# SIMULTANEOUS ASSESSMENT OF COTTON YIELD MONITORS

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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 measures spatial yield variability. Yield maps, which are produced with data from yield monitors, are extremely useful in providing a visual image to clearly show the variability of yield across a field. In response to the demand for a reliable and accurate cotton yield monitor, several have recently become commercially available. We assessed the AgLeader, Agri–Plan, FarmScan, and Micro–Trak cotton yield monitors in southern Georgia for five harvest seasons from 1997 to 2001. During 2001 we also assessed a prototype yield monitor. Each year, two or more yield monitors were mounted on a cotton harvester and were used during the harvest of several farmer–owned and managed fields. The accuracy of each yield monitor was tested by comparing the weight of each harvested load to data produced by the yield monitor. Yield maps from each yield monitor were also produced with the respective software packages and compared. Features of the monitors were also compared. Each of the cotton yield monitoring systems we assessed has something to offer a user interested in creating yield maps. All are capable of producing an adequate yield map provided the system is properly calibrated, operated, and maintained.

Keywords. Precision farming, Precision agriculture, Yield monitor, Cotton, Evaluation, Assessment, Georgia.

n the United States, cotton is grown in 17 states and is a major crop in 14 of those states. The Cotton Belt spans the southern half of the United States, stretching from Virginia to California. Over the last three years, the area planted to cotton ranged from 5.1 to 6.3 million ha (12.6 to 15.6 million acres). Declining prices and increasing global competition have raised American farmers' interest in precision farming as a means of reducing production costs and improving profitability (Searcy and Roades, 1998; Valco et al., 1998; Durrence et al., 1999; Sassenrath–Cole et al., 1999).

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, and pest pressure. Now, technological breakthroughs in the miniaturization of computer technology, development of new sensors and detectors, and public access to GPS allow us to better address within-field variability with precision farming.

The most essential component of precision farming is the yield monitor — a sensor or group of sensors installed on harvesting equipment that dynamically measures spatial yield variability. Typically, yield measurements are combined with accurate location data, provided in the form of latitude and longitude by a GPS receiver with differential correction (DGPS), to create a yield map. Yield maps are extremely useful in providing a visual image that shows 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 because yield maps can be used to determine if there is enough variability to justify the use of precision farming; as a final exam because 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 et al., 1996; Arslan and Colvin, 1999; Lee et al., 1999; Grisso et al., 2002), 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), citrus (Miller and Whitney, 1999; Whitney et al., 1999), and peanuts (Vellidis et al., 2001). 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).

Because cotton is entirely machine harvested in the United States, it lends itself well to the use of machine– mounted yield monitors. By 1997, two cotton yield monitors were available on the market. Many cotton growers were interested in adopting precision farming techniques but were reluctant to make the transition until the reliability of cotton

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yield monitors was established. As a result, many university researchers, including the authors, focused their efforts on evaluating and/or developing cotton yield monitors. Perry et al. (1998), Searcy and Rhodes (1998), Durrence et al. (1999), Khalilian et al. (1999), Sassenrath–Cole et al. (1999), Wolak et al. (1999), Perry et al. (2001), and Wilkerson et al. (2002) reported on commercially available systems.

In response to continued farmer demand for unbiased and comprehensive assessment of these systems, The University of Georgia Precision Farming Team purchased all commercially available systems and performed careful simultaneous assessment of the yield monitors under conventional harvest conditions. We continued to assess commercially available and prototype cotton yield monitors through the 2001 season. This article presents the results of these assessments and provides a detailed description of each of the four commercial systems and one prototype system we assessed.

# **MATERIALS AND METHODS**

Cotton is mechanically harvested when most of the cotton bolls are open and the leaves have fallen off the stalk. Most modern cotton pickers can simultaneously harvest four or more rows of cotton. A picking unit containing the equipment used to remove the cotton bolls from the stalks is dedicated to each row of cotton. As the harvester's picking unit approaches a cotton stalk, pressure plates force the plant into the picking zone and hold it so that the spindles which remove the cotton bolls from the stalks can come into contact with the lint. The lint, which also includes cotton seeds, is grabbed by the spindles, pulled off the stalk, and transported by a high velocity airstream through a delivery duct or chute into the collection basket of the cotton picker. Because there is very little mixing of the lint within the picking unit during harvest, yield sensors located on the delivery chutes can measure yield almost instantaneously without the complicating factor of convolution encountered by grain and peanut combines (Boydell et al., 1999; Vellidis et al., 2001).

## **COMMERCIALLY AVAILABLE COTTON YIELD MONITORS**

Over the 5-year evaluation period, four commercially available cotton yield-monitoring systems were evaluated. All of the commercially available yield monitors used optical sensing techniques to measure yield. The sensors consisted of two parts — a light emitting component and a light–sensing component (fig. 1). The two components are mounted and aligned on opposite sides of a cotton picker's delivery chute such that cotton passing between the emitter and receiver pair attenuates transmitted light. Attenuation per unit time is converted to actual mass flow rate by proprietary algorithms unique to each yield monitor. None of the systems contained a moisture sensor; therefore, each system recorded "wet yield" with no correction for moisture. The yield reported was for seed cotton and not lint cotton. The next few paragraphs describe the four systems in alphabetical order while table 1 provides a comparison of their operating features.

