A Dynamic Model of *Pudrición del Cogollo disease* Control in the Colombian Palm Oil Industry

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Selected Paper prepared for presentation at the Agricultural & Applied Economics Association 2012 Annual Meeting, Seattle, Washington; August 12-14, 2012

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1. Introduction

While much work has explored crop diseases in annual crops, less attention has been given to diseases in perennial crops. Perennials differ from annual crops in that perennials involve a long-term investment including a substantial initial capital outlay, usually require a number of years before trees reach maturity, and, once established, are costly to remove. Most importantly, pests and diseases can become established in perennial crops and affect the crop for many years (Spreen, et al., 2003). Crop rotation, an important pest control strategy for annual crops, is not a short-term option for perennial crops.

Pudrición del Cogollo (PC), a disease affecting the Colombian oil palm industry is one such disease that requires special considerations due to the perennial nature of the palm oil crop. We develop a forestry model to obtain the optimal control strategy and optimal moment of replanting after PC disease attacks. We compare two scenarios: a benchmark consisting of an oil palm field with no PC incidence and an identical oil palm field with PC. For the field with PC, we consider a continuum of strategies: ranging from “do nothing” to an active management strategy that immediately removes known infected tissue.

The proposed model represents a novel approach in that, to the best of our knowledge, this is the first time this sort of model has been applied to a pest on perennial crops. Additionally our model has several important policy applications. It provides a tool for determining what fair compensation would be for growers forced to eradicate their perennial crops in the interest of reducing negative externalities. Additionally, it provides growers with optimal replanting times based on disease rates, palm oil prices, and costs.

This paper is organized as follows: the first section of this paper presents background information on the Colombian oil palm agroindustry and on the main aspects of PC, such as causal agent, symptoms, suggested management and economic impact. In the second section we present the theoretical model and refer to our data sources. In the third section we present our results, and in the fourth one our concluding remarks.

1.1. Colombian oil palm agroindustry

In Colombia, oil palm cultivation has increased rapidly during the past three decades, at a yearly growth rate of 7.2%. In 2011, the total area in Colombia planted with oil palm reached 850,000 acres. It is expected to keep increasing, not only because global demand for fat and oils has increased, but also because of increasing demand for biofuels including diesel produced from palm oil (Carter et al., 2007; Fedepalma, 2011). In Colombia as opposed to Malaysia and Indonesia, the oil palm agroindustry has not been the subject of criticism of its environmental impacts, since more than 90% of the area planted with oil palm has replaced activities such as cotton, banana, and rice production or extensive cattle ranches, activities that if not properly managed may cause adverse effects on ecosystems such as erosion (Gomez, et al., 2005).

With respect to the economic importance, the Colombian oil palm agro-industry accounts for 4% of the contribution of all Colombian crops to gross domestic product in 2010 (Fedepalma, 2011). Even though it is relatively small, it has increased over time, from less than 0.1% in the 1960s to more than 4% in 2010. Additionally, this figure only accounts for the value of crude palm oil and as such does not capture the full economic impact of the industry given the interdependency of several other sectors and the oil palm industry. For example the industry is a major purchaser of raw materials such as fertilizers and other chemicals and provides an input for many Colombian industries which otherwise may need to import oil palm substitutes.

The Colombian oil palm agroindustry's main products are crude palm oil and crude kernel oil. Both of them are very versatile and they are used in many industrial processes that one could group into four types of goods: direct human consumption, animal feeds, manufacture of inedible products and oleo chemicals (Gomez, et al., 2005). This versatility makes oil palm products popular among producers since it prevents them from being too exposed to international demand and price fluctuations as compared with coffee or flowers, the main Colombian export crops.

At the government level, oil palm is a highly appreciated crop because it is labor intensive and represents a source of stable income for rural communities. Additionally, there is evidence that oil palm provides a higher average income for workers. When comparing crop harvesters' income, oil palm workers earned on average of US$15/day and were hired on a daily basis (oil palm is harvested all year long), while workers in alternative sectors earned an income of US$6/day and were only hired for the harvest season (Mosquera and Garcia, 2005). Oliveira et al. (2011) conducted a study that concludes that 70% of oil palm workers are granted health insurance and retirement fund monthly payments from their companies, which is very rare in Colombian rural areas. Oliveira et al., also found that welfare indexes on municipalities whose main economic activity is oil palm are higher than other similar areas that rely on other economic activities.

In synthesis, oil palm in Colombia has many features that lend itself to sustainable rural development. However, the Colombian oil palm industry is challenged by the presence of pests due to increased acreage devoted to oil palms, failure to enforce necessary sanitary regulations, and the area's humid tropical conditions.

1.2. *Pudrición Del Cogollo disease* (PC)

The most important pest affecting the Colombian oil palm cultivars is *Pudrición del Cogollo* (PC) (Torres et al., 2010). PC is caused initially by *Phytophthora palmivora Butl*, but after its attack many other opportunistic fungi attack the palm (Martinez et al., 2009). PC affects immature tissues of the emerging leaves of oil palms and interferes with the processes of creation and maturation of new leaves, leading to stunting and death of the oil palms. As the disease develops on a palm, decomposition of tissues spreads to the meristem, where new tissue formation occurs, eventually causing the plant to die (Figure 1). An added threat results from the fact that the decomposing tissue also attracts insects, such as *Rhynchophorus Palmarum,* that bring additional concerns since they damage both diseased and nearby healthy oil palms (Martinez et al., 2009).

