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Optimal Timing of Removal and Planting of Perennial Crops in Anticipation of a New Cultivar

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We develop a perennial-crop vintage-investment decision model that incorporates the dynamics of growers' endogenous removal and planting decisions with uncertainty in the future release date of a new variety. We apply the model to coconut cultivation to examine the effects of a new cultivar's higher yield, lower input requirements, and lower discard rates on the removal and planting decisions for various vintages of current trees and different announced release dates of new cultivars. Results show that if the new variety is highly (moderately) profitable, growers will alter their planting and removal decisions to plant the new variety sooner (later).

Key words: Coconuts; New Cultivar; Perennial Crops; Vintage-Investment Decision Model

Introduction

Perennial tree-crop growers must make long-term investment decisions related to removal and planting in anticipation of scientists releasing new cultivars[1] with enhanced characteristics. Breeders release new perennial crop varieties with higher yields, greater resistance to pests and diseases, lower input requirements, fewer physiological disorders, and greater drought tolerance. New cultivars in perennial crops are released infrequently because successful breeding generally takes many years,[2] and scientists need to grow the new variety to assess the varietal improvement, which can take several years before it can be released publicly to growers. Consequently, breeders undertake research and development (R&D) for many years in advance of the release of a new cultivar.[3] Furthermore, given the complexity involved in developing a new variety, uncertainty regarding the timing of the release of a new variety is an inherent part of the breeding process. This study focuses on the effects of improved characteristics of a new cultivar on the removal and planting decisions of perennial crops for vintages[4] of current trees in the field and announced release dates of new cultivars.

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[1] We use cultivars and varieties interchangeably.

[2] Common approaches to discovering new varieties include traditional breeding and hybridization. Another approach to producing new varieties is through selection, which is common in releasing new coconut varieties. Under this approach, researchers collect coconuts from farmers' best-yielding trees (at least for 5-6 years) to grow seedlings at a research station. These seedlings are grown into trees and evaluated by testing yields for 3 years. If yields are promising, the coconuts from these trees are used to grow and sell seedlings commercially. Biotechnology and transgenic breeding in coconuts are still in the infancy stage.

[3] For instance, in the case of coconuts, breeders release new varieties about once every 8-12 years (TNAU). As another example, research for the Cosmic Crisp apple variety started about 22 years before it became commercially available for cultivation (Abadi and Palmer, 2020).

[4] In the context of perennial crops, vintages refer to tree ages (with corresponding yields and other characteristics) of a variety. For example, a grower may have one hectare of 10-year-old trees, another hectare of 20-year-old trees, etc.

Perennial crop growers often become aware of a promising new cultivar before it is publicly released via communication with breeders or breeders' announcement of a forthcoming new variety.[5] Uncertainty about the release date of a new variety could occur because of delays in R&D or approval by government agencies. In anticipation of the release of a new variety, growers, depending on the vintage of the existing trees in the field, need to make important long-term investment decisions, such as when to remove the existing trees and plant the new variety. As Devadoss and Luckstead (2010) observe, optimal removal and planting decisions are key elements in determining the profitability of perennial crop production. Therefore, the timing of the adoption of a new cultivar is critical, and growers would prefer to know the release date—which is often uncertain given the complexities of R&D and government approval delays—of a new cultivar so that they can make judicious removal and planting decisions. Specifically, depending on the timing of the announcement relative to the future release date and characteristics of the new variety, growers face the following decisions: a) the optimal time to remove trees of a particular vintage that are in the field, b) if it is optimal to remove the current trees of a particular vintage before the new variety becomes available, then farmers need to decide whether to *replant* the current cultivar or grow short-term crops, and c) the optimal time to plant the seedlings and remove the trees of the new variety.

Perennial tree-crop investment decisions are highly complex because of a large initial investment, a long gestation period between planting and first harvest, an extended lifespan, a changing pattern of productivity with an inverted U-shaped yield curve over the life cycle(Mitra, Ray, and Roy, 1991), intercropping opportunities,[6] and costly tree removal at the end of economic viability. Furthermore, the initial investment costs of perennial crops are sunk costs and cannot be recovered if production ceases. Sunk costs are in contrast to fixed-capital costs, such as investments in machinery, because the latter can be partially recovered by selling the used machinery if production ceases. While farmers can generally adopt new varieties of short-term crops relatively quickly, possibly in the next planting season, perennial crop growers may not remove the current trees and replant with the new variety for several years, because the current trees in the field may still be profitable and immediate switching to a new variety is costly and can lower the stream of net present value (NPV) of profits. Consequently, investment analyses of perennial crops are complex as growers must consider removal and investment decisions simultaneously. This study analyzes these optimal decisions for coconut cultivation in India.

We study coconut trees in India because coconuts have increasingly become an important cash crop for farmers in India.[7] For instance, coconut area has steadily risen from 0.7 to 2.2 million hectares—a 198% increase—over the period 1961 to 2020 in India (FAO, a). Four southern states in India account for about 90% of total coconut cultivation: Kerala (34.6%), Tamil Nadu (26.0%), Karnataka (22.7%), and Andhra Pradesh (7.6%) (AgriExchange). For this study, we chose the state of Tamil Nadu because data is available from the breeders and horticulturalists at research stations and representative farms.[8] In Tamil Nadu, the area under coconut cultivation has increased from 323,485 hectares in 2000 to 457,717 hectares in 2020, a 41.5% increase.[9] Because the productive life cycle of coconut trees can last over 60 years,[10] obtaining primary data on input use, input prices, yield, coconut price, etc. for several farms in Tamil Nadu is not feasible. Therefore, for this study,

[5] For simplicity, in this paper, we refer to growers becoming aware of a new variety before it is released to the public as "an announcement" by scientists.

[6] Growers intercrop at the initial phase of coconut cultivation, and the most common intercrops are bananas and vegetables such as eggplant and okra. Other intercrops include chilies, amaranthus green, coriander, ginger, turmeric, fodder, cocoa, and nutmeg.

[7] Furthermore, coconut is a key ingredient in South Indian cooking, particularly in the state of Tamil Nadu.

[8] Two types of coconuts (tender and cooking) are grown in India. Tender coconuts are used for drinking while cooking coconuts are used for culinary purposes and oil production. In the state of Tamil Nadu, 31,000 hectares (comprising 6.8% of total coconut hectares) are under tender coconut cultivation, and 426,717 hectares (93.2%) are under cooking coconut cultivation. Since the latter is the largest portion of coconut cultivation, this study focuses on cooking coconuts.

[9] The common varieties that are being cultivated in Tamil Nadu include Deejay, ALR1, ALR2, ALR3, VPM1, VPM2, VPM3, VPM4, VPM5, VHC1, VHC2, and VHC3.

[10] Coconut trees can survive for 100 years or longer, but yields decline considerably in the latter stages of the tree's life.

we collected data from a representative farm in the state of Tamil Nadu and supplemented it with data from coconut research stations, which allowed us to study farm-level investment and production decisions.

Perennial crop supply-response studies are scant because of a lack of farm-level data for several key variables (yield, input use, output prices, and input prices) for the entire life cycle of trees and the complexities of modeling investment and production decisions. We review past studies in this area and highlight how our work differs from these studies and advances the literature. One limited strand of studies utilizes dynamic optimization to derive and then econometrically estimate reduced-form supply response models that typically include uprooting, replanting, new planting, and yield functions (Wickens and Greenfield, 1973; Akiyama and Trivedi, 1987; Hartley, Nerlove, and Peters Jr, 1987; Devadoss and Luckstead, 2010). French and Matthews (1971) and French, King, and Minami (1985) are empirical studies that econometrically estimate supply-response functions using the vintage production approach of perennial crops. Kalaitzandonakes and Shonkwiler (1992) and Knapp and Konyar (1991) utilize a state-space model to estimate new planting and replanting as part of their perennial crop supply function. In a recent study, Arellano-Gonzalez and Moore (2020) examine the implication of climate change and water scarcity on investment decisions of perennial crops.

One study related to coconut trees is Tisdell and Silva (1986), which examines the steady-state age distribution of coconut trees to mitigate yield fluctuation and finds the steady-state path relies primarily on the existing age composition of coconut trees. Relevant to our work is Gotsch and Burger (2001), who utilize a vintage-investment decision model for Malaysian cocoa trees to independently determine the optimal age to remove trees of the current and new varieties. More recently, Feinerman and Tsur (2014) study the impact of drought hazards on the profitability of perennial crop production.

The specific objectives of our study are fourfold: First, to develop a long-term perennial-crop vintage-investment decision model that accounts for the announcement of the release of a new variety at a future date. Second, to study the effects of uncertainty in the release date of a new cultivar, given unanticipated R&D problems or government regulations in the discovery of a new variety on growers decisions. Third, to empirically implement this new model to analyze the impact of various characteristics (e.g., higher yield, resistance to pests, etc.) of the new variety on planting and removal decisions. Fourth, to quantify the NPV of profit streams of these investment decisions for all possible vintages in the field and various announced release dates of the new variety for coconut cultivation. Our modeling approach allows us to compare the optimal removal age from our model to that of the existing vintage-investment decision model in the literature.

Our work differs from earlier studies in that we examine the impact of various characteristics of new cultivars on farm-level removal and replanting decisions of perennial crops with uncertainty embedded in the timing of the release of the new variety. In doing so, we contribute to the economics of perennial crop literature in three dimensions. First, with the initial investment in perennial crops being a sunk cost, our study is the first to model simultaneously—in anticipation of the arrival of a new cultivar with enhanced characteristics—five endogenous decisions for each vintage in the field: (i) optimal timing of the removal of the trees current variety, (ii) when to replant the current variety or cultivating a short-term crop, (iii) the optimal age to remove the trees of the current variety if it is replanted, (iv) when to plant the new cultivar, and (v) optimal age to remove the trees of the new cultivar. Second, our model accounts for the announcement of the release date of a new variety and focuses on a grower's *ex-ante* investment decisions given the uncertainty around the actual release date. Third, we examine the impact of various vintages of the current variety in the field, announced release year, and characteristics of the new cultivar on the NPV of profits. These are long-term commitments that require large investments, and therefore, perennial-tree growers must make judicious choices. The methodology that we develop can be used for any tree crops in developing countries (e.g., coconuts, coffee, cocoa, nuts, etc.) and developed countries (e.g., apples, pears, cherries, nuts, etc.). Thus, our model and analysis are applicable to real-world situations of perennial-crop production.

Investment Decision Models

This section first presents the vintage-investment decision model found in the literature and its shortcomings. Second, it describes our proposed vintage-investment decision model that takes into account the announcement of the future release of a new cultivar.

Vintage-Investment Decision Model

As elaborated in the introduction, investment in perennial crops is a long-term commitment and unique from other capital investments because tree crops have an extended gestation period, an inverted U-shaped yield profile over the life cycle of the crop, and costs that vary by vintage. Also, perennial crops can survive and produce beyond their economically viable age. Therefore, growers need to determine the economically optimal tree age at which to remove current trees and plant new seedlings. To this end, consider the following vintage-investment decision model (variants of this model have been used in past studies, Gotsch and Burger, 2001).