## Agleader7

For the 2000 season, AgLeader (Ames, Iowa), which for the past several years has offered a grain yield monitor, began offering an optical cotton yield sensor under license from Case Corporation (Racine, Wis.). This sensor was developed by Wilkerson et al. (2001; 2002) at the University of Tennessee. The cotton sensor interfaced to AgLeader's PF3000 console that is also used by the grain yield monitoring system.



Figure 1. Schematic showing the operation of an optical yield monitor.

Parameter	AgLeader7	Agri–Plan7	FarmScan7	Micro–Trak7
Sensor sets recommend by manufacturer for 4-row picker	2	2 or 4	2	2 or 4
	(fig. 2)	(fig. 4)	(fig. 6)	(fig. 8)
Photo detectors per sensor	5 (fig. 3)	3 (fig. 5)	4 (fig. 7)	8 (fig. 9)
Method used to attach sensor housing to mounting brackets installed on picker chute	Two thumb screws	Hinged with thumb screw	Magnetic	Hinged with two retaining clips
Size of rectangular holes cut into chutes for sensors, cm (in.)	$20.3 \times 9.5$ (8 × 3.75)	$12.2 \times 8.6$ (4.75 × 3.4)	$14.4 \times 2.8$ (5.7 × 1.1)	$23.4 \times 2.5$ (9.2 × 1)
Required external sensors or inputs	Head height, fan speed, ground speed	None	None – head height optional	Head height, ground speed
GPS requirements	DGPS	GPS provided, RTCM required	DGPS	DGPS
Data storage medium	Standard FLASH PCMCIA card	4–MB Linear FLASH PCMCIA card	SRAM 2–MB PCMCIA card	SRAM 2–MB PCMCIA card
Item cost for two sensor sets excluding DGPS (US\$)	5000	7000	5000	5000
Cost of mapping software (US\$)	500	Included	Included	Included

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Figure 2. The AgLeader PF3000 user interface console.

The standard PF3000 console (fig. 2) required installation of new cotton firmware that prevented the operator from using the console for other purposes until the initial firmware was reestablished. The PF3000 allows the operator to view harvest variables such as current yield, total load, current ground speed, area harvested, etc., to select Field and Load identifiers, to set system settings, and to perform system diagnostics. The AgLeader console had membrane function buttons and a multi–line, back lit, easily read liquid crystal display (LCD). The AgLeader SMS Basic version 1.00 software was used to process the yield data. The SMS software provided for mapping, archiving, report generation, etc.

## Agri-Plan<sup>®</sup>

In 1997 the Zycom Corp. (now known as Agri–Plan Corp., Stow, Mass.) released its Agri–Plan cotton yield monitor that could be mounted on any 2– or 4–row cotton picker. This system is commonly known as the Zycom yield monitoring system and was upgraded in 1998 and 2000.

The 2000 harvest season version of the system consisted of an Agri–Plan 600 cab–mounted user interface console (shown in fig. 4) that had three toggle switches and a three–window, single–line light emitting diode (LED) display. The console provided the following information during harvest: current yield, total pounds, acres harvested, field identifier, and sensor diagnostics. Field identifiers could be changed but the console offered no way to separate loads. The system required the use of an Agri–Plan 8–channel GPS receiver but also required an external RTCM (differential) correction signal. Agri–Plan software was used to process and map the yield data. The software was required to initialize/format the PCMCIA data cards (table 1).



Figure 4. Agri–Plan 600 user interface console with the three toggle switches (lower right).

## Farmscan<sup>®</sup>

The FarmScan system was first released in 1999 by Computronics, an Australian agricultural electronics firm. Between 1999 and 2000, the firmware was modified significantly including making the display and menus more user friendly, adding the ability to read larger data cards, and allowing the operator to view harvest parameters in both metric and English units.

The Can–Link 3000 console (fig. 6) allowed the operator to view harvest variables such as current yield, total load, current ground speed, area harvested, etc., to select Field identifiers (referred to as "trips"), to set system settings, and to perform system diagnostics. Field identifiers could be changed but the console offered no way to separate loads. The FarmScan console had membrane function buttons and a multi–line, easily read back–lit LCD display. The Computronics FarmScanDM software was used to process and map the yield data. The software was also required to initialize/ format the PCMCIA data cards (table 1).

#### Micro-Trak<sup>®</sup>

The Micro–Trak cotton yield monitoring system was first released in 1997 by Micro–Trak Systems (Eagle Lake, Minn.), which also markets a grain yield monitor. The sensors were developed in Australia and licensed by Micro–Trak Systems. The cotton sensor interfaced to Micro–Trak's Grain–Trak console and Data–Trak data storage module (fig. 8) that was also used by the grain yield monitoring system. A firmware update by the manufacturer was necessary before the Grain–Trak was enabled for cotton yield monitoring.

