Optimal Harvest Time of Florida Valencia Oranges to Maximize Grower Returns

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Objectives

The goals of this research are to estimate the optimal harvest time of Valencia oranges for Florida growers and to determine the economic consequences of harvesting outside the optimal window. The grower's optimal harvest window is defined as the period in which growers harvest their crop to maximize on-tree revenues. This optimal window is a function of fruit quality, fruit quantity, and harvest costs. The research model will estimate the optimal time fruit should be harvested and calculate the economic costs to the grower from missing the optimal harvest window. As mechanical citrus harvesters begin to play a larger role in the Florida citrus harvest, a more complete understanding the economic consequences of harvesting at optimal and suboptimal times will aid growers in their harvesting decisions.

Background

Florida is the world's second largest producer of orange juice, with 96% of the state's oranges processed into juice during the 2003-04 season (Spreen, 2006). The current logistics for harvesting and processing of oranges for juice have evolved under a system of manual harvest labor. Crews of seasonal workers who pick each piece of fruit by hand harvest almost all citrus grown in Florida between September and July. The orange crop consists of several different varieties, with the Valencia being the dominant late season orange. The Valencia harvest in Florida typically begins in February and continues into July.

Valencias picked near the beginning or end of the usual harvest period must be carefully monitored to assure they meet minimum quality standards as required by the

Florida Citrus Commission (FCC). Minimum standards during the Valencia harvest require that processed oranges contain juice with a total soluble solids level not less than 8%. The FCC also enforces a minimum allowable Brix to acid ratio, or more precisely, the ratio of total soluble solids to anhydrous citric acid. Over the course of the season, the minimum ratio requirements decrease as the soluble solid content of the juice increases. At the minimum allowable total soluble solid level of 8%, the minimum ratio is 10.50 to 1. With each 0.1% increase in soluble solids contained in the juice, the minimum required solids to acid ratio decreases by .05 to 1. For any juice with a soluble solid content of greater than 11%, the minimum ratio is 9 to 1. Unlike minimum standards in place for early season fruit, there are no minimum requirements for juice content, acid, or color break for oranges harvested after December 1st and processed for canning or concentrating (FCC, 1949).

Growers and processors monitor how fruit quality changes on the tree so that at time of harvest, the fruit meets minimum processing standards. While growers are concerned with the overall quality of their crop, their payment for processed fruit is dependent almost entirely on the pounds solids delivered to the processor. Pounds solids are a measure of the sugar content of the orange juice. To calculate pounds solids, the density of the juice is first measured to determine the percentage of total soluble solids. The density is measured in degree Brix using a hydrometer and is corrected for temperature. Standardized tables are used to convert the corrected Brix measurement to the percentage of soluble solids. In addition to sugars, the measurement of soluble solids also includes citric acid, vitamins, salts, and flavor compounds. Pounds solids per box are then determined by multiplying the calculated percent of soluble solids by the pounds of juice per 90 pound box of oranges (Jackson, 1991). Acid levels in the juice are calculated with a standard alkali and phenolphthalein indicator with the total acidity calculated as anhydrous citric acid (FCC, 1949). The Brix to acid ratio is simply the corrected degree Brix divided by percentage of acid in the juice.

Scheduling fruit to the processor is an important management function because fruit quality is continuously changing on the tree and then quickly deteriorates after harvest. Once harvested, fruit held longer than 24 hours can begin to degrade or spoil, depending on weather and storage conditions. To assure smooth processing, many Florida citrus growers contract with processors well before harvest to purchase their fruit. The processor schedules a grower's fruit to be delivered at regular intervals to the plant throughout the season. A grower's weekly allotment of fruit is usually determined by the processing plant's capacity and the percentage of outstanding contracted fruit the grower holds. The number of loads a grower is allocated is prorated based on the number of boxes of fruit the grower has contracted to be delivered. Limited load allocations are necessary due to limited processing and storage capacity of processing plants. This allocation system is flexible, and changes are made if fruit is immature or if quality is rapidly degrading.