The grower plants a perennial crop on A hectares of land in the current period. The index $i = 1,\cdots,I$ denotes both years and the age of the tree. That is, $i = 1$ denotes the first year and represents the year of the initial investment of planting the seedlings and trees are 1 year old, $i = 2$ denotes the second year and 2-year-old trees, ..., and $i = I$ represents the final year when trees are removed and I-year-old trees. The net income (π) from trees of age i is

$$\pi_i = (P_i Y_i - C_i) A_i - F A + N_i, \quad i = 1,\ldots,I, \tag{1}$$

where P_i is the output price per coconut, Y_i is the per-hectare yield (number of coconuts), C_i is the per-hectare variable cost, A_i is the remaining hectares of trees after discarding diseased or dead trees, F is the per-hectare initial investment cost in $i = 1$ and is zero for $i = 2,..,I$, and N_i is net income from intercropping when the perennial crop is of age i.[11] To keep the model tractable, we assume price and yield expectations are formed with perfect foresight, which is common in this line of literature (for example, see Knapp, 1987). Such a modeling framework is appropriate because, given the long-run nature of perennial crops, farmers make investment decisions based on expected prices and yields, rather than focusing on volatility.

At each vintage, some perennial-crop trees may succumb to pests and diseases, and growers discard these trees. Consequently, only a fraction of trees may survive until the economically viable age. Following the vintage model of Burger and Smit (1997b), the remaining hectares after the removal of discarded trees are given by $A_i = A \times disc_i$, where

$$disc_i = \frac{1 - e^{-\frac{1}{\gamma\mu}}}{1 + e^{\frac{\mu - i}{\gamma\mu}}}, \tag{2}$$

is the share of the area with trees of age i that is discarded, μ is the age at which half of the trees have been discarded due to random death or disease, and γ denotes the rate at which discarding increases as trees grow older and become more susceptible to disease. Thus, if a grower initially starts with A hectares of the perennial crop, then the number of hectares with surviving trees of age i is given by A_i. Therefore, as trees age, the number of surviving trees on the A hectares decline.[12]

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[11] Net income from intercropping is equal to total revenue minus total cost, which depends heavily on the types of perennial crops and intercrops. Also, intercropping is common only in the initial phase when perennial trees do not block the sunlight.

[12] This discard rate is also employed by Kazianga and Masters (2006).

The NPV of net income from investing in A acres and removing the surviving trees at age I is

$$NPV_I = \sum_{i=1}^{I} \frac{\pi_i}{(1+r)^i} - \frac{R_I}{(1+r)^I}, \ \forall I, \tag{3}$$

where r is the real interest rate and R_I is the cost of tree removal in period I. The tree removal age I can vary from 1 to the life-span of the tree. In perennial crop cultivation, tree removals are a costly endeavor and can influence the timing of the removal and replanting decisions.[13] In this standard vintage-investment decision model, the final harvest occurs in year I, and the trees are uprooted in the same year right after harvest. Since uprooting trees is a time-consuming and expensive endeavor, we assume that the grower replants in the following year $(I + 1)$ and incurs the investment cost.

Assuming perennial-crop farming is inherited by future generations (Burger and Smit, 1997a), the NPV of infinite cycles, given by the everlasting series, of trees of age I is obtained using the geometric series:

$$NPVE_I = \frac{NPV_I}{1 - \frac{1}{(1+r)^I}}, \ \forall I. \tag{4}$$

The maximum NPV of an everlasting series determines the economically optimum age, $\hat{I}$, to remove the trees:

$$NPVEMAX = \max_I \{NPVE_I\}. \tag{5}$$

Since this equation yields the maximum NPV, removing the perennial crop one year before or after will lower this NPV.

From the maximization in equation (5), we can ascertain the optimal removal age for any variety that is available for cultivation. In this model, new cultivars are readily available to farmers without any foresight into the timing of the release of new varieties. Thus, farmers are aware of new varieties only after they are released, and there is no uncertainty surrounding the release date. Therefore, if a new variety becomes available, it does not impact $NPVEMAX$ or the optimal removal age, $\hat{I}$, of any existing variety. Consequently, the decisions between removing one cultivar and planting another are *independent*. In reality, growers become aware of new cultivars before they are commercially available through communication with or announcements by breeders. Under such circumstances, the decisions to remove the current trees and replant with the current or new cultivar are *interdependent*. For instance, if growers become aware of the varietal attributes of a new cultivar, they may remove the existing trees and replant with the new cultivar sooner that if they did not know about new variety. Our investment-decision model in the next subsection tackles these issues by accounting for the growers' knowledge of the new cultivar and its potential date of release.

Vintage-Investment Decision Model with an Announcement of New Cultivars

Consider A hectares of the current variety of trees of vintage v (i.e., the age of the trees at the time of the announcement when the new cultivar should become available), which could range from 1 year to the economically viable age. As in any crop research, breeders of perennial crops constantly work toward releasing new cultivars. The major purpose of any such R&D is to release new variety (n) with higher yields than the current variety $\left(Y_i^n > Y_i\right)$; lower input requirements and lower variable costs $\left(C_i^n < C_i\right)$; and lower death rates $\left(disc_i^n < disc_i\right)$ due to enhanced resistance to pests, disease, and drought.

Since the duration of perennial tree crops spans several decades, growers are keen on keeping appraised of any varietal developments. Consequently, R&D scientists announce in the current

[13] However, past perennial-crop models, such as Gotsch and Burger (2001), do not account for removal costs.

period that a new perennial crop variety should be available in τ years. However, the actual release date may differ because of inherent uncertainty involved in the research process in crop breeding, particularly in perennial crop breeding, and delays in approval by government agencies. Consequently, we model the probabilistic occurrence of many potential actual release years θ: $\tau - k$, ... ,$\tau - 1$, τ, $\tau + 1$, ... , $\tau + m$, each with probabilities $\rho(\theta)$ and $\sum \rho(\theta) = 1$. Since delays in the breeding process are more common than an accelerated release, $k < m$. Once scientists announce that a new cultivar should be available in τ years, the optimal age to remove the trees in the field is likely to change because the stream of future incomes will change as they depend on planting and removal decisions of both the current and new cultivars. In this investment process, a farmer has five decisions to make: (i) the optimal age $\left(\hat{I}^c_{\tau\nu}\right)$ to remove the current trees (c) of vintage ν in the field given the announcement that the new cultivar should be released in τ years, (ii) if the optimal age to remove the current trees is before the actual release date of the new variety, then the grower needs to decide whether or not to replant the current variety or cultivate a short-term crop until the new variety becomes available, (iii) if the current variety is replanted (r), what is the optimal age $\left(\hat{I}^r_{\tau\nu}\right)$ to remove the trees of the replanted current variety, (iv) when to plant the new cultivar (n), which depends on $\hat{I}^c_{\tau\nu}$ and $\hat{I}^r_{\tau\nu}$, and (v) the optimal age $\left(\hat{I}^n_{\tau\nu}\right)$ to remove the new cultivar. The number of years until the release (τ) of the new cultivar, the vintage (ν) currently in the field, yield profiles of the current variety and new cultivar, and price and cost of cultivation of the current and new varieties determine the optimal time to remove the current trees and replant the current variety or plant the new cultivar.

To determine the above five optimal timing decisions, we optimize the sum of the sequence of NPV of profits from the (a) current cultivar on the field, (b) replanted current cultivar, (c) intercrops, and (d) new cultivar over the endogenous variables $I^c_{\tau\nu}$, $I^r_{\tau\nu}$, and $I^n_{\tau\nu}$. Once the optimal values of these three endogenous variables are determined, the other two decisions (when to replant the current variety and when the plant the new variety) are automatic. For example, replanting of the current variety occurs the year after the removal of the trees of current variety in the field. Similarly, the new varieties are planted after the removal of the trees of the current variety or short term crops.

Our analysis starts at the year when scientists announce a new cultivar should be released in τ years. First, the NPV of the remaining economically profitable years of one hectare of the current variety of trees of vintage ν at the time of the announcement is

$$NPV_{I^c_{\tau\nu}}(\theta) = \sum_{i=\nu}^{I^c_{\tau\nu}} \frac{\pi^c_i(\theta)}{(1+r)^{i-\nu}} - \frac{R_{I^c_{\tau\nu}-\nu}}{(1+r)^{I^c_{\tau\nu}-\nu}},\ \forall I^c_{\tau\nu} \quad , \tag{6}$$

where $\pi^c_i(\theta) = (P_{i-\nu} Y_i - C_{i-\nu}) A_i - F A + N(i)_{i-\nu}$. The variable definitions are as in equation (1). The index $i = \nu,...,I^c_{\tau\nu}$ refers to the tree age of the current variety in the field for the given vintage ν, and this tree age is a constant and refers to the tree age at the time of the announcement. Thus, $i - \nu$ is a time index (where $i - \nu = 0$ indicates the initial year when the announcement is made), and $I^c_{\tau\nu} - \nu$ denotes the number of years remaining until growers remove the current trees. For example, if the vintage of the tree $\nu = 20$ and growers remove the trees at age 50 $(I^c_{\tau\nu} = 50)$, then they have a 30-year $(I^c_{\tau\nu} - \nu = 30)$ time horizon to obtain income before the removal of the current variety. $N(i)_{i-\nu}$ is the net income in year $i - \nu$ from intercropping when the current variety of perennial trees are of age i. The sunk-investment cost, F, is incurred only once at the time of planting for $\nu = 1$, and hence $F = 0$ for $\nu > 1$, and the sunk planting costs do not impact the grower's decisions. If $I^c_{\tau\nu} = 0$, then the grower's optimal decision is to not plant the seedlings of the current variety.

Second, given $\hat{I}^c_{\tau\nu}(\theta)$, the NPV of one cycle of the replanted current variety (r) is

$$NPV_{I^r_{\tau\nu}}(\theta) = \sum_{j=0}^{I^r_{\tau\nu}} \frac{\pi^r_j(\theta)}{(1+r)^{\hat{I}^c_{\tau\nu}-\nu+1+j}} - \frac{R_{\hat{I}^c_{\tau\nu}-\nu+1+I^r_{\tau\nu}}}{(1+r)^{\hat{I}^c_{\tau\nu}-\nu+1+I^r_{\tau\nu}}},\ \forall I^r_{\tau\nu} \quad , \tag{7}$$

where the income from replanted current variety is $\pi^r_j(\theta) = \left(P_{\hat{I}^c_{\tau\nu}-\nu+1+j} Y_j - C_{\hat{I}^c_{\tau\nu}-\nu+1+j}\right) A_j - F_{\hat{I}^c_{\tau\nu}-\nu+1} A + N(j)_{\hat{I}^c_{\tau\nu}-\nu+1+j}$. Replanting of the current variety occurs in year $\hat{I}^c_{\tau\nu} - \nu + 1$ (i.e., one year after the grower removes the existing trees in the field), and with $I^r_{\tau\nu}$ indicating the tree-age at which the grower removes the replanted current variety, the tree removals occur in year $\hat{I}^c_{\tau\nu} - \nu + 1 + I^r_{\tau\nu}$. Note that if $\hat{I}^r_{\tau\nu} = 0$ in equation (7), then the optimal decision is not to replant the current variety.

