Precision Farming Applications in Florida Citrus

J. D. Whitney, W. M. Miller, T. A. Wheaton, M. Salyani, J. K. Schueller

Abstract. *A cooperative effort between researchers, manufacturers, and growers has been investigating precision farming applications in Florida citrus. Citrus yields, based on the location of volume-based containers, were mapped using a conventional fruit-loading truck, manual harvesters (> 99% of Florida citrus is manually harvested), and GIS/GPS components. These maps were overlaid on geo-referenced aerial photographs of the tree canopies. Two fruit weighing systems were mounted on a fruit-loading truck and integrated with the GIS/GPS components to investigate mapping weight-based yields. Results to date indicate the truck-mounted weighing systems were within 1 to 6% of certified scale weights on 20 t loads of fruit. Electronically recording harvester identity is being integrated with yield mapping to make the entire system more reliable and attractive to harvesters and growers.*

Keywords. *GPS, GIS, Yield mapping, Citrus.*

It has long been recognized that crop behavior and soils are not uniform within a given field or grove and astute growers have generally responded to such variability by taking appropriate actions such as improving drainage, changing nutrition, etc. (Nielsen and Bouma, 1984; Carr et al., 1991). But large acreages coupled with high levels of mechanization of modern crop production and contracted applications make such actions less frequent than desired. For over a decade there has been significant research and commercial implementation of machinery systems to use technology to document or respond to the variability. This type of technology is known by such terms as precision agriculture, precision farming, or spatially variable crop production.

To a large extent, spatially variable crop production has been technology-driven. Advances in electronics and computers, such as the global positioning system (GPS) and geographic information systems (GIS), have led to new tools which have been applied to agriculture. As technology advanced, a gathering momentum of activity and development has been documented in the literature (Schueller, 1988, 1992, 1997; Robert et al., 1993; Auernhammer, 1994; Stafford, 1996).

The automatic mapping of yield on combine harvesters (Pierce et al., 1997) has been particularly successful; there were as many as 17,000 yield monitoring devices on American combines during the 1997 harvest. Yield mapping of grain and soybeans have been followed by yield mapping of other row crops. Commercial systems are now available for cotton. Potato yield measurement with load cells on the harvester (Schneider et al., 1996; Persson, 1998) is also commercialized. Sugar beet (Walter et al., 1996) and sugar cane yield have similarly been measured. Peanut combine yield mapping has also been demonstrated (Thomas et al., 1999).

In horticultural crops, precision farming research has been reported in Oregon (Righetti, 1997). Yield and soil fertility mapping are discussed along with variable rate nutrient and herbicide applications. Yield mapping for citrus crops have been proposed in the USA and Australia. However, outside of some experiments in a commercial grove in Florida and work on deciduous tree fruit in the Pacific Northwest, research and commercialization are limited. As with other horticultural crops, the techniques for citrus yield mapping need to be developed.

Soil mapping is a common precision farming practice, especially in the U.S. grain belt. Field boundary maps are based on data from GPS-equipped all-terrain vehicles. Soil characteristic maps (nutrient, pH, cation exchange capacity, organic matter, etc.) are based on manual individual soil tests and interpolation by geostatistical methods. There have been substantial efforts to develop soil property sensors to avoid sampling costs and problems (Hummel et al., 1996).

Probably the least costly mapping benefit is strategic decision-making by the farm or grove manager. The manager could change the block (field) or subblock boundaries so that more uniform conditions existed in individual blocks. Mapping may also show that a portion of a grove should have artificial drainage installed. The first grain yield map of Searcy et al. (1989) demonstrated yield loss due to machinery traffic compaction and that the machinery traffic should be routed around that particular field. Mapping provides the information necessary to

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evaluate problems and potential opportunities due to management changes.

When most agriculturalists think of precision farming, they think about tactical control, rather than strategic decision-making. The maps of crop or soil characteristics can easily be used to control field operations. Chemicals are a large expense for most crops and needs are variable. Agricultural equipment manufacturers sell various types of equipment to apply fertilizers, pesticides, and manures in spatially variable amounts. Spatially variable application of fertilizer is common on both research and commercial farms. For herbicides, spraying only where weed patches exist have significant economic and environmental advantages. These techniques, more common in the corn and wheat belts, need to be adapted to citrus.