To some degree, the current system of load allocations is an artifact of a manual harvest system. Harvest productivity of a worker ranges from 8 to 12 boxes per hour. Hence, a crew of 20 men working 10 hours can load approximately four 500 box trailers in one day. By spreading the load allocations across a number of growers and grove locations, a processing plant can better insure that its daily capacity needs are met.

Motivation

Since 1995, the Florida citrus industry has been aggressively pursuing mechanical harvesting. While availability of legal workers has been an ongoing concern, the primary motivation for mechanical harvesting is the potential to significantly reduce harvesting costs and close the competitive cost gap between growers in Florida and Sao Paulo, Brazil. During the 2004-2005 season, about 25,000 acres were mechanically harvested by nearly 30 growers (Bryant, 2005). Mechanically harvested acreage increased to more than 30,000 acres during the 2005-2006 season and a number of new harvesting systems have been purchased for the 2006-20007 season. Continuous canopy shake and catch systems have the capacity to harvest more than 300 trees and enhance worker productivity by 10-fold over their counterparts in manual harvesting crews. Manual crews, working in groves yielding between 400 and 500 boxes per acre, harvest an average of 10 boxes per hour (Roka and Emerson, 1998).

If mechanical harvesting systems are to achieve their inherent economies of scale and significantly lower harvest costs, several structural changes will have to occur within the industry. For example, individual harvesting systems will require larger number of daily trailer allocations in order to operate efficiently. Such a change will concentrate daily harvests in fewer geographic locations. Another industry change will be with respect to the time at which a grove is harvested. Currently, hand harvest crews pick relatively small blocks of fruit from many different locations. This harvesting system works well with hand crews but can be inefficient when using mechanical harvesters. To capture scale efficiencies, mechanical harvesters must operate near capacity for extended periods of time in a single location. In addition to current determinants of harvest time such as fruit maturity and load allocations, mechanical harvesting systems may require adjacent groves to be harvested in succession due to their relative location. These changes could force some growers to alter their harvesting schedule. A change in a harvesting schedule may adversely affect grower returns if they are forced to harvest fruit at a less than the optimal time in the growing and maturing cycle.

Concentrating daily harvest locations to fewer geographic locations may have implications for a processor's fruit quality parameters. While growers focus on pound solids, processors define quality in terms of ratio and color as well as solids. In addition, high volume harvesting systems may induce changes in juice storage and juice inventory management strategies. A constrained optimization model that incorporates all the components of "optimal" harvest timing from both grower and processor perspectives could serve as an important tool to identify potential trade-offs and estimate their costs.

Model Development

Assuming exogenous market forces determine juice prices, growers are price takers. Payments are then based solely on the pounds solids per box times the quantity of boxes delivered to the processor. Growers also consider the harvest cost of picking and delivering fruit to the processing facility. So in an attempt to maximize on tree revenue at the time of harvest, the grower will maximize the pounds solids per box times the boxes per acre, less the harvest cost times the number of boxes harvested.

One way to express this optimization is through an application of a generalized assignment problem. Letting Xit = 1 if block i is harvested in time period t, otherwise Xit = 0, the growers objective function is to maximize on-tree revenue, Π.

$$\Pi = \sum_{i=1}^{I} \sum_{t=1}^{T} \left(P\ PS_{it} B_{it} - HC_t B_{it}\right) X_{it}$$

Subject to

$$\sum_{t=1}^{T} X_{it} = 1 \quad where \;\; i = 1 \ldots I$$ harvest dummy constraint

$$LB \le \sum_{i=1}^{I} B_{it}\ X_{it} \le UB \quad where\ t = 1 \ldots T$$ load allocation constraint

∏ represents on-tree revenue, *i* designates a block of trees, *t* is the time period, *P* is the exogenous market price per pound solid, *PS* is the pounds solids per box of processed fruit, *B* is the boxes of fruit harvested per acre, and *HC* is the harvest cost per box.