The symptoms of PC depend on the severity of the disease. In general terms, one finds necrosis on the youngest leaves, and if severely infected, the leaves then collapse. Once PC reaches the plant's meristem, it dies. It has been documented that throughout tropical Latin America, PC disease has caused eradication of entire plantations in Surinam, Ecuador and Colombia (Martinez, 2010).

In order to categorize the severity of PC, a scale developed by Cenipalma (Colombian Oil Palm Research Center), which associates damage of the youngest leaf surface, is used (See Figure 2). If the youngest leaf does not have any kind of damage, the oil palm is rated as Degree zero (healthy palm). Brown spots on the surface of the youngest leaf are characteristic of early stages, characterized as Degree 1 or 2 depending on the percent of surface damage. Trees are designated as Degrees 3, 4, or 5 depending on the percent of internal leaf damage When the youngest leaf is necrotic and collapsed, and the plant has not emitted new leaves, it is said to be in the "crater" stage (Figure 2).

The most efficient way of controlling PC disease is likely to be the development of plants resistant to the disease, but these breeds are still in the development stages. Until a resistant, high-yielding variety can be achieved, growers must manage PC disease with the following methods.

To manage PC, Cenipalma suggests a thorough training of PC disease readers, searching for PC symptoms at an individual level on a regular basis and keeping accurate records of diseased palms and PC severity degree. When a diseased palm is detected, its infected tissues are cut off and the wound is covered with pesticides (insecticide, fungicide and bactericide). A white plastic roof is placed above the wound in order to avoid direct contact of solar rays and rain, which wash away the chemicals (Figure 3). Additionally, diseased and surrounding palms' young tissues are sprayed with pesticide, until the diseased palm recovers (Torres et al., 2010).[1] This PC management strategy has been tested with successful results, but its cost effectiveness depends on early detection. Depending on the severity of the disease it might be more advisable to eradicate the considered standing. Many of the oil palm plantations with advanced levels of infection choose not to eradicate, trying to obtain as much output as possible before the trees die.

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[1] Note, nine palms are sprayed in total. Pesticide sprayings are carried out following a schedule of six applications, each of them consisting of a different combination of products. The six applications are named after "a round". Applications are in place for the diseased and the surrounding palms, until the diseased one fully recovers, which means that seven healthy new leaves are emitted (about four and a half months). Due to the fact that pesticide applications' frequency depend upon disease pressure, we considered weekly applications, which indicates one completes eighteen applications (3 complete rounds).

However, as pointed out by Martinez et al. (2009), this constitutes an exponentially growing source of the causal agent.

In the municipality of Tumaco, Colombia and surrounding areas, more than 70,000 acres of oil palm were eradicated. This destruction yielded a crop loss valued in the vicinity of $2,300 per acre out of $14,500 per acre of average net profits expected during 25 years of an oil palm project (Mosquera, 2007). This estimate is very conservative since it represents only direct costs to producers and does not reflect the secondary (spill over) costs resulting from the multiplier effects.

2. Theoretical Model

As mentioned above, we use a forestry model to address the rotation problem (Clark, 2005), modified by including income from continuous sales of fruits, as opposed to selling all output (wood in the typical forestry model) in the final period. We evaluate two scenarios. An orchard which has not been attacked by the disease and an identical orchard attacked by the disease. Both models seek to maximize the net present value by choosing the optimal time period to replant, and for the second scenario, by also choosing the optimal level of control.

2.1. Scenario without PC

We begin by considering the optimal rotation length for a field without PC disease. This scenario may be considered as the benchmark or the grower's planned scenario. For one rotation, the net present value (NPV) is given by:

$$NPV = \int_0^T pY(t)e^{-rt}dt - R\,e^{-rT} \qquad (1)$$

where p is net price defined as the unit price less unit cost of production (for simplicity we will consider it fixed), $Y(t)$ is the production of oil palm fruit at period t, which in this case may be interpreted as the tree's age, T represents the time horizon considered to be the economic life of the crop, r is the discount rate and R represents the replanting cost. The net present value of perpetual rotations is given by:

$$NPV = p\int_0^T Y(t)e^{-rt}dt - R\,e^{-rT} + \left(p\int_0^T Y(t)e^{-rt}dt\right)e^{-rT} - Re^{-r2T} + \cdots \tag{2}$$

Using a geometric series, we can express the problem as:

$$Max_T NPV = p\int_0^T Y(t)e^{-rt}dt + \left[p\int_0^T Y(t)e^{-rt}dt - R\right]\frac{1}{(e^{rT}-1)} \tag{3}$$

The first order condition is:

$$\partial NPV/\partial T = 0 \tag{4}$$

which can be re-arranged to yield:

$$pY(T) = r\left[p\int_0^T Y(t)e^{-rt}dt - R\right] + \left[p\int_0^T Y(t)e^{-rt}dt - R\right]\frac{r}{(e^{rT}-1)} \tag{5}$$

The left hand side of expression (5) represents the marginal benefit of harvesting (waiting to replant), which is the benefit from selling the harvested fruit in the next period. The first term in the right hand side represents the interest on the whole stream of profits (which was delayed for an extra year); and the second term represents the "site rent", this is the value at which the bare ground could be sold.

