,615.09
9	28,335	0.96	27,315.35	0.67	18,984.73	15,320.58	10,648.12
10	30,441	1.12	34,063.57	0.74	22,556.84	17,783.95	11,776.50
11	23,979	1.30	31,244.93	0.82	19,686.94	20,708.21	13,047.92
12	13,638	1.49	20,375.01	0.91	12,383.21	23,743.72	14,430.59
13	10,456	1.63	17,011.28	1.01	10,528.80	25,857.45	16,003.97
14	6,235	1.80	11,235.19	1.12	6,964.32	28,638.68	17,752.17
15	5,384	1.98	10,655.11	1.24	6,676.27	31,451.69	19,706.97
16	9,608	2.17	20,868.24	1.38	13,239.61	34,518.98	21,900.16
17	3,503	2.38	8,348.01	1.53	5,366.83	37,872.35	24,347.64
18	4,363	2.61	11,390.92	1.71	7,442.71	41,495.88	27,112.98
19	4,774	2.86	13,645.49	1.90	9,076.30	45,421.39	30,212.06
20	2,453	3.14	7,693.46	2.12	5,203.39	49,839.56	33,708.45
21	1,773	3.44	6,105.47	2.37	4,199.72	54,734.52	37,649.85
22	3,018	3.77	11,382.76	2.65	8,002.04	59,931.44	42,131.59
23	3,611	4.13	14,898.70	2.97	10,724.47	65,573.35	47,201.37
24	6,147	4.51	27,745.57	3.33	20,480.34	71,739.73	52,954.53
25	7,773	4.94	38,359.64	3.75	29,109.80	78,430.56	59,518.23
26	15,456	5.39	83,340.66	4.21	65,133.07	85,693.53	66,971.91
27	10,409	5.89	61,257.94	4.75	49,391.49	93,528.64	75,410.94
28	7,277	6.42	46,705.83	5.34	38,868.16	101,999.46	84,883.00
29	7,646	6.03	46,108.25	5.99	45,787.10	95,833.09	95,165.59
30	3,507	6.54	22,934.87	6.54	22,934.87	103,938.37	103,938.37
Total	476,782						
Total Gain			713,820.34		548,054.74	1,252,854.70	962,208.68
Total Gain (USD $\times 10^6$)			388.32		298.14	681.55	523.44
Percentage of Correct Value						175.51%	175.57%

a longer period of time, and then when they rotate, the next rotation is not as valuable as it would be if the replanting and production costs were the same as the current variety. As a result, seemingly small changes add up to a substantial loss in value.

For any crop disease, the resistant variety is likely to differ from the current variety in terms of yields, costs, and/or price received. As these results show, smaller changes in parameters can have substantial effects on the value of the variety over the entire stream of its use because of the complicated ways in which parameters affect the rotation length and optimal disease stock values.

Conclusions and Policy Implications

Several conclusions follow from this analysis. First, for tree diseases that persist in the field after rotation, the age at which the disease first infects trees will determine how the rotation length should be adjusted and, in the case of an interior solution, how much control should be applied. Interestingly, for an interior solution, the optimal level of control will likely vary during the rotation, based on tree age.

Second, in our application, the existence of PC without a resistant variety or with a resistant variety while following Cenipalma's

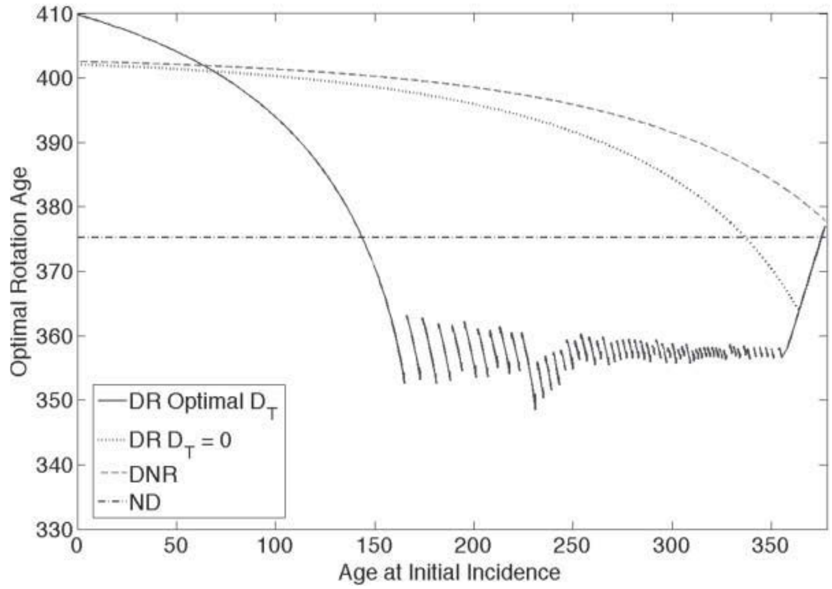

Figure 6. Optimal initial rotation length as a function of age at initial incidence when the resistant variety has higher replanting costs and a lower net price