Third, a situation may arise where farmers pull out trees of the current variety (which is no longer economically viable) before the new variety becomes available for planting. Instead of replanting the current variety, farmers may grow a short-term crop (e.g., the intercrop) until the new variety is available.[14] This possibility could occur when the actual release year of the new variety is beyond the end of the economic life of the current variety. Mathematically, this condition occurs when $\hat{I}^c_{\tau\nu} - \nu + 1 < \theta$.[15] For example, consider a hectare of trees of vintage $\nu = 64$, an optimal tree age to remove the current variety of $\hat{I}^c_{\tau\nu} = 66$, and the actual number of years until the new variety becomes available is $\theta = 5$. In this case, $\hat{I}^c_{\tau\nu} - \nu + 1 = 3 < \theta = 5$, and the grower earns more profit by uprooting the current variety of trees in three years, cultivating a short-term crop for two years, and planting the new variety in five years. If $\hat{I}^c_{\tau\nu} - \nu + 1 < \theta$, the model needs to account for income generated from the short-term crop. The NPV of these incomes is

$$NPVSC(\theta) = \sum_{w=1}^{T} \frac{N(w)_{\hat{I}^c_{\tau\nu}-\nu+w}}{(1+r)^{\hat{I}^c_{\tau\nu}-\nu+w}} \tag{8}$$

where

$$T = \begin{cases} \theta - \left(\hat{I}^c_{\tau\nu} - \nu\right) & \text{if } \hat{I}^c_{\tau\nu} - \nu < \theta \\ 0 & \text{if } \hat{I}^c_{\tau\nu} - \nu \geq \theta. \end{cases}$$

Here, $\hat{I}^c_{\tau\nu} - \nu - \tau$ does not include a "+1" because growers can plant the short-term crop in the same year the grower removes the trees.

Fourth, given $\hat{I}^c_{\tau\nu}$ and $\hat{I}^r_{\tau\nu}$, the NPV of the new cultivar starting $\hat{I}^c_{\tau\nu} - \nu + 1 + \hat{I}^r_{\tau\nu}$ years in the future is

$$NPV_{I^n_{\tau\nu}}(\theta) = \begin{cases} 0 & \text{if } \hat{I}^c_{\tau\nu} - \nu + 1 + \hat{I}^r_{\tau\nu} + 1 < \theta, \\ \sum_{k=0}^{I^n_{\tau\nu}(\theta)} \frac{\pi^n_k(\theta)}{(1+r)^{\hat{I}^c_{\tau\nu}-\nu+1+\hat{I}^r_{\tau\nu}+1+k}} \\ \quad - \frac{R_{\hat{I}^c_{\tau\nu}-\nu+1+\hat{I}^r_{\tau\nu}+1+I^n_{\tau\nu}}}{(1+r)^{\hat{I}^c_{\tau\nu}-\nu+1+\hat{I}^r_{\tau\nu}+1+I^n_{\tau\nu}}}, \forall I^n_{\tau\nu} & \text{if } \hat{I}^c_{\tau\nu} - \nu + 1 + \hat{I}^r_{\tau\nu} + 1 \geq \theta, \end{cases}$$

where the income from the new variety is

$$\begin{aligned} \pi^n_k(\theta) &= \left(P_{\hat{I}^c_{\tau\nu}-\nu+1+\hat{I}^r_{\tau\nu}+1+k} Y^n_k - C^n_{\hat{I}^c_{\tau\nu}-\nu+1+\hat{I}^r_{\tau\nu}+1+k}\right) A^n_k \\ &\quad - F_{\hat{I}^c_{\tau\nu}-\nu+1+\hat{I}^r_{\tau\nu}+1+k} A + N(k)_{\hat{I}^c_{\tau\nu}-\nu+1+\hat{I}^r_{\tau\nu}+1+k}. \end{aligned}$$

Planting of the new cultivar occurs in year $\hat{I}^c_{\tau\nu} - \nu + 1 + \hat{I}^r_{\tau\nu} + 1$ (i.e., one year after the grower removes the replanted current variety), and with $I^n_{\tau\nu}$ indicating the tree-age at which the grower removes the new cultivar, the tree removals occur in the year $\hat{I}^c_{\tau\nu} - \nu + 1 + \hat{I}^r_{\tau\nu} + 1 + \hat{I}^n_{\tau\nu}$. The NPV of the everlasting series of tree age $I^n_{\tau\nu}$ is obtained using the geometric series:

$$NPVE_{I^n_{\tau\nu}}(\theta) = \frac{NPV_{I^n_{\tau\nu}}(\theta)}{1 - \frac{1}{(1+r)^{I^n_{\tau\nu}}}}, \ \forall I^n_{\tau\nu}. \tag{9}$$

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[14] We assume that farmers plant the short-term crop in between the perennial tree space and therefore do not incur additional costs in preparing the land for the short-term crop or planting the new variety. Therefore, growing short-term crops is more of a place-holding operation, and farmers do not incur switching costs, as modeled in Song, Zhao, and Swinton (2011).

[15] If the grower is planting the short-term crop, the optimal tree age to remove the replanted current variety is $\hat{I}^r_{\tau\nu}(\theta) = 0$ (i.e., current variety is not replanted).

The four streams of NVP in equations (6, 7, 8, and 9) run in a sequence, i.e., the tree life cycle in equation (6) ends first, which is followed by the tree cycle in (7), then (8), and finally (9). Therefore, the grower needs to optimize the expected sum of four potential streams of NPV to choose the optimal removal ages of current trees, replanted current variety, and new cultivar $I^c_{\tau\nu}$, $I^r_{\tau\nu}$, and $I^n_{\tau\nu}$, given the vintage currently in the field ν and the announced release date of the new cultivar τ:

$$\text{(10)} \qquad \mathrm{E}\left[NPVMAX_{\tau\nu}\right] = \max_{I^c_{\tau\nu}, I^r_{\tau\nu}, I^n_{\tau\nu}} \left[\sum_{\theta=\tau-k}^{\tau+m} \rho(\theta)\, NPV_{\tau\nu}(\theta)\right],$$

where $NPV_{\tau\nu}(\theta) = NPV_{I^c_{\tau\nu}}(\theta) + NPV_{I^r_{\tau\nu}}(\theta) + NPVSC(\theta) + NPVE_{I^n_{\tau\nu}}(\theta)$.

Because tree age may vary across farms or a farm may have multiple fields with different vintages and the actual year the scientists release the new cultivar may vary, we conduct the analysis for all possible vintages ν and for different announced release dates τ.

Data

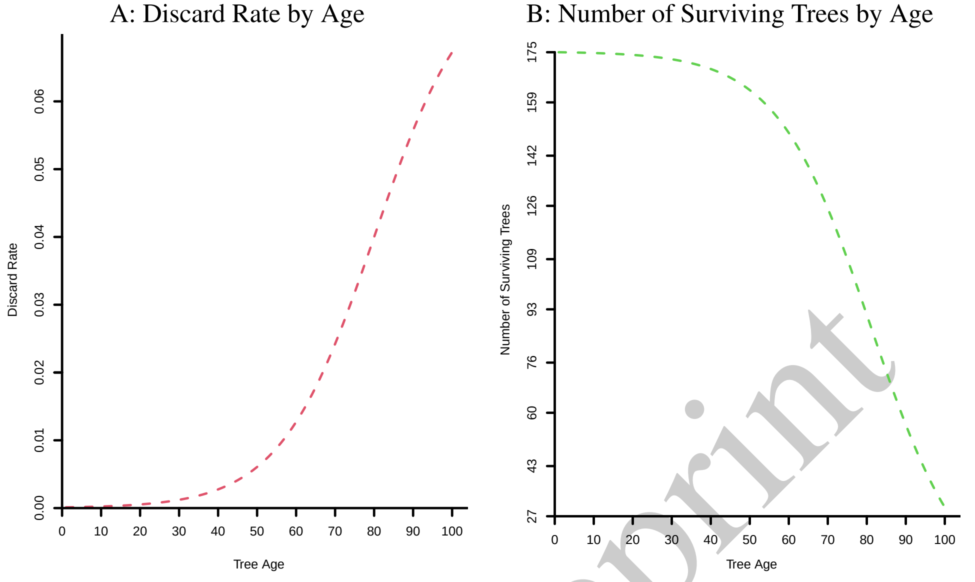
The optimization model requires data for the yield profile of coconut trees, coconut price, variable costs (input quantities and input prices), fixed costs, and cost and returns of intercrops. We collected annual data on a per-hectare basis for these variables, which we discuss next.

For the initial fixed-planting costs, we obtained data on the number of seedlings (175 per hectare), price of seedlings (100 Rs/seedling), labor days for field preparation for planting the seedlings, wage rate (Rs/day), number of tonnes of soil for getting the field cultivable, price per tonne of soil, and other planting costs (for weeding, building canals, and bed preparation around the seedlings). Because bananas are a commonly cultivated intercrop, we obtained revenues and costs of banana cultivation, which vary with the coconut tree age. Net revenues for intercropped bananas decline after 4-5 years because of less sunlight and more shade covering the intercrop as coconut trees grow taller.

Given the long life span of the coconut trees, inputs are applied throughout the productive years. We collected data on the quantity of organic manure (tonnes), price of manure (Rs/tonne), labor days to apply manure, quantity of NPK (nitrogen, phosphorus, and potassium) fertilizers in kilograms, price of urea (Rs/kg), price of super phosphate (Rs/kg), price of mutate potassium (Rs/kg), labor days to apply NPK fertilizer, number of liters of chemical pesticide, price of pesticide (Rs/liter), labor days to apply chemical pesticide, number of liters of irrigated water per tree, labor days to irrigate the trees, and cost of irrigation. We gathered data on yield per tree (number of coconuts), price per coconut, labor days to harvest, and the wage rate for harvesting. Input applications steadily increase in the early stage of the tree cycle, reach the maximum at the most productive middle period, and slowly decline during the senescence phase. The coconut-yield profile follows a similar trend as input uses. We collected the data for all other variables from a representative coconut grower and from agronomists, horticulturalists, and agricultural economists in the state of Tamil Nadu. The Indian government highly subsidizes certain inputs (e.g., fertilizer, electricity), and consequently, these input prices do not increase at the same rate as inflation. Based on the information provided by agricultural economists, these input prices increase at the rate of 1.85% per year and other input and coconut prices increase at the rate of 3.7%, which is the average inflation rate over the period 1991 to 2021 based on FAO (b). We use an interest rate of 10.66% (IMF).

For the discard function (2), we use parameter values $\gamma = 0.15$ (the speed at which coconut trees' death rate increases as they age) and $\mu = 80$ (the age at which half the trees on a hectare of land would be discarded) based on the information provided by horticulturalists. Panel A in Figure 1 plots the discard function, which indicates that discard rates are lower at the early stage of the tree cycle but increase as trees age. For instance, the discard rate for 20-year-old trees is 0.05% and for 80-year-old trees is 4.00%. Panel B in Figure 1 plots the number of trees that survive after a hectare of land is planted with 175 seedlings. For instance, after 20 years, 174 trees survive,

Figure 1. Discard Rate and Number of Surviving Trees



but after 80 years, only 88 trees survive. For uncertainty related to the release date of the new variety, we assume $k = 1$, $m = 3$, and $\rho(\theta) \in [0.05, 0.4, 0.30, 0.15, 0.1]$, implying a 5% chance of releasing one year early, a 40% chance of releasing on time, 30% change of a 1-year delay, 15% chance of a 2-year delay, and 10% change of a 3-year delay. Consequently, the announced release year τ is different from the expected value of the actual release year $E(\theta) = 0.05(\tau - 1) + 0.4(\tau) + 0.30(\tau + 1) + 0.15(\tau + 2) + 0.1(\tau + 3)$.

Empirical Analysis and Results

We employ the data described in the above section to numerically optimize the objective function in the vintage-investment model without an announcement of the future release of a new cultivar (equation 5), described in subsection . Then, we optimize the objective function in the vintage-investment model with an announcement of a new cultivar proposed in this study (equation 10), presented in subsection , to analyze the impact of three characteristics—yield, variable input cost, and discard rates—of the new cultivar on growers' planting and removal decisions and NPVs of profit streams.