X is a harvest dummy variable that represents each block of trees during each time period. The harvest dummy variable is set equal to 1 if block *i* of trees are harvested in time *t*. The harvest dummy constraint represents the grower's decision of when to harvest a block of trees and forces each block to be harvested in only one time period. During the harvest season, the timing of harvest is the only remaining grower controlled factor that will determine economic returns. Knowing when to harvest to maximize returns is complicated, in part, due to the unknown box yield from a block of trees and the fixed allotment of fruit boxes allowable at the juice plant. The choice to harvest a set block of trees must be based on the estimated box yields from that block, given the fruit allotted by the processor. These contrasting units of measure suggest the use of a generalized assignment problem.

The load allocation constraint represents the limited loads growers are permitted to deliver to the processor. *UB* represents the upper bound quantity of field boxes allowed to be delivered to the processor each time period. *LB* is the lower bound quantity of boxes that must be delivered to the processor in each time period. The processor will inform the grower of their load allocation and the grower is responsible for delivering the requested quantity of fruit. While there is always an upper bound quantity of fruit that can be delivered to the processor, the lower bound is often less restrictive. Additional loads delivered to the processing plant will not be accepted and growers that consistently deliver below their allocation may have their load allocation reduced.

Pounds solids, boxes per acre, and harvest cost are determined outside of the optimization model and are a function of time. The estimated average pounds solids per box as a function of time can be estimated by the function:

$$PS = \alpha t^2 + \beta t + \gamma$$

Estimated average boxes per acre as a function of time can be estimated by the function:

$$B = \chi t^2 + \psi t + \upsilon$$

The quadratic terms in both preceding functions are expected to be negative and the linear term should be positive. Estimated average harvest costs as a function of time are expected to be relatively constant until May 15th and then increase linearly for the remainder of the season. After May 15th, average harvest costs as a function of time can be estimated by the linear function:

$$HC = \rho t + \sigma$$

The estimated parameter values for pounds solids, boxes per acre, and harvest costs can be adjusted to fit an individual grower's Valencia crop. These values may vary widely based on many factors, including but not limited to grove location, tree and soil characteristics, and weather. Estimates generated in this analysis will attempt to represent a typical Florida grove.

Data

Data were gathered from FASS, industry contacts, previous published research, grower and processor records. Data on fruit quality characteristics, fruit yield per acre, and harvest costs per acre must be reported weekly, biweekly or monthly. Specifically, these data include pounds of sugar solids, boxes harvested per acre, juice volume, ratio of total soluble solids to total acid, and percent of fruit drop before harvest. Harvest cost data must be reported weekly or monthly and are based on the average cost fluctuation during the harvest season. While the cost data are primarily based on manual hand harvesting, mechanical harvesting does directly influence the cost for hand harvesting. Using the previously described data, estimates of the optimal harvest window will be expressed as a function of citrus quality attributes, yield, and harvest cost changes over time.

Growers closely monitor pounds solids because they are paid per pound solid extracted from the fruit they deliver to the processor. Valencia oranges increase in sugar concentration, and thus pounds solids, as they mature. Figure 1 shows the pounds solids for a sample grove during the 2005-2006 growing season increasing at a decreasing rate from February 1st until June 1st. Pounds solids per box eventually peak late in the season and are thought to decrease with increasing temperatures. Fruit harvested before or after sugar concentrations peak will contain sub optimal pounds solids and will return lower revenues to the grower. The line regressed on the pounds solids measurements from the sample in Figure 1 estimates how the solids changed during the 2005- 2006 season. The estimated equation, $y = -0.0004t^2 + 27.178t - 527122$, is a second order polynomial with a positive linear term and a relatively small negative quadratic term. While the parameter values will vary seasonally, the signs and relative size of the parameters should be consistent such that solids increase early in the harvest season, flatten out to a peak in May or June, and then decrease late in the season.

Juice yield per box determines growers' payments even though growers are not compensated directly on juice yield. Multiplying the percentage of pounds solids by the juice volume equals the amount of pounds solids. So as the volume of juice per box decreases, it is possible to have reductions in the pounds solids delivered to the plant. Figure 2 shows how juice yield per box changed during the 2005-2006 season in FASS sample groves (FASS, 2006). The sample groves saw juice yield peak near the beginning of the harvest season and gradually decrease during the season. While not depicted in Figure 2, the juice yield will continue to decrease through the summer as the fruit loses moisture. Valencias held on the tree until June or July may show drying at the stem end and continued decreases in juice yield.