2.2 Scenario with PC

For the case of a field with PC disease, we use the NPV of one rotation, the grower faces a disease incidence, $D_{t,}$ (the number of diseased trees) and chooses the number of diseased trees to treat, H_t, as well as the optimal rotation time, *T* to maximize his net present value. At the end of the rotation, some growers have chosen to abandon their fields due to PC disease (Martinez, 2010) and others may replant with newly developed breeds with some degree of PC resistance. Consequently, unlike the Faustmann model, we utilize a scrap value. The scrap value, determined by land market values, will measure the value of the land in its highest valued use which may or may not include additional oil palm rotations (Deininger, et al., 2008). The grower's optimization problem is:

$$Max\ NPV = \int_0^T \left[p * Y\left(D_{t,}a_t\right) - c(H_t)\right] e^{-rt} dt + \phi(T, D_T) \quad (6)$$

Subject to:

$$\dot{D}\ (D_t, H_t)\ = b + cD_t - H_t \quad (7)$$

$$0 \leq H_t \leq H_{Max} \quad (8)$$

$$\mathrm{T, Free} \quad (9)$$

$$\mathrm{D_T, Free} \quad (10)$$

where, p is net price defined as above; $Y\left(D_{t,}a_t\right)$ is the production of oil palm fruit at age a_t with disease incidence $D_{t,}$; $c(H_t)$ is control costs as a function of diseased palms treated, H_t; r is the monthly discount rate; and $\phi(T, D_T)$ represents the scrap value function (Leonard & van Long, 1992).

Equation (7) displays PC disease incidence dynamics $\dot{D}\ (D_t, H_t)$. The disease grows exponentially at a rate of *c*, but growers also face outside pressure at a rate of *b*. Treatment is the only way to reduce disease incidence. Constraint (8) indicates that the number of palms treated ranks from 0 to H_{Max} where H_{Max} in time period *t* equals D_t. Finally, equations (9) and (10) are endpoint conditions. Specifically, we use the following functional forms, obtained from the available data:

$$\mathrm{Y\left(D_{t,}a_t\right) = (\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2) * (1 - \beta D_t - \delta D_t^2)} \quad (11)$$

$$\mathrm{c\left(D_{t,}\delta_t\right) = F + \gamma H_t} \quad (12)$$

$$\phi(T, D_T, L) = \left(L * (1 - 0.001 * D_T)\right)e^{-rT} \tag{13}$$

In equation 13, L corresponds to the average land value for the Colombian conditions (9.8 million of Colombian pesos per hectare), figure estimated by using survey data (Fedepalma, 2008).

To solve the optimization problem, we use an optimal control problem strategy, with a control variable, H_t, and a state variable, D_t. Special attention must be devoted to the control variable H_t because it enters the problem linearly. This implies that we face a bang-bang optimal control problem (Chiang, 2000). The Hamiltonian is given by:

$$\mathcal{H} = p * \left((\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2) * (1 - \beta D_t - \delta D_t^2)\right) - F - \gamma H_t + \lambda_t(b + cD_t - H_t) \tag{14}$$

which yields the following first order conditions:

$$\text{FOC 1: } \frac{\partial \mathcal{H}}{\partial H_t} = -\gamma - \lambda_t = 0 \text{ then}, H_t = \begin{cases} -\gamma > \lambda_t & \text{, then } H_t = 0 \\ -\gamma = \lambda_t & \text{, then } H_t = H^{SS}(a_t) \\ -\gamma < \lambda_t & \text{, then } H_t = H_{Max} \end{cases} \tag{15}$$

$$\text{FOC 2: } -\frac{\partial \mathcal{H}}{\partial D_t} = -\left[p\left((\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2) * (-\beta - 2\delta D_t)\right) + \lambda_t c\right] = \dot{\lambda}_t - r\lambda_t \tag{16}$$

$$\text{FOC 3: } \frac{\partial \mathcal{H}}{\partial \lambda_t} = \dot{D} = b + cD_t - H_t \tag{17}$$

From FOCs 1 and 2, we solve for the singular path of disease incidence:

$$D_t^{SS} = \frac{\gamma(r-c)}{2\delta p(\alpha_1 + \alpha_2 a_t - \alpha_3 a_t^2)} - \frac{\beta}{2\delta} \tag{18}$$

Note the denominator of the first term of the RHS of equation (18) is always positive, so the first term's sign, will depend exclusively on its numerator. Since r is considered on the range 0.004 to 0.0125 (5% and 15% discount rate), we observe that the first term of $D_t^{SS} \leq 0$. Additionally the second term is also negative (Figure 4). Given that the number of cases cannot be negative we conclude that $D_t^{SS} = 0$. This means, growers are required to keep PC cases at zero at any age. The latter indicates that the steady state value for PC cases (disease incidence) is zero. In other words, there is no level of disease incidence, for any considered age, at which the grower can relax the control strategy.