No Announcement of New Cultivar

The baseline simulation maximizes the objective function (5) of the vintage-investment decision model to determine the optimal age to remove the current trees in the field with no announcement. The results suggest that the optimal age for the grower to remove the current trees is 65, even though trees can survive and produce coconuts after the age of 65. Since the standard vintage-investment decision model does not account for any information related to the new variety, it does not allow for analyses related to the sequence of planting and removal decisions of the current variety and new variety or cultivation of short-term crops.

With Announcement of New Cultivar

Next, we consider how improved attributes of a new variety impact optimal decisions related to the removal of current trees, replanting of the current variety, and planting of the new cultivar by considering four cases: (i) 25% higher yield, (ii) 25% reduction in variable input requirements, (iii) 25% increase in the age (μ) at which half the trees are discarded, and (iv) all three features together. For these four cases, we maximize the objective function (10) presented in subsection to generate the results of the optimal age to remove the current variety $\left(\hat{I}^c_{\tau\nu}\right)$, the replanted current variety $\left(\hat{I}^r_{\tau\nu}\right)$, and the new variety $\left(\hat{I}^n_{\tau\nu}\right)$ for a given vintage ν of the current variety and anticipated release date τ of the new variety. We then repeat this analysis for different vintages ν and announced release date τ to solve for various $\hat{I}^c_{\tau\nu}$, $\hat{I}^r_{\tau\nu}$, and $\hat{I}^n_{\tau\nu}$.

The optimal number of years until the removal of the current variety also indicates the years until the grower replants the old variety or plants the new variety because planting occurs the year after removal. For example, if the grower removes the current variety at $\hat{I}^c_{\tau\nu} = 45$ years and it is not optimal to replant old variety (i.e., $\hat{I}^r_{\tau\nu} = 0$), then the grower replants the new variety in the 46$^{\text{th}}$ year. Furthermore, as discussed above, if $\hat{I}^c_{\tau\nu}(\theta) - \nu \leq \theta$ (i.e., the optimal removal year minus the vintage is less than or equal to the actual year that breeders release the new variety), then the grower plants a short-term crop in the interim until the actual release and planting of the new variety.

While uncertainty in the release date is an important part of the objective function (10), it impacts the grower's decisions only under specific conditions. For instance, if current trees are removed $m + 1$ (maximum delay plus one) years after the announced release date τ of the new variety, the uncertainty has no impact on the grower's decisions because the new variety will be planted after the removal of the current trees. By contrast, uncertainty matters only if the grower removes the current trees in the field before scientists release the new variety, and $\hat{I}^r_{\tau\nu} = 0$. The reason is, if the grower removes the current trees and scientists unexpectedly delay the release of the new variety by a few years, then the grower will lose income. As a result, the grower may uproot the current variety a year or two later than they would have under perfect information to avoid this negative income shock. Furthermore, whenever uncertainty plays a role and the grower removes the existing trees before the new cultivar is available, the grower will cultivate the short-term crop to earn income while waiting for the release of the new variety.

New Cultivar with Higher Yield

As with most varietal improvements, scientists release new cultivars with higher yields. Since the magnitude of the yield increase is unknown *a priori*, we consider a 25% increase in the yield profile of the new cultivar. We present the simulation results of this yield increase in Figure 2, which plots the optimal age to remove the current variety (red squares), the optimal age to remove the replanted current variety (green circles), and the year the new variety is planted (blue triangles) for different vintages ν of the current variety in the field (ranging from 1 to 65 in the x-axis) at the time of the announcement that the new variety is released in $\tau = 1$ year (Panel A), $\tau = 7$ years (Panel B), and $\tau = 14$ years (Panel C). The vertical axis in Figure 2 and the ensuing figures indicate the number of years until the grower removes the current variety and the number of years until the grower plants the new variety. Figure 3 graphs the total NPV obtained from equation (10) (black $\times$) and NPV of each component: the current variety in the field (blue diamonds), the replanted current variety (green inverted triangles), the short-term crop (yellow stars), and the new variety (red squares) for various vintages ν of the current variety and announced release dates of the new variety is in $\tau = 1$ year (Panel A), $\tau = 7$ years (Panel B), and $\tau = 14$ years (Panel C). For illustration, for $\tau = 1$, suppose the vintage of the current variety is 40, NPV from the current trees is Rs 2,863,992, and after these trees are removed and the grower plants the field with the new variety, the grower earns NPV of Rs 253,792, yielding the total NPV of Rs 3,117,784.

Figure 2. Impact of Higher Yield on Removals and Plantings

Announcement that the New Variety will be Available in

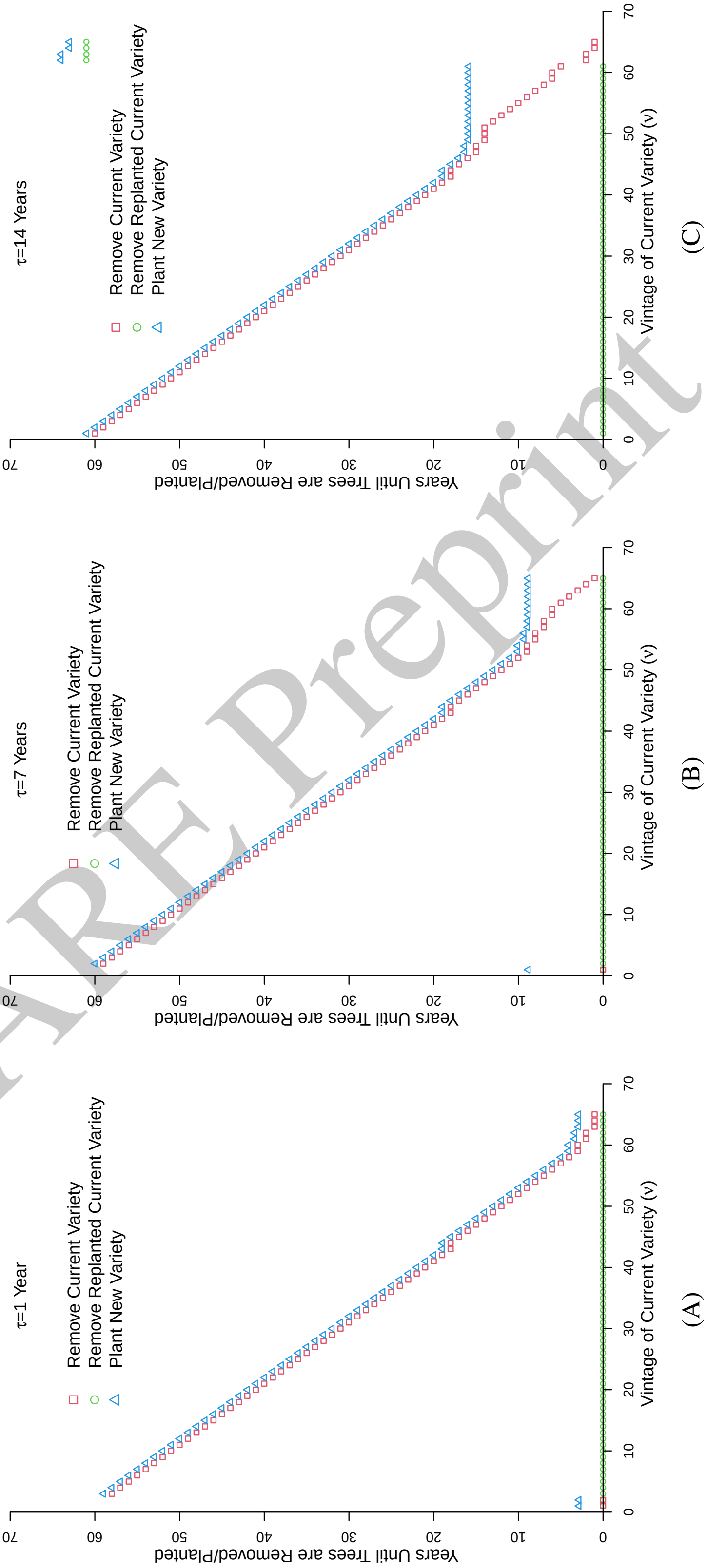
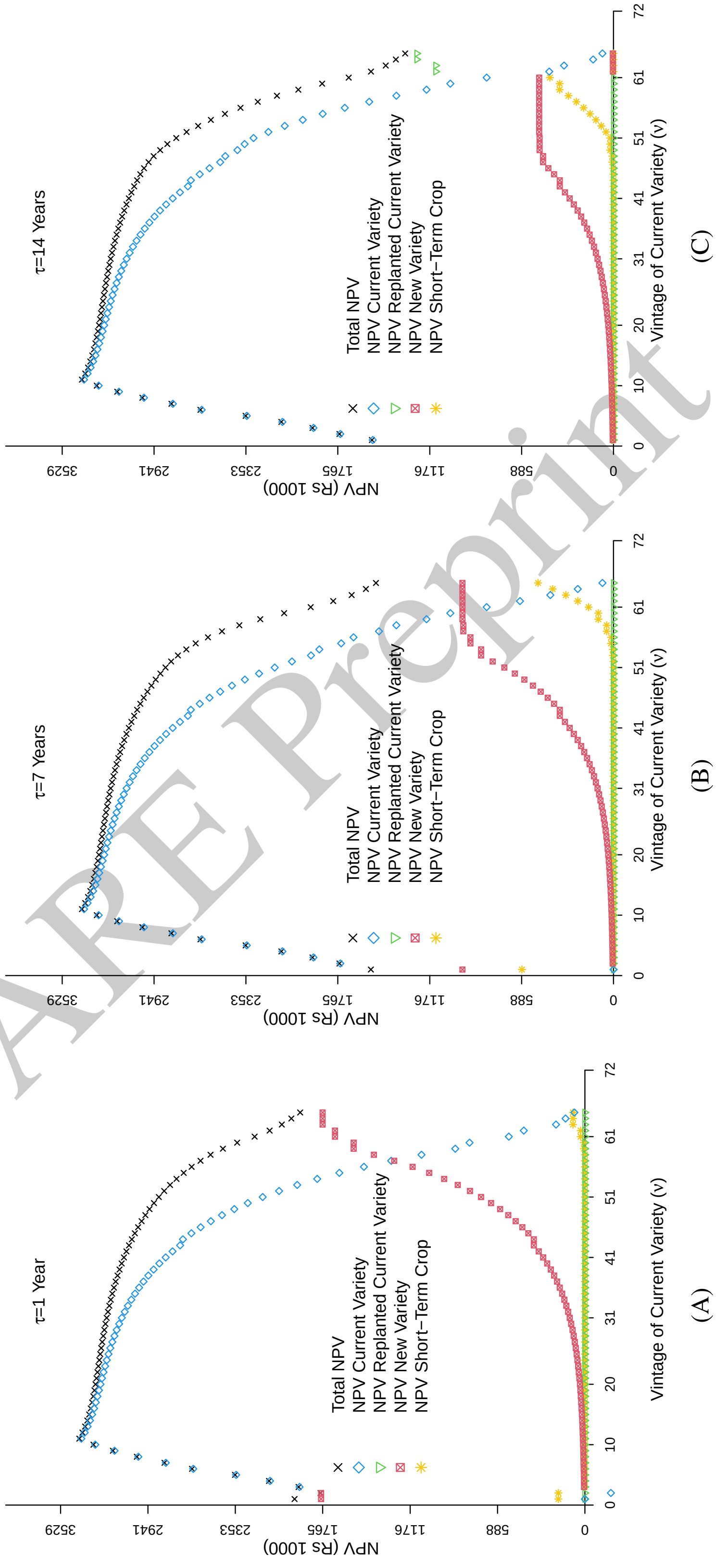


Figure 3. Impact of Higher Yield on NPV

Announcement that the New Variety will be Available in



Consider profits under the higher yielding variety:

$$\pi_i^n = P_{i-\nu} Y_i^n A_i - C_{i-\nu} A_i - F A + N(i)_{i-\nu}.$$

The variables are as defined before, with Y_i^n representing the higher yield of the new variety. Under this scenario, revenue increases, but costs are unaffected. Thus, this increase in revenues is the key mechanism that drives the results in this scenario. By expressing the net profit on a per-unit basis,

$$\frac{\pi_i^n}{Y_i^n A_i} = P_{i-\nu} - \frac{C_{i-\nu}}{Y_i^n} - \frac{F A}{Y_i^n A_i} + \frac{N(i)_{i-\nu}}{Y_i^n A_i},$$

we see the higher yield lowers the average variable cost, average fixed cost, and thus average total cost, and also leads to lower average net income from the short-term crop. Therefore, higher yield impacts the per-unit profit through lower average total costs and average income from short-term crops.

