# Improving the Economic Viability of Florida Citrus by Enhancing Mechanical Harvesting with the Abscission Agent CMNP

Fritz M. Roka
Jacqueline K. Burns
Jim Syvertsen
Tim Spann
Barbara Hyman

**University of Florida**
**Institute of Food and Agricultural Sciences**

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## Executive Summary

The Florida processed citrus industry faces a serious competitive threat from foreign producers, particularly Brazil, based upon the differential in manual harvest labor cost. The Florida industry has addressed this issue by developing mechanical harvesting systems that can bring costs in line with those of Brazilian hand labor. However, widespread adoption and full realization of the efficiencies of mechanical harvesting require an abscission agent harvesting aid that will selectively loosen fruit. The introduction of an abscission agent is the missing component from what is expected to be a new model for citrus harvesting systems.

The Florida citrus industry is comprised of more than 6,000 farms and employs more than 5,000 people full time, with an additional 20 to 25,000 workers during the harvesting season. Sweet orange production and juice processing contribute more than $9 billion annually to Florida's economy. As the 2008-09 season begins, orange growers in Florida confront serious challenges from global competition, labor availability, diseases, and urban development. Continued profitability of the Florida citrus industry depends on developing and implementing new technologies that lower production costs, especially those that reduce dependence on manual labor to harvest fruit. Mechanical harvesting systems encompass a collection of technologies that hold significant potential to reduce harvest costs, lessen demand for manual harvest labor by 90%, and create job opportunities for a new skilled work force. Savings generated from mechanical harvesting will allow Florida citrus growers to remain economically competitive within the global market place for orange juice and will offset rising costs from cultural management strategies.

The Florida Department of Citrus (DOC) has led an aggressive effort to develop and adopt mechanical harvesting technologies. The use of mechanical canopy and trunk shakers has steadily increased since 1999 and during the 2007-08 season, more than 9.6 million 90-lb (40.1 kg) boxes of oranges were mechanically harvested from 31,000 acres. Growers who have adopted mechanical harvesting have lowered harvesting costs by 10-20% as compared to conventional hand harvesting. Widespread adoption of mechanical harvesting is predicted to save growers more than 50% over current harvesting costs and reduce concerns with labor availability. Despite the current and potential cost savings, many growers have been slow to embrace mechanical harvesting and the adoption rate of mechanical harvesting has reached a plateau at seven percent of total acreage. In order to achieve widespread adoption, the mechanical harvesting process must be complemented with an abscission agent.

The most significant concern among growers is the inability to harvest 'Valencia' sweet orange cultivar during the "late season" without significant yield losses. Mechanically harvesting during May and June can inadvertently remove young developing 'Valencia' fruit and reduce next year's yield by as much as 50%. Many commercial industry and grower cooperative members believe that a suitable abscission agent would solve the late season harvesting challenge. A suitable abscission agent will selectively loosen mature fruit so that reduced mechanical shaking frequency can be used to harvest. In doing so, mature fruit selectively loosened with an abscission agent will be harvested, while young fruitlets will not be removed

and next year's yield will be preserved. Solving the late season harvesting challenge would be the boost needed to increase mechanical harvesting acreage and maximize economic benefit for citrus growers. Thus, the economic potential of mechanical harvesting will be maximized by the use of a suitable abscission agent. Published research supports the premise that application of the abscission agent CMNP (5-chloro-3-methyl-4-nitro-1*H*-pyrazole) will greatly enhance the capacity of existing mechanical harvesting equipment for the following reasons: 1) extend mechanical harvesting operation through the entire 'Valencia' late-season harvest window, 2) allow equipment to operate faster, thereby harvest more boxes per hour, and 3) improve fruit recovery percentage.

Another reason for delayed grower acceptance is the perception that visible tree damage incurred by harvesting equipment will adversely affect tree health and long-term production. Published research does not support this perception, and well-managed citrus trees show no effect on crop yields or tree mortality. With an abscission agent application, mechanical harvesters will be able to operate at a lower intensity, thus leading to a reduction in cosmetic tree damage. This improvement in the harvesting process should help lessen grower concerns about adverse effects from mechanical harvesting on crop yields and tree health. An additional benefit of reducing harvesting intensity in combination with the loosening effect of an abscission agent is the delivery of cleaner loads of fruit to the processing facilities due a reduction in limb and leaf debris.

Research supporting the above criteria for CMNP has been published since the 1970s. Economic models predict that mechanical harvesting coupled with CMNP application would significantly expand acreage to be mechanically harvested. More efficient use of harvesting equipment coupled with CMNP application would lower overall costs of harvesting and bring the costs of harvesting Florida citrus into parity with its largest international competitor, Brazil.

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# 1. General Situation and Industry Overview

Sweet oranges hold a special cultural significance in Florida as the state's signature agricultural crop. The orange adorns the official state license tag, orange juice is designated as the official state beverage, and the orange blossom is recognized as the official state flower (Online Sunshine, 2008). Oranges for juice processing are Florida's primary citrus crop. Florida produces more than 75% of the oranges grown in the United States, and of the total Florida orange crop, 95% is processed into juice (FASS, 2008).

The Florida orange juice industry faces stiff competition from foreign producers, particularly from Brazil, where growers enjoy a significantly lower cost of manual harvest labor. In addition to global competition, the Florida citrus industry confronts serious challenges with respect to labor availability, disease pressures, and urban development. Mechanical harvesting is emerging as a key technology that could simultaneously address these multiple threats by lowering overall costs and reducing the demand for manual labor. The development of mechanical harvesting is part of the industry's long history of meeting challenges with technological ingenuity. Triple-strength frozen concentrate orange juice (FCOJ) was invented during the 1940s by a team of researchers from the Florida Department of Citrus (FDOC) and United States Department of Agriculture (USDA) as a way to ensure freshness and consistency of large quantities of orange juice. When more than 20% of Florida's citrus production was lost during the 1980s from devastating freezes, acreage was replanted in the southern "flatwood" region, which carried a low historic freeze probability but required the development of new production systems to handle higher water tables; within seven years, citrus production exceeded record levels. In more recent years, Not-from-concentrate (NFC) orange juice has been developed, in part, to counter Brazilian low-cost production of FCOJ. Today's challenges call upon the Florida citrus industry to make progressive changes in the way it harvests fruit. The path the Florida citrus industry has chosen to overcome this current challenge has again highlighted its ingenuity and assures its continuing success.

Mechanical harvesting embraces two consensus principles developed by citrus industry leaders, university scientists, and government officials. First, the continued economic viability of the Florida citrus industry depends on developing and implementing new technologies that lower production costs. Second, future citrus production practices, most notably harvesting, must depend on fewer people. Mechanical harvesting encompasses a collection of technologies that hold significant potential to reduce harvesting costs and to lessen the demand for manual labor currently required to harvest Florida's citrus crops. While existing mechanical systems can effectively harvest fruit, they face a number of significant obstacles. A critical component missing from current harvesting systems has been identified to be an effective abscission agent. An abscission agent is a compound sprayed on mature fruit. The purpose of an abscission agent application is to loosen mature fruit and enhance the overall performance of harvesting machines. An effective abscission agent will facilitate the full realization of mechanical harvesting efficiencies and thereby lower net costs of harvesting. The savings generated from mechanical harvesting will offset rising production costs and allow Florida citrus growers to remain economically competitive within a global market place for orange juice.

## 1.1 Objectives

The purpose of this paper is to compile evidence in support the following statements:

1. Widespread adoption of mechanical harvesting is critical for long-term economic viability of the Florida citrus industry.
2. Maximizing economic potential of mechanical harvesting will depend on the inclusion of an effective abscission agent.

The primary objective of mechanical harvesting is to reduce growers' harvesting costs. Mechanical harvesting refers to any system that replaces manual labor to remove and collect fruit from citrus trees. Mechanical harvesting can be facilitated with the application of an abscission agent that substantially lowers the detachment force required to remove fruit from trees. An effective abscission agent will significantly improve the efficiency of mechanical harvesting equipment and lower unit harvesting costs.

## 1.2. Importance of Florida processing orange production

**1.2.1. Worldwide production and Florida**. Citrus fruit are among the world's most important and nutritious commodities, contributing over 27% of total dietary vitamin C content per serving (NASS, 2008). Oranges account for approximately two thirds of the world production of all citrus fruit. Worldwide orange production is 46.8 million tons per year. About 40% of the total tonnage is processed into commercial juice, whereas the remaining is sold for fresh fruit consumption. The two most important orange juice processing regions are Florida, USA, and Sao Paulo, Brazil. Together, Florida and Brazil account for 53.7% of total global commercial orange juice production (FASS, 2008).

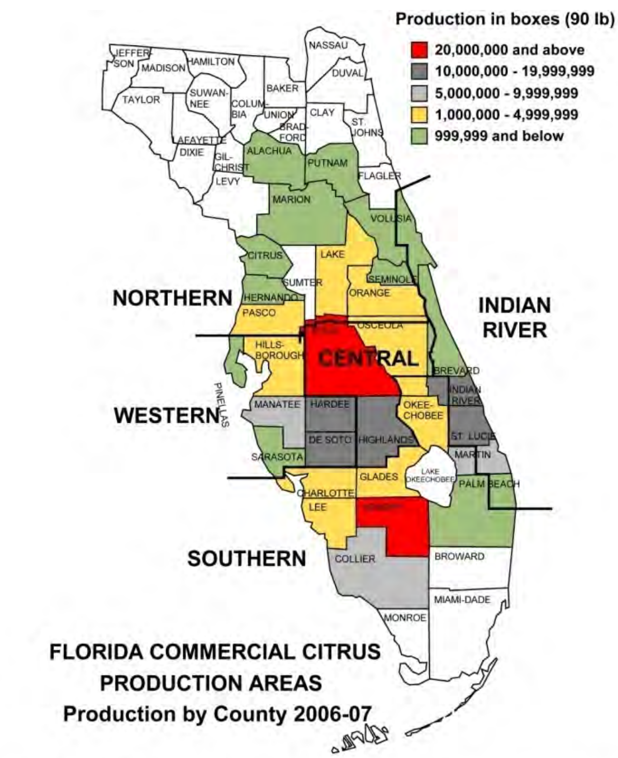


Figure 1. Florida citrus producing regions and counties, 2006-07.