We utilize the transversality conditions to determine the optimal D_T and T (Leonard & van Long, 1992). D_T free implies that

$$\lambda_T = \frac{\partial \phi(D_T, L)}{\partial D_T} \xrightarrow{\text{yields}} \lambda_T = (-0.001 * 9{,}800{,}000)e^{-rT} \tag{19}$$

However, as shown in equation (insert # once you have switching function), we do not know the value of λ_T ex ante. To determine D_T, we use backwards induction. In the final period $\frac{\partial \phi(D_T,L)}{\partial D_T}$ represents the marginal value of control which is less than the marginal cost of control. Consequently, in the final period, all disease will be removed, yielding D_T=0. Since we end on the singular path, we must remain on the singular path for the entire rotation.

T free implies that:

$$\mathcal{H}(T) + \frac{\partial \phi}{\partial T} = 0 \tag{20}$$

$$\mathcal{H} = p * \left((\alpha_1 + \alpha_2 a_T - \alpha_3 a_T^2) * (1 - \beta D_T - \delta D_T^2)\right) - F - \gamma H_T + \lambda_T(b + cD_T - H_T) -$$

$$r\left(L * (1 - 0.001 * D_T)\right)e^{-rT} = 0 \tag{21}$$

Knowing that $D_T = 0$ implies that $H_T = b$. We can substitute into (21) to yield:

$$\mathcal{H} = p * (\alpha_1 + \alpha_2 a_T - \alpha_3 a_T^2) - F - \gamma b - rLe^{-rT} = 0 \tag{22}$$

From equation 22 we solve for optimal T, knowing that $a_T = a_0 + T$, where a_0 indicates the PC infection time period.

2.3 Data

While many bioeconomic models lack certain parameter values, we are fortunate to have a rich dataset with which to parameterize the model. In what follows we briefly describe the information sources we use in our model (Table 1). The Appendix contains the functional forms used for estimation. The spatial scale of our model is a hectare, and the time scale is one month.

We required production costs and also the market price of a kilogram of oil palm fruit. Regarding the production costs we used costs records from Cenipalma's Research Station, Campo Experimental el Palmar de La Vizcaina (CEPLV) to calculate the costs per kilogram of oil palm fresh fruit bunches (FFB). Regarding the FFB market price we used monthly information for the past twenty years, which is available at the Colombian Federation of Oil Palm Growers, Fedepalma (Fedepalma, 2011). Due to price fluctuation we set five different price levels[2] and from each of them we subtracted the cost per unit, so we used five different net prices in order to perform sensitivity analyses.

We calculated the monthly yield trend from a Colombian oil palm plantation for thirty years, based on information from the Fedepalma yearly costs survey. We could establish that oil palm yield function is concave since it goes through a developing stage and then after maturity a maximum is reached, and from the maximum there is a negative trend caused by the fact that older palms tend to produce bigger FFB (the proportion of fruits' weight to total weight decreases with age), but fewer of them (Figure 4). Additionally, harvesting tall oil palms imply greater harvest losses due to fruit losses (when the bunch impacts the ground at harvest) and difficulties in determining the bunch ripening degree. This yield function constitutes what may be considered the potential yield in the absence of disease (Lichtenberg, et al., 1986). In the case

[2] Mean price, mean price plus a standard deviation (S.D.), maximum price, mean price less a S.D. and minimum price.

of a plantation with PC, we used information from plantations in the Tumaco area, relating incidence levels and decrease in the potential yield.

The control strategy proposed by Cenipalma was tested under actual PC pressure, once PC attacked the CEPLV; the strategy displayed good PC control. Records on every activity and input required for PC management were kept by Cenipalma's researchers. Labor requirements were studied at CEPLV by means of time and motion studies which provide labor costs associated with PC control. From this information we modeled the cost per hectare, in such a way that: monitoring is set as a fixed cost once PC is present, there is a maximum of 180 palms to be treated with preventive pesticide applications, and the costs of cutting off diseased tissues were calculated on a per palm basis. We obtained a linear function of costs relating the number of diseased palms to actual control expenses; its intercept represents PC control fixed costs.

The number of cases of PC as a function of time depends upon whether or not the PC control strategy presented above is employed. If there is no effort inputted in controlling PC, it spreads from two sources: an "environmental" or exogenous PC infestation pressure that we recovered from CEPLV information and consists of the number of new cases, even though treatment is in place. 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 on Tumaco plantations. Finally, information from CEPLV indicates that by using correctly the Cenipalma PC control strategy, it is possible to control PC spread, by avoiding diseased oil palms from constituting a pathogen's source.