There has been essentially no precision agriculture research or implementation in citrus. However, the economic value of citrus and the vulnerability of the Florida environment makes precision farming a technology with great potential. A research project has been initiated to develop a precision farming system in Florida citrus with the following objectives:

1. Develop a system to map citrus yields using conventional manual harvest labor and electronically record harvester identity associated with each citrus container loaded in the grove.
2. Develop a system to measure and map tree location, canopy volume, and height in a citrus grove.
3. Determine the feasibility of using GPS/GIS for variable rate application of fertilizers and pesticides, and for monitoring, tracking, and controlling grove equipment.
4. Determine what GPS/GIS information is most valuable and how it may be used effectively to improve management of production and harvesting operations.

The major thrust of the work reported in this article deals with developing a yield mapping system of objective 1.

Background

As with any crop, gross returns are determined by yield. An accurate yield mapping system will help the citrus grower determine the variability in yields and the yield response corresponding to any site specific input changes. Currently, citrus yields are available by the whole block or grove.

Although there are mechanization efforts to harvest processed citrus in Florida, essentially all the crop is harvested manually. Crews of up to 50 persons work with ladders and picking bags and place the harvested fruit in field containers (tubs or pallet bins) which nominally have a capacity of 10 field boxes (approximately 0.7 m^3 by volume). Because each crew member is paid by piece rate (by field box), each field container is filled by a single crew member for tallying purposes. The foreman or crew leader tallies the field boxes of each crew member as he/she loads the contents of the full field containers on a "goat" truck with a hydraulically actuated loader boom. For fresh fruit, filled pallet bins are loaded on the flat bed of the goat truck and eventually are delivered to the packinghouse where the pallet bins are emptied. For processed fruit, filled tubs are dumped into a bulk storage bin on the goat truck, after which the empty tub is placed back on the ground. The full storage bin on the goat truck is dumped into a semi-tractor trailer which delivers the fruit to the processing plant.

Accurate yield mapping with a manual harvesting system is different than the mechanical harvesting of other crops. The fruit used to fill each field container represents an area chosen by the harvester, and the assumption that the container is near the centroid of that area is probably valid because the harvester will want to minimize the average distance he carries the fruit. Recording the position of each full container with a GPS system allows maps of yield to be generated. One method of recording the position is to have the goat truck operator actuate a position determination switch each time a container is picked up. But experience has shown that the operator is often so busy manipulating the loader boom and tallying the containers that actuating the switch is often forgotten. It would be better if the actuation was automatic.

The filled container is only an estimate of the yield (by volume). Florida statutes define a box of oranges as 40.8 kg (90 lb) and the grower is paid for fruit on a weight basis or "weight" boxes, not field boxes or "volume" boxes as tallied in the field. Fruit size, juice content, etc., affect the weight of the fruit in the container. Therefore, the fruit in each container should be weighed to develop an accurate yield map.

Methods

Equipment

Yield data were obtained by recording the location and weight of each full container (tub or pallet bin) of harvested fruit at the time it was loaded by a conventional goat truck. A GPS (Trimble Lassen-SK8 Board) combined with a proprietary embedded computer (GeoFocus, Gainesville, Fla.) recorded the longitude, latitude, date, time, and analog to digital voltage from the load cell weighing system underneath the truck bed (fig. 1). This required the truck operator to push an external button on the computer. The load cell weighing system utilized four

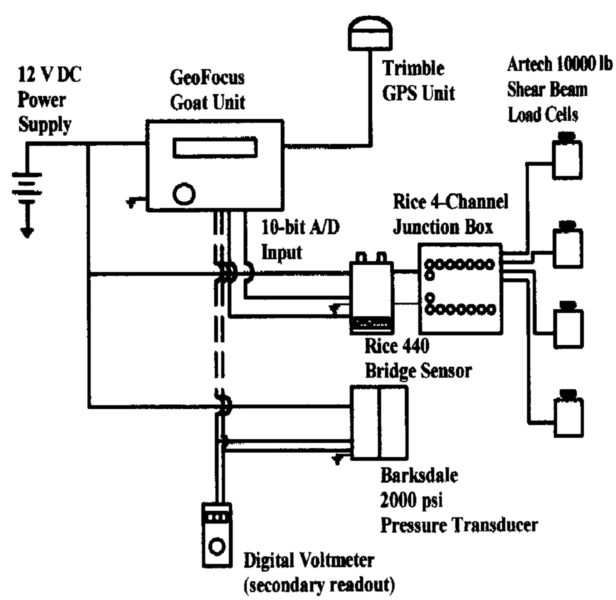

Figure 1—Schematic of two weighing systems for citrus.

