

# THE PEANUT YIELD MONITORING SYSTEM

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**ABSTRACT.** *The most essential component of precision farming is the yield monitor, a sensor or group of sensors installed on harvesting equipment that dynamically measure spatial yield variability. Yield maps, which are produced using data from yield monitors, are extremely useful in providing the farmer a color-coded visual image clearly showing the variability of yield across a field. University of Georgia scientists recently completed development work on PYMS, the Peanut Yield Monitoring System. PYMS uses load cells for instantaneous load measurements of harvested peanuts and has proven to be accurate to between 2% and 3% on a trailer-load basis and to approximately 1% on a field basis when using data collected during combine operation. PYMS data are accurate to around 1% on a basket-load basis when using data collected under static conditions. The instantaneous accuracy of PYMS was calculated to be 700 kg/ha. Basing management decisions on the yield of individual pixels of PYMS yield maps is not realistic. The strength of PYMS is in differentiating yield trends and evaluating management practices. The system was extensively and successfully field-tested over a 3-year period and evaluated by 11 users during 1999, all of whom were able to use the resulting yield maps to evaluate current management practices or to develop future management plans. The University of Georgia has submitted a patent application for PYMS, and the technology has been licensed.*

**Keywords.** *Precision farming, Precision agriculture, Yield monitor, Peanuts, Load cells, Georgia.*

**B**efore the advent of large agricultural machinery, farmers plowed behind a mule and harvested by hand. While this was back-breaking work, it gave the farmers an in-depth knowledge of the land's soils, landscape, and yield potential. Farmers adjusted their fertilizer applications to compensate for low and high yielding areas of the field. They knew how to manage site-specifically because the application of seed, agrochemicals, or organic matter was done manually. As the scale of agricultural machinery grew in the 20th century, farmers lost the ability to address the specific needs of individual areas within fields. Instead, production systems moved to larger fields fertilized or planted at rates representing field averages. Now, technological breakthroughs in the miniaturization of computer technology and public access to GPS allow us to address within-field variability with precision farming.

Precision farming is a catch-all term for techniques, technologies, and management strategies aimed at addressing within-field variability of parameters that affect crop growth. These parameters may include soil type, soil organic matter, plant nutrient levels, topography, water availability, weed pressure, insect pressure, etc.

The most essential component of precision farming is the yield monitor, a sensor or group of sensors installed on harvesting equipment that dynamically measure spatial yield variability. Typically, yield measurements are combined with accurate location data, provided in the form of latitude and longitude by a GPS receiver, to create a yield map. Yield maps are extremely useful in providing the farmer a color-coded visual image clearly showing the variability of yield across a field. Yield maps can be viewed as both the entrance and the final exam for precision farming. As an entrance exam, yield maps can be used to determine if there is enough variability to justify the use of precision farming. As a final exam, they can subsequently be used to determine if the investment in precision farming was worthwhile.

Although grains have monopolized yield-monitoring research (De Baerdemaeker et al., 1985; Searcy et al., 1989; Stafford et al., 1991; Birrell et al., 1993; Murphy et al., 1995; Birrell and Borgelt, 1995; Arslan and Colvin, 1999; Grisso et al., 1999; Lee et al., 1999), other important crops have recently attracted the attention of the research community. Research is continuing on yield monitors for forages (Auernhammer et al., 1995; Kromer et al., 1999) and citrus (Miller and Whitney, 1999; Whitney et al., 1999). Yield monitors have been developed and are commercially available for root crops (Campbell et al., 1994; Rawlins et al., 1995; Panneton and St-Laurent, 1999) and cotton (Perry et al., 1998a; Durrence et al., 1999b; Khalilian et al., 1999).

During 1999, development work was completed on the Peanut Yield Monitoring System (PYMS) at the University of Georgia. PYMS uses load cells for instantaneous load

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Article was submitted for review in July 2000; approved for publication by the Power & Machinery Division of ASAE in May 2001. Presented at the 2000 ASAE Annual Meeting as Paper No. 00-1128.

Supported by funds from the Georgia Agricultural Commodity Commission for Peanuts, the Georgia Research Alliance – Georgia Environmental Technology Consortium, and by Hatch and State funds allocated to the Georgia Agricultural Experiment Stations.

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measurements of harvested peanuts. PYMS evolved from concept evaluation with a single 2-row combine on 2 ha during 1994 to extensive beta testing with 11 combines on nearly 400 ha during 1999. The focus of the first three years was to evaluate concepts and instrumentation developed prior to each harvest season (Durrence et al., 1999a; Thomas et al., 1999; Perry et al., 1998b.) The focus of the final three years was to perfect the design and increase the user-friendliness of PYMS. The objective of this article is to summarize the final three years of PYMS development work, describe the system in detail, and provide data from three years of field-testing.

## MATERIALS AND METHODS

### MECHANICAL PEANUT COMBINE HARVESTING

Peanut plants develop pods, which contain the desirable peanut kernels, in the soil. To prepare for harvest, peanut plants are dug, the pods shaken free of soil, and the whole plant is inverted before being laid back on the soil surface to dry to a moisture content suitable for harvest. Once peanuts have been dug and inverted, a grower has a window of only a few days to harvest the crop before quality begins to deteriorate. Typically, two rows of plants are inverted into a single windrow. Thus, a 2-row peanut combine harvests one windrow at a time. Tractor-pulled 4-row and 6-row combines and a self-propelled 8-row peanut combine are currently in production.

A peanut combine harvests the peanuts in much the same way as a grain combine fitted with a windrow pickup (fig. 1). This pickup feeds the vine-like plants onto a throat elevator where they are drawn into a series of picking cylinders and over sieves, where the pods are separated from the vegetative section of the plant and fall through stemmer saws. At this point, peanut combine design follows one of two options. In some peanut combines, after the stemmer saws, the pods fall into a collecting hopper where a cross auger moves them across the bottom of the machine and into an air-duct, which then delivers them up and into a collecting basket on the top of the combine. In other machines, the hopper and cross auger are replaced by an air duct that spans the width of the machine and wraps up the side of the combine. In both options, powerful centrifugal fans propel the pods through the ducts and deliver them into the collecting basket.