Fruit quantity is usually measured in field boxes, defined by the industry as 90 pounds of Valencia oranges. The quantity of fruit produced per acre is determined by many characteristics known to the grower, such as number of trees per acre, age of trees, rootstock variety, and soil characteristics. However, some determinants of a grove's box yield per acre are less predictable from season to season. Two important factors that fluctuate both annually and during the season are fruit size and the fruit droppage rate. Fruit size increases early in the growing period but during the Valencia harvest period size is relatively constant. For processing to juice, both the grower and the processor usually prefer medium sized fruit; large fruit have a lower juice yield and small fruit can slow the juicing process. The fruit droppage rate is more variable and can have a direct negative effect on boxes harvested per acre. Fruit drop reduces the quantity of fruit available for harvest and decreases the pounds solids delivered to the processor. Fruit drop that occurs before harvest is possible will be considered a sunk cost and not affect the harvest decision. Only fruit drop occurring during the harvest season will affect the grower's harvest decision. The FASS reported a drop rate of 14-15% for the 2005-2006 Valencia crop (FASS, 2006). The droppage rate can increase later in the harvest season as temperatures increase and severe weather becomes more likely.

The Brix to acid ratio has little effect on the payments a grower will receive but it does limit the window in which fruit can be delivered to the processor. The FCC requires a minimum Brix to acid ratio that ranges between 9 to 1 and 10.5 to 1, depending on the percentage of pounds solids in the juice. In addition to industry regulations, stricter ratio limitations are usually agreed to when the processor contracts for purchase of the fruit. The processor wants to assure the ratio is within a range such that, with minimal blending, the final product is acceptable to the end consumer. Figure 3 shows the changes in Brix to acid ratio that were recorded during the 2005-2006 FASS test groves. Increases in sugars and decreases in acid concentrations cause the Brix to acid ratio to increase at an increasing rate during the harvesting season. The ratio during the 2005-2006 season reached the minimum required level in February, defining the beginning of the allowable Valencia harvest season.

In addition to the biological factors that affect on-tree revenues, there are several non-biological factors that determine grower returns and harvest timing. Growers attempting to maximize returns closely scrutinize two of these non-biological factors, allowable load allocations and fluctuating harvest costs.

As previously outlined, loads are allocated based on their remaining balance share, assuming that the fruit to be harvested is chemically ready to be picked. This scheduling system limits a grower's ability to process fruit within the optimal harvest window. Instead, fruit is harvested and processed at somewhat regular intervals over the course of the season. For example, a grower may be allotted 1000 boxes, or 2 trailers, of Valencia per week for 18 weeks between February and June. If the characteristics of the fruit are changing as the fruit matures over the course of the season, it can be assumed that a portion of the fruit was harvested at a suboptimal time to maximize grower returns. Processor estimates suggest there is a six-week window during which the fruit is at its peak quality (Anonymous processor, 2006). Assuming a similar optimal window for maximum grower returns, then during only 6 of the 18 harvest weeks is fruit harvested within the grower's optimal harvest window. Under these assumptions, two-thirds of the grower's crop would be harvested and processed at a suboptimal time. The grower may have received higher returns if allowed to deliver the entire crop within the optimal window. Conversely, revenues would have declined if the grower was only permitted to deliver fruit during suboptimal times.

The cost to harvest Valencia oranges fluctuates with respect to time. While annual changes are present in the industry, more important in this analysis is the change in cost during the harvest season. Only cost changes occurring during the season will be incorporated into this model as a function of time. Assuming all previously incurred production and management costs are sunk costs, the only relevant costs at the time of harvest are those for harvest and delivery to the processor. The average harvesting costs for Florida oranges for 2007 are estimated to be $2.010/box to pick and $2.512/box to roadside. These estimates assume a 4.25% three-year average annual increase in total harvesting costs (Muraro, 2004). This average cost does not account for difference in fruit variety or time of harvest.