Artech (Artech, Inc., Riverside, Calif.) 4545-kg (10,000-lb) capacity shear beam load cells, one at each corner of the truck lift bed. The bed on which the fruit was loaded was supported by a pantographic mechanism and could be lifted by one hydraulic cylinder used to dump processed fruit into a semi-tractor trailer. A second weighing system measured the analog voltage with a digital voltmeter from a Barksdale (Barksdale, Inc., Los Angeles, Calif.) 13 800 kPa (2,000 psi) pressure transducer which sensed the hydraulic pressure in the lift cylinder and required the bed to be lifted a few cm above the Artech load cells. To record data for a container after it had been loaded, the truck operator would normally push the computer button for GPS and load cell readings, lift the truck bed to record the pressure transducer readings, and then lower the truck bed for the next set of readings. Additional information about the two weighing systems can be found in Miller and Whitney (1998).

The two weighing systems were calibrated by adding 450-kg (1,000-lb) pallets of citrus to the lift bed and recording voltage outputs. Calibration of both weighing systems indicated a sensitivity of about 1.2 mV/kg.

Weighing Systems Accuracy Tests

Besides recording the GPS data, when the button was pushed the computer was programmed to record 10 consecutive digital voltage readings at 100 ms intervals from the load cell weighing system. The mean voltage reading of the 10 values was used to calculate the fruit weight in the container. For the pressure transducer weighing system, one voltage reading was recorded manually after the digital display had stabilized (usually within 3 s), and that reading was used to calculate the fruit weight in the container. To calculate the fruit weight for a loaded semi-tractor trailer, the net voltage changes for each goat truck load (from empty to full) dumped onto the semi-tractor trailer were added and a weight calculated from the calibration curves. This reading was compared to the weight boxes certified on five semi-tractor trailer loads of fruit at the packinghouse or processing plant.

Yield Maps

The yield mapping study was conducted in a 3.6-ha grove of citrus trees centered at long. 82.2775°W and lat. 27.6423°N. The trees were 'Hamlin' orange on 'Carrizo' rootstock which were planted in 1986 with a spacing between rows of 9.1 m and an in-row spacing of 4.3 m. The trees had formed a continuous hedgerow at the time of this study and were 4 to 5 m high. The site was typical of flatwoods areas in Florida with poorly drained soils, relatively high water table, with citrus planted on two-row elevated beds with microsprinkler irrigation. The predominant soil series were Waveland and Pomello. The trees were in good condition with yield well above the Florida state average. The fruit was harvested manually by commercial harvesters and placed in tubs (10 field box capacity) using standard operations described above. As is normally done on two-row beds, the tubs were only placed between the two rows on the top of each bed or between every other middle (aisle between adjacent rows) in the grove.

The GPS data associated with each tub location was converted to DGPS by post processing software developed by GeoFocus. Preparation of a yield map required converting the location of each tub to tub density (tubs of fruit per unit area). Yield maps were prepared both as surface interpolated and contour maps. A boundary was drawn around the harvested area to confine the mapping to the harvested area and to avoid edge effects (dilution) due to averaging areas outside the harvested area. ArcView 3.1 and Spatial Analyst extension 1.1 were used to create a yield surface using the parameters listed in table 1. Yield contour maps were prepared using the same procedure. The final products were surface maps color coded for yield in t/ha. To do this, the 10 field box tubs were assumed to be 0.408 t (900 lb).

Authenticity of the yield maps, or ground truthing, was established by dividing the harvested area into square cells two rows wide (18.2 m) and determining the yield (number of tubs) in each cell. The estimated yield from the interpolated map was compared to the ground truth yield in each cell using the Pearson Correlation Coefficient.