### FEASIBILITY STUDIES

A crop yield monitor must be positioned so that all of the crop passing through the harvester is sensed. Within a peanut combine, there are several positions that provide opportunity for yield measurement. A number of concepts and technologies were evaluated for each position, including adapting existing grain yield monitors. Despite some

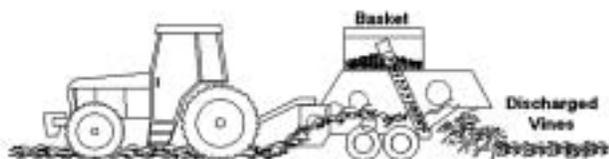


Figure 1. Schematic of a tractor-drawn peanut combine.

similarities between grain and peanut combines, grain yield monitors were not successfully adapted to peanut combines (Durrence et al., 1999a) and new concepts were evaluated.

In combines with a cross auger, the hopper itself can be weighed or a sensor placed at the mouth of the hopper can be used to quantify mass peanut flow as peanuts drop into the airstream that delivers them to the collection basket. Both of these methods were evaluated and showed some promise (Durrence, 1997) but were eliminated from further consideration because no combines under production at the time used a cross auger.

Optical, acoustic, dielectric, and physical impact concepts and technologies were evaluated for quantifying mass peanut flow through the air duct that delivers the peanuts to the collection basket. Peanuts pass through the duct at velocities sometimes approaching 30 m/s. Accompanying the peanuts is a significant amount of foreign material consisting of dust, soil particles and clods, pea gravel-sized to fist-sized rocks, plant material, and occasionally snakes and rodents. Foreign material typically comprises 1% to 5% of the mass flowing through the duct. The environment within the duct is extremely abrasive and hostile to sensors. Consequently, all concepts and technologies evaluated were unsuccessful in the duct environment.

### LOAD CELLS

The yield-monitoring concept ultimately adopted uses load cells to quantify the load of peanuts accumulating in the collecting basket during harvest. On all peanut combines, the collecting basket is attached to two L-shaped basket arms (fig. 2). Hydraulic cylinders mounted to the arms and attached to the basket extend to tip the basket and unload the accumulated peanuts into trailers alongside the combine. During tipping, the basket rotates around pivot points on the top of the L-shaped basket arms.

After experimentation, the Rice Lake EZ Mount 1 Load Cell Mounting Kit was selected to support the basket arms, as shown in figures 2 and 3. The EZ Mount 1 is designed to provide an extremely accurate method for weighing medium and large capacity tanks and hoppers that are subject to vibration forces (Rice Lake, 1997). The design uses a double-ended shear beam load cell, transmits the load with a sliding pin on the load-bearing groove of the cell, and

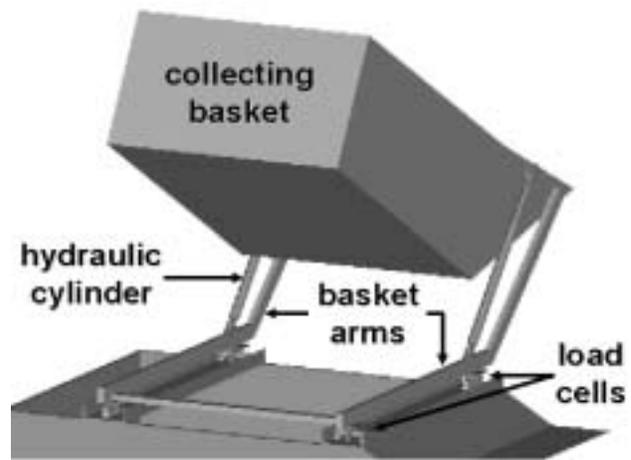


Figure 2. A typical peanut basket in tipping mode. The L-shaped basket arms are supported by the four load cells.

allows for shifting and lifting of the basket without binding. Four stainless steel RL70000, 2270 kg (5000 lb) capacity, 700  $\Omega$  bridge, load cells with a full-scale output of 3.000 mV/V were used.

With most conventional load cell mounts, the “play” in the mounts allows them to shift and bind against the load cells during tipping, and occasionally during harvesting, resulting in unsatisfactory load cell response (Thomas et al., 1999). The EZ Mount 1 is designed to allow for lateral movement in the direction perpendicular to the longitudinal axis of the load cell. To allow the load cell mounts enough freedom to avoid binding, but to prevent the basket from shifting in any direction, the load cells were mounted so that each cell was perpendicular to the cells adjacent to it and parallel to the cell diagonally opposite it (fig. 2).

Heavy steel channel (0.3 m diameter) was bolted to the combine frame to provide a firm and stable base for the load cells, an absolute requirement for accurate load measurement. The load cells were bolted to the channel, and the basket arms were bolted to the top plate loading brackets of the load cell mounts. The sliding pin design eases load cell replacement without the need to lift the basket off the mounts (fig. 3). The load cell mounts resulted in the basket resting approximately 10 cm above its originally position, which required the air duct delivering peanuts to the collection basket to be extended by 10 cm.

#### IDENTIFICATION AND CHARACTERIZATION OF MEASUREMENT ERRORS

The accuracy of any yield monitor is a function of its measurement errors. Four major categories of potential error were identified for the PYMS: slope effects, harmonic operating noise, noise induced by uneven field terrain, and errors related to combine crop transport dynamics. Each potential source of error was thoroughly characterized and addressed in the final design of PYMS.

##### *Slope Effects*

Because load cells are designed for vertical loading, pitching and yawing of the peanut combine resulting from slope changes can decrease the accuracy of load

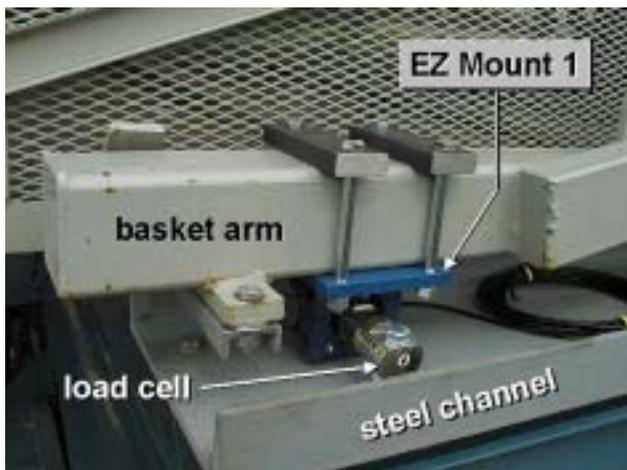


Figure 3. Load cell and mounting hardware used to support the basket arm of a 4-row Amadas combine. Heavy steel channel was bolted to the combine frame to provide a firm and stable base for the load cells.

measurements. A laboratory test was conducted to determine the sensitivity of the load cells to slope. The four load cells were mounted to a test apparatus in the configuration used on the combine and loaded with a 316 kg weight. The test apparatus was then tilted from the horizontal to 6° in 1° increments. Load cell response to increasing slope is a parabolic relationship, with very small errors at small slopes (Thomas et al., 1999). Measurement error was less than 0.1% for angles of up to 2° (3.5% slope) and less than 0.3% for angles up to 4° (7% slope). Because soils suitable for peanut production are general characterized by slopes of less than 5%, the slope error was found to be negligible.