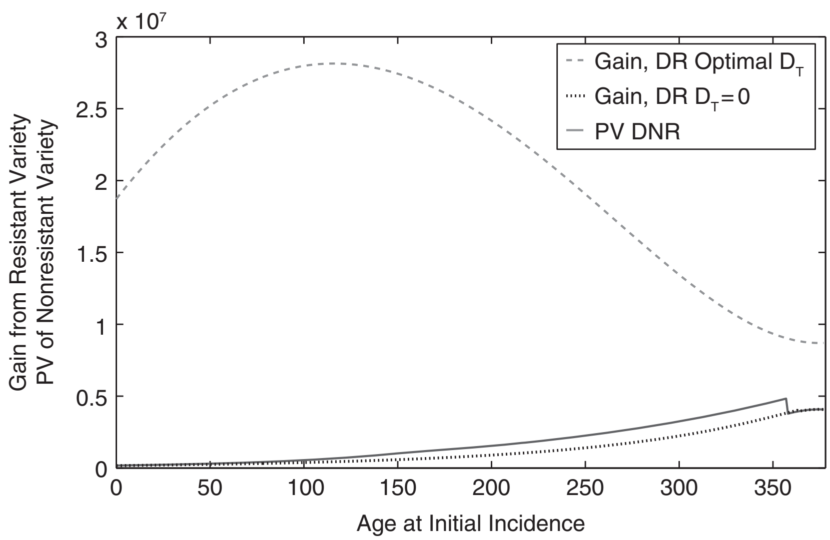

Figure 7. Gain from a resistant variety as a function of age at initial incidence with the present discounted value of the nonresistant variety for reference when the resistant variety has higher replanting costs and a lower net price

strict control recommendations lengthens the optimal rotation length relative to the no disease case and relative to current grower practices. The degree of lengthening depends on the age of initial incidence. This result is a function of the perennial nature of oil palm, its age-dependent yields, and its long rotation length. This is in contrast with the forest fire literature in which growers shorten their rotation length to lessen the probability of catastrophic losses. However, it coincides with Roosen and Hennessy (2001), who find that limiting fire blight control options available to apple growers results in an increase in rotation length.

In the presence of a resistant variety, allowing growers to let disease incidence increase as the end of the rotation approaches would be optimal for the individual grower. However, there are many diseases where spatial spread across growers could result in the

Table 3. Potential Value of the Resistant Variety with Higher Replanting Costs and Lower Net Price for Two Terminal Disease Incidence Scenarios under the 2013 Age Distribution

		Optimal D_T		$D_T = 0$	
Age (years)	Area Planted (Ha)	Value/Ha ($\times 10^6$)	Total Gain ($\times 10^6$)	Value/Ha ($\times 10^6$)	Total Gain ($\times 10^6$)
1	27,243	0.20	5,530.33	0.19	5,067.20
2	31,178	0.23	7,170.94	0.21	6,391.49
3	32,481	0.26	8,542.50	0.23	7,340.71
4	51,387	0.30	15,364.65	0.25	12,795.31
5	37,436	0.34	12,840.55	0.28	10,294.90
6	39,142	0.39	15,421.95	0.30	11,899.17
7	25,476	0.45	11,540.72	0.34	8,560.00
8	22,651	0.52	11,846.47	0.37	8,380.87
9	28,335	0.61	17,142.93	0.41	11,617.52
10	30,441	0.70	21,369.64	0.45	13,789.81
11	23,979	0.82	19,591.02	0.50	12,037.57
12	13,638	0.95	12,942.36	0.56	7,569.03
13	10,456	1.09	11,417.53	0.62	6,430.20
14	6,235	1.21	7,537.93	0.68	4,245.93
15	5,384	1.33	7,139.30	0.76	4,070.37
16	9,608	1.46	13,989.03	0.84	8,051.38
17	3,503	1.60	5,591.03	0.93	3,261.43
18	4,363	1.75	7,625.94	1.04	4,519.72
19	4,774	1.91	9,119.27	1.15	5,500.21
20	2,453	2.09	5,134.70	1.28	3,145.10
21	1,773	2.29	4,056.13	1.43	2,535.08
22	3,018	2.50	7,546.25	1.60	4,814.51
23	3,611	2.73	9,857.84	1.78	6,438.29
24	6,147	2.98	18,304.46	1.99	12,256.24
25	7,773	3.25	25,231.08	2.23	17,357.06
26	15,456	3.54	54,653.67	2.50	38,687.25
27	10,409	3.85	40,044.06	2.81	29,218.53
28	7,277	4.18	30,433.74	3.15	22,901.72
29	7,646	4.54	34,737.94	3.52	26,930.89
30	3,507	3.23	11,341.19	3.92	13,746.89
Total	476,782				
Total Gain (Colombian Pesos $\times 10^6$)			463,065.16		329,854.39
Total Gain (USD $\times 10^6$)			251.91		179.44
Percentage of "Perfect" Variety's Value			64.87%		60.19%

social optimality of strict control. This possibility would depend on the ages of trees surrounding the grower of interest, the rate of spatial spread, and any spatial differences in control costs and quantity and quality of yield. Further work should be done to assess the social benefits of strict control when the neighboring grower is still producing with the nonresistant variety.

Relative to an annual crop, the value of a resistant variety for perennial crops is likely to be lower due to the long rotation lengths. Additionally, careful consideration of benefits at each age and the age distribution of the crop is necessary to determine the value of a resistant variety when considering a perennial crop. For crops with a young age distribution, the value of the resistant variety will be lower than for crops with an older age distribution. Additionally, the development of a resistant variety often results in other less desirable traits in the variety. These could include reduced yields, increased replanting or maintenance costs, or reduced output quality. Any of these attributes will result in a further delay of adoption of the resistant variety and further reduce the value of developing the resistant variety. Neither of these conclusions have been considered thus far in previous literature on resistant variety valuation, despite the fact that they have strong policy relevance.

Government and private agencies that fund the development of resistant varieties of perennials should consider the possibility of lower and delayed benefits when determining the net benefit of such funding. Additionally, outreach efforts to growers should take into consideration that, even though a resistant variety is available, it may not be economically optimal for growers to adopt the new variety. High replanting costs necessitate delayed adoption.

Supplementary Material

Supplementary material is available at http://oxfordjournals.org/our_journals/ajae/online.

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