Commercial cultivation of oranges intended for large-scale processing into fruit sections and juice began in Florida in the 1920s. In the late 1940s, FCOJ developed for home preparation led to a rapid growth in orange juice consumption throughout the USA. As a result, the cultivation and processing capacity of oranges in Florida grew rapidly. Severe frosts in Florida drastically reduced fruit yields and killed many trees during the 1960s, 1970s and 1980s. In response to production disruptions in Florida, several US orange juice companies formed partnerships with Brazilian agri-business interests to secure a more stable supply of orange juice for the US market. Orange tree acreage was expanded in Brazil and the first juice concentrate plant in Brazil was built in the early 1960s. Brazilian orange acreage and processing capacity continued to expand during the 1970s and 1980s. In 1983, Brazil surpassed Florida as the world's leading orange producer (Tetra Pak, 1998).

**1.2.2. Florida production trends and processed oranges**. Citrus is grown in 30 of Florida's 67 counties (Figure 1). Today, more than 80% of the citrus crop is grown within 10 counties located south of the I-4 Interstate that bisects the peninsula through Tampa, Orlando, and Daytona Beach. The top two counties in citrus production are Polk and Hendry (highlighted in red; Figure 1). A breakdown of citrus acreage by county is provided (Appendix 1). More than 93% of total acres are bearing trees with the balance non-bearing, or trees less than 3-years-old (FASS, 2006b). Freezes during the 1980s reduced bearing tree acreage by one-third from 758,000 acres in 1980 to 508,000 acres in 1985 (FASS, 1998). Bearing tree acreage rebounded to more than 815,000 acres by 1996 with large new plantings in southwest Florida counties of Charlotte, Collier, Hendry and Lee. Large crops from both Florida and Sao Paulo, Brazil, in the mid to late 1990s drove market prices downward, and incentive to further expand citrus acreage in Florida ceased.

Table 1. Trends in total bearing citrus, orange, and Valencia acreage (thousands of acres) since 1996 in Florida.

| Season | Total Bearing Citrus Acreage (1,000 ac) | Total Bearing Orange Acreage (1,000 ac) | Valencia Acreage (1,000 ac) | Orange Proportion of Total Citrus (%) | Valencia Proportion of Total Orange (%) |
|---|---|---|---|---|---|
| 1996 | 815.1 | 624.9 | 296.0 | 77% | 47% |
| 1997 | 785.9 | 609.2 | 291.8 | 77% | 48% |
| 1998 | 777.1 | 612.6 | 294.9 | 79% | 48% |
| 1999 | 762.4 | 602.1 | 295.4 | 79% | 49% |
| 2000 | 756.0 | 605.0 | 302.9 | 80% | 50% |
| 2001 | 727.6 | 586.9 | 300.5 | 81% | 51% |
| 2002 | 718.1 | 587.6 | 304.6 | 82% | 52% |
| 2003 | 679.0 | 564.8 | 298.5 | 83% | 53% |
| 2004 | 641.4 | 541.8 | 292.5 | 85% | 54% |
| 2005 | 576.4 | 491.0 | 270.6 | 85% | 55% |
| 2006 | 554.4 | 475.9 | 263.2 | 86% | 55% |

Source: FASS, 2008

Since 1996, bearing acreage has steadily declined to 554,000 in 2006 (Table 1). While bearing tree acreage has declined, the relative importance of orange production has increased. As a percentage of total bearing tree acreage, orange varieties have increased from 77% in 1996 to 86% in 2006. 'Valencia' acreage has grown relative to the other important orange variety, 'Hamlin.' In 1996, 'Valencia' acreage accounted for 47% of the total acreage in oranges. By 2006, more than 55% of the Florida orange acreage was planted to 'Valencia' trees.

Oranges do not ripen quickly, but instead mature slowly over time. They must remain on the tree to attain full sweetness, proper acidity, and flavor. Unlike bananas, which continue to ripen after harvest, citrus fruit and juice quality begin to deteriorate after picking. Consequently, the time between picking fruit and processing it into juice must be as short as possible. Harvesting schedules are timed so that the juice is extracted from oranges within 24 hours of arrival to the processing plant. In large processing plants, the complete fruit is utilized. By-products from pulp, peel, and oil are produced to maximize profits and minimize waste. Juice processors coordinate harvesting schedules throughout the season to best match fruit quality with juice requirements and, at the same time, minimize the costs of their juice processing and storage operations. Some storage of juice is necessary to bridge fruit production gaps and ensure consistent juice quality year-round. Juices from early and late fruit varieties differ in quality with regard to color and sugar content. To deliver products of specified and consistent quality throughout the year, FCOJ suppliers blend concentrates produced from different orange varieties. Several varieties are grown with different maturation periods (Figure 2) to provide a season-long product. Varieties are grouped by early-, mid-, and late-season harvest periods. In Florida, early season harvest begins with the variety 'Hamlin' in mid-October and extends through June with the late-season harvest of 'Valencia' oranges. 'Pineapple' is an example of a mid-season variety whose harvest period overlaps with both 'Hamlin' and 'Valencia' oranges. Most growers plant multiple varieties to prolong the harvest season and capitalize on each variety's strengths while minimizing their inherent weaknesses. 'Valencia' is considered the best quality fruit in terms of juice color and solids (sugar) production. 'Valencia' juice has become an important constituent for NFC blends. In some cases, "premium" NFC product is made exclusively from 'Valencia' fruit.

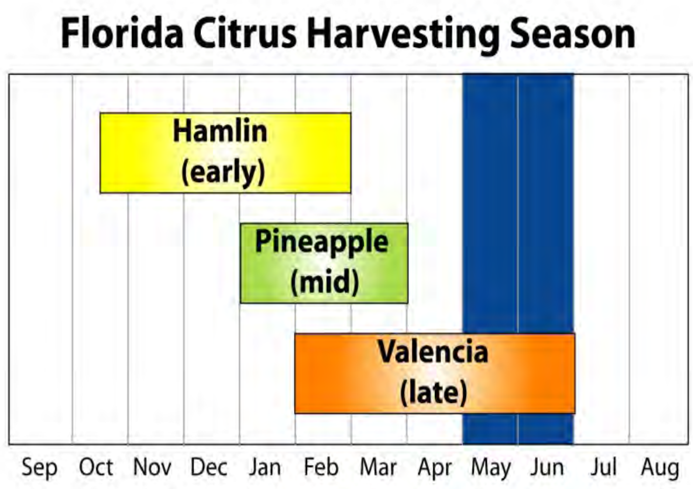


Figure 2. The Florida citrus processed sweet orange harvesting season. Varieties are indicated in boxes. Dark blue shading shows relative time of year for late season Valencia harvesting.

**1.2.3. The economic importance of processed citrus to Florida**. With the exception of the 1998-99 season when a freeze diminished tree yields, total orange production remained over 200 million boxes between 1996 and 2003 (Table 2). Hurricanes in 2004 and 2005 adversely affected every citrus production region in Florida, and production effects lingered into the 2006-07 season. Production rebounded to more than 170 million boxes during the 2007-08 season, and the upcoming 2008-09 season was projected to yield 166 million boxes of oranges (USDA, 2008). Offsetting the recent production setbacks have been favorable market prices. Cash receipts for oranges in the 2006-07 season were $1.18 billion, an historic high despite 113 million fewer boxes than what was produced in 2003. The annual farm-gate value of Florida's agricultural commodities exceeds $7.7 billion, and fruit sales of citrus contribute more than 20% (DACS, 2007). During the 2006-07 season, on-tree value of all citrus fruit surpassed $1.3 billion (FASS, 2008). More than 6,000 farms produce citrus in Florida (USDA, 2009). These farms collectively employ more than 5,000 workers in grove care activities and an additional 20 to 25,000 seasonal

Table 2. Orange Production (millions of boxes), boxes and percentage of total orange crop processed into juice, and total value of on-tree production of oranges (millions of dollars).

| Season[1] | Total Orange Production (MM box) | Total Orange Processed (MM box) | Proportion of Total Orange Production - Processed (%) | Total Orange Value ($MM) |
|---|---|---|---|---|
| 1996 | 226.2 | 215.5 | 96% | $801.3 |
| 1997 | 244.0 | 233.0 | 95% | $900.8 |
| 1998 | 186.0 | 175.1 | 94% | $900.0 |
| 1999 | 233.0 | 223.6 | 96% | $856.1 |
| 2000 | 223.3 | 213.6 | 96% | $716.1 |
| 2001 | 230.0 | 220.6 | 96% | $797.6 |
| 2002 | 203.0 | 193.3 | 95% | $643.8 |
| 2003 | 242.0 | 232.1 | 96% | $699.9 |
| 2004 | 149.8 | 142.4 | 95% | $522.9 |
| 2005 | 147.7 | 140.4 | 95% | $813.3 |
| 2006 | 129.0 | 122.6 | 95% | $1,310.8 |
| 2007 preliminary | 170.2 | 164.3 | 96% | $1,057.4 |
| 2008[2] projected | 166.0 | | | |

Sources: [1]FASS, 2008; [2]USDA, 2008.

people to harvest the fruit (Spreen, et al., 2006, on page 30 reports 15,863 full time equivalents directly employed by Florida citrus growers. For harvesting, at least two people equate to one full time equivalent since a single harvester works typically between 5 and 7 months per year). Florida citrus supports important Florida manufacturing sectors of juice processing and fresh fruit packing. A total economic impact of the Florida citrus industry, as defined from fruit production through juice processing during the 2005-06 season, was estimated to be $9.3 billion (p.30, Spreen et al., 2006). Annual sales of citrus juice, fresh fruit, and associated by-products account for $3.7 billion. Another $5.6 billion of "indirect" and "induced" impacts are associated with the Florida citrus industry. Indirect impacts accrue to firms that supply materials, equipment, and services to citrus growers, harvesters, processors, and packers. Induced impacts are created when employees of citrus operations and their suppliers spend their wages and earnings on consumer goods. Despite changes in production, consumer preferences and spending, the overall importance of the citrus industry in Florida has remained stable. An earlier study utilizing 2003 data, estimated total economic impact from Florida citrus to be $9 billion (Hodges et al., 2006).