##### *Harmonic Operating Noise*

Under dynamic operating conditions, load cell response is subject to noise introduced by acceleration of a moving mass, which on a peanut combine is created by harmonic operating noise and jolts resulting from traveling over uneven ground. To evaluate the harmonic vibration noise present during combine operation, a combine was instrumented with a 100 Hz bandwidth accelerometer. This frequency range was assumed to encompass any vibration spectra exhibited during normal operating conditions. The assumption was based on the known frequencies of the internal mechanisms and their expected harmonics. For the vibration tests, the combine’s internal mechanisms were engaged, but the machine remained stationary. High sampling rates were used to protect against aliasing. Spectral analyses were performed to identify the significant frequency components of the signal. The principal spectral component was centered at 4.7 Hz with integer multiples of this harmonic centered at 9.4 and 14 Hz. No significant harmonic components were observed beyond 30 Hz. To address the measured harmonic noise, we developed analog anti-aliasing filtering for the data acquisition system and sampled at rates greater than 60 Hz.

##### *Noise Induced by Uneven Surfaces*

Field data indicated the bumps, dips, and other field anomalies that jolt the peanut combine introduce transient harmonics into load cell response and consequently can introduce measurement errors. A test was designed to evaluate the effect of such jolts on the performance of PYMS. The fully instrumented combine was driven over a series of bumps created by placing landscaping timbers on a paved surface. The timbers were spaced far enough apart to ensure that induced harmonics dissipated before the next bump was encountered. The combine was operated at normal picking speed, the basket loaded and unloaded, with all picking mechanisms engaged but with no crop harvested. Positive and negative errors as large as 270 kg and 40 kg were induced by large bumps under unloaded and loaded basket conditions, respectively (Durrence et al., 1999a). An 11-point digital median filter was found to effectively remove these outliers from the data stream.

##### *Combine Transport Dynamics*

The accuracy of yield monitors and any resulting yield maps relies not just on the ability of the monitor to record incoming crop flow but also on the system’s ability to relocate these yield measurements back to the space from which they originated (Eliason et al., 1995). Convolution is

inherent to all harvesters that thresh a crop and is characterized by two components: a time lag and a mixing component.

The time lag between when a crop is collected at the header and when it is measured at the yield monitor has previously been described by Boydell et al. (1999), Whelan et al. (1996), Murphy et al. (1995), Borgelt and Sudduth (1992), and Searcy et al. (1989) and is a critical parameter in the monitoring system for the accurate mapping of yield. Commercially available yield-monitoring systems for grain use a combine-specific time lag measurement along with a record of combine speed to reposition the measured yield a calculated distance back along the combine's travel path.

Time lag measurements for a 2-row peanut combine were determined by Boydell et al. (1999) and Durrence et al. (1999a). A 1 s pulse of peanuts entering a peanut combine requires up to 45 s to entirely reach the basket. They defined time lag as the time required for 50% of the peanut mass in the pulse to reach the basket, a value determined to be 14 s.

The mixing component exists because a peanut pod traveling through a peanut combine has alternative flow routes between the pickup reel and the air duct. The route taken is not a purely random process and is determined by the interaction between the threshing and separation mechanisms within the combine and the strength of the connection between the pod and the vegetative sections of the peanut plant. The net result is that pods from the same plant may reach the delivery air duct at different times and mix with pods collected at different locations in the field. Boydell et al. (1999) developed a Fourier Transform-based algorithm for deconvoluting peanut yield data from a 2-row peanut combine. Their work showed that peanut combines subject harvested product to significant convolution, but the deconvolution algorithms they developed were not robust for real-time processing. Because of this, only the 14 s time lag correction was incorporated into PYMS. Work is continuing on a real-time deconvolution algorithm.

#### **PYMS DATA ACQUISITION SYSTEM**

Two different data acquisition systems (DAS) were used during development of PYMS. The first, used in 1997, was a research system consisting of a self-contained, multipurpose, portable data acquisition board, a notebook computer, and several power supplies, all of which were installed in the cab of a tractor. Load cells feature a full Wheatstone bridge configuration, so a regulated excitation source is needed for accurate measurements. Because common full-scale output for load cells ranges from 20 to 30 mV, an instrumentation amplifier is needed to provide accurate differential amplification suitable to the analog-to-digital converter (ADC) used. Isolation and high common mode rejection are also essential to accurate bridge output measurements. Signal conditioning modules were used as an interface between the ADC card and the load cells to excite the load cells and to amplify their millivolt response. The analog anti-aliasing filter discussed earlier was added to the input of the 16-bit A/D converter used in the DAS. Data were collected at 256 Hz but were averaged and stored at 1 Hz to match GPS data throughput. The output of the signal conditioning circuit used for the load cells was trimmed to remove the dead load of the empty basket from the yield data. A manual harvest indicator switch ("pick flag") was used to

tag data collected while harvesting peanuts. Details of the DAS were provided by Durrence (1997) and Perry et al. (1997).

#### ***Peanut Yield Monitor Data Acquisition System (PYMDAS)***

The second DAS, subsequently referred to as the Peanut Yield Monitor Data Acquisition System, or PYMDAS, was developed during 1998 after many of the yield monitor design parameters had been finalized. It was designed to be rugged, user-friendly, and incorporate a significant amount of signal conditioning to filter harmonic operating noise and noise induced by uneven surfaces. It consisted of a handheld personal computer used for some data processing, data storage, and as a user interface; a small peripheral I/O device connection box; and a custom-designed circuit board used for power regulation, signal conditioning, and analog-to-digital conversion.

The multi-purpose input/output PYMDAS circuit board was designed by the authors but commercially manufactured. It is powered by the tractor's 12 VDC power system. Onboard filtering and voltage regulation ensure proper power levels to various board components. The circuit board is controlled by a Siemens C167 microprocessor with FLASH memory for programming and data storage.

The circuit board was designed with provisions for analog, digital, and RS-232 data inputs. It can read 4 load cell inputs, a DGPS RS-232 input, 8 auxiliary analog inputs, and 8 auxiliary digital inputs. Although it has output capabilities, they are only employed for RS-232 communication with the handheld personal computer. The software running on the circuit board is stored in the board's FLASH memory until another version is transmitted from the handheld personal computer. This type of programming, in comparison with traditional EPROM or EEPROM programming, simplifies program revisions. Data storage was not provided on the circuit board.