Two factors that increase the cost per box of harvest during the season are decreasing labor supply due to increasing temperatures and less consistent picking schedules, and the increasing demand for hand labor in other agricultural crops. Early and mid season citrus harvest takes place when few other agricultural crops are being harvested. However, during the late season harvest, hand harvest labor demand increases in other regions of the country. Increasing employment opportunities, often offering higher wages and better working conditions, encourage the migrant sector of the labor pool to leave citrus harvesting crews. Some growers expect about a 10% weekly decrease in available labor after April 10th (Personal correspondence, July 2006). The final day of public school also plays a role in increasing harvest costs. Migrant workers with school aged children often wait for summer school closings before leaving the state to pursue additional employment.

Another harvest cost issue becoming increasingly important is the additional costs that arise after about May 15, the latest date that mechanical harvesters can be used. Hand harvest costs that may have been relatively constant until May 15th can increase suddenly as growers who were using mechanical harvesters switch over to hand crews. Figure 4 shows the rates to pick and roadside Valencia oranges for sample harvesting company during the 2003 – 2004 season. This shock to the hand labor market will induce a sudden change to the demand for harvest labor. A demand spike for labor accompanied by a supply decrease due to hotter picking conditions and increasing employment opportunities will act together to increase growers harvesting costs. This harvest cost increase is seen with late season fruit only; early season harvest is not affected.

Factoring together the expected changes in biological characteristics of the fruit, load allocations, and harvest costs, there is thought to be a several week window during which fruit is at an economic optimum for the processor to harvest and process. Assuming an 18-week period where most of the Valencia crop is harvested, the harvest could be separated into three sections. This hypothetical scenario could include a six-week early harvest, a six-week optimal harvest period, and a six week late harvest period. Estimates of the economic gains and losses to growers when harvest occurs during each harvest period could aid growers in harvest timing decisions.

Expected Results

There is expected to be a several week period during which harvesting and processing Valencia oranges will yield maximum profits for the grower. Deviating from this optimal harvest window should cause average grower profits to decrease due to either decreased fruit quality, decreased juice quantity, or increases in production costs. Over time, increases in profits could be realized from increases in fruit size and number of boxes or accumulation of sugars in the fruit.

For example, assume that a grower expects to harvest 48,000 boxes of Valencia oranges to be processed during the 20 weeks from the middle of February until the middle of July. Given a load allocation of 2,400 boxes per time period, the grower will deliver the upper bound each time period in order to process all fruit. This assumes that average revenue per box is greater than average cost per box to harvest. Assuming a low yielding crop of about 200 boxes per acre, the grower would harvest 12 acres of fruit per time period to fill the load allocation. Receiving a price of $1.00 per pound solid from the processor, returns for all fruit harvested during the season would be $267,849. As the upper bound load allocation is increased, the grower will begin to adjust fruit shipment to the processor in an attempt to maximize profits. More blocks of fruit would be harvested during time periods when pounds solids and yield per acre is higher and harvest costs are lower. If the grower were permitted to deliver all 48,000 boxes during the optimal time period, grower revenue would be $279,892. If forced to harvest the entire crop in the period with the lowest return, the crop is estimated to be worth only $237,663. Table 1 gives examples of other harvesting scenario outcomes when facing different crop yields and prices.

Discussion

The fact that quality attributes of the fruit change throughout the season is central to this research. Quality changes over time affect the price the grower receives for the fruit and the value of the fruit to the processor. While this research initially examines grower production decisions, the processor is also making a similar but more complex decision, which will also be evaluated. Insights gained from analyzing a grower's harvest problem should aid future research into identifying the optimal harvest window for a processor. The processor attempts to maximize returns while managing additional constraints and meeting additional quality standards; this more difficult harvesting problem entails scheduling the harvest, plant operations, storage, bottling, and shipment to retailers.