When considering the discount rate for our model we used the safest interest rate for investments in Colombia which corresponds to deposits at a fixed term, which has averaged 6%

during the last five years, but we will also consider 10% and 15%, as a way of introducing investment's risk and carry out sensitivity analyses.

3. Results and Discussion

3.1. Optimal Replanting Period without PC

To determine the optimal replanting period without PC, we considered three different price levels, at three discount rate scenarios (5%, 10% and 15% per year). The optimal replanting period for Colombian oil palm cultivars that are highly productive, and that are not affected by PC, ranges between 28-36 years, depending upon price level and discount rate. This assumes fixed prices along the oil palm project's lifespan. It was found that the optimal replanting period has an inverse relationship with respect to net price per kilogram of oil palm fruit produced (Table 2). If net prices are low, the optimal replanting period occurs at older periods, when compared to high net prices scenarios.

If oil palm price were low at 56 (mean net price minus one standard deviation) oil palm standings should remain between 31 (if 5% annual discount rate is assumed) and 36 (if 15% annual discount rate is assumed) years. The lower the discount rate (5%), the lower is the grower's risk expectation. Now, assume a grower faces a net price corresponding to the mean price reported along the past two decades, which is the most likely scenario. In that case, our results indicate that the rotation length should vary according to the discount rate from 29 to 33 years.

Note that a higher discount rate corresponds to a longer rotation length. The discount rate enters into equation (5) on the right-hand side, or on the side of the marginal cost of waiting a year to replant. It enters in multiple places. First, it enters in the interest on the whole stream of profits that gets delayed by one year and in the interest on the site rent. The effect of increasing the interest rate, holding the value of the site rent and stream of profits constant, would be an increase in the marginal cost of waiting and a shortened rotation length. However, the interest rate also enters into the stream of profits and site rent. An increase in the discount rate decreases the NPV of the stream of profit because later periods in the rotation, which have higher yields than earlier periods, are more heavily discounted. This effect is a decrease in the marginal cost of waiting. For our parameter values, we find that the latter effect dominates, and an increase in the interest rate lengthens the rotation period. In short, with a high interest rate, keeping current trees in the ground is optimal for a longer period of time because rotating brings low yields in early periods and higher yields in later periods which are heavily discounted.

3.2. Optimal replanting period with PC Disease

Our first result concerning the PC diseased scenario follows easily from the FOCs; D^{SS} was found to be negative at all times. It indicates that PC disease should not be tolerated in oil palm fields, and that growers should follow Cenipalma's instructions for thorough scouting and immediate treatment of any disease tissue detected.

Table 3 displays the results for optimal replanting period relative to the detection period. It illustrates the effects of PC on optimal T for different ages of PC infection. Optimal T in the diseased scenario is inversely related to the age of the trees at first PC detection and the relationship is concave (Figure 6).

For the diseased case, net price is positively related to optimal replanting period. This may be interpreted as if PC disease is present, the larger the net price the larger the optimal replanting period, result contradicts the findings from the non-diseased scenario

Note if one considers a specific level of net price, when one considers that infection is detected and treated properly from the start of the oil palm project ($a_0 = 1$), there is a positive relationship with respect to discount rate. However, the same relationship becomes negative, when one considers the moment ($a_0 + T = a_0$), this is the specific period in which PC detection tells the grower to abandon the oil palm project.

Comparing the diseased and the non-disease scenarios can be done for the case in which the disease is established and properly managed since the start of the project ($a_0 = 1$) (Table 4). The results show that when keeping constant the net price level at 108 or 160, the disease established scenario implies waiting for longer periods to replant. However the difference between replanting periods becomes less pronounced (diseased vs. non diseased) when facing higher risk expectations (higher discount rates).

On the other hand, note that for scenarios corresponding to net price equal to 56 (minimum net price level considered), there is not a clear trend. Additionally, when one considers the disease established scenario at r=0.0125 it is not possible to find a solution, which means the grower should not produce at all with low prices, high risk and PC disease because PC treatment costs are so high relative to the low yields that one experiences early in the life of the orchard.

4. Concluding remarks

This paper makes an important contribution to the literature. To our knowledge, no similar model has been presented in order to answer the question of optimal replanting age when disease is present in perennial crops.

Our results are informative for oil palm growers, in terms of providing a specific moment in time at which replanting makes economic sense, under different price scenarios with and without PC. This was an unsolved question for productive oil palm plantations under Colombian conditions. However, future research should include different levels of technology adoption and differing yields, among other interesting cases.

The disease scenario results are very important for Colombian oil palm growers. We found that growers must be alert and carrying out thorough scouting for PC disease since zero disease incidence is optimal for all tree ages. Infrequent scouting and less than 100% disease remove will lead to reduced profits relative to the case of perfect control.