# 2. Challenges to the Florida Citrus Industry

Harvesting cost and labor supply, global competition, disease and pest infestations, and urbanization are major challenges confronting the Florida citrus industry. These challenges add cost and/or threaten economic sustainability of the citrus industry. In response to recent disease and pest challenges, Florida citrus growers through a self-imposed box-tax have augmented the annual citrus research budget to more than $20 million. The industry has worked closely with other agricultural organizations to draft federal legislation seeking to provide legal foreign guest workers that will allay fears of labor shortages. Most importantly, the industry is working to incorporate mechanical harvesting technologies to address threats arising from disease pressures, labor supply insecurities, and economic implications from global competition. Since 1995, the Florida Department of Citrus has invested $15 million of grower taxes into mechanical harvesting and abscission research and development.

## 2.1. Harvesting cost and labor supply

**2.1.1. Harvesting cost**. The steps involved in harvesting oranges for juice processing for both hand and mechanical systems are presented in Appendix 2. Until recently, harvesting was done exclusively by hand labor. Workers in hand harvesting crews are hired to remove, or pick, fruit from the trees and fill collection tubs positioned at the base of trees. Labor productivity for citrus harvesters averages 8 to 12 boxes per hour (Roka and Emerson, 1999; Polopolus, et al., 1996). As one box equals 90 pounds, on average a citrus harvester picks between 720 and 1,080 pounds of fruit per hour of work. If trees yield 3 boxes, a single worker harvests between 2 and 4 trees per hour. Demand for harvest labor occurs throughout the harvest season that spans from October through June. Total labor demand for harvest workers is between 20 and 25,000 people during mid-February: considered the peak week of citrus harvesting (Polopolus et al., 1996).

Citrus harvesters are paid a piece rate for every box they pick. For processed oranges, the harvesting piece rate ranged between 70 and 75 cents per box until the 2004 season. Lower crop yields and competition for workers from the construction industry increased average piece rates to over 80 cents per box. Average hourly earnings (piece rate in $/box multiplied by worker productivity in boxes/hr) of citrus harvesters range between $7 - 8 per hour (Roka and Emerson, 1999), but effective unit costs of picking increased with increases in Florida’s minimum wage. If a worker’s productivity is low such that he fails to earn minimum wage, his total earnings are supplemented until the minimum wage threshold is covered. Effective January 1, 2009, Florida minimum wage increases from $6.79 to $7.21 per hour and as of July 24, 2009, the U.S. federal minimum wage will surpass the Florida rate at $7.25 (USDOL, 2008). For a worker who picks an average of 8 boxes per hour, a 70 cent piece rate met minimum wage requirements in 2004 when both the state and federal minimum wage rates were $5.15 per hour. By the start of the 2009 harvest season, the “effective” piece rate for a worker who picks 8 boxes per hour will have to be increased to at least 91 cents per box in order for the worker to earn the minimum wage of $7.25 per hour.

In addition to the piece or pick rate, a grower pays for “roadsiding.” This is the charge to move fruit from collection tubs in the grove to a bulk trailer that transports fruit to a processing plant (see Appendix 2). Roadside charges cover the costs of a field supervisor (crew leader), equipment, employment taxes (FICA, workman’s comp, etc), insurance, and contractor profit. In general, roadside charges are equivalent to the pick rate.

The sum of pick and roadside charges equals the unit cost to harvest with manual labor and serves as the economic reference point against which mechanical harvesting systems will be evaluated. Additional costs associated with harvesting machines include equipment ownership, fuel, and repairs. As such, harvesting machine costs would be insulated from rising market wages for labor. ‘Hauling’ charges include costs associated with transport of bulk semi trailers of fruit to the processing plant. These charges are the same for either hand or mechanical harvesting methods. Haul costs vary with fuel costs and distance to the processing plant, but are generally less than 33% of the cost of picking and roadsiding.

The cost for Florida growers to hand harvest and haul oranges to processing plants exceeds the cost of production. During the 1990s, costs ranged from $1.80 and $1.90 per box to pick, roadside, and haul fruit to a processing plant (Figure 3; Muraro, 2008). By 2002, harvesting costs increased to more than $2.60 per box during the 2005-06 season. Strong competition for labor from the booming construction industry after 2002 put upward pressure on hand labor costs. Since late 2006, residential and commercial construction has waned significantly, forcing more workers back toward agricultural jobs. Despite increased labor availability and better tree yields, hand harvest pick, roadside and haul costs have only dropped slightly in the past two seasons, from $2.64 in 2005-06 to $2.53 per box in 2007-08 (Muraro, 2008).

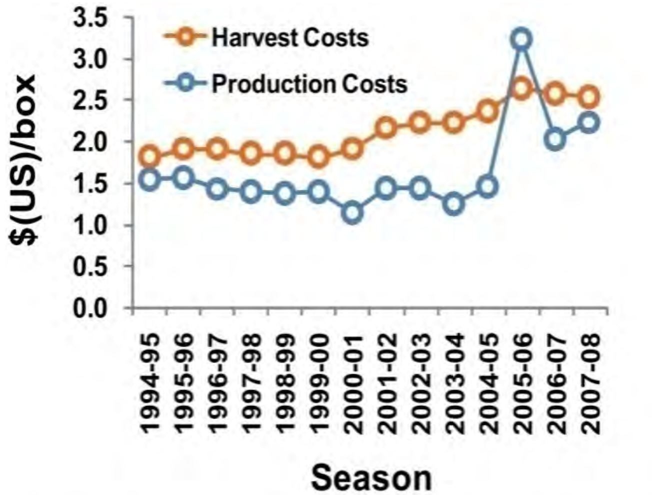

Figure 3. Comparison of Florida harvesting (pick and roadside) and production costs ($(US)/box) between the 1994-95 and 2007-08 harvest seasons.

A spike in production costs occurred during the 2005-06 season. The marked increase in production costs was a result of growers spending significant dollars to reset and rehabilitate trees damaged during 2004 and 2005 hurricanes. Production costs in 2006 and 2007 continued an upward trend due to increased costs from controlling citrus greening and canker diseases. Marked increases in production costs emphasize the need for harvesting technologies that offset rising production costs.

**2.1.2. Labor supply**. The recent debate over immigration reform has heightened concerns about availability of workers to harvest citrus (Kates, 2006; Sparks, 2008). More than 80 percent of harvest workers are foreign born, and between 50% and 75% of all harvesters are working without legal documentation (NAWS, 2005). The No-Match rule, drafted by the U.S. Dept of Homeland Security (DHS) in August 2007, outlines stiff penalties on employers/growers who hire workers without a valid social security number. Implementation (has not yet become official) of the No-Match rule could significantly disrupt the flow of workers that Florida citrus growers rely upon to harvest their crops. One option for growers would be to recruit foreign guest workers under the existing H2-A program. This program, however, is administratively cumbersome, costly, and difficult to implement. An employer of guest workers pays for housing and transportation to and from their country of origin and guarantees that all guest workers will be paid for at least 75 percent of the contract period and be paid no less than the adverse effect wage rate (AEWR). The AEWR for citrus harvesters in Florida during the 2007-08 season was $8.56 per hour and will likely increase in the future. Beyond the AEWR, harvesters utilizing the H-2A program are facing local concerns over providing housing for these guest employees. During 2007 and 2008, local governments citing public concern halted two large housing projects presented by local growers, even though the projects met zoning requirements (Bouffard, 2008;

Sica, 2008). Growers and harvesting companies will continue to work within the current program, but are actively asking for alternatives. These alternatives will present themselves as new harvesting technologies and program reforms.

## 2.2. Global competition

Brazil is the largest worldwide producer of oranges. In 2006-07, Brazil produced over 18,200 metric tons of oranges, whereas Florida produced about 6,800 metric tons (FASS, 2008). China produced 4,800 metric tons of oranges in 2006-07 and is currently third in worldwide production. The 3 top world producers face significant challenges from disease and pest infestations (see below). Brazil and China, however, currently enjoy an inexpensive and abundant labor pool and lack many regulatory constraints faced by Florida citrus producers. It is critical that Florida producers adopt technologies such as mechanical harvesting that will lower total costs and enable the state to successfully compete in the global marketplace.

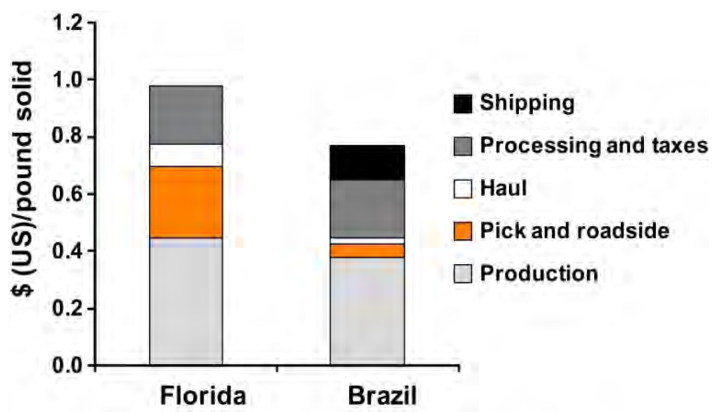


Figure 4. Comparison of costs ($(US)/pound solid.) between Florida and Sao Paulo, Brazil, to produce, harvest (pick and roadside), and haul fruit, and to process and ship FCOJ to the port of Tampa, FL, 2000-01 season.