The larger scope of this research is to identify industry changes necessary for industry wide adoption of mechanical citrus harvesters. A shift from the labor-intensive hand harvesting process currently being used to a more capital-intensive mechanical harvesting process has been a goal for many in the citrus industry for over half a century. Technology is currently available to mechanically harvest oranges to be processed to juice. Mechanical harvesters have the potential to replace the majority of the required hand labor and to dramatically change the structure of the industry.

To assure a successful transition from manual to mechanical citrus harvesting, the most significant industry problems hindering adoption of mechanical harvesters must be identified and quantified in terms of potential economic consequences. The findings of this research will be used to develop a model to quantify and aid in solving the grower's decision to use mechanical harvesters.

Figure 1: Unadjusted Maturity Tests - Pounds Solids Average of Regular Bloom Fruit from Sample Groves, 2005-2006 season for late fruit

source: FASS 2006

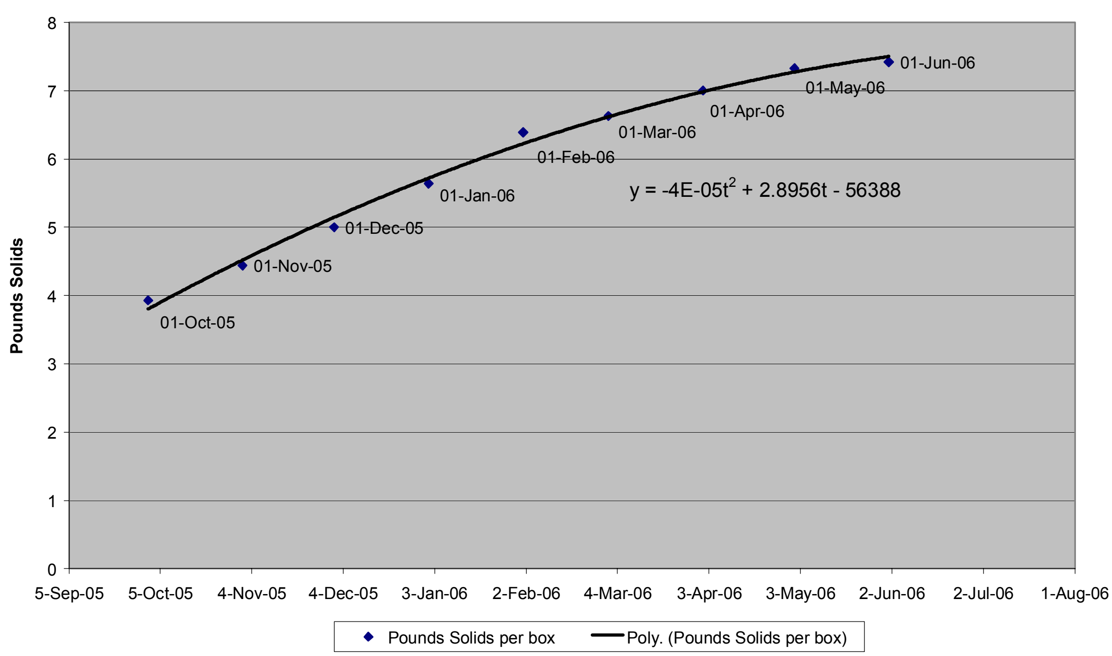

Figure 2: Unadjusted Maturity Tests - Average Unfinished Juice Yield per Box of Regular Bloom Fruit from Sample Groves, 2005-2006 season for late fruit
Source: FASS 2006