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Table 1. Parameters Used for Estimation

Discount rate	5% a year	0.004
	10% a year	0.008
	15% a year	0.0125
Net prices	Mean - 1 S.D.	56
	Mean	108
	Mean + 1 S.D.	160
Yield	α_1	320.4161
	α_2	27.2652
	α_3	0.0668
Effect of disease on yield	β	0.00322
	δ	0.00002
PC control costs	F	50900
	γ	6332
PC dynamics	b	0.4500
	c	0.2000
Land Price	L	9,800,000

Source: own calculations

Table 2 Optimal Replanting Age According to Different Discount Rates and Price Levels in the Absence of PC*

	P=56	P= 108	P=160
r=0.0040	372	350	342
r=0.0080	413	387	377
r=0.0125	439	401	386

P=net price per kilogram of oil palm fruit

Table 3 Optimal Replanting Ages in the Presence of PC, According to PC Detection Period

Net price	discount rate	Initial PC infection period (a_0)							
		1	50	100	150	200	250	300	350
56	r = 0.004	376	326	274	221	168	114	59	2
56	r = 0.008	379	328	277	223	169	105	30	
56	r = 0.0125	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
108	r = 0.004	398	349	297	249	195	144	93	39
108	r = 0.008	399	345	295	248	194	141	84	28
108	r = 0.0125	399	352	301	249	197	143	87	10
160	r = 0.004	405	356	305	255	204	153	102	51
160	r = 0.008	406	357	306	256	205	153	100	45
160	r = 0.0125	408	358	308	257	206	154	98	40

*PC disease is established and the grower will manage it as suggested by Cenipalma

N.S.: Indicates no solution could be found for the specified parameters

Table 4. Comparison Between Diseased and No Diseased Scenarios

	P=56		P= 108		P=160	
	No disease	Disease established	No disease	Disease established	No disease	Disease established
r=0.0040	372	376	350	398	342	405
r=0.0080	413	379	387	399	377	406
r=0.0125	439	N.S.	401	399	386	408