Orange juice is a commodity, and as such, a distinct competitive advantage goes to low-cost producers. A comparison of citrus production, harvesting, hauling, processing and shipping costs between Florida and Brazil highlights cost inequities. A cost analysis of orange production during the 2000-01 season indicated that Brazilian growers were able to grow, harvest, process, and ship FCOJ to the port of Tampa for 20 cents per pound-solid (a unit of measurement for oranges sold for juice processing and the basis for grower payment; one box of oranges equals approximately 6 pound-solids) less than what it would cost a Florida grower (Figure 4; Muraro et al., 2003). The greatest cost disadvantage, or conversely, the greatest opportunity for cost reduction for the Florida industry, lies in the harvesting (pick and roadside) operation. Pick and roadside costs have been approximately three times higher in


Figure 5. Comparative pick and roadside costs between Florida and Brazil.

Florida than in Brazil (Figure 5).

## 2.3. Disease and pest infestations

Two diseases currently confronting Florida citrus growers are canker and huanglongbing (HLB or citrus greening). Multiple hurricane events in a two-year period (2004 and 2005) spread canker bacteria throughout Florida citrus production regions. In January 2006, canker eradication efforts were terminated and management of the disease became the strategy. Barring infected fruit from fresh marketing channels is the primary economic impact from canker. Fruit with canker lesions can be used for juice processing but is not suitable to be sold as fresh fruit.

HLB is a more significant disease because it threatens to destroy trees, or at least diminish crop yields to uneconomic levels. While HLB is spread throughout the world, it is relatively new to Florida, having been first confirmed in the Miami-Dade area in August of 2005. As of fall 2008, the disease has spread to 32 of Florida's 64 counties. The disease is vectored by the Asian citrus psyllid. The psyllid has been endemic in Florida since 1998 and has numerous alternate hosts common to Florida (Halbert et al., 2008). For these reasons, APHIS-USDA announced in 2005 that it would not pursue an eradication program for HLB (Spreen et al., 2006). Current management and control recommendations include quarterly tree scouting, increased pesticide applications to control psyllid populations, and removal of symptomatic trees. Scouting, psyllid control, and tree replacement costs are estimated to increase grove care costs by at least \$300 per acre (Muraro, 2008). Along with the increased costs associated with controlling pests and disease, increased management is needed to limit worker exposure to pesticides. Recommendations for the control of psyllid populations advise applications of various control agents up to eight times a year, most of which occur during the harvesting season (Rogers, 2009). Mechanical harvesting allows agricultural workers to conduct the harvesting process within enclosed machinery, protected from the grove environment. An increased harvesting rate with mechanical harvesting will also allow management to schedule the harvest with greater ease and flexibility.

The Florida citrus industry remains confident that a solution to HLB will be found. The long-term solution for HLB will be to develop disease resistant varieties. Until then, growers must implement new production strategies and technologies that allow increased annual per-acre profits. One such technology, mechanical harvesting coupled with the application of a fruit abscission agent, will reduce harvesting costs and increase on-tree returns. Such economic gains are critically important to offset higher costs associated with emerging management strategies. The fact that citrus groves may be replanted on a more frequent basis due to disease pressures may work to the advantage of evolving mechanical harvesting technologies. New planting architectures can be tailored for mechanical harvesting so that its full cost advantage can be realized.

## 2.4. Urbanization

Florida's subtropical climate is ideal for processing orange production. Florida sunshine, however, also attracts new residents from temperate climate areas in the United States and beyond. Between 1990 and 2000, Florida's population grew more than 23%, from 12.9 million to nearly 16 million people. By 2010, the state's population will be approaching 20 million people (EDR, 2008).

Urban development, once confined to the coastline, has begun pushing inland, removing existing grove land and driving up the price of remaining open land. Unimproved pasture land values increased from $2,600 in 2004 to $7,700 per acre in 2007. Transitional lands, located in close proximity to urban development, currently average more than $25,000 per acre in the southern region of Florida (Clouser et al., 2008; Clouser et al., 2007; Reynolds, 2006).

Rising land values impact citrus and agricultural operations in two ways. First, if new land is purchased with a mortgage, higher land prices increase production costs directly through higher interest payments. Second, and more importantly, rising land values eventually create an economic incentive to "cash-out" of agriculture by selling land for residential and/or commercial development.

Mechanical harvesting promises to augment existing citrus land profits by reducing harvesting costs per unit area, thereby increasing on-tree returns. Although mechanical harvesting technology may not change the eventual conversion of land from citrus to non-agricultural uses, enhancing income from citrus production through mechanical harvesting could significantly delay or prevent "cash-out" decisions.

# 3. Citrus Mechanical Harvesting

## 3.1. History

Initial efforts to develop mechanical harvesting systems were motivated by concerns over labor supply. Development of citrus mechanical harvesting systems began in Florida during the late 1950s. Citrus acreage and production in Florida had been steadily increasing since World War II and growers began to worry over whether a sufficient number of workers would be available to harvest the expanding crop volume. As a result of such concerns, labor-saving technologies were explored (Whitney, 1995). While some research was directed toward harvest aids such as man-positioners, the bulk of the research focused on mechanical picking systems. Limb, trunk, and area canopy shakers achieved fruit removal rates of up to 90% on early and mid-season varieties with minimal effect on future crop yields. The value of an abscission, or fruit loosening, agent was quickly recognized as a necessity for harvesting 'Valencia' oranges during the latter part of the harvesting season. Trunk shaking trials during the late 1960s and early 1970s indicated that mechanically harvesting 'Valencia' trees during late May and June caused crop yields to decline by up to 40% the following season (Whitney, 1976). It was widely viewed that a suitable abscission agent could selectively loosen the current year's mature crop without affecting next year's emerging crop (Whitney, 2006).

For several reasons, the pace of mechanical harvesting and abscission agent research slowed during the late 1970s, and by the early 1980s stopped altogether. First, early mechanical systems provided only a three-fold increase in labor productivity, and thus, not a sufficiently strong economic justification for commercial investment into mechanical harvesting systems. Second, the prevailing USDA policy discouraged development of "labor-saving" technology and consequently, federal funding for mechanical harvesting research ceased. Third, a series of devastating freezes occurred during the 1980s, and statewide citrus production fell by more than 20%. Market prices of fruit rose, and with less fruit to harvest, manual labor was available in sufficient numbers. Without the incentive of lower harvest costs and no imminent threat of labor shortages, research and development of mechanical harvesting systems and abscission agents ended.

One outcome of successive freezes during the 1980s was to stimulate expansion of citrus acreage into the flatwood soils of southwest Florida that were viewed to be less prone to citrus-killing freezes. Citrus acreage in southwest Florida expanded from 51,760 acres in 1980 to 179,093 acres in 1995 (FASS, 1982; 1998). Much of the expansion in southwest Florida was led by corporate operations which planted citrus in large contiguous blocks. Single tree rows averaged 1,500 feet long. Uniform tree planting, large acreage and long rows proved to be conducive for efficient operation of mechanical harvesting equipment.

Interest in citrus mechanical harvesting renewed during the mid 1990s for reasons similar to those that initiated interest in mechanical harvesting during the late 1950s. Expanding acreage and production in southwest Florida once again raised industry concerns about whether there were sufficient numbers of harvest workers. But unlike the situation in the 1950s, Brazil had ascended to the position of world leader in orange juice production. Lower land development costs and less costly labor enabled Brazilian growers in Sao Paulo state to harvest and process oranges into FCOJ at less cost than Florida growers (Muraro et al., 2003). In addition, Florida growers began to face low fruit prices during the mid 1990s as resurging Florida production augmented Brazilian output to push market prices of fruit downward. The interest in mechanical harvesting was revived, but with low fruit prices and low-cost foreign competition, more focused attention was directed on reducing harvest costs through mechanical systems.

A series of industry-wide task force symposia held in 1993, 1994 and 2002 focused on critical harvesting needs and cost reduction strategies. Consensus was reached to develop mechanical harvesting technologies and to identify and register suitable abscission agents viewed critical for economic viability (DOC, 2002). In 1995, the DOC commissioned the Harvest Research and Advisory Council and hired Dr. Galen Brown as its first harvesting program administrator. Unlike earlier harvesting research efforts which focused on developing new harvesting technologies, Dr. Brown and the Council encouraged the innovation of existing equipment for citrus

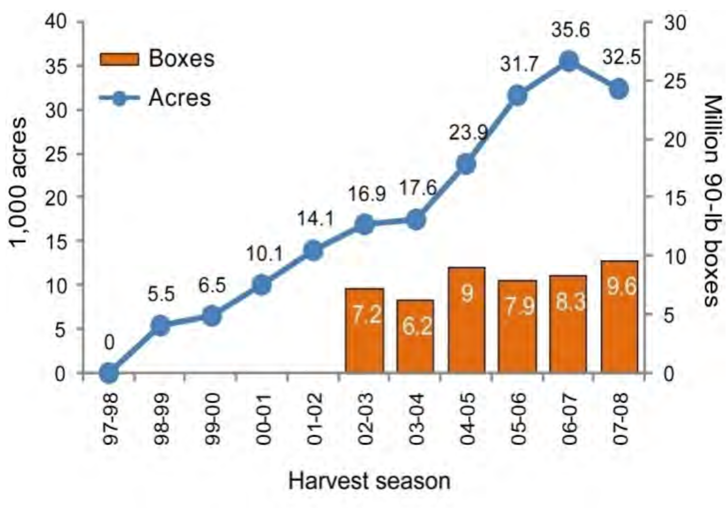


Figure 6. Acreage and boxes harvested by mechanical harvesting systems since 1997-98.

harvesting. “Development loans” were awarded to private companies to stimulate manufacture of harvesting equipment and formation of commercial enterprises to mechanically harvest citrus.

During the early 1990s, one commercial company, Fruit Harvesters International, operated trunk shakers in southwest Florida. By the beginning of the 1999 harvest season, DOC efforts attracted attention of commercial enterprise and the number of companies utilizing mechanical harvesting equipment increased. Total acreage mechanically harvested during the 1999-00 season increased to 6,500 acres. By the 2006-07 season, more than 35,000 acres were mechanically harvested (Figure 6).

New investments into harvesting equipment prior to the 2006 season occurred during a period of intense national debate on illegal immigration. Strong political rhetoric called for deportation of 12+ million workers already in the U.S. without legal documentation. Citrus harvesting companies were concerned that political rhetoric could result in concrete action, and consequently their ability to remain in business would be jeopardized.