Additional map layers were used to provide insight into the sources of spatial variability in yield. These included site characteristics such as soil type, elevation and slope, geo-referenced aerial photography, and maps of percent ground area covered by tree canopy which is an indication of tree size and potential production. Gray scale density slicing was used to select the tree canopy from the digitized aerial photography and a map of percent canopy cover was developed in ArcView.

Table 1. Parameters used in ArcView to create maps (figs. 2-4)

A. Density Calculation
1. Highlight the tub location shape file containing latitude, longitude, tons of fruit per tub.
2. Select Analysis/Calculate Density.
3. Output grid extent—select the line shape file that defines the harvest area—cell size default.
4. Population field— tons.
5. Search radius— 18.2 m.
6. Kernel density.
7. Area units— hectares.
B. Map Calculation
1. Highlight the Density Surface created in the preceding steps and select Analysis/Map Calculator.
2. Double click on the Density Surface to move it into the calculation box to evaluate (Density Surface × 1) Integer.
C. Shape File
1. Highlight the Map Calculator theme.
2. Select Theme/Convert to Shapefile.
D. Merging Point and Polygon Shapefiles
1. Open the attribute table for the map calculator theme.
2. Highlight the Shape field of that table.
3. Open the attribute table for the original tub location point file.
4. Highlight the Shape field of that table, and join the two tables.
E. Surface Interpolation
1. Highlight the point shape file created in D4.
2. Select Surface/Interpolation grid.
3. Output grid extent— use the same line shape file used in A3.
4. Cell size— default.
5. Type of interpolation— IDW.
6. Z-value— gridcode from joined table.
7. Search radius as in A5, with a power of 2.
8. Barrier— same line file as in A3.

Results

Weighing Systems Accuracy Tests

For the semi-tractor trailer loads of citrus, the certified scale readings of the packinghouse and processing plant were in the range of 22 to 25 t (48,000 to 55,000 lb). The calculated load cell readings were 1.5 to 6% lower than those at the certified scale. The calculated pressure transducer readings were 0.8% less to 1.6% greater than those at the certified scale. It would appear the pressure transducer weighing system was more accurate, although the method of recording voltages was different and may have been biased in favor of the pressure transducer.

Yield Maps

The map of tub locations superimposed on the aerial photography illustrates the raw data used for yield mapping (fig. 2). Spatial variability in yield is not readily apparent in this map. However, considerable spatial variability is evident when interpolated yield is calculated, classified in five ranges, and prepared as a surface map (fig. 3). This spatial variability is equally apparent when presented as a contour map (fig. 4).

The resolution or appearance of interpolated yield maps must be easy to interpret to be useful in production management. Color coded maps are much easier to interpret than the monochrome maps for this publication. The parameters used in ArcView for creating a yield map influence both the calculated average yield and the range of yields. One of the most important parameters is the search radius used in calculating fruit density. Since the fruit placed in the tubs in this grove was harvested from two rows at a time (fig. 2), the width of a harvest unit (equivalent to swath width in grain harvesting) is twice the between row spacing or 18.2 m. The GPS placement of the tubs is in the center 3-m aisle or drive middle of this 18.2-m swath. The problems in mapping based on non-representative tub placement were corrected by using a search radius equivalent to the width of two rows. The resulting area of 0.1 ha is an appropriate size for a production management unit.

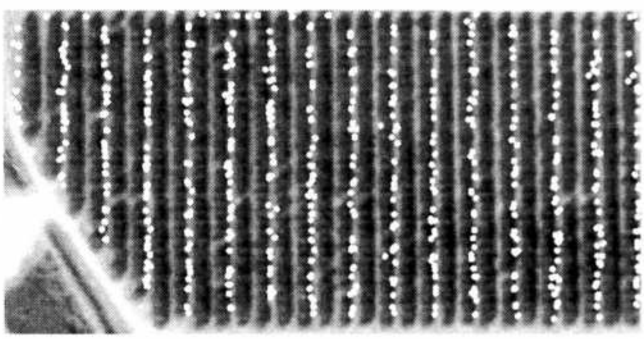

Figure 2—Location of tubs of harvested fruit (white dots) overlaid on an aerial image of the 3.6 ha grove. Each tub is designed to contain 0.408 t of oranges.