The PYMDAS circuit board provides analog and digital filtering tailored for the sensors used with PYMS. The load cell sensors have very low-level analog outputs that are extremely sensitive to vibration noise. The PYMDAS board features a summing junction circuit designed for the load cell outputs. This circuit combines the individual load cell signals into a single output, which is then passed through an anti-aliasing filter (RC low-pass filter with 10 Hz cutoff frequency). The output of the filtering circuit is then passed to a high-resolution (16-bit) analog-to-digital converter capable of resolving low-level differential signals. This device is external to the microprocessor, so the summed, filtered, and digitized load cell output is then passed to the microprocessor. The load cell signal is over-sampled at a rate of 64 Hz for digital signal processing. The over-sampled signal is reduced to one sample per second by simple averaging, and the median filter is then used to remove outliers from the data stream. The individual samples of the load cell output represent instantaneous weight estimates of the cumulative peanut load.

The circuit board was installed in a metal weatherproof box that was mounted toward the front of the peanut combine. Easy-to-uncouple connectors were used to secure the four load cell cables and the main communication cable to the

box. All the connectors on the box were hard-wired to the PYMDAS circuit board.

The communication cable connected the circuit board to the small peripheral I/O device (PIOD) connection box located in the tractor cab. It is the only cable that must be disconnected to separate the tractor from the combine. The PIOD serves to interconnect the circuit board with GPS, the handheld personal computer, and the tractor's power system. A cable with a single fused power point adapter provided 12 VDC to the entire data acquisition system. Easy-to-uncouple connectors are used for the communication cable, fused main power cable, GPS cable, and handheld computer power and serial cables. A plastic rocker switch was mounted on the PIOD for on/off operation of the entire system, including GPS, handheld computer, and PYMDAS circuit board. The PIOD also has a connector for an external speed sensor.

### GPS

Any differential global positioning system (DGPS) receiver can be connected to the PYMDAS circuit board via the PIOD to provide coordinate information (latitude/longitude). The PYMDAS searches for several standard (NMEA) data strings from the receiver and parses the incoming strings to retrieve latitude, longitude, GPS time, GPS speed, and GPS differential quality.

### The User Interface

A handheld (palmtop) personal computer using the Microsoft Windows CE operating system was selected as the user interface, display, and data storage unit. It is an "instant-on" computing device with no moving parts (i.e., hard disk drive, floppy drive, etc.), making it ideal for the tractor cab environment. The palmtop has both CompactFlash and PCMCIA expansion slots, infrared and RS-232 serial ports, 60 MHz CPU, 8 megabytes of memory, natural white backlit 640 × 240 pixel touch-screen display, and desktop-type keyboard.

### Operating Software

PYMS software consisted of the following three components: PYMDAS CPU software code, a user-operated calibration program, and a user-operated harvest program. The CPU code was written in assembly language and consisted of instructions to the CPU regarding signal processing, sampling, averaging, etc. The instruction code was stored in a text file on the palmtop and was downloaded to the PYMDAS CPU each time either the Calibration or Harvest programs were executed. The Calibration program was used to calibrate and null the system and to set the crop row spacing and the default number of rows harvested in a pass, typically the header width of the peanut combine.

The Harvest program had multiple functions. The foremost function was to provide a user interface to the data collected by PYMS during harvest. The Harvest program displayed the following information on its primary HARVEST screen (see fig. 4):

- Operational status (Run/Hold)
- Instantaneous yield in lbs/acre (5-second average)
- Speed in miles/hr (5-second average) from GPS or speed sensor (if available)

- Total load in basket (lbs) as read by the load cells during the most recent update
- Number of rows currently being harvested
- GPS status ("OK" for DGPS)
- Acres harvested

The user could change the number of rows being harvested in real time by pressing the arrow keys. The up arrow increased the number of rows by one, and the down arrow decreased the number of rows by one. On the secondary STATUS screen, the software allowed the user to record the number of the drying trailer currently being filled by the peanut combine and make two additional entries, typically used to enter the name of the field and the peanut variety.

The Harvest program stored the information displayed on the HARVEST and STATUS screens, as well as latitude, longitude, and three additional GPS parameters, once per second to a CompactFlash memory card in binary format. To maximize the capacity of the CompactFlash card and to reduce the amount of irrelevant data, the Harvest program only stored data when the combine was actively harvesting. Data collection began when the user tapped the RUN button on the HARVEST screen, or pressed the space bar, and ended when the on-screen button was tapped or the space bar pressed again.

Under normal operating conditions, the user initiated data collection at the beginning of a row and stopped it at the end of a row. A new file was created every time data collection was initiated, and the file was closed when data collection was terminated. To account for the time lag discussed earlier, the software was designed to collect an additional 12 seconds of data after the user stopped data collection. Calculations required to generate the displayed and stored data were performed by the Harvest program in real time.

### Calibration

PYMS calibration is performed by harvesting approximately 1/2 to 2/3 of a basketful of peanuts. The user runs the calibration program, empties the basket into a trailer that can be accurately weighed on scales, enters the scale weight of the peanuts into the program, and then exits the program. PYMS automatically corrects for any difference between the PYMS weight and the scale weight of the load. The user then harvests one additional basket load and compares the PYMS value to the scale value of this load to ensure that the system has been properly calibrated. A difference of less than 0.5% indicates that the system is calibrated.

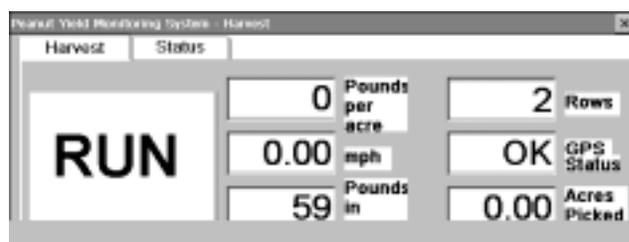


Figure 4. Primary screen of the Harvest program. The RUN button indicates harvesting is in progress. If the button or space bar are tapped, then data collection is suspended and the button displays HOLD.

## Data Management

Data were downloaded from the CompactFlash card to a notebook or desktop computer by the user every two or three days. A conversion program was developed to convert multiple files from the binary format to a single, comma-delimited text file that can be directly imported by most desktop spreadsheet and mapping software. A yield map could be created directly from these data by plotting yield versus coordinates.