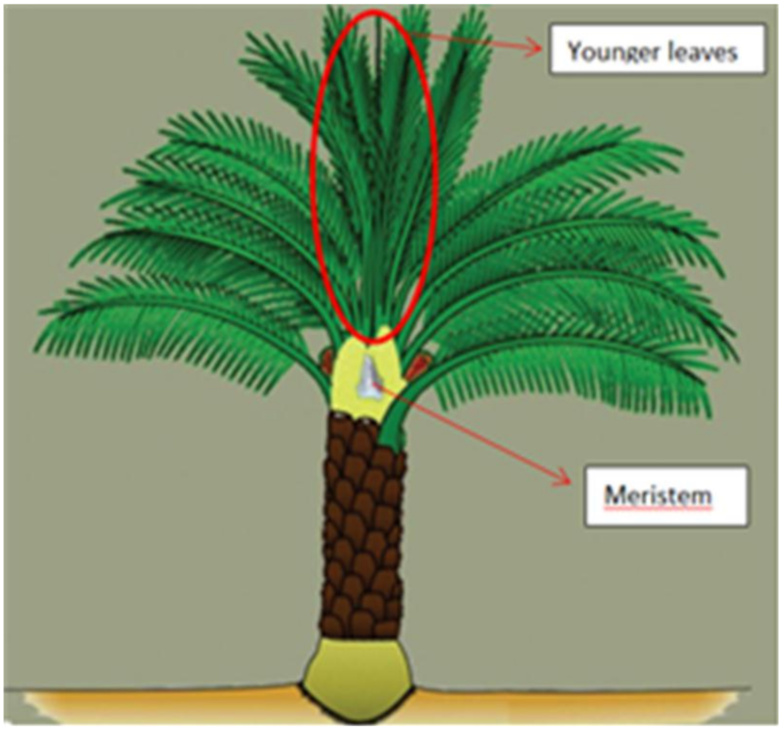


Figure 1 Oil Palm Tree Diagram

Source: excerpted from Martinez et al.,2009

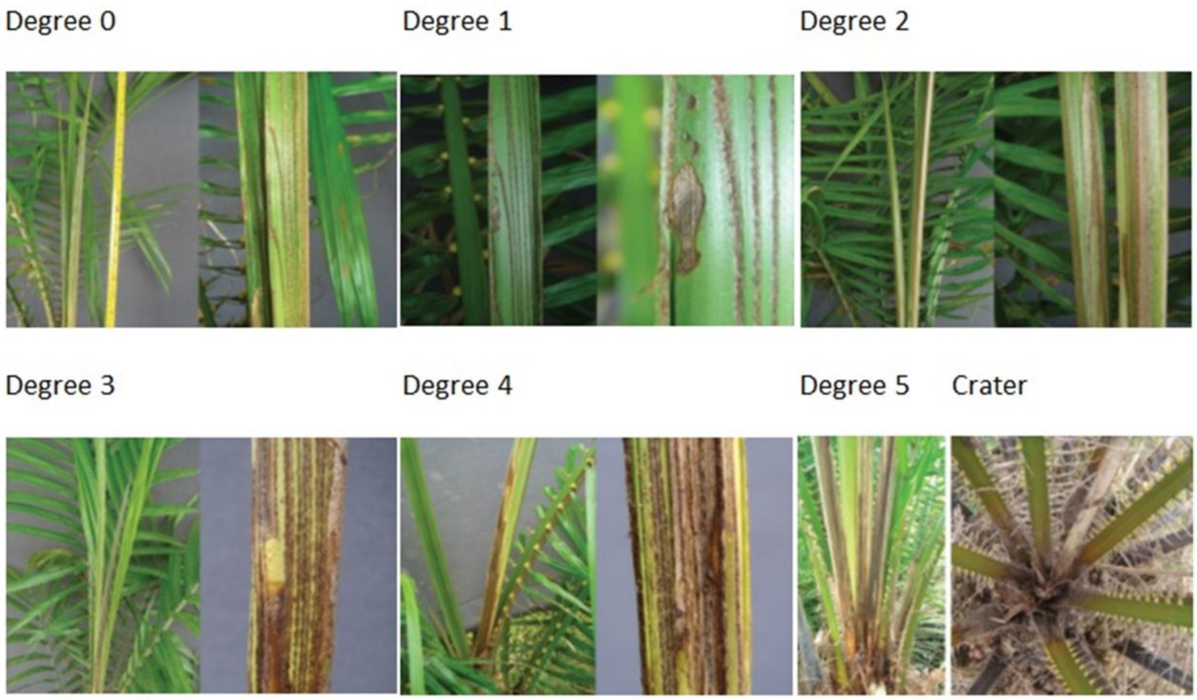


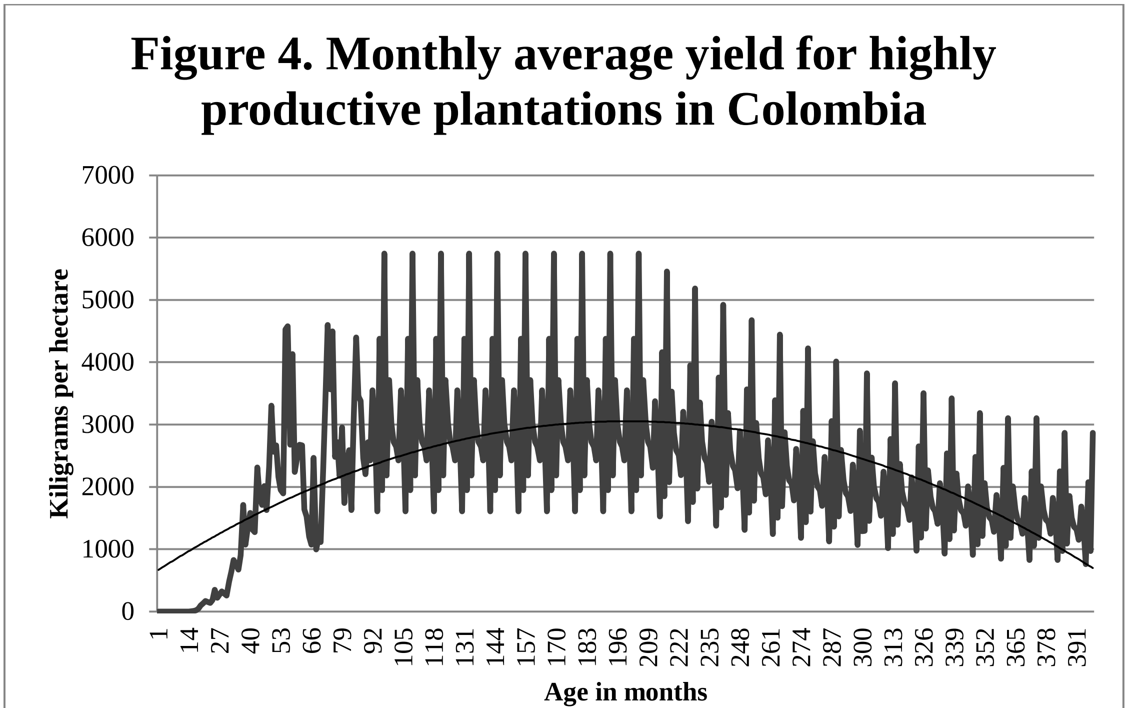
Figure 2 Monitoring PC, According To Severity Scale By Cenipalma

Source: Excerpted from Martinez et.al, 2009

Cutting off diseased tissues   Pesticide paste application   Protecting the surgery