Acreage harvested by machine measures the spatial impact of mechanical harvesting, whereas the number of boxes measures annual volume of mechanical harvesting. While acreage has increased, the number of boxes mechanically harvested has remained flat. These trends are explained by hurricane damage sustained during 2004 and 2005 that caused average orange yields to decline from 428 boxes per acre in 2003-04 to 271 in 2006-07 (FASS, 2008). Mechanically harvested acreage decreased during the 2007-08 season by 9% from the previous year. The number of boxes mechanically harvested, however, increased by more than 1.3 million.

### 3.2. Mechanical harvesting systems working in Florida

Three commercial mechanical harvesting systems have operated in Florida since 2000: continuous canopy shake and catch (CCSC), tractor-drawn canopy shaker (T-CS), and trunk shake and catch (TSC). The CCSC is a system with mirrored harvesting sets traveling on both sides of the canopy simultaneously. One CCSC set includes a minimum of four machines--two harvesting units and two field trucks (Figure 7). Most CCSC sets utilize four field trucks that allow harvesting units to continue operating while the first pair of field trucks transports fruit to a bulk trailer. CCSC units work in tandem, on either side of the tree row. A CCSC system travels between 1 and 2 mph down the row. Rows of six-foot tines are mounted on a “whirl” that resembles a giant spherical hairbrush. Tines penetrate the canopy, oscillating side to side with variable speed and intensity to remove fruit. Fruit

Figure 7. Continuous canopy shake-and-catch harvesting system side-view (top) and pair showing fruit conveyance and collection (bottom).

separated from the tree falls on to a catch frame positioned underneath the canopy, where fruit are conveyed to a trailing field truck. Trees have to be "skirted" (removal of ground-hanging foliage) and lower scaffold limbs pruned to avoid unnecessary tree damage and to allow effective performance of the catch frames. Harvesters have found that the CCSC system is most efficient in larger groves with long rows of uniform size trees.

A second mechanical harvester system, the T-CS, operates with the same fruit removal technology, or whirl of tines, as found on the CCSC (Figure 8). A single T-CS unit travels between 1 and 2 mph down one side of a tree row to harvest fruit; thus, an 'up-and-down' pass on the same row is required to completely harvest both sides of trees. Fruit fall to the ground as the unit engages with the canopy, then are collected by hand and placed into 1,000-lb collection tubs. Harvesting field trucks (or "goats") transport collection tubs to bulk trailers. The advantage of the T-CS unit is that it is able to work under variable grove conditions typical of the Central Florida Ridge. The harvester removes fruit as effectively as a CCSC unit, but since there is no catch-frame, trees do not have to be skirted or pruned and fruit must be collected from the ground. While the T-CS system does not harvest and catch the fruit as efficiently as the CCSC system, it provides a more efficient alternative to hand harvesting in non-uniform groves. The Oxbo Corporation has been working to develop a "pick-up" machine to work in conjunction with a T-CS unit. As of the beginning of the 2008 harvest season, a commercial pick-up machine has not been perfected.

Figure 8. Tractor-drawn canopy shaker.

The third mechanical harvesting system, the TSC, is composed of a shaker unit, a receiver unit, and one field truck (Figure 9). The shaker unit clamps the trunk of a tree and shakes the tree for periods up to 10 seconds; such action creates a whipping motion that detaches fruit from a tree. Falling fruit is deflected into the receiver that is positioned opposite of the shaker. A conveyer on the receiver moves fruit to an attached 70-box cart, after which the fruit is dumped into a harvesting field truck for transport to a bulk trailer. In some cases, one field truck can service two TSC units. The TSC system is well suited for long rows and trees less than 16 feet high. Trees must have a clear trunk of at least 12 inches and should be "skirted" to allow optimal performance of the catch

Figure 9. Trunk shake-and-catch harvesting system.

frame. Since a TSC unit shakes individual trees, increasing tree densities per area will increase the harvest time per acre. As with the CCSC system, the TSC system performs most efficiently in large groves with long rows of uniform trees.

### 3.3. Mechanical harvesting system efficiency and productivity

Efficiency measures for harvesting systems include percentages of fruit removal and recovery, harvest speed, runtime, and harvest labor productivity. These measures are defined as:

1. ***Removal*** *(%)*. The percentage of canopy tree fruit removed during the shaking action.
2. ***Recovery*** *(%)*. The percentage of canopy tree fruit that is removed *and* delivered to a bulk trailer.
3. ***Harvest speed*** *(trees/hr).* The number of trees harvested per hour of operation.
4. ***Labor productivity*** *(box/hr)*. Total boxes harvested per hour divided by the crew size of the harvesting system. Productivity measures for either hand or mechanical crews do not include field supervisors or shop mechanics. Time spent on routine or field repairs is included for mechanical crews because at least one equipment operator in a mechanical harvesting crew serves as a mechanic.

The average performance values of TSC and CCSC systems are summarized in Table 3. These data reflect multiple 2-hr observation periods between 2000-04 (Roka and Hyman, 2004). Growing conditions were consistent in that nearly all mechanical harvesting occurred in blocks with 150 trees per acre, yielding between 3 and 3.5 boxes per tree. As expected, ‘Valencia’ blocks produced less yield than ‘Hamlin’ blocks. Removal and recovery percentages averaged nearly 95% and 90%, respectively, and were similar between CCSC and TSC systems. Differences observed between removal and recovery rates often occur in harvesting situations and may be due to improper sealing of the catch frame around the trunk, operator errors, non-uniform tree canopies, and inadequate tree preparation. On average, a CCSC system harvested between 361 and 466 trees per hour, as compared to 190 and 229 trees per hour for a TSC system. Differences in harvest labor productivity between TSC and CCSC narrows because a CCSC system requires 6 people, whereas the TSC only requires 3. Average labor productivity of either CCSC or TSC system increases by at least 8-fold when compared to average productivity of hand crews (8 to 10 boxes/hr; Polopolous et al., 1996). Gleaning is a separate activity in the operation of TSC and CCSC systems and is not included in the labor productivity estimate. Although gleaning reduces the economic advantage of machine harvesting, growers typically send gleaning crews into previously mechanically harvested blocks when fruit prices are high.

A T-CS system utilizes a hand crew to collect fruit shaken to the ground. The hand crew effectively recovers almost 100% of the available fruit (Table 3). Since T-CS equipment only harvests one side of a tree per row pass, overall harvest speed was half that of a CCSC system. Overall labor productivity, while double the productivity of a hand crew, was substantially less than either CCSC or TSC units operating with catch frames. The use of a hand crew with T-CS equipment is not considered gleaning because the hand crew is an indispensable part of the overall system. If and when a mechanical pick-up machine is developed for T-CS, gleaning may be considered as a separate activity from the mechanical system.

Table 3. Performance measures of hand harvesters and three mechanical harvesting systems.

| | | TSC | | CCSC | | T-CS | | Hand |
|---|---|---|---|---|---|---|---|---|
| | | Hamlin | Valencia | Hamlin | Valencia | Hamlin | Valencia | All Oranges |
| Avg. Yield | bx/ac | 554 | 371 | 460 | 375 | 377 | 312 | 400 |
| Fruit Removal | % | 95 | 95 | 95 | 95 | 91 | 90 | 99 |
| Fruit Recovery | % | 87 | 88 | 90 | 90 | 99 | 99 | 99 |
| Harvest Speed | tree/hr | 190 | 229 | 361 | 466 | 184 | 298 | 2-5 |
| Labor Productivity | bx/man-hr | 96 | 76 | 103 | 122 | 16 | 20 | 8-10 |

Sources, Roka and Hyman, 2004; Polopolous, et a., 1996

### 3.4. Framework to analyze mechanical harvesting costs and benefits

A grower's decision to adopt a mechanical harvesting system or continue with hand harvesting should be based on several factors. The harvest method with the lowest "net" cost is one of these considerations. Growers must also take into account their grove design. Tree density, height and variability are important factors when deciding on an appropriate harvest system.

A grower would select mechanical harvesting only if the "net" cost to mechanically harvest is less than the best hand-harvesting option. Total cost savings from mechanical harvesting are be calculated as the difference in unit costs between hand and mechanical systems multiplied by the total number of boxes harvested. Even with "gleaning," mechanical harvesters do not recover 100% of the available fruit. Therefore, total savings from mechanical harvesting must be adjusted downward by the value of non-harvested fruit. Further, there may be additional tree and grove repair costs with mechanical harvesters that would not be incurred by a hand crew. An online tool is available to help growers account for the changes in harvesting costs and compare net harvesting costs by harvest method (Roka, 2008).

Gleaning is an important consideration when utilizing a mechanical harvesting system. Gleaning involves a crew of workers who follow harvesting machines with catch-frames to collect fruit missed in the trees or wholesome fruit on the ground that was missed by the catch-frame. Since 2002, harvesting contractors with CCSC and TSC systems charged between \$1.25 and \$1.45 per box to harvest a citrus block with at least 300 boxes per acre. This price included gleaning services, which guaranteed at least 97 percent of a grower's crop delivered to a bulk trailer, and is the comparable number to the pick and roadside costs of a hand harvest crew. Costs to hand pick and roadside oranges in 2008 averaged \$1.85 per box (Muraro, 2008).

A contract price that includes “gleaning” should be viewed as a weighted average of two activities, the machine harvest and the manual gleaning service. Contractors have estimated that mechanical harvesting could be priced close to $1 per box if gleaning were not required. Hence, an implied price of gleaning can be estimated given the following assumptions: 1) overall fruit yield of 400 boxes per acre, 2) 90 percent fruit recovery by a mechanical system, 3) $1.25 per box cost with gleaning, and 4) $1 per box cost without gleaning. Under these conditions, the implied cost of gleaning is $3.50 per box delivered to a bulk trailer. Increasing overall fruit recovery by mechanical systems is an important economic goal to eliminate the need for relatively expensive gleaning services and reduce the overall “net” harvesting costs.