Percent moisture content of the harvested peanuts and percent foreign material in each peanut trailer are two variables that can affect the accuracy of the yield data but are not directly measured by PYMS. Because peanut fields are typically harvested over several days, the moisture content of peanuts can vary by as much as 10% across a field. Similarly, percent foreign material in a trailer full of harvested peanuts can vary from near 0% to as high as 6%.

Under the current U.S. peanut marketing and grading system, this information is available upon request to the grower for each trailer brought to a peanut buying point. The grower can then incorporate the information into the data file, and with some simple arithmetic, correct the yield data for percent field moisture and percent foreign material on a trailer-by-trailer basis.

## FIELD TESTING

The year 1997 was critical, as we shifted from the evaluation phase to a concerted effort to develop a yield monitoring system suitable for commercialization. In addition to the 2-row combine that had been on loan to us since the inception of the project, Kelley Manufacturing Company (KMC) of Tifton, Georgia, loaned us a model 3355 KMC peanut combine fitted with a 4-row head. This configuration, known as “the wide body,” is extremely popular with growers because its large throughput allows harvesting at approximately the same rate as a 6-row combine but with much greater maneuverability.

### 1997 Harvest Season

The “wide body” was equipped with the EZ Mount 1 load cell modules, an Omnistar OS7000 DGPS receiver, ground speed radar, a notebook computer, and the portable research data acquisition system described earlier. The computer also served as the user interface for the driver, providing a graphical display of sensor outputs and facilitating control of data logging.

Two irrigated fields, A10 and A71, 11.3 ha and 26.3 ha in size, respectively, located in Early County, Georgia, were harvested with our PYMS-equipped combine. During harvest, the crop weight indicated by the yield monitor and the actual crop weight were recorded in a field notebook each time the combine basket was filled and emptied into a peanut trailer. Truck scales were used to obtain the tare and loaded weights for each peanut wagon, as described in Perry et al. (1998b). Each wagon identification number was recorded for comparison to buyer data sheets.

The majority of data processing was done after the harvest. The data files from each field were divided so that the scale weight of each wagonload harvested could be compared to its respective yield data. The pick flag data were used as an indicator to remove data collected when the combine was not actually harvesting (e.g., during a dump or

turning around at the end of a windrow). The digital filtering techniques discussed earlier were used to remove noise from the data.

Data sheets for the wagonloads were collected from the grower’s buying point to obtain data for correcting the recorded yield measurements. This data included the field moisture content and foreign material percentages as measured at the buying point. These percentages were combined to calculate a correction factor for each wagonload, and these factors were applied to their respective data sets. To create profit maps, the average state production cost for irrigated peanuts during 1997 was subtracted from the monetary return associated with each corrected yield datum within the field.

### 1998 Harvest Season

Prior to the 1998 harvest, the PYMDAS was designed to incorporate the analog and digital filtering techniques found to be useful during analysis of the 1997 data. To reduce costs, the ground speed radar was replaced by a magnetic speed sensor mounted to the rear tractor axle.

In contrast to the research-oriented approach of previous years, field-testing during the 1998 harvest season was designed to obtain feedback on the performance and dependability of PYMS from end-users. PYMS was installed on six peanut combines in Georgia (the University of Georgia 2-row and 4-row wide body KMC peanut combines, two grower-owned conventional 4-row KMC peanut combines, and two grower-owned 4-row Amadas peanut combines) and one combine in Texas (a Texas A&M University-owned 4-row wide body KMC peanut combine). Both University of Georgia combines (fig. 5) were loaned to growers for the season, so a total of six growers in Georgia and one research team in Texas evaluated PYMS performance.

The project team performed the installation of all the yield monitors in Georgia, assisted the users with calibration, and provided technical support throughout the season. Overall, approximately 280 ha were harvested by the seven PYMS-equipped combines. All harvest data were analyzed, and yield maps were created by the project team after the harvest season.

No hardware problems were encountered with the load cells, the circuit board, or the cabling. However, numerous problems were encountered with the palmtop user interface and the operating software. Clearly, some of the problems



Figure 5. University of Georgia 4-row KMC peanut combine harvesting during the 1998 season.

resulted from inherent software problems. Many problems, however, resulted from the limited computer literacy of some users. Three of the six combines in Georgia were operated by farm hands with limited experience with computers and software. Despite our efforts to train them, provide simple printed instructions, and assist with troubleshooting over the phone, these users were often unable to recover even from simple problems like inadvertent keystrokes, multiple entries, etc. Many problems occurred during startup or shutdown when a rigid sequence of steps was required for proper operation.

Reflecting on these problems after the season, the project team concluded that we had implicitly assumed that all users would have a high degree of computer literacy, an unrealistic assumption that may be the downfall of many improperly designed precision agriculture technologies. The software was significantly redesigned for the 1999 harvest season to make it as user-friendly and as crash-proof as possible. Versions of the software were evaluated prior to the season by some users to catch problems. The software architecture was also modified to minimize use of the palmtop keyboard and to allow for easy installation of updated versions of the software during the season.

### 1999 Harvest Season

Four additional grower-owned combines, three in Georgia and one in Alabama, were equipped with PYMS prior to the 1999 season, for a total of 11 operational systems during the season (fig. 6). The magnetic speed sensors were eliminated, and travel velocity was recorded from GPS speed. This was done to simplify installation and to evaluate the reliability of GPS speed. Approximately 400 ha were harvested with the 11 combines. Although it was feasible for growers to develop their own yield maps from the PYMS data files, only one user chose to do so. The remainder relied on the project team to develop yield maps. Yield data were transmitted by the users to the project team via electronic mail or copied to zip drives and sent by surface mail.

Some programming errors were discovered by users. In response, the software was modified to address the problems as they were identified, and new versions were installed as they became available. Installation consisted of copying three files to the palmtop. Some conflicts between Windows

CE and the PYMS software continued to cause occasional problems throughout the season. Most of these problems were resolved by troubleshooting with the users over the phone. On occasion, a site visit was required to resolve the problem. Again, no PYMS-related hardware problems were encountered.

## RESULTS AND DISCUSSION

The results presented here are structured to demonstrate the measured accuracy of PYMS, to demonstrate the ability of PYMS to identify peanut yield variability, and to illustrate the ways yield maps have been used to manage farm operations.

### PYMS ACCURACY

During the 1997 harvest, PYMS performance was monitored under static conditions each time the combine basket was filled and emptied into a peanut trailer. The crop weight indicated by the yield monitor and the actual crop weight indicated by the truck scales were compared. The yield monitor weight was recorded when the tractor was idling and the combine motionless. PYMS values were typically within 1% of scale values for each basket load, and well within 1% for each trailer load. PYMS data were collected with the research data acquisition system described earlier.