Figure 3 PC control strategy

Source: Excerpted from Torres et al., 2010



Source: Fedepalma

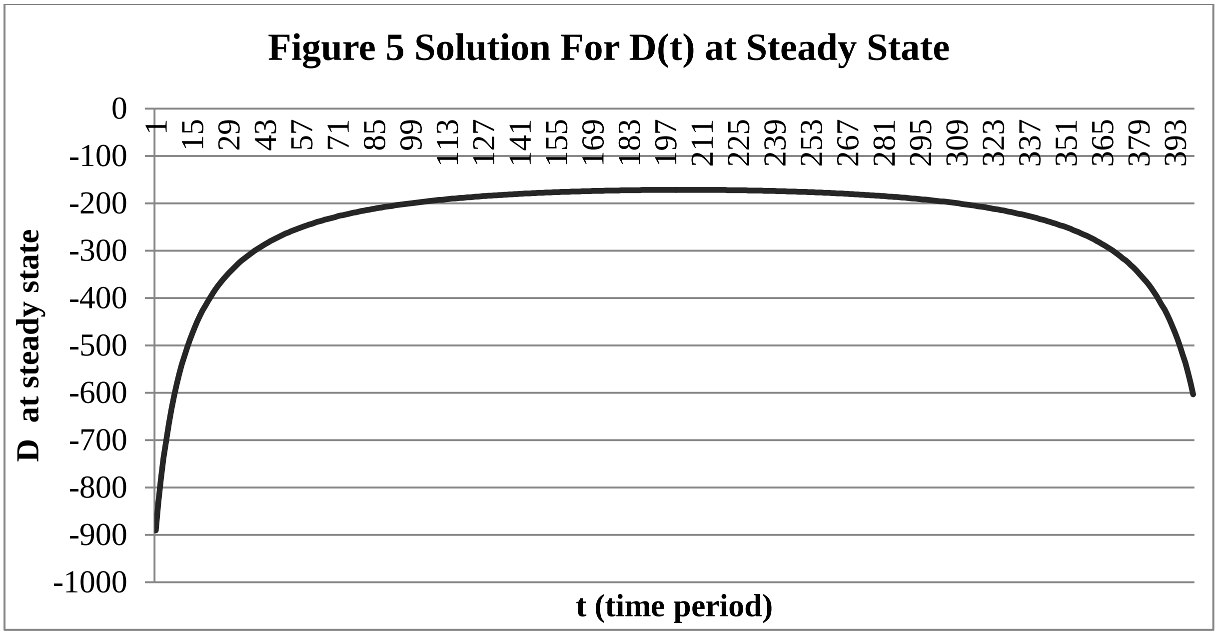


Figure 5 Solution For D(t) at Steady State
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
1
15
29
43
57
71
85
99
113
127
141
155
169
183
197
211
225
239
253
267
281
295
309
323
337
351
365
379
393
D at steady state
t (time period)

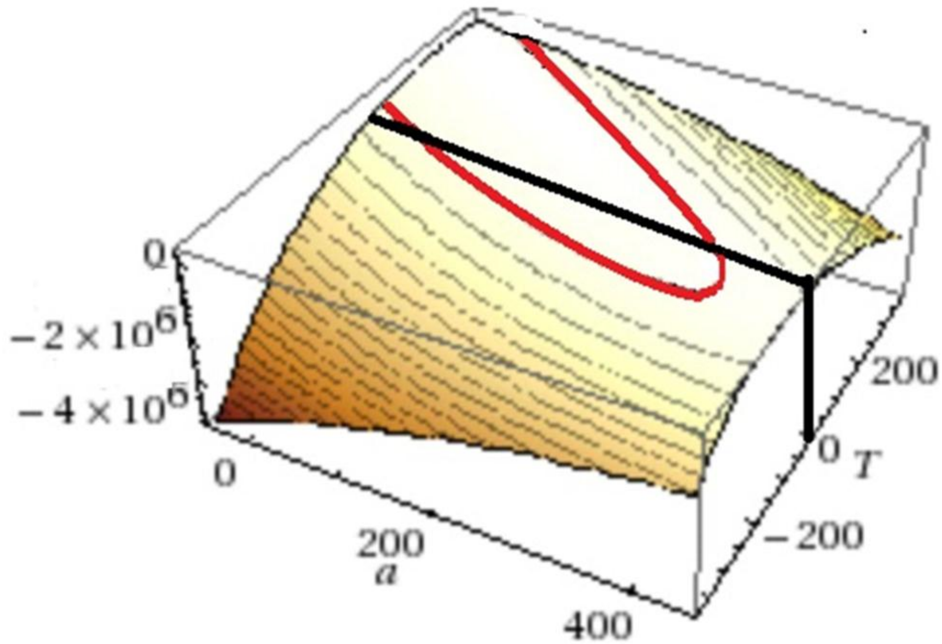


Figure 6. Meshgrid for optimal T(Diseased case)

Appendix 1

Empirical functions: the set of empirical functions and parameters we obtained from available information consisted of:

Net price: Mean minus 1 S.D. (56); Mean (108); Mean plus 1 S.D. (160)

Potential yield: $(t) = (320.4161 + 27.2652 * a_t - 0.0668 * a_t^2)$ (Kilograms per hectare), in this case a_t corresponds to age expressed in months.

Yield in the presence of PC:

$$Y\left(D_{t,}a\right) = (320.4161 + 27.2652 * a_t - 0.0668 * a_t^2) * (1 - 0.00322 * D_t - 0.00002 * D_t^2)$$

(Kilograms per ha).

Costs of PC control strategy:

$$c(D_t; \delta_t) = 50900 + \ 6{,}332 * H_t$$ (Pesos per hectare)

PC spreading:

$$\dot{D}_t = 0.45 + 0.2D_t - H_t$$

Scrap Value function:

$$\phi(D(T), L) = 9{,}800{,}000 * \left(1 - 0.001 * D(T)\right) * e^{-rT}$$ (pesos per hectare)