As a result of lower yields from hurricane damage in 2004 and 2005, unit costs to harvest by hand or mechanical methods increased. The differential between hand and mechanical harvesting options, however, remained constant with mechanical systems costing between 20 and 30 cents per box less than hand harvesting crews. At a 20-cent unit cost savings and average production of 300 boxes per acre (2006-07 early and mid season average orange production yield in southwest Florida, FASS, 2008), a grower who mechanically harvested in 2006-07 increased his on-tree returns by $60 per acre.

Such increases in on-tree returns are positive, but the potential for mechanical harvesting systems to reduce harvest costs and increase grower returns is much greater. If mechanical systems exploit their inherent “scale” economies, harvest costs could be reduced by at least 50-cents per box and grower on-tree returns increased by at least $200 per acre. Scale economies are achieved by enhancing harvesting capacity of existing equipment. Harvesting capacity can be enhanced by increasing the number of boxes/hr, hrs/day and/or days/season the equipment operates. Costs such as depreciation, interest payments, and liability insurance are fixed costs associated with ownership of a harvesting machine that are paid regardless of whether the equipment operates or whether the equipment is parked. As harvesting equipment is used more intensively, the average cost of mechanical harvesting declines.

# 4. Obstacles to Widespread Adoption of Mechanical Harvesting

The FDOC has led an aggressive effort to develop and adopt mechanical harvesting technologies. Even though growers who have adopted mechanical harvesting have enjoyed a cost advantage over conventional hand harvesting, most growers have been slow to embrace mechanical harvesting options. There are several reasons that explain this relatively slow transition toward mechanical harvesting. Two of the most important are the perception of tree damage and the “late-season” challenge. Once these obstacles are overcome, it is widely perceived that the rate of mechanical harvesting adoption will rapidly increase.

## 4.1. Perceptions of tree damage

Many factors contribute to the lack of widespread adoption of mechanical harvesting by the Florida citrus industry. Among these factors is the aesthetic appearance of a grove immediately after mechanical harvesting operations, which become a grower's first impression of mechanical harvesting. A harvest machine can cause visible physical injuries to the trees, including shedding of leaves, flowers, and young fruit, breaking branches, scuffing of bark, and exposing roots (Halderson, 1966). Although there is no evidence that visible injuries could seriously weaken citrus trees, tree health after mechanical harvesting remains a concern to growers. Despite the fact that secondary infections after immediate injuries have been blamed for tree decline in some mechanically harvested fruit crops (De Vay et al., 1968; Glenn, et al., 1995), long-term studies revealed that fruit yield and mortality of citrus trees was not affected by mechanical harvesting (Hedden et al., 1988).

Recent investigations on mechanical harvesting effects on citrus tree physiology demonstrated that visible injuries caused by a properly operated mechanical harvester did not induce significant physiological stresses in well-managed citrus trees. Trees under environmental stresses were more vulnerable to any physiological stress. The small physiological consequences of mechanical harvesting, when present, are minimal, and trees fully recover to the same status as hand harvested trees (Li and Syvertsen, 2004; 2005; Li et al., 2005).

## 4.2. The "late season" challenge

'Valencia' is a high quality orange variety that commands a price premium from juice processors. Processors value the sugar content and rich color that allows 'Valencia' oranges to be processed directly into premium NFC juice. The relative importance of 'Valencia' has been increasing over the past 10 years and now occupies more than 55% of the bearing tree acreage (see Table 1). Florida 'Valencias' require 13 to 15 months to produce mature fruit. During the harvest period, 'Valencia' trees support two crops – this year's mature fruit and next year's growing fruitlets (Figure 10). Trees flower during February/March and harvest begins in early March of the following year. Harvest continues through June and sometimes into July depending on crop size, fruit maturity, and processing plant scheduling. By mid May, next year's young fruitlets reach sufficient size and weight to be susceptible to mechanical removal. It is harvesting at this point in time and thereafter that is referred to as "late-season" harvesting. During a typical year, fruit harvested during the "late-season" accounts for approximately 1/3 of the total 'Valencia' crop.

Figure 10. Close-up of 'Valencia' branches showing young developing fruitlets and mature fruit on the same tree.

Although the one-inch (2.5 cm) diameter size of a young 'Valencia' fruitlet has become an important benchmark for predicting young fruit removal by machines (Coppock, 1972), research continues to define precise fruitlet weight and diameter that is susceptible to mechanical removal. Nevertheless, significant numbers of young fruitlets can be inadvertently mechanically removed when trying to remove larger mature fruit during this "late-season" harvest period, resulting in as much as 50% reduction of next year's yield (Roka et al., 2005; Whitney, 1975; Whitney and Hedden, 1973). The inadvertent removal of young developing 'Valencia' fruit during late season harvesting is a major deterrent to wide-scale adoption of mechanical harvesting.

Many commercial industry and grower cooperative members believe a suitable abscission agent will solve the late season challenge. Published research supports the positive benefits of abscission agent application for more selective removal of mature fruit (Burns et al., 2006a; 2006b). A suitable abscission agent will selectively loosen mature fruit so that reduced mechanical shaking frequency and intensity can be used to remove them. In doing so, young fruitlets will not be removed and next year's yield will be preserved. Without late-season mechanical harvesting success, mechanical harvesting systems not only lose access to additional acreage during the late season period, but also lose acreage during the early- and mid-season harvest period as well. The reason for this is that growers and harvesting contractors are not willing to reduce their harvest labor force during the early- and mid-season harvest periods for mechanical systems, only to find labor unavailable in May when the late-season harvest need arises. Successful late season harvesting will increase grower confidence and result in more acreage being available for mechanical harvesting. As more acreage is available to mechanical harvesting systems, economies of scale will be captured and costs will also decline for early and mid-season harvest periods, resulting in broad adoption of mechanical harvesting throughout the orange harvest season.

# 5. An Effective Abscission Agent for Mechanical Harvesting

## 5.1. History, criteria, and physiological action

Historic precedent in citrus has influenced grower thinking on the need for an abscission agent. Few can argue the promise of an abscission agent for mechanical harvesting when treated fruit detach so easily from the tree. However, the true benefit of an abscission agent for the citrus industry is demonstrated only when it enhances the value of mechanical fruit removal. CMNP action causes a clear fruit/pedicle abscission layer to form (Burns, 2002), resulting in clean separation of fruit from the stem. The benefit of CMNP has been demonstrated by its ability to increase mechanical fruit removal, increase machine capacity, and make late season 'Valencia' mechanical harvesting possible. It is anticipated that CMNP will be applied to early- and mid-season oranges as well to improve machine efficiencies and provide added benefits of economy of scale to harvesting throughout the season.

An effective abscission compound must meet an important set of criteria to be considered as a viable component of a successful harvesting system. A suitable abscission compound must 1) be selective for mature fruit, 2) have minimal impact on tree health and yield, 3) be suitably phytosafe over a relatively wide range of concentrations and weather conditions, 4) likely be approved for registration with EPA, and 5) be economical to apply. Research supporting the above criteria for CMNP has been published between 1970 and 1980, and between 2000 and 2008. In 2004, an independent assessment of several abscission candidates in the UF/IFAS abscission program indicated that CMNP was the best choice for Florida citrus. From that point forward, the DOC led efforts to fund CMNP registration.

Early work (Wilson et al., 1977, and references within) demonstrated the efficacy and selectivity of Release. Release was a trade name for formulated material (Abbott Laboratories, Libertyville, IL) containing 17.12% 5-chloro-3-methyl-5-nitro-1*H*-pyrazole (CMNP). Later work confirmed mature fruit selectivity properties and contrasted selectivity of other abscission agents such as ethephon. Application of 200 $mg \cdot L^{-1}$ CMNP to citrus canopies reduced fruit detachment force (FDF; the force required to detach fruit from the stem) from 12 kg-force to 2 kg-force (5.5 to 0.9 lb-force) 4 days after application, or 90% of the original value, whereas 200 $mg \cdot L^{-1}$ ethephon reduced FDF by only 40% (Burns, 2002). Moreover, CMNP did not cause unwanted leaf drop when applied in concentrations of 1000 $mg \cdot L^{-1}$ or less, but ethephon caused high amounts of defoliation when used at concentrations necessary for effective fruit loosening (Burns 2002; Burns et al., 2003; Yuan and Burns, 2004; Pozo et al., 2004).

Numerous studies have shown no effect of repeated annual applications of CMNP on return yield (Whitney, 1975; Whitney, 2003; Burns et al., 2006b). Despite this, growers who must understand impact and interaction of CMNP with established citrus management strategies are interested to learn more about short- , intermediate- , and long-term health effects. Leaf water content, dry weight, mid-day water potential, and photosystem II efficiency were not affected by CMNP application at recommended rates (Li et al., 2008). Excessive rates, however, of 1,000 $mg \cdot L^{-1}$ or greater reduced photosystem II efficiency, and temporarily reduced net gas exchange of leaves and young fruit growth. CMNP application at recommended application rates (200 to 300 mg/L, see below) reduced peel total ATP temporarily, decreased alcohol dehydrogenase activity, but increased lipoxygenase and secretoryphospholipase $A_2$ activity (Alferez et al., 2005). Simultaneous treatment of phospholipase $A_2$ inhibitors reduced peel damage associated with CMNP application but also reduced efficacy (Alferez et al., 2006). Juice % acid and Brix were not affected by CMNP application at harvest (Pozo et al., 2004).