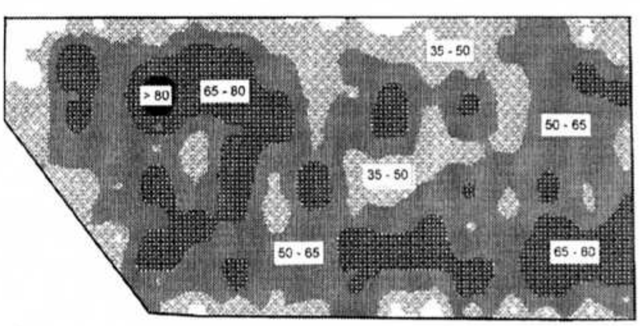

Figure 3—An interpolated surface map (t/ha) showing spatial variation in yield.

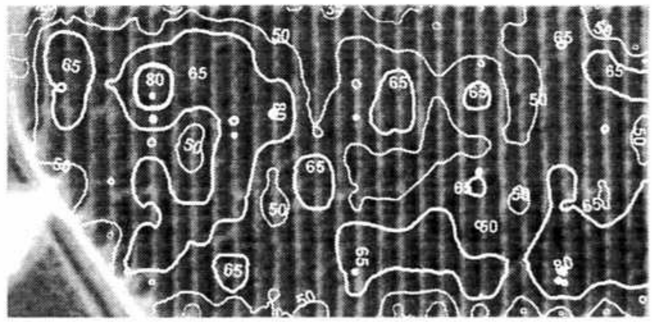

Figure 4—Yield contour lines (t/ha) overlaid on an aerial image of the 3.6 ha grove.

Table 2. Yield (t/ha) range and standard deviation (S.D.) for ground truth and corresponding yield estimates from the density calculation and the interpolated surfaces

		Yield (t/ha)			
	N	Mean	Min.	Max.	S.D.
Ground truth	127	52.10	10.94	120.3	19.94
Density grid	125	56.02	24.0	96.0	13.99
Interpolated surface	127	56.27	28.00	93.00	12.53

The yield surface was confirmed by comparing this estimate of yield throughout the grove to actual yield of grove subunits. The "ground truth" yield was compared with the value of the yield surface corresponding to the location for each cell (table 2). The range in ground truth yield was large, as expected, but there was a good correlation between ground truth and the yield surface ($r = 0.83$, $p = 0.0001$).

The grove appeared to be quite uniform based on the aerial photography (fig. 2). However, yield estimated from the yield surface map varied substantially (fig. 3). The regression of yield per ha on percent canopy ground cover demonstrated an association between tree canopy size and fruit production ($r = 0.45$, $p = 0.0001$). This relationship can be visually observed by careful examination of the contour map superimposed on the aerial photograph (fig. 4).

One problem with this prototype system was the reliability of the operator for pushing a button to initialize data acquisition each time a tub or pallet bin of fruit was loaded. More data were lost due to failure to push the button than were lost from poor GPS data. Another problem was the length of time required for post processing, checking data of outliers, and formatting it for input into ArcView. Post processing was most time consuming, and can be avoided by providing differential correction in real time (DGPS). Continuing cost reductions make DGPS a more attractive alternative.

Conclusions

Although the field work on this project has been limited and was conducted during only one harvest season, the following conclusions can be raised:

Data →	Information →	Actions
Container Locations	Maps	Strategic
Container Weights	Nonspatial Summary Data	Boundaries
Fruit Quality	Real-Time Control Algorithms	Rootstock Selection
Soil Type & Parameters		Soil Modification
Tree Size		Drainage
Tree Canopy		Replant (Reset)
Remote Sensing		Tactical
Pest Pressure		Irrigation
Available Soil Moisture		Fertilization
		Pesticide Application
		Operation Scheduling
		Marketing

Figure 5—Example of integrated system which may be used in precision farming of citrus.

1. The spatially variable yield of hand-harvested citrus (and other hand-harvested crops) can be mapped based upon GPS to record container locations.
2. The weights of semi-tractor trailer loads of citrus can be determined within 1 to 6% accuracy with weighing systems on the fruit handling truck in the field.
3. The initial yield maps show spatially variable yield to be correlated to tree canopy size.