PYMS performance was also evaluated under dynamic conditions. We used the summation of 1 s weight data recorded by PYMS during harvest to calculate the weight of each trailer filled by the combine. These data were recorded while the combine was operating and thus incorporated whatever errors were introduced by machine vibration, field bumps, and other noise. The calculated weight was compared to the recorded truck scale weight of each trailer.

Table 1 summarizes the data collected during harvest of field A71. Harvested area was calculated by integrating the ground speed data over the sampling interval and number of rows harvested (Durrence et al., 1998). Trailer scale data represent the load of peanuts in each full trailer as recorded by the truck scales. PYMS data represent post-processed dynamic data. Percent difference reflects the difference between the PYMS data and the scale data. Moisture and foreign material data drawn from buying point records were used to calculate corrected yield. Moisture content was adjusted to 9.5%, the current marketing standard.

The average yield (corrected for moisture and foreign material) for field A71 was 3434 kg/ha, and the average percent (absolute) difference between the yield monitor and wagon scales was 2.06%. The maximum wagonload error was 5.70%. The total field error of less than 1% is comparable to the reported accuracy of some grain yield monitors.

The average yield (corrected for moisture and foreign material) for field A10 was 3845 kg/ha, and the average percent (absolute) difference between the yield monitor and wagon scales was 3.11%, which was higher than that for field A71 because power supply problems affected the accuracy of the first 2 loads harvested in the field.

The corrected yield data were used to develop the maps shown in figures 7 and 8. Pixels in these and subsequent maps represent 1 s data collected by PYMS.

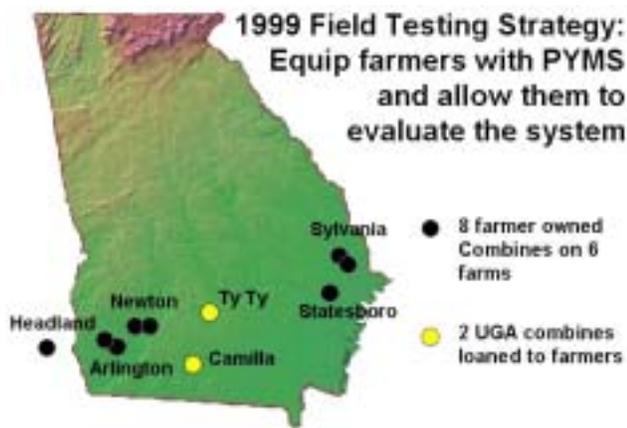
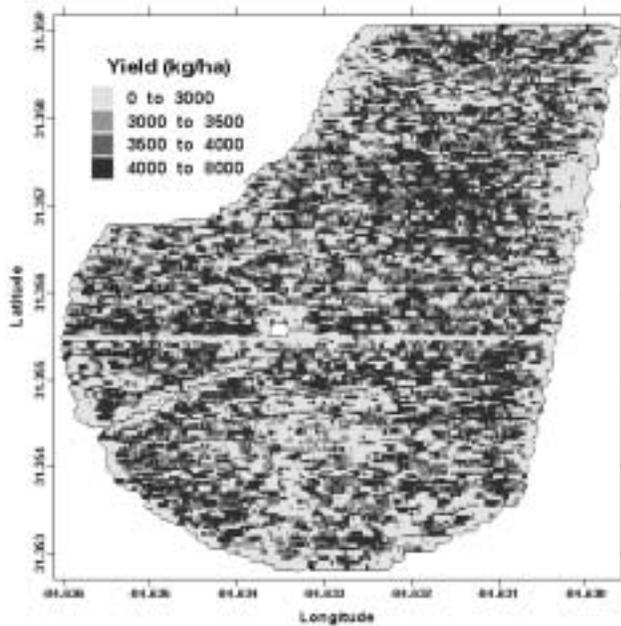


Figure 6. Field-testing locations of PYMS-equipped combines.

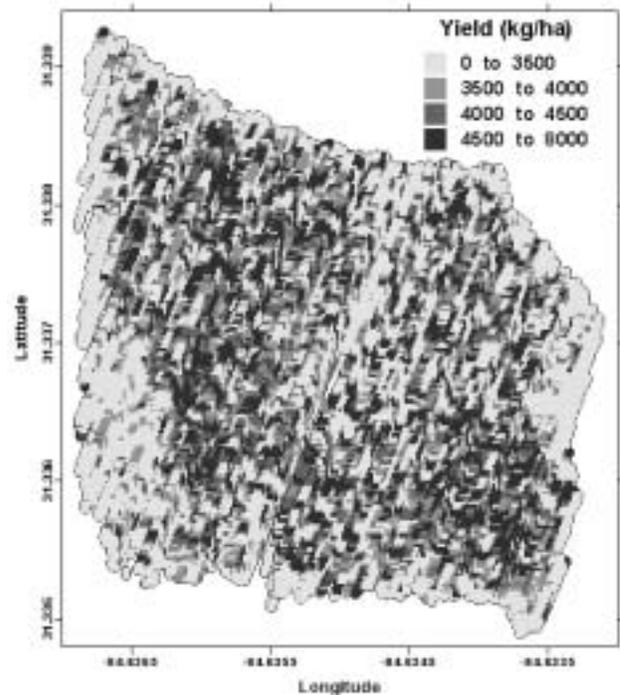
**Table 1. Summary of yield data from Field A71.**

Trailer Load Number	Harvested Area (ha)	Trailer Scales (kg)	Dynamic PYMS (kg)	Difference (%)	Foreign Material (%)	Moisture Content (%)	Corrected Yield (kg)
1	1.2	5039	5089	-0.98	1	20.3	4005
2	1.2	4901	5020	-2.42	1	20.3	3951
3	1.1	4742	4472	5.70	3	19.4	3470
4	0.9	3885	3938	-1.37	2	18.8	3119
5	0.9	4382	4272	2.51	3	18.8	3341
6	1.0	4574	4755	-3.96	3	16.8	3814
7	1.1	4915	4975	-1.24	2	19.5	3906
8	0.9	4198	4372	-4.15	2	18.3	3484
9	0.4	1567	1538	1.88	1	18.3	1241
10	1.1	4969	5002	-0.67	4	16.3	3987
11	1.1	4965	4947	0.35	2	16.3	4042
12	1.1	4587	4587	0.00	1	17.7	3729
13	1.1	4656	4639	0.36	3	17.7	3679
14	1.1	4851	4965	-2.36	2	17.7	3988
15	1.1	4990	5097	-2.15	3	20.0	3924
16	1.1	4633	4614	0.42	3	20.0	3553
17	0.4	1669	1687	-1.06	2	19.2	1329
18	1.0	4910	5006	-1.95	4	22.5	3680
19	1.0	4701	4537	3.50	3	18.0	3584
20	1.2	4894	4953	-1.20	3	18.0	3913
21	1.3	5280	5127	2.90	3	17.3	4086
22	0.6	2059	2096	-1.78	3	15.8	1702
23	1.0	3973	3761	5.35	3	19.5	2914
24	1.2	5364	5187	3.30	4	19.5	3968
25	1.1	5114	5022	1.80	4	18.5	3892
26	1.3	5420	5415	0.11	1	18.5	4359
Totals	26.4	115,241	115,073	0.15	—	—	90,658



**Figure 7.** Peanut yield map of field A71 from the 1997 season. The low-yielding streak running east-west on the map is artificial and was caused by harvesting one windrow instead of the normal two windrows. PYMS software now allows the user to enter the number of rows being harvested.