## 5.2. Application of CMNP in Florida citrus groves

Important commercial processing cultivars ‘Hamlin’ and ‘Valencia’ react similarly to CMNP; however, ‘Hamlin’ appears to be slightly more sensitive. In general, FDF of untreated fruit is approximately 1 to 2 kg-force (0.5 to 0.9 lb) lower than ‘Valencia’ at developmentally similar stages (Hartmond et al., 2000). As fruit naturally mature and senesce, FDF declines in both cultivars (Pozo et al., 2004) but never reaches the value necessary to cause fruit drop in the course of a commercial harvest season (2 kg-force or less). Effective CMNP concentrations to loosen ‘Hamlin’ are 250 mg/L at the beginning of the season (October-November) and drop to 200 mg/L at the end of the season (January-February), whereas for ‘Valencia’, the concentrations are 250 mg/L at the beginning of the season (February-March) and rise to 300 mg/L at the end of the season (May-June). This reversed trend for ‘Valencia’ is governed by the need to ensure adequate efficacy for late-season fruit removal at low frequency/intensity machine harvest. Applying CMNP at a volume recommended for conventional air-blast sprayers (300 gal/acre), the amount of active ingredient (a.i.) needed would be 227, 284, and 341 g/acre (560, 701, and 842 g/ha) for 200, 250, and 300 mg/L, respectively. If new application technologies such as multihead air-blast sprayers are adopted, a.i./acre or a.i./ha would be less because these sprayers distribute material more effectively in less volume.

CMNP-fruit loosening begins between 2 and 3 days after application if temperatures remain above 60ºF (15.5ºC; Burns, 2002; Yuan and Burns, 2004). When temperatures are higher, the time to initiate loosening does not change but the rate of loosening accelerates once initiated. Under normal harvest situations, fruit would be harvested before significant fruit drop occurred, i.e., 3 to 5 days after spray application. If not harvested, fruit loosening will continue up to 10 days after application. Leaving fruit on the tree after maximum loosening is achieved will result in high fruit drop. In most cases, not all of the fruit will drop. Loosened fruit remaining on the tree have an incompletely digested abscission zone, and consequently, the zone cells rebuild adhering connections. Such actions result in retightening action in affected fruit. For mechanical harvesting purposes, fruit drop should be minimized in cases where catch-frames are used. In most cases, mechanical harvesting should be scheduled 3 to 5 days after application (Burns et al., 2005).

Fruit treated with CMNP have a characteristic visible “ring” on the blossom end of the fruit. This ring is cosmetic and has no impact on quality or marketability of processed fruit. Adequate peel contact is required for CMNP efficacy (Alferez et al., 2005). For this reason, spray drift, where it occurs, generally does not impact fruit loosening in adjacent rows. High volumes in excess of 900 gal/acre (>8,500 L/ha) were applied with conventional air-blast sprayers in previous work to ensure adequate coverage on fruit so that the majority would drop to the ground (Whitney, 1975; 1976). Today the goal is not to drop fruit to the ground, but to loosen it sufficiently to ensure ease of machine removal and collection in the catch frame. Current estimates are that a 50% reduction in FDF is necessary to maximize machine removal (Burns et al., 2005). Organosilicate or penetrant-type adjuvants improve CMNP efficacy. For this reason, any CMNP-related product may benefit from adjuvant in the final formulation or a recommendation to add adjuvant to the spray tank before application. At least 8 hours of rain-free conditions after application will ensure maximum loosening, although newer formulations could have more efficient uptake properties. Proper application timing during the day can also improve CMNP efficacy. Mid-day CMNP applications reduced FDF more than applications shortly after dawn or before dusk (Pozo et al., 2007; Malladi and Burns, 2008). Temperatures during the first 24 hours after application appear to be critical for maximum efficacy. During this time, temperatures below 60ºF (15.5ºC) reduce CMNP-associated mature fruit loosening (Yuan and Burns, 2004). If temperatures during the initial 24 hours post application drop below 60˚F (15.5˚C), CMNP-associated fruit loosening will be less effective and may be delayed until 5 to 7 days after application.

In summary, based on research spanning several decades, current recommendations are for application of 200 to 300 mg/L CMNP with adjuvant, delivered at 300 gal/acre to Florida processed citrus cultivars using a standard air-blast sprayer. Application should be with nozzles delivering medium- to large- sized droplets during mid-day, with rain-free conditions for at least 8 hr. Temperatures should be above 60ºF (15.5ºC) for the first 24 hours after application to maximize CMNP-induced fruit loosening. To minimize unwanted fruit drop, harvesting should be scheduled 3 to 5 days after CMNP application.

## 5.3. Anticipated benefits of CMNP application

**5.3.1. Solving the "late-season" challenge**. A major deterrent to the widespread adoption of mechanical harvesting has been grower concern about successful late-season 'Valencia' harvesting. As much as 50% reduction in next season's yield occurs when mechanical harvesting is performed (Roka et al., 2005) because young developing fruit are inadvertently removed. Selective mature fruit loosening with CMNP allows less aggressive, lower frequency machine harvesting, resulting in high (over 90%) mature fruit removal percentage, little fruitlet loss and no significant yield impact the following season (Burns et al., 2006). Without CMNP application and low frequency harvesting, fruit removal was below 70%. Solving this "late-season problem" will assure growers that laborers will not be needed to harvest late season 'Valencia'. In doing so, growers will be more willing to commit acreage to machines throughout the entire harvest season.

**5.3.2. Increasing mechanical harvesting speed**. CMNP application increased harvesting capacity of canopy and trunk shakers by reducing the time necessary to harvest each tree, while at the same time maintaining high percent mature fruit removal (Burns et al., 2005). Increased capacity can be measured in boxes of removed fruit per hour, per block or per season.

**5.3.3. Improving fruit removal and recovery percentage**. Application of CMNP at recommended rates can boost fruit removal. Without CMNP application, mechanical harvesting fruit removal can range between 70% and 85% under typical commercial machine settings. Coupled with CMNP application, mature fruit removal can range between 90% and 98% (Burns et al., 2005; Burns et al., 2006b). Fruit recovery percentage, or the amount of fruit that can be transported out of the grove to the processing plant, may also improve. Due to high FDF, mechanical harvesting without CMNP can result in 'slinging' fruit away from the catch-frame. Verification of recovery improvements with CMNP application, however, has proven difficult because of catch-frame inefficiencies.

**5.3.4. Reducing cosmetic tree damage**. Machine harvesting frequency and intensity can be reduced when CMNP is applied. Fruit are easier to remove as fruit detachment force is lowered by CMNP action. Less energy applied to the tree means less visible cosmetic damage to trunks and limbs, and less mechanical defoliation. Less cosmetic damage during mechanical harvesting will lessen grower perceptions about long term adverse tree health effects and improve grower acceptance of mechanical harvesting technologies.

**5.3.5. Reducing debris in trailer loads**. The shaking mechanism that effectively harvests mature citrus fruit can also remove large quantities of leaves and stems, or dead branches (collectively termed "debris"). Debris makes its way into loads of fruit delivered to the processor. Some of this debris can be eliminated via de-stemmers on the harvest machinery, but these devices cannot remove all debris and not all processing machines are equipped with de-stemmers. Each pound of debris that makes its way into a load is one less pound of fruit that can be hauled in that load, thereby increasing transport costs. The increased volume of debris flowing into processing plants from mechanical systems increases the operational costs of the feed mill (Spann, 2007). CMNP-treated fruit have fewer attached stems and leaves, and overall fruit loads have significantly less debris than untreated hand and mechanically harvested loads.

**5.3.6. Enhancing economic benefit of mechanical harvesting**. Growers utilizing mechanical harvesting are currently saving between 10 and 30 cents per harvested box without the advantage of abscission agent application. Depending on crop yields, these harvest savings translate to an increase in grower profits of between $50 and $150 per acre.

Estimates of the potential economic benefits from CMNP application have been modeled under the following assumptions of anticipated changes in equipment performance:

1) mechanical systems would operate at least 4 weeks, or 160 hours longer per season;
2) harvesting speeds would increase throughout the year (i.e., early- , mid- , as well as late-season crops), resulting in a 25% increase in harvested boxes per acre hour; and
3) fruit recovery would increase from 90% to 95%.

An analysis of how these improvements in equipment performance suggests that grower savings could be increased as much as 75 cents per box, or between $250 and $300 per acre increase in grower income. Economic benefits attributable to abscission agent application, therefore, are estimated to be between $150 and $250 per acre above that of mechanical harvesting alone. These savings, however, will only be realized when adoption of mechanical harvesting with abscission agent application becomes widespread and the existing mechanical systems are being utilized to their maximum harvesting capacity. This analysis indicates that mechanical harvesting coupled with CMNP application will bring the cost of harvesting Florida citrus into parity with Brazil, its largest international competitor.

# 6. Anticipated Changes to Citrus Production, Harvesting, and Processing upon Adoption of Mechanical Harvesting and CMNP Application

Successful implementation of mechanical harvesting systems and abscission agent application will change how citrus is produced, harvested and processed in Florida. The demand for hand labor to harvest citrus will decline incrementally as growers begin to realize the economic benefits of utilizing the mechanical harvesting system.

## 6.1. Production practices

Fruit production and harvesting functions will become more integrated as maximizing dollars per acre becomes a more important goal than boxes per acre. Efficiency or productivity of a hand harvester is not significantly affected by grove layout and tree architectures. With mechanical harvesting equipment, however, tree shaping (skirting, pruning, hedging, and topping) activities will become a priority, not only to manage the bearing tree canopy surface but to facilitate efficient operation of harvesting equipment and fruit catch frames. Furthermore, mechanical harvesting will reinforce the importance of maintaining good tree health, practicing good horticultural management techniques that work toward higher yields per-acre. In other words, mechanical harvesting should encourage a grower to more intensively manage each acre of his or her operation. While more intensive management typically leads to higher costs, overall unit cost of production should decrease from both the use of mechanical harvesting equipment and higher per-acre fruit yields. The application of CMNP, or any abscission agent, will add another step to grove operations. More importantly, abscission agent application must be done in close coordination with the availability of the harvesting equipment. In order to ensure the best possible outcome of mechanical harvesting with abscission agent application, it may be necessary for the harvesting division, not the grove management division, to assume responsibility for product application. If mechanical harvesting is contracted through an independent company, the cost of abscission agent application may need to be built into the overall price of mechanical harvesting.