In Panel A of Figure 2, for growers deciding whether or not to plant the current variety (i.e., ν = 1) at the time of the announcement that the new variety should be available in one year (i.e., τ = 1), the results indicate that not planting the current variety (i.e., $\hat{I}^c_{\tau\nu} = 0$ as shown by the red squares at zero in Panel A), ergo saving the fixed cost, and cultivating the short-term crop are optimal (see the yellow star corresponding to $\nu = 1$ in panel A of Figure 3 for the positive NPV from cultivating the short-term crop) until scientists release the new variety. The reason for this result is that saving from not planting the current variety and the higher revenue stream from the new variety make it more profitable to not plant the current variety and cultivate the short-term crop in the interim before planting the new cultivar. Because the grower has not planted the current variety, is uncertain about the release date, and has to wait for the actual release of the new variety, uncertainty impacts the grower's NPV and planting and removal decisions. The expected wait time until scientists release the new cultivar is $\mathrm{E}[\theta] = 1.85$ years, computed from the assumptions on the values of θ and the corresponding probabilities. Since the grower plants the new variety one year after its release, Panel A shows that, for $\nu = 1$, the grower expects to plant the new variety in 2.85 years. During the interim time, the grower's sole income is from the short-term crop.

Interestingly, when current trees are of vintage 2, because the fixed planting costs of the current variety are sunk and the wait time for the new variety is short (τ = 1), the grower finds it optimal to incur the cost to uproot the younger current trees (see below the x-axis the blue diamond at $\nu = 2$ in Panel A of Figure 3 for the negative income from removing the current variety) and earn positive net income from the short-term crop while waiting for the new variety. Uprooting the 2-year-old trees of the current variety is optimal because the grower incurs variable costs but earns no revenues for the first five years of tree growth. The result that the grower removes 2-year-old trees to plant the new variety is an important insight because, in reality, growers are likely to succumb to the 'sunk cost fallacy' and not remove the 2-year-old trees since they incurred the planting cost in the previous year before the announcement of the new variety.

However, for vintages 3-43, the expected NPV is maximized when current vintage trees are left in the field for the remainder of the economically productive life, the current variety is not replanted ($\hat{I}^r_{\tau\nu} = 0$, green circles are zero), and the new variety is planted the year after the removal of the current variety. With a higher-yielding variety available for planting, the optimal removal age of current trees for these vintages is 61 years, which is 4 years earlier than the results from investment model with no announcement (see subsection) because the grower can earn a higher income stream by planting the new variety earlier. For example, for $\nu = 25$, the grower removes the current trees in 36 years. However, for older vintages of 44-59 where discounting of future earning from the new variety is lessened, the optimal removal age increases by one year to 62. For the vintages 3-58, uncertainty does not play a role because the grower plants the new variety well past the longest possible release date of $\tau + m = 4$ years (note $\tau = 1$ in Panel A, and $m = 3$ is the maximum lag in the release of the new variety).

For the vintages of 59 and older, uncertainty plays a role in the grower's decision to remove the current trees, cultivate the short-term crop, and plant the new variety. To mitigate the adverse impact of a delay in the release date and because of the lessened impact of discounting on the stream of income, the grower's optimal decision is to postpone the removal of the current trees in the field. For example, for $\nu = 62$, the optimal removal age is $\hat{I}^c_{\tau\nu} = 64$, which is 3 years later than the removal age of vintages ranging from 3 to 43. And, for trees of vintage 64, the optimal removal age is $\hat{I}^c_{\tau\nu} = 65$, which is 4 years later than the removal age of vintages ranging from 3 to 43. However, under some cases, the grower will plant the short-term crop. For example, for $\nu = 59$, the grower removes the current trees in three years at $\hat{I}^c_{\tau\nu} = 62$, but a possible outcome is that the new variety is released in four years ($\theta = \tau + m = 1 + 3 = 4$) and planted in the fifth year. Consequently, in this situation, the grower would utilize the land by cultivating the short-term crop in the fourth year, as indicated by the positive income from the short-term crop in Panel A of Figure 3. Furthermore, for $\nu = 64$, the current trees are removed in the following year as $\hat{I}^c_{\tau\nu} = 65$, and if the realized release of the new variety is delayed by $m = 1, 2,$ or,3 years, then the grower will plant the short-term crop for 1, 2, or 3 years to earn income. Graphically, the *expected value* of the duration the grower cultivates the short-term crop is illustrated in Figure 2 by the vertical distance between the blue triangle (years until the new variety is planted) and the red square (years until removal of the current variety), which increases from 1.1 for $\nu = 59$ to 1.9 for $\nu = 65$.

The results show the optimal removal age of the new variety $\hat{I}^n_{\tau\nu}$ is constant (and thus not included in the plot) at 74 years irrespective of the vintage of current trees and announced release dates of the new variety. The constant removal age occurs because the optimal removal age of the new variety does not depend on when it is planted as, for a given discount rate, the shape of the $NPVINF_{I^n_{\tau\nu}}(\theta)$ function in equation (9) does not change for all possible τ and ν. A 25% increase in yield extends the economically viable age of the new cultivar by 9 years compared to the optimal removal age of 65 for the current cultivar with no announcement (see subsection).

As seen from Panel A of Figure 3, for $\nu = 1$ and 2, the majority of the grower's NPV of profit is from the new variety as the NPV of profit from the short-term crop is small and the current variety is zero ($\nu = 1$) or negative ($\nu = 2$). For vintages 3-57, NPV derived from the current variety is higher than the NPV from the new variety because of discounting. However, for vintages 58 and older, the majority of the grower's NPV comes from the new variety. For all vintages, because of the short time between the announcement and release date of the new variety ($\tau = 1$), the grower does not find *replanting* the current variety optimal, as seen by $\hat{I}^r_{\tau\nu} = 0$ in Figure 2 and zero NPV in Figure 3.

Finally, the grower's largest total NPV of profit is when the vintage of the current variety is 11, where almost all of the income comes from the current variety; this result occurs because yield reaches its peak when trees are 11 years old. At the time of the announcement, the NPV of profits for future years is computed for each vintage; in this case, the vintage is 11. Thus, revenues and costs incurred before the announcement do not factor into the grower's decisions. Therefore, the NPV for $\nu = 11$ for the current variety does not include (a) the planting cost, (b) the negative profit from the younger trees when the grower incurs variable costs without reaping any revenue, or (c) the income from the early years (6-10) of revenue generation when yield has not yet reached its peak.

In Panel B of Figure 2, the announced release date of the new variety is $\tau = 7$ years, and growers preparing to plant seedlings of the current variety ($\nu = 1$) find it optimal not to plant the current variety, ergo saving the fixed cost, and cultivate the short-term crop until scientists release the new variety. In addition, as seen in Figure 3 for $\nu = 1$, the grower's NPV of profit from the short-term crop in Panel B is larger compared to that in Panel A with $\tau = 1$ because the grower cultivates the short-term crop for more years. Furthermore, the NPV of profit from planting the new variety in Panel B is substantially lower compared to that in Panel A because of the additional discounting of 6-10 years depending on the realization of θ.

In contrast to the results in Panel A of Figure 2, for $\nu = 2$ and $\tau = 7$, the grower, who planted the seedlings and incurred the sunk cost in the previous year and has 2-year-old trees at the time of the announcement, do not uproot the current trees until they reach the optimal removal age and then plant the new variety in the following year. The reason for this result is that it is not to wait for a longer period to plant the new variety. For trees of vintage 2-43, the grower removes the trees when they reach $\hat{I}^c_{\tau\nu} = 61$ years old and replants the new variety in the following year. For vintages between 43-53 at the time of the announcement, the optimal age to remove the current trees increases to 62 due to the diminished role of discounting.

For vintages over 53, the maximum number of years until scientists release the new variety is greater than the number of years until the grower removes the current variety $\left(\tau + m > \hat{I}^c_{\tau\nu} - \nu\right)$, and in these cases, uncertainty starts to impact the grower's decisions. Specifically, for $\nu = 54$ and 55, the grower removes the current variety in the field at the age of 63; for $\nu = 56$ and 57, at the age of 64; for $\nu = 58$ and 59, at the age of 65; and for $\nu = 60$ to 65, at the age of 66. Furthermore, with uncertainty playing a role, the grower cultivates the short-term crop to bridge the gap between the removal of the current variety and the actual release of the new variety, as shown by the positive income from the short-term crop in Panel B of Figure 3. The expected value of the duration the grower cultivates the short-term crop increases from 1.1 for $\nu = 53$ to 7.85 for $\nu = 65$, also illustrated in Figure 2 by the vertical distance between the blue triangle and the red square.

In Panel C of Figure 2, the announced release date of the new variety is 14 years. In this case, for $\nu = 1$, because of the long wait time for the new variety to become available, the grower finds it optimal to incur the planting cost of the current variety, as opposed to not planting and waiting for the new variety to become available as in the case of the announced release date of 1 year (Panel A) and 7 years (Panel B). For vintages 1-43, the optimal removal age of the current trees is 61. For vintages between 44 and 46, as discounting starts to play a diminishing role, the grower removes the coconut trees when they reach the age of 62. For vintages 46-61, $\tau + m > \hat{I}^c_{\tau\nu} - \nu$ and uncertainty impacts the grower's decision as the grower might remove the trees before the release of the new variety and cultivate the short-term crop. The expected value of the duration of the short-term crop ranges from 1.1 years for $\nu = 46$ to 10.85 years for $\nu = 61$. The optimal removal age ranges from 62 years for $\nu = 46$ to 66 years for $\nu = 61$.

For vintages 62-65, because the grower removes the current variety in 1 to 2 years and of the long time before scientists release the new variety, the grower finds it optimal to replant the current variety (as seen by the positive numbers for the green circles in the northeast part of Panel C) and plant the new variety after removing the replanted current variety at the age of 61. The number of years until the grower plants the new variety is the number of years the current variety is in the ground (2 years for $\nu = 62$ and 63 and 1 year for $\nu = 64$ and 65) plus the 61 years until the grower removes replanted current variety plus one. Thus, for $\nu = 62$ and 63, the new variety is planted in 64 years and for $\nu = 64$ and 65, it is planted in 63 years.