During the 1999 season, two forms of data were available for evaluating the performance of PYMS. The first consisted of a limited number of PYMS basket load to truck scale comparisons for each combine and a total of 27 for the



**Figure 8.** Peanut yield map of field A10 from the 1997 season. The south-western low-yielding area is drought-prone, while the eastern low-yielding area is usually too wet during planting.

10 combines operating in Georgia and Alabama. These data were collected while the combine was in static mode during

calibration procedures. The largest absolute error measured was 3.79%, the mean absolute error was 0.93%, and the standard deviation of the 27 errors was 0.82%.

Another evaluation method consisted of summing the PYMS calculated yield for an entire field, correcting for moisture content and foreign material, and then comparing this value to the yield determined from the buying point data sheets. The PYMS yield for field A (27 ha) near Sylvania, Georgia, was 102,464 kg. This field was harvested by two PYMS-equipped Amadas 4-row combines, and the yield value represents the sum of the yield measured by both machines. The buying point yield totaled 101,419 kg with a resulting error of 1.03%. Figure 9 shows the seven fields (122 ha) harvested by this grower with his two PYMS-equipped combines. Even at this scale, one can see that fields B and D greatly outperformed the other fields. Incorporating data from two yield monitors to create a single yield map was straightforward, as the binary files from both systems were easily converted to a single comma-delimited text file with the conversion program.

### THEORETICAL RESOLUTION

The theoretical resolution of a load cell weighing system is primarily a function of the full-scale output of the sensor and the number of bits in the ADC. An  $n$ -bit ADC has a theoretical resolution equal to the full-scale output divided by  $2^n$  V/bit. Similarly, the load resolution is the load corresponding to full-scale output divided by  $2^n$  kg/bit (N/bit). The resolution indicates the minimum change in weight that can be detected using the given ADC. The theoretical resolution of each 1 s datum or pixel collected with PYMS was calculated to be 700 kg/ha.

Therefore, comparing individual map pixels is meaningless unless yield differences are dramatic, as is sometimes observed while traversing a waterway, a bare spot in the field, or other anomalies. A series of pixels that fluctuates between several yield categories may be difficult to interpret, and the variability may be due as much to system noise as to agronomic factors. In our experience, however, a series of several pixels in one yield category almost always represents a real yield trend. Clearly, basing management decisions on the yield represented by individual pixels of yield maps is not realistic. The strength of PYMS is in differentiating yield trends.

### MANAGEMENT USES OF PEANUT YIELD MAPS

Figure 10 presents the second yield map developed with PYMS. Although it dates to 1996, it is still one of the most powerful images we have to demonstrate the power of the yield map. The grower was aware that parasitic nematodes were affecting peanut yields in field A11 but was not able to quantify the spatial extent of the nematode population nor their impact on yield. To establish a link between yield and nematode damage, we visually inspected every peanut plant in a 4 ha section of field A11 after the plants had been inverted and were drying prior to harvest. A small surveying flag was placed alongside every plant on which nematode damage to peanut pods was visible. Afterwards, the locations of all the flags were geo-referenced with a backpack GPS unit, and a map showing incidence of nematode damage on peanut pods was created (fig. 10, right side). The same 4 ha section of the field was harvested with the 2-row combine equipped with the 1996 version of PYMS, and the yield map (fig. 10, left side) was created.

There is a clear correlation between the area of the field with lower yield and high incidence of nematode damage. This information allowed the grower to evaluate a number of management options. First, he could see that nematode damage was concentrated on the northern 1/4 of the field. Nematodes could be effectively controlled by applying nematicide to only the heavily infested area, at a cost savings of \$148/ha or a total savings of \$444 over blanket application of nematicide to the entire 4 ha. Second, he could evaluate the approximate loss in yield associated with the infested area and determine whether nematicide application was justified, considering that peanuts were grown in that field one of every 3 years. The grower decided that nematicide was not justified because sandier soils in that section of the field also affected yield and a net gain would not be achieved by treating.

Figure 11 shows a 1998 yield map from Screven County, Georgia. In this generally high yielding 24 ha field, the grower decided to evaluate strip-till peanuts, a management practice highly recommended by some growers but not readily accepted by most. The grower evaluated strip-till on two 2-ha bands within the field. The yield maps indicated that although yield in the strip-till bands was still quite high, it was considerably lower than yield achieved with conventional production practices.

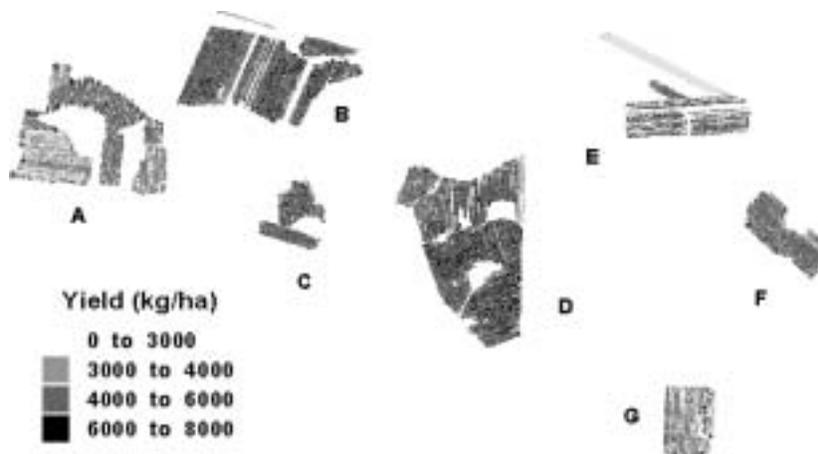


Figure 9. Seven fields harvested by a grower with two PYMS-equipped Amadas combines near Sylvania, Georgia. Field sizes in hectares: A = 27, B = 25, C = 6, D = 35, E = 11, F = 9, G = 9.