### 6.2. Juice processing

Processing plants have been built and managed to handle a certain volume of fruit daily. The criteria to operate a processing plant at minimum cost are the same whether fruit is harvested by hand or machine. A plant manager wants to operate as close to the plant's physical capacity as possible and operate the plant for as many days as fruit can be harvested. In this regard, mechanical harvesting and abscission agent application should have minimal effect on plant operations. What will change, however, are the number of daily harvesting sites. Enhanced capacity of mechanical harvesting equipment will require fewer daily harvesting sites, as more loads per site can be delivered by mechanical systems. Allocating more bulk trailers to a specific harvesting site will become solely a logistical issue. The various industry players will need to consider forthcoming technologies and adjust current practices accordingly.

Managers of juice processing plants are concerned about additional volumes of debris being transported from mechanically harvested sites. Improvements in equipment design to eliminate unwanted debris coupled with the use of CMNP should alleviate concerns about excess debris at the processing plant. Currently, processing plants assess additional fees or charges on harvested loads that transport an excessive amount of debris. The added fees compensate the processing plant for their added costs in debris handling. Results showing that CMNP reduces overall debris should lead to lower processing costs and more favorable acceptance of mechanically harvested loads.

### 6.3. Labor management

A significant amount of human and financial resources currently are devoted to managing a citrus harvesting work force. Insuring that workers are paid properly (wage and hour laws) and that work environments are safe (worker protection standards) require constant and diligent attention on the part of harvesting companies and employers. Widespread adoption of mechanical harvesting systems will reduce the number of people directly involved in citrus harvesting and lessen the costs associated with labor management. For those workers who remain in citrus harvesting, they will transition from hand harvesters to equipment operators. Equipment operators are considered more highly skilled workers, and in general, are more highly paid than hand harvesters.

Aspects of worker safety will likely change with mechanical systems but to what extent is as yet difficult to fully predict. The sheer reduction in the overall number of workers in a grove should mitigate against the risks from unintentional pesticide exposure. Further, the injuries associated with hand harvesters, such as back fatigue, eye injuries and skin scratches from small limbs and thorns, and ladder injuries should be greatly diminished if not eliminated with mechanical harvesting. Equipment operators, however, face their own safety risks and while the number of accidents may diminish with mechanical systems, the severity of an accident occurrence may be accentuated.

The shift in harvest technology from manual labor to mechanical basically represents a shift of risk from managing people to managing financial investments. Reducing the number of people involved with citrus harvesting reduces the risks associated with managing people. Mechanical harvesting systems, however, require a substantial financial investment (in some cases, in excess of $1 million) before the first box of oranges is picked. Costs such as depreciation, interest, and equipment insurance are paid regardless of the volume of boxes that are harvested during a season.

# 7. Concluding Comments

Widespread adoption of mechanical harvesting is critical for long-term economic viability of the Florida citrus industry. Maximizing economic potential of mechanical harvesting will depend on an effective abscission agent. The application of the abscission agent CMNP expands the overall harvesting capacity of existing canopy and trunk shakers by 1) extending mechanical harvesting operation through the entire 'Valencia' late season harvest window, 2) allowing equipment to operate faster, thereby harvest more boxes per hour, 3) improving fruit recovery percentage, and 4) reducing cosmetic damage caused by mechanical harvesting equipment and lessening grower concerns about adverse effects from mechanical harvesting on crop yields and tree health. Economic models predict that mechanical harvesting, coupled with CMNP application, should enhance the long term economic sustainability of the Florida citrus industry by bringing the cost of harvesting into parity with its largest global competitor, Brazil.

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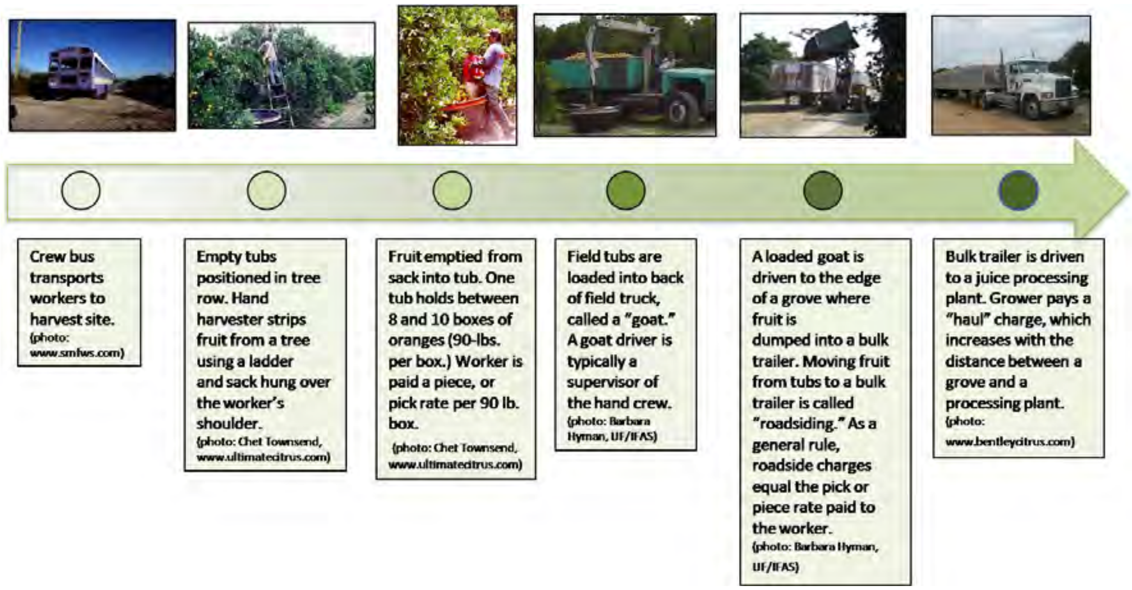
**Appendix 1.** Table of Florida commercial citrus acreage and production by county, 2006-07 season.

| County | Acreage (ac) | Total Citrus Production (1,000 Boxes) |
|---|---|---|
| Polk | 86,398 | 22,370 |
| Hendry | 79,726 | 21,414 |
| Highlands | 62,671 | 16,744 |
| DeSoto | 61,083 | 15,832 |
| St. Lucie | 51,387 | 13,337 |
| Hardee | 45,084 | 12,003 |
| Indian River | 40,191 | 12,280 |
| Martin | 35,038 | 6,830 |
| Collier | 33,394 | 8,390 |
| Manatee | 18,548 | 5,439 |
| Lake | 15,198 | 3,739 |
| Hillsborough | 14,783 | 4,127 |
| Osceola | 12,170 | 3,632 |
| Charlotte | 11,883 | 2,996 |
| Lee | 10,658 | 2,583 |
| Okeechobee | 9,222 | 2,227 |
| Glades | 8,555 | 2,372 |
| Pasco | 8,190 | 1,990 |
| Brevard | 5,080 | 871 |
| Orange | 4,548 | 1,053 |
| Palm Beach | 1,668 | 510 |
| Sarasota | 1,652 | 487 |
| Volusia | 1,231 | 230 |
| Marion | 1,185 | 233 |
| Hernando | 921 | 181 |
| Seminole | 529 | 104 |
| Putnam | 182 | - |
| Citrus | 145 | - |
| Other | 53* | 76** |
| **Totals** | **621,373** | **162,050** |

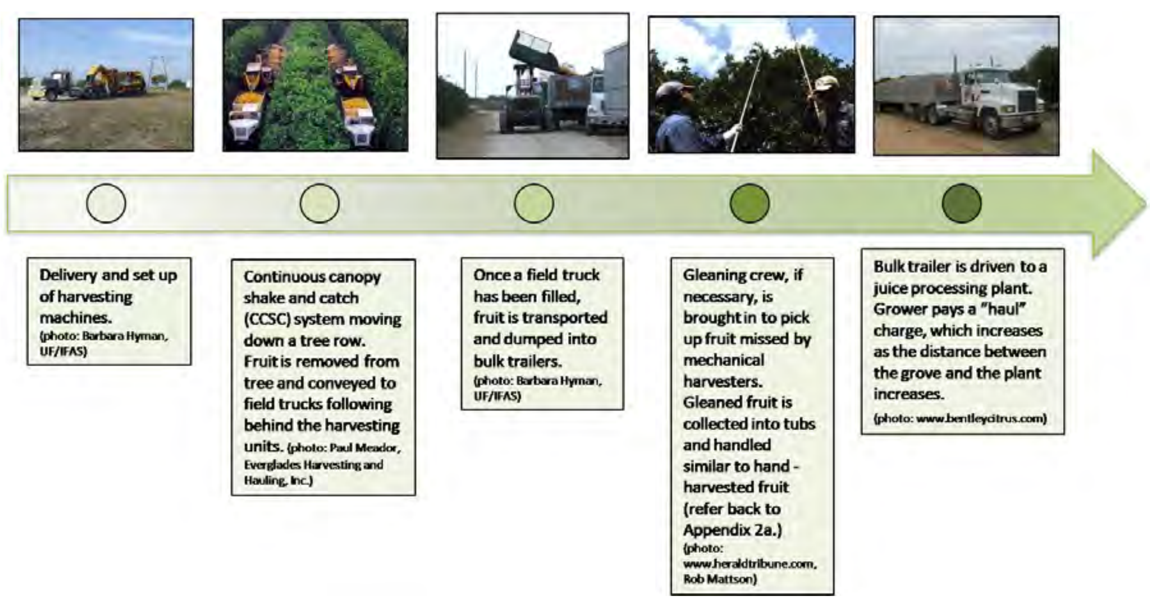
* Includes Alachua and Pinellas counties.
** Includes Alachua, Citrus, Pinellas and Putnam counties.

# Appendix 2

## a. Steps in Hand Harvesting of Citrus for Juice Processing




## b. Steps in Mechanical Harvesting of Citrus for Juice Processing



Appendix 3. Average annual harvest dates for major processing orange cultivars (upper half) and biological events occuring in a citrus tree (lower half). Placement of an event on the calendar is an approximation of dates of occurance. The grey box delineates the estimated dates and span of time devoted to 'late season' Valencia harvest and the biological events occurring at that time. Note that mature Valencia fruit from the previous year and young developing fruitlets from the current year are on the tree simultaneously when late season harvesting with machines is planned.