As the results from the three Panels in Figure 2 indicate, the optimal removal and planting decisions can vary across different vintages in the field and the number of years until the new variety is likely to be released.

New Cultivar with Less Input Requirements

Since scientists aim to release a new variety that requires less variable inputs, in this scenario, we consider a 25% reduction in input use of the new coconut cultivar, *ceteris paribus*. For this scenario, we present the optimal planting and removal decisions in Figure 5 and the NPV of various profit streams in Figure 4.

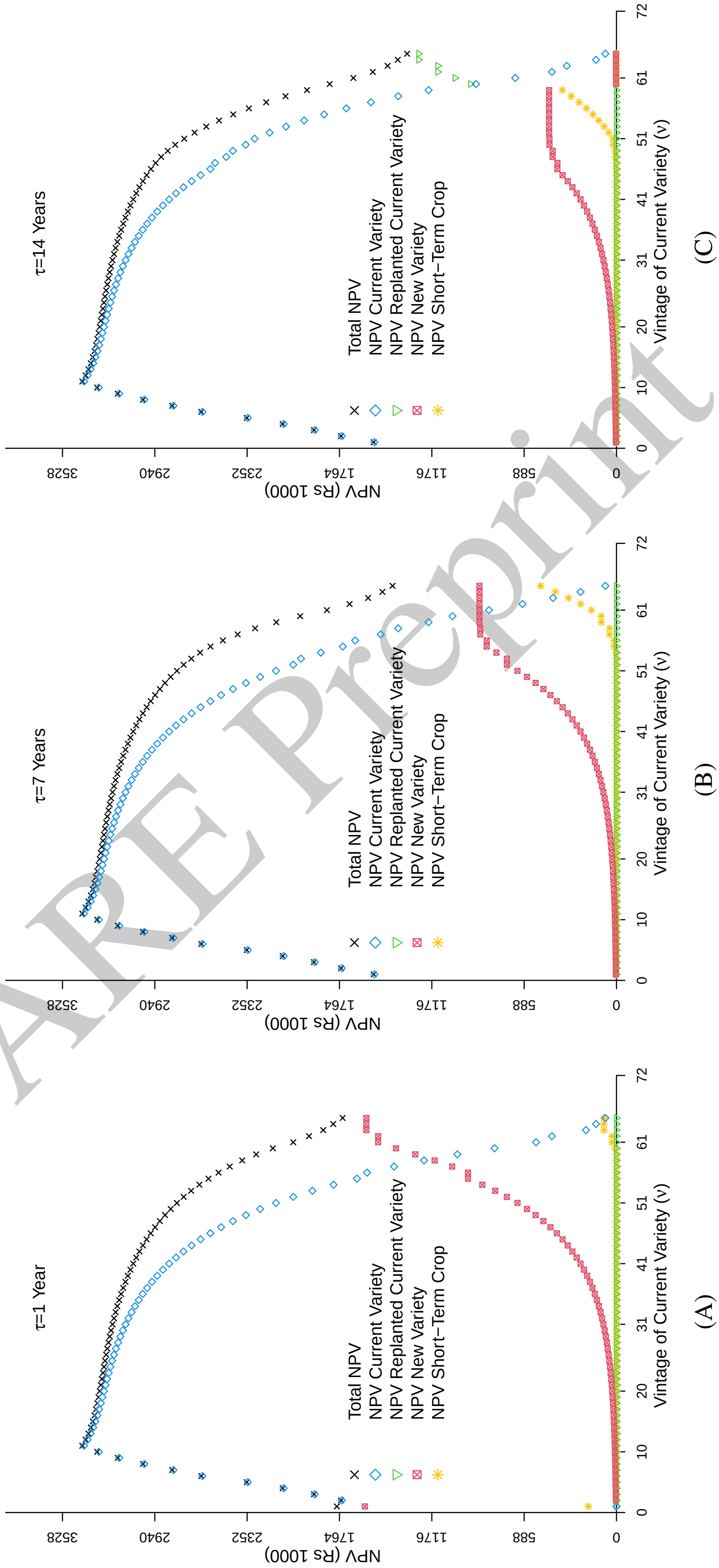
The increase in profits due to the reduction in variable cost is

$$\pi^n_i = P_{i-\nu} Y_i A_i - C^n_{i-\nu} A_i - F A + N(i)_{i-\nu},$$

where $C^n_{i-\nu}$ is the lower variable cost. Unlike in the higher-yield scenario, revenue is not impacted in this scenario, and lower variable cost is the key mechanism that drives the results in this scenario.

Figure 4. Impact of Lower Variable Cost on NPV

Announcement that the New Variety will be Available in



Profit on a per-unit basis is

$$\frac{\pi_i^n}{Y_i A_i} = P_{i-\nu} - \frac{C_{i-\nu}^n}{Y_i} - \frac{F A}{Y_i A_i} + \frac{N(i)_{i-\nu}}{Y_i A_i},$$

which indicates a lower average variable cost, but average fixed costs of coconut cultivation and average net income from the short-term crop are not impacted. Thus, the difference between a 25% increase in yield (from the scenario in subsection) and a 25% decline in input use (from the current scenario) is that the latter does not impact average fixed costs of coconut production and average net income from short-term crops. These differences entail that, for an identical percent increase in yield and decrease in variable input use, the grower is better off with the yield increase. For instance, NPV of total profits for $\tau = 7$ and $\nu = 7$ is Rs 2,829,656 for the yield-increase scenario and Rs 2,828,832 for the current scenario with a reduction in input use. These differences influence the removal and planting decisions. This can be seen from Panel B of Figure 5 for the announcement of a new variety to be released in $\tau = 7$ year.

For $\tau = 1$, even though the grower cultivates the short-term crop as opposed to planting the current variety for $\nu = 1$ in both scenarios, the grower does not uproot $\nu = 2$ trees to plant the new variety sooner in this variable-input-reduction scenario as the grower does in the yield-increase scenario of Panel A of Figure 2. Furthermore, when scientists announce the new variety should be available in $\tau = 7$ years, the grower plants the current variety for $\nu = 1$ for the variable-input-reduction scenario (Panel B of Figure 5) because the increase in NPV of profits from the new variety is not large enough for the grower to wait for the new cultivar. This is in contrast to the yield-increase scenario where the grower cultivates the short-term crop until the new variety becomes available because the increase in NPV of profits from higher yield is large enough for the grower to wait to plant the new cultivar (Panel B of Figure 2).

For this variable-input-reduction scenario, when $\tau = 14$ and $\nu \geq 60$, the grower finds it optimal to replant the current variety (as seen by the positive numbers for the green circles) and plant the new variety after removing the replanted current variety (Panel C of Figure 5) as opposed to $\nu \geq 62$ (Panel C of Figure 2) in the higher yield scenario. The optimal removal age of the current variety ranges from 62 for $\nu = 1$ to 66 for $\nu = 65$. However, the optimal removal age of the new variety $\hat{I}_{\tau\nu}^n = 75$, which is one year more than that in the yield increase scenario.

New Cultivar with Lower Discard Rates

Resistance to pests and diseases is a key characteristic that scientists develop in releasing new varieties, which translates into lower discard rates as fewer trees succumb to maladies. Therefore, for this scenario, we consider a 25% increase in μ, the age at which half of the trees have been discarded due to random death or disease, *ceteris paribus*, which results in growers discarding fewer trees. We illustrate the optimal planting and removal decisions in Figure 7 and the NPVs of various profit streams in Figure 6.

Profits in this scenario is

$$\pi_i^n = P_{i-\nu} Y_i A_i^n - C_{i-\nu} A_i^n - F A + N(i)_{i-\nu},$$

where A_i^n is the area with fewer discards. Unlike in the previous two scenarios, the reduction in the discard rate impacts the grower's decision through higher revenues and higher variable costs as more trees are under cultivation. Profit on a per-unit basis is

$$\frac{\pi_i^n}{Y_i A_i^n} = P_{i-\nu} - \frac{C_{i-\nu}}{Y_i} - \frac{F A}{Y_i A_i^n} + \frac{N(i)_{i-\nu}}{Y_i A_i^n},$$

which indicates that, with the yield profile not changing, the average variable cost is not impacted, while average fixed cost decreases and average net income from short-term crops falls. Because