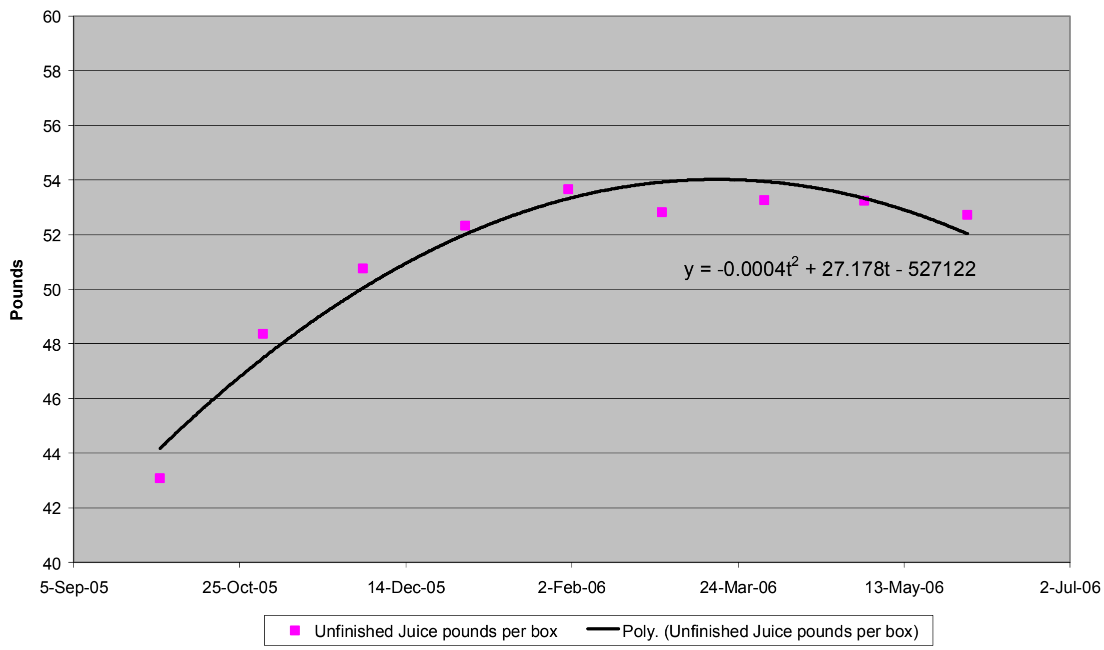

Figure 3: Unadjusted Maturity Test - Brix to Acid Raito Average of Regular Bloom Fruit from Sample Groves, 2005-2006 season for late fruit
Source: FASS 2006