Future Research Needs

The accuracy and reliability of the weighing systems need to be evaluated further to determine if they can be used to map weight yields by container and by truckload. Harvester tracking or electronically recording harvester identity with fruit containers should be integrated with yield mapping to make the system more useful and reliable for the harvester and grower. Tree canopy mapping either by real-time sensors, aerial photography, or remote sensing needs to be developed as part of the GIS data base to assist with tree management and inventory. Eventually integrated systems such as the example in figure 5 may be feasible.

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References

Auernhammer, H., ed. 1994. Special issue: Global positioning systems in agriculture. *Computers & Electronics in Agric.* 11(1): 1-95.

Carr, P. M., G. R. Carlson, J. S. Jacobsen, G. A. Nielson, and E. O. Skogley. 1991. Farming soils, not fields: A strategy for increased fertilizer profitability. *J. Prod. Agric.* 4: 57-61.

Hummel, J. W., L. D. Gaultney, and K. A. Sudduth. 1996. Soil property sensing for site-specific crop management. *Computers & Electronics in Agric.* 14(2/3): 121-134.

Miller, W. M., and J. D. Whitney. 1998. Development of a yield monitoring system for Florida citrus. ASAE Paper No. 98-1098. St. Joseph, Mich.: ASAE.

Nielsen, D. R., and J. Bouma, eds. 1984. Soil spatial variability. In *Proc. Int. Soc. Soil Sci. & Soil Sci. Soc. Am. Workshop.* Wageningen, Netherlands: PUDOC Publishers.

Persson, A. 1998. Potato yield mapping with an optical sensor. In *Proc. 1st Int. Conf. Geospat. Info. in Agric. & Forest.* 2: 618-623.

Pierce, F. J., N. W. Anderson, T. S. Colvin, J. K. Schueller, D. S. Hamburg, and N. B. McLaughlin. 1997. Yield mapping. In *The State of Site Specific Management for Agriculture*, eds. F. J. Pierce, and E. J. Sadler, 211-243. Madison, Wis.: ASA/CSSA/SSSA.

Righetti, T. L. 1997. Precision horticulture: Applying information technologies to orchards. *Precision Farming* (Supplement to GPS World) April: 19-26.

Robert, P. C., R. H. Rust, and W. E. Larson, ed. 1993. *Proc. Soil Specific Crop Manage.: A Workshop on Research and Development Issues.* Minneapolis, Minn., 14-16 April 1992. Madison, Wis.: ASA/CSSA/SSSA.

Schneider, S. M., S. Han, R. H. Campbell, R. G. Evans, and S. L. Rawlins. 1996. Precision agriculture potatoes in the Pacific Northwest. In *Proc. 3rd Int. Conf. Precision Agric.*, eds. P. C. Robert, R. H. Rust, and W. E. Larson, 443-452, Minneapolis, Minn., 23-26 June.Madison, Wis.: ASA/CSSA/SSSA.

Schueller, J. K. 1988. Machinery and systems for spatially variable crop production. ASAE Paper No. 88-1608. St. Joseph, Mich.: ASAE.

_____. 1992. A review and integrating analysis of spatially variable control of crop production. *Fertilizer Res.* 33(1): 1-34.

_____. 1997. Technology for precision agriculture. In *Proc. 1st European Conf. on Precision Agriculture* 33-44, 8-10 September. Oxford, UK: BIOS Scientific Publishers.

Searcy, S. W., J. K. Schueller, Y. H. Bae, S. C. Borgelt, and B. A. Stout. 1989. Mapping of spatially variable yield during grain combining. *Transactions of the ASAE* 32(3): 826-829.

Stafford, J. V., ed. 1996. Special issue: Spatially variable field operations. *Computers & Electronics in Agric.* 14(2/3): 99-253.

Thomas, D. L., C. D. Perry, G. Vellidis, J. S. Durrance, L. J. Kutz, C. K. Kvien, B. Boydell, and T. K. Hamrita. 1999. Development and implementation of a load cell yield monitor for peanut. *Applied Engineering in Agriculture* 15(3): 211-216.

Walter, J. D., V. L. Hofman, and L. F. Backer. 1996. Site-specific sugarbeet yield monitoring. In *Proc. 3rd Int. Conf. Precision Agriculture,* eds. P. C. Robert, R. H. Rust, and W. E. Larson, 835-844, Minneapolis, Minn., 23-26 June. Madison, Wis.: ASA/CSSA/SSSA.