Figure 5. Impact of Lower Variable Cost on Removals and Plantings

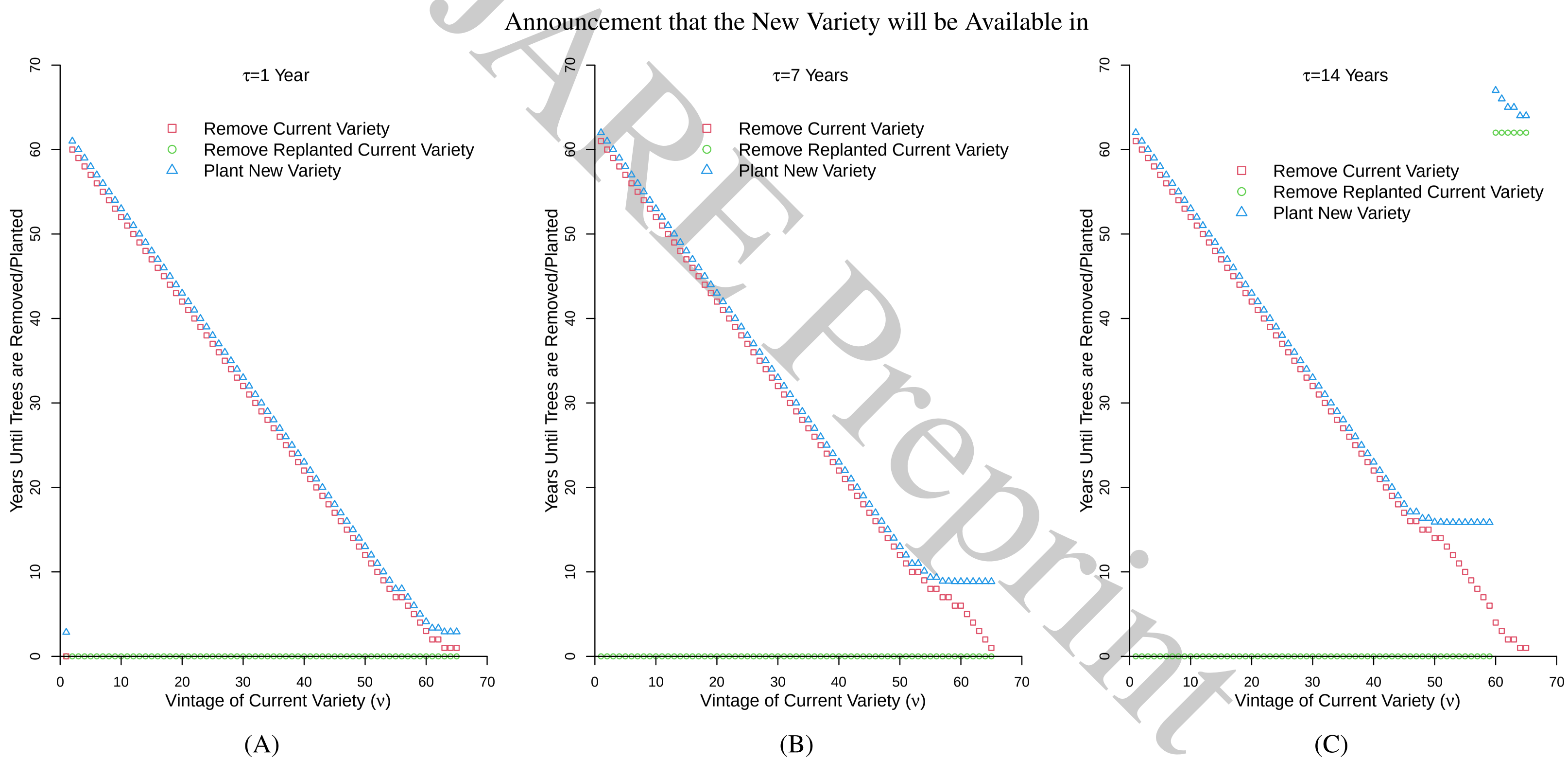
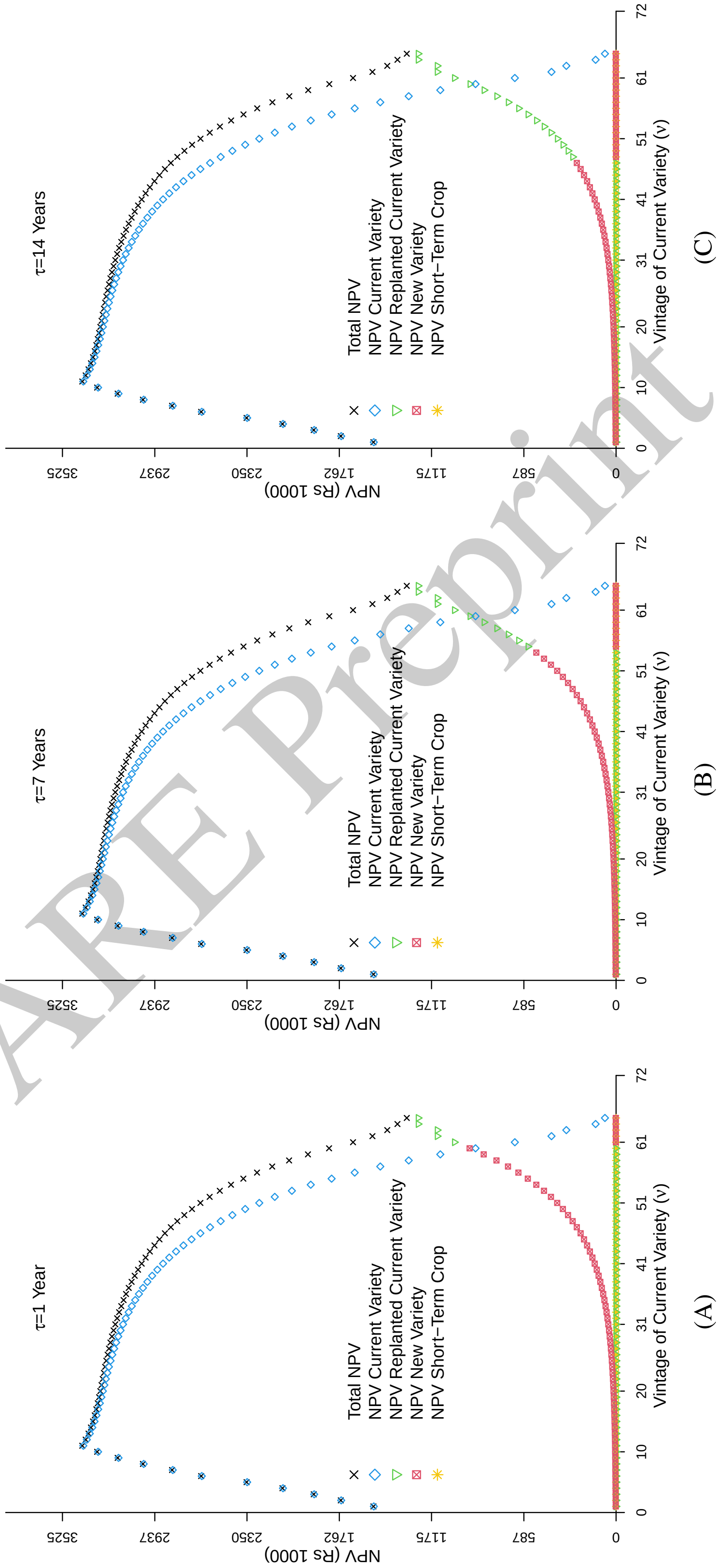


Figure 6. Impact of Lower Discard Rate on NPV

Announcement that the New Variety will be Available in



per-tree net revenue is positive, total net revenue increases. Since the new variety increases both revenue and variable cost, it is not as profitable as in the higher-yield scenario or the input-reduction scenario. For example, the NPV of total profits for $\tau = 7$ and $\nu = 7$ is Rs 2,826,980 in this scenario, which is less than that in the higher-yield scenario (Rs 2,829,656) and input-reduction scenario (Rs 2,828,832). Comparison of the NPV of total profits in the respective Panels A, B, and C of Figures 3, 4, and 6 reveals that the NPV of total profits is higher for all vintages under the higher-yield scenario, followed by the lower-input scenario and the lower discard-rate scenario.

Because the increase in NPV of profits from the new variety is relatively small, the grower plants the current variety for $\nu = 1$ even though the release of the new variety is imminent for $\tau = 1$ (Panel A of Figure 7). For the announced release year $\tau = 1$, uncertainty starts to impact the grower's decisions only when the vintage is above 60 because $\tau + m = 4 > \hat{I}^c_{\tau\nu} - \nu = 3$ where the optimal removal age is $\hat{I}^c_{\tau\nu} = 64$. For vintage above 60, the grower is not willing to endure the risk of the new variety being delayed and thus replants the current variety, which is then removed after $\hat{I}^r_{\tau\nu} = 64$ years. These results are similar to the cases where the announced release date for the new variety is 7 and 14; however, uncertainty starts to impact the grower's decisions at $\nu = 55$ for $\tau = 7$ with an optimal removal age of $\hat{I}^c_{\tau\nu} = 64$ and at $\nu = 48$ for $\tau = 14$ with an optimal removal age of $\hat{I}^c_{\tau\nu} = 64$. The optimal age to remove the new variety is $\hat{I}^n_{\tau\nu} = 71$.

New Cultivar with All Three Features

For this scenario, we analyze the combined impacts of a 25% increase in yield, a 25% reduction in variable input use, and a 25% increase in the age at which half of the trees have been discarded. A new variety with all three features will be highly profitable, and the grower will favor the new variety over the current variety more than the ones with a single characteristic. For instance, when the announced release date for the new variety is in one year ($\tau = 1$), the grower does not plant the current variety ($\nu = 1$) and uproots the young trees of vintages 2, 3, and 4 to plant the new variety (as seen by the red squares corresponding to $\hat{I}^c_{\tau\nu} = 0$ and blue triangles corresponding to the average planting year of the new variety in 2.85 years in Panel A of Figure 8). Furthermore, because of the greater positive attributes of the new variety, the optimal removal age of the current variety is sooner: 60 for vintages 5 through 56, which then increases from 61 for $\nu = 57$ to 66 for $\nu = 65$.

As with the yield-increase scenario, for the announced release date of the new variety $\tau = 7$, the grower does not plant the current variety and waits for the new variety for $\nu = 1$. However, the grower does not uproot the already planted young trees (see Panel B of Figure 8 where the number of years until the removal of the current variety ranges from 58 for $\nu = 2$ to 1 for $\nu = 65$), which is in contrast to the results for $\tau = 1$ in Panel A.

For all three announced release years, as uncertainty starts to impact the planting and removal decisions sooner—starting at $\nu = 58$ for $\tau = 1$, $\nu = 52$ for $\tau = 7$, and $\nu = 44$ for $\tau = 14$—the grower plants the short-term crop if the grower removes the trees before scientists release the new variety. It is worth noting that with the highly profitable new variety, the grower does not replant the current variety (i.e., $\hat{I}^r_{\tau\nu} = 0$, green circles) for all ν and τ cases. The optimal removal age of the new variety $\hat{I}^n_{\tau\nu}$ is 77 across all vintages and announced release dates, implying a new variety with all three features extends the economically viable age of the new variety by 12 years compared to the current variety. Figure 9 depicts the NPV for all vintages for the announced release dates of 1, 7, and 14 and shows that the cultivar with all three features is the most profitable for the growers.

Conclusion

The discovery of a new variety in any crop is a time-consuming process, and considerable risk exists in R&D, particularly for perennial crops. Perennial crop cultivation involves complex long-term and large-scale investment decisions regarding planting and removal, which are further complicated by