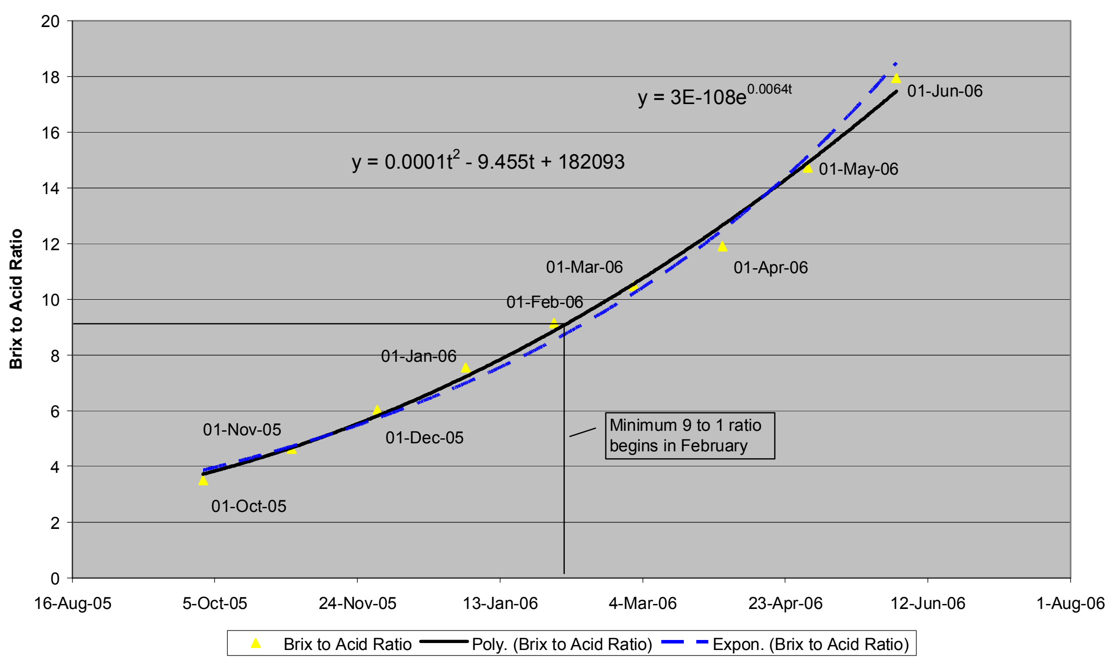

Figure 4: Pick and Roadside Rates to Harvest Valencia Oranges for a Sample Harvesting Company during the 2003 - 2004 Season
Source: Hyman 2004

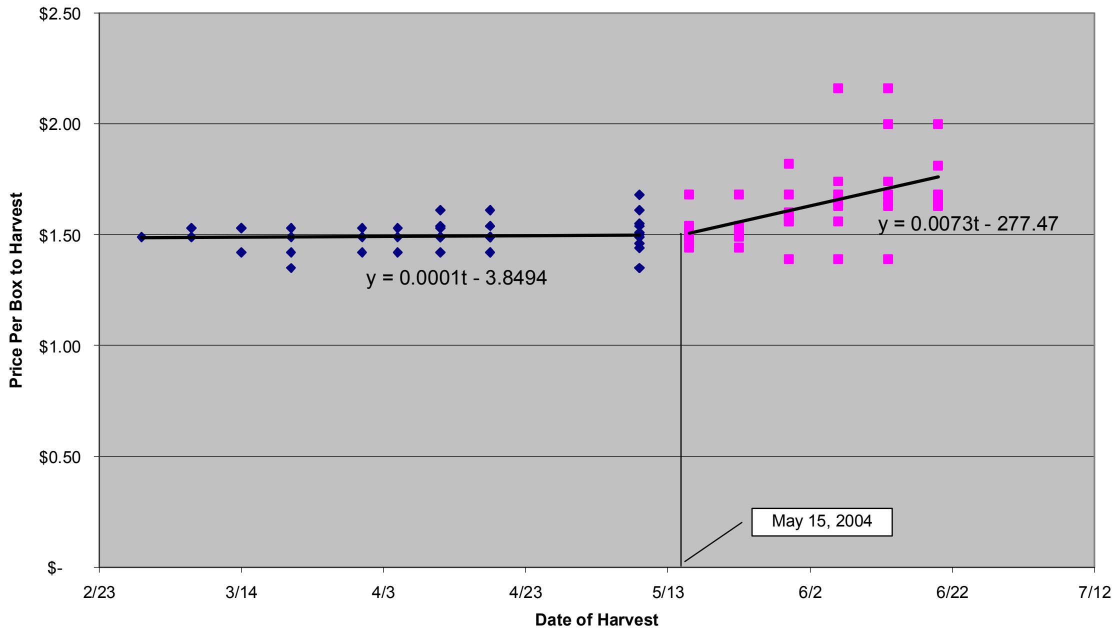

Table 1: Estimated Grower Returns from Valencia Harvest at Optimal and Suboptimal Harvest Dates, assuming 48,000 boxes harvested

Price Per Pound Solid	Box Yield Per Acre	Optimal Harvest Period	Returns from Complete Harvest in Optimal Period	Returns from Equal Quantity Harvested Each Period	Loss from Suboptimal Harvest	Optimal Harvest Returns Per Acre
$ 1.00	200	June, week 2	$ 279,892	$ 267,849	$ 12,043	$ 23,324
$ 1.00	400	June, week 2	$ 279,884	$ 267,842	$ 12,042	$ 46,647
$ 1.00	600	June, week 2	$ 279,895	$ 267,850	$ 12,045	$ 69,974
$ 2.00	200	July, week 1	$ 643,502	$ 610,962	$ 32,540	$ 53,625
$ 2.00	400	July, week 1	$ 643,490	$ 610,952	$ 32,538	$ 107,248
$ 2.00	600	July, week 1	$ 643,507	$ 610,965	$ 32,543	$ 160,877

Source: FASS, Hyman

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