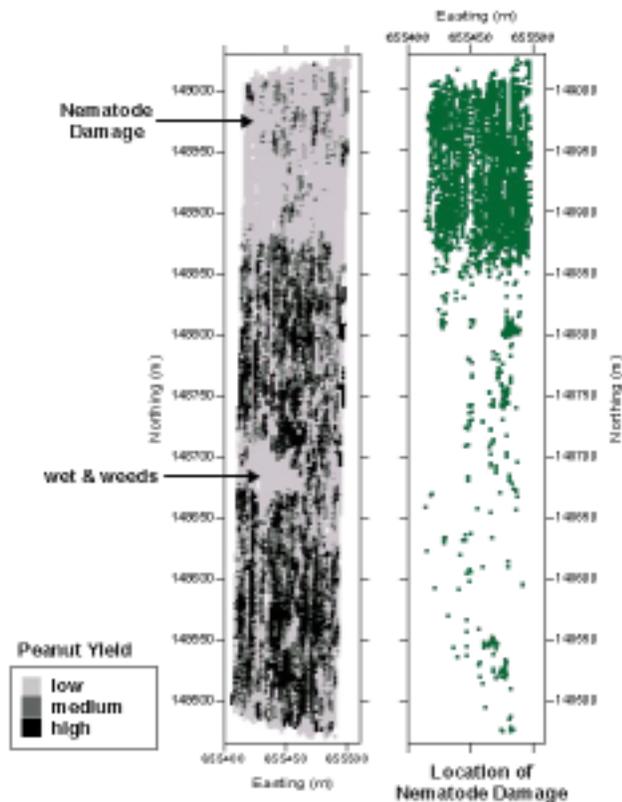


Figure 10. Maps of peanut yield (left) and incidence of nematode damage on peanut pods (right) from the 1996 season.

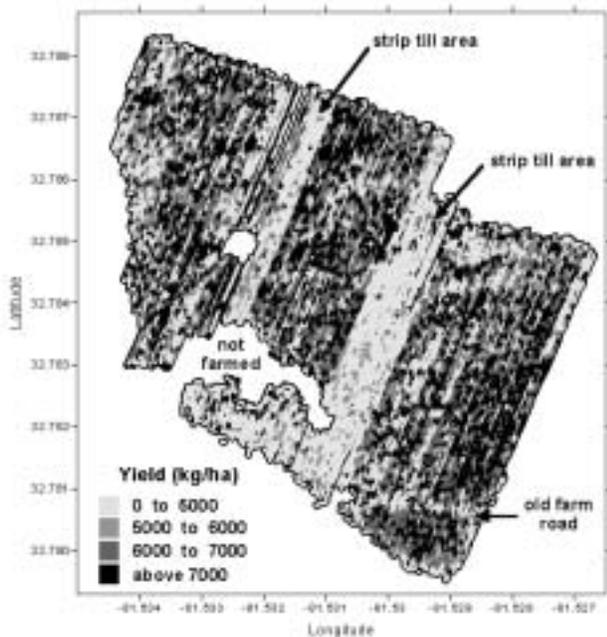


Figure 11. Yield map used by the grower to evaluate strip-tilled vs. conventionally grown peanuts. The strip-till sections were consistently low-yielding than the rest of the field.

Although yield maps are powerful in illustrating yield variability, they still lack the impact of profit maps, which quickly show a grower which parts of the field are profitable and which are not. A profit map of field A10 (fig. 12) shows

that even with the U.S. price support program for peanuts, which in 1997 was at \$300/ton, approximately 1/3 of the field was marginally profitable to highly unprofitable. At the 1997 international market price of \$150/ton, 75% of this field would have been unprofitable.

In this field, corn profit maps from previous years showed similar trends. The availability of a peanut profit map, which showed that a significant percentage of the field was unprofitable even for the most profitable crop in the rotation, forced the conclusion that overall profitability can be significantly improved by leaving portions of this field out of production. During the 2000 season, this grower dedicated portions of the field deemed unprofitable for conventional row crops to ornamental native vegetation that can be sold to niche markets.

## CONCLUSIONS

The Peanut Yield Monitoring System (PYMS), developed by University of Georgia scientists, was extensively and successfully field-tested over a 3-year period. PYMS uses load cells for instantaneous load measurements of harvested peanuts and has proven to be accurate to between 2% and 3% on a trailer-load basis and to approximately 1% on a field basis when using data collected during combine operation. PYMS data are accurate to around 1% on a basket-load basis when using data collected under static conditions. The instantaneous accuracy of PYMS was calculated to be 700 kg/ha.

Clearly, basing management decisions on the yield of individual pixels of PYMS yield maps is not realistic. The strength of PYMS is in differentiating yield trends and evaluating management practices. The system was evaluated by 11 users during 1999, all of whom were able to use the resulting yield maps to evaluate current management practices or to develop future management plans.

The University of Georgia has submitted a patent application for PYMS, and the technology has been licensed. Concerns remain over the ability of potential users to dedicate enough time to create and interpret their own yield maps from the yield data in light of the high demands put on their time by the year-round cropping systems typical of the southeastern United States.

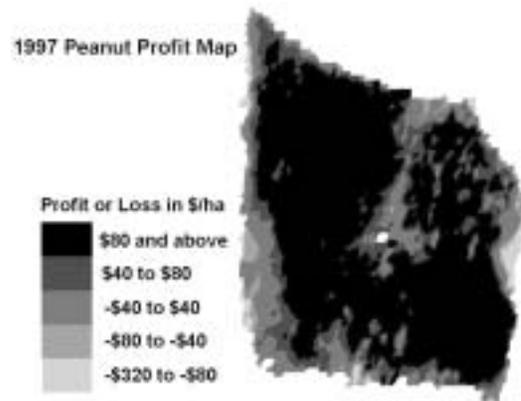


Figure 12. Profit map created from the yield map of field A10 (fig. 8). Approximately 1/3 of the field is marginally profitable or not profitable.

## ACKNOWLEDGEMENTS

We wish to thank all our grower partners, but particularly Mr. Tony Smith and his late father, Mr. W. P. Smith, who allowed us to conduct our research on their farms and provided us with valuable insight during the past several years. We also wish to thank Kelley Manufacturing Co. of Tifton, Georgia, which loaned us two new peanut combines for the development of PYMS. This work could not have been done without these partners.

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