Figure 7. Impact of Lower Discard Rate on Removals and Plantings

Announcement that the New Variety will be Available in

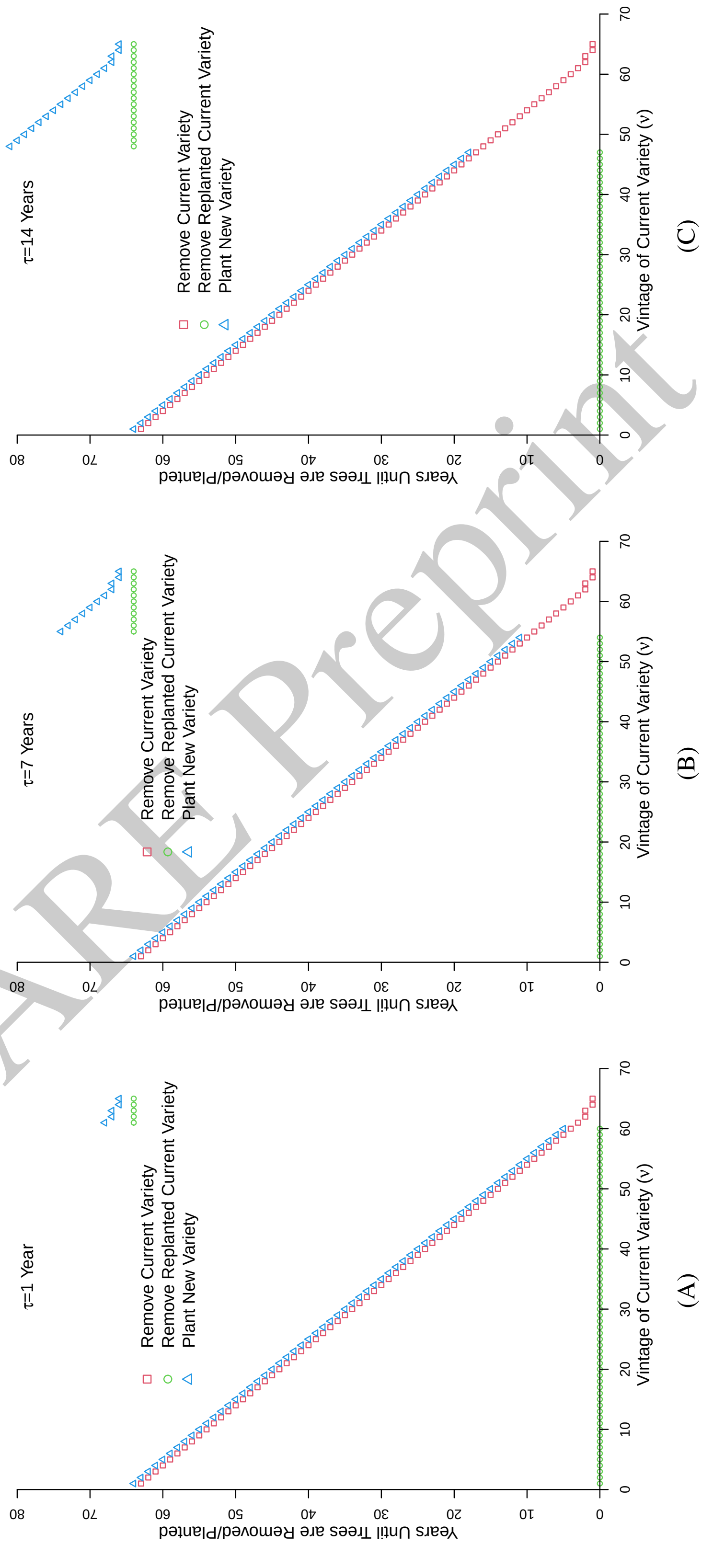


Figure 8. Impact of All Three Feature on Removals and Replantings

Announcement that the New Variety will be Available in

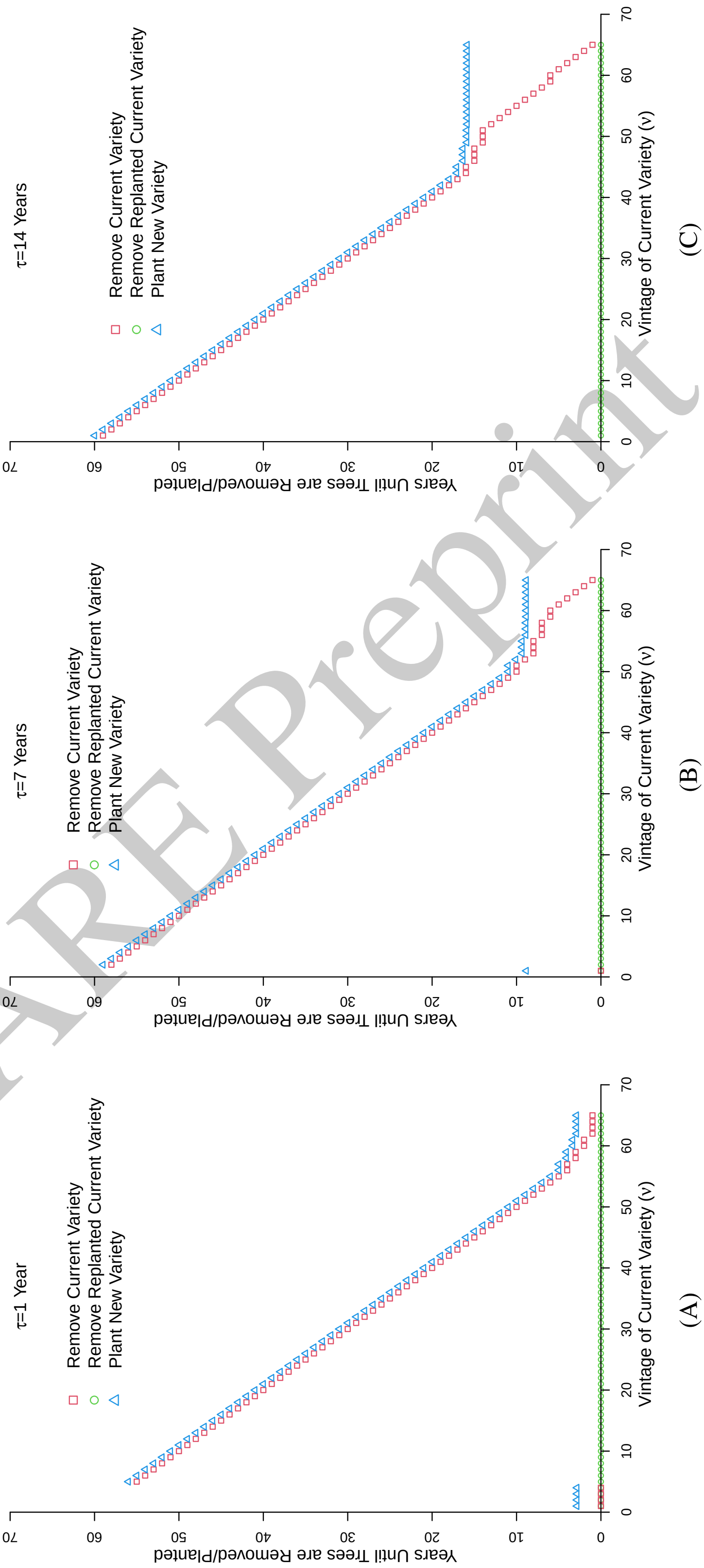
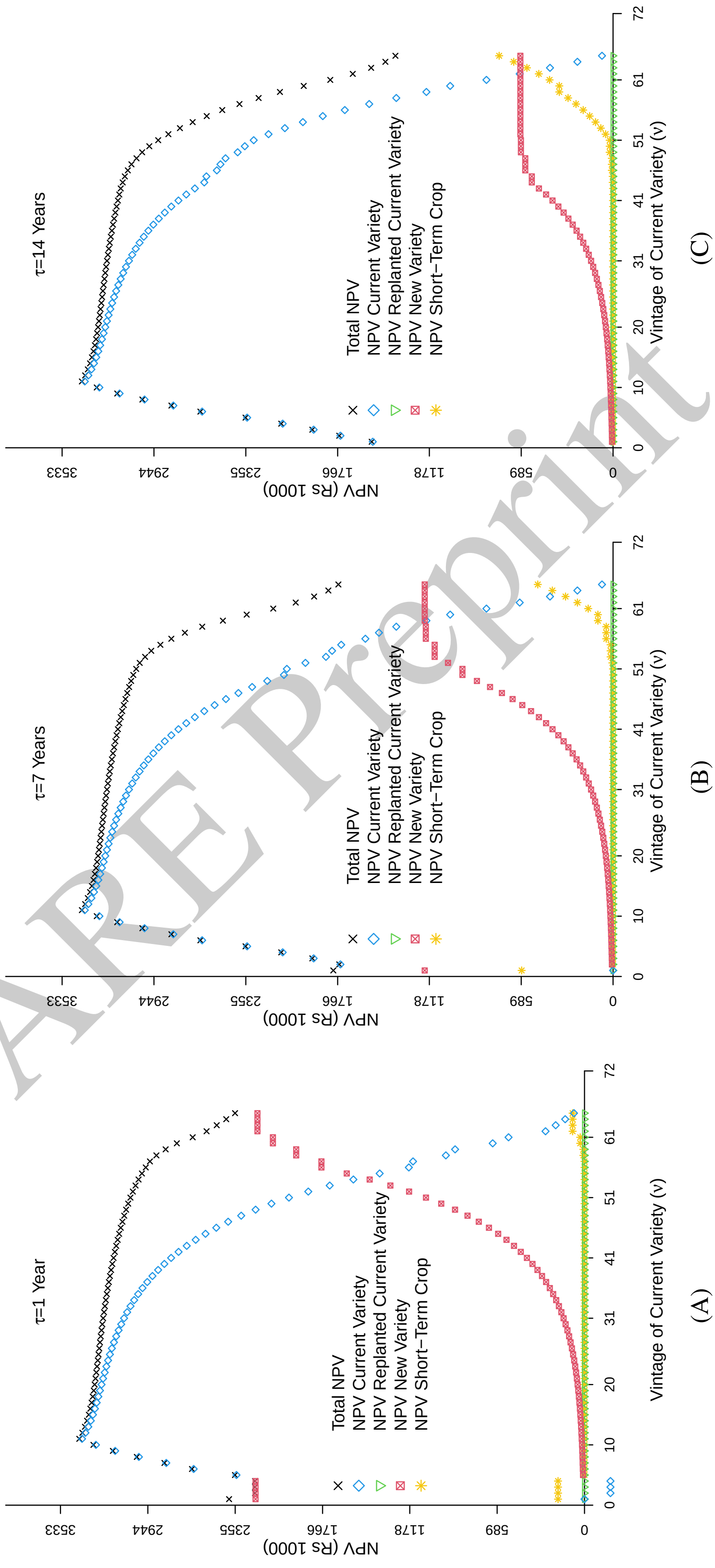


Figure 9. Impact of All Three Feature on on NPV

Announcement that the New Variety will be Available in



the significant time requirements for and uncertainty surrounding the release of a new perennial crop cultivar. Hence, growers must make judicious decisions. Our study furnishes this information based on rigorous economic analysis to examine the impacts of characteristics of a new variety on the horizon on the timing of the grower's optimal removal and planting decisions and net present value (NPV) of profits. Specifically, we study how an announcement of the release of a new cultivar at a future date will impact the optimal age to remove current trees of a given vintage and replant the current variety or grow short-term crops in the interim and plant the new variety when it becomes available.

We develop a new vintage-investment decision model for perennial crops that incorporates the dynamic aspects of farm-level investment choices as the grower anticipates the release of a new variety. In this mode, the removal and planting decisions are endogenous and depend on present and future streams of revenues and costs, which vary with tree age. Our model provides rich insights into growers' investment decisions compared to a standard investment-decision model because our model endogenizes the timing of the uprooting of existing trees, the replanting of the current cultivar, the possibility of cultivating short-term crops, and the planting of the new cultivar.

We apply our model to study coconut cultivation in the state of Tamil Nadu, India. We analyze the impacts of an announcement of a new perennial crop cultivar with enhanced characteristics under four scenarios—(i) a 25% increase in the yield profile, (ii) a 25% reduction in input use, (iii) a 25% increase in the age at which half of the trees are discarded, which decreases the discard rate, and (iv) these three attributes combined—on planting and removal decisions.

These analyses generate the following four key results. First, if the new variety is highly profitable (as in the yield or three combined-features scenario) and its release is imminent, growers not only skip planting the current variety if they have not planted at the time of the announcement but even uproot the young trees to plant the new variety sooner. Second, if the new variety is not very remunerative (as in the discard-rate scenario), then growers will not take any risk of waiting for the new variety if a delay in its release is possible. Under such circumstances, the grower replants the current variety after removing the existing current trees in the field. Third, for the same percent changes, growers prefer a new variety with a higher yield than lower input requirements or the age at which half of the trees are discarded because the NPV of profits is higher under the former than in the latter two scenarios. The higher NPV of profit in the yield scenario is due to the scale effect of lowering the average variable cost, average fixed cost, and average total cost. The input-reduction scenario does not have the scale effect of lowering the average variable cost. The lower discard rate is the least profitable scenario because, even though revenue increases, cost also rises as more trees survive, resulting in a lower stream of profits. Fourth, if the grower removes the curret trees and scientists delay the release of the new variety, the growers will cultivate a short-term crop to provide a cushion against a reduction in profits.

Based on the investment-decision model without an announcement, the optimal age to remove the current variety is 65 years-old. However, with the announcement of the new variety, for the scenario with three improved characteristics of the new variety, the growers remove the current variety sooner at 60 years old for vintages 5-56 or delay in removing the current variety until they are 66 years old for the oldest vintage of 65. The optimal age to remove the new variety ranges from 71 years old in the lower discard-rate scenario to 77 with all three enhanced features.

Our modeling approach is applicable not only for perennial crop (e.g., coconut or cocoa) cultivation in tropical countries but also for any perennial crop (e.g., stone fruits and nuts) cultivation in temperate climate countries. Growers of these trees are also likely to face the decision of removal and planting in anticipation of a newer variety being on the horizon.

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