The Grain–Trak featured a backlit LCD display of various harvest parameters such as load, field, and season counters, current or average yield, number of rows being harvested, setup and calibration parameters, including sensor check,



Figure 3. 2000 version of the AgLeader yield monitor sensors mounted on the front of a chute. This sensor has five photo detectors.



Figure 5. Agri–Plan sensor mounted on the front side of a cotton picker chute. The sensor is in the open position for inspection.



Figure 6. FarmScan Can-Link 3000 user interface console.

GPS differential confirmation, ground speed, and distance or area harvested. The Grain–Trak provided three toggle switches to navigate through menus, make selections, and change values in such settings as number of rows, manual run/hold, active counter displayed (load, field, season), counter zeroing, and calibration/setup parameters. It was mounted to a bracket with a suction cup mount. This mounting mechanism allowed easy attachment to the front windshield of a picker for easy viewing and control. The Data–Trak module provided a PCMCIA memory card drive and a DGPS interface to the Grain–Trak module and used SRAM memory cards to store yield, area, and position data.

#### **PROTOTYPE COTTON YIELD MONITOR**

During the 2001 harvest season, we also evaluated a prototype cotton yield monitoring system under development at Mississippi State University (MSU) (Sui and Thomasson, 2001; Thomasson and Sui, 2000). The MSU cotton yield monitor consists of two optical sensors, one for each of two chutes on a picker, and a data acquisition system enclosed in a plastic box that processes data and records it to a Flash PCMCIA memory card. The sensors detect cotton flow and provide an output signal to the data box. Yield information is displayed on the screen of the data acquisition box in the picker's cab. In contrast to all the other cotton yield monitoring systems whose sensors require the emitter and receiver to be on opposite sides of a chute, the MSU sensors have the emitter and receiver pair mounted in one housing on the same wall of a picker chute, thus requiring only one hole to be cut in the chute and eliminating the problem of aligning the emitter/receiver pairs.

Temperature and stray–light are two main factors that affect the accuracy of optical flow sensors (Thomasson and Sui, 2000; Sui and Thomasson, 2003). Specific measures to reduce the temperature and stray–light effects have been used



Figure 8. Micro–Trak user interface console with the Grain–Trak (top) and Data–Trak (bottom) modules.

in the design of the MSU cotton yield monitor (Sui and Thomasson, 2002). Test results indicated that, at operating temperatures between 4°C and 31°C, and with large stray–light variations, the performance of the cotton flow sensor was not significantly affected (Sui and Thomasson, 2003). The MSU system is scheduled to be commercially available for the 2003 harvest season.

#### FIELD TESTING

Beginning with the 1997 harvest season, we initiated an intensive assessment of cotton yield monitors as they became commercially available. The systems were installed on a University of Georgia (UGA) John Deere 9965 four-row cotton picker – one of the most commonly used pickers in the Cotton Belt – and were used to harvest farmer–owned and managed cotton fields located in southern Georgia. The fields represented different production practices, terrain, soil types, irrigation practices, yield levels, etc. Yield monitor assessment was both labor and time intensive and consisted of comparing yield values estimated by yield monitors to scale–measured values of yield.

In 1997, yield monitor assessment entailed emptying picker basket loads into a cotton trailer and manually packing it until it was full. To obtain the weight of the cotton, trailers had to be weighed empty and loaded. Weighing stations were often several miles away and had scales of unknown accuracy. Borrowed cotton boll buggies instrumented with load cells proved to be highly inaccurate. Our inability to obtain accurate weights in a timely manner proved to be a



Figure 7. 2000 version of the FarmScan sensor mounted on the front of a cotton picker chute.



Figure 9. Micro–Trak sensor installed on the front of a cotton picker chute.

tremendous problem during calibration, particularly as neither of the two yield monitoring systems used in 1997 would allow back–calibration of harvested loads. If the calibration was not correct at the time of harvest, the data had to be post–processed.

To resolve this problem, a method of accurately weighing cotton in the field was needed. A four–wheel boll buggy and Model PT300 Intercomp wheel load scales were purchased prior to the next harvest season. The scales each had a 4550–kg (10,000–lb) capacity and 2.3–kg (5–lb) resolution. During the 1998–2001 seasons, harvested basket loads of cotton were weighed by bringing the picker alongside the parked boll–buggy resting on the wheel load scales, recording the load data from each yield monitor console, emptying the basket–load of cotton into the boll–buggy, recording the weight, then emptying the boll–buggy into a module builder or cotton trailer (fig. 10). The wheel load scales were placed under the four wheels and tongue jack of the boll–buggy. The tongue jack was used to ensure no load was transferred to the tractor.

Calibration requirements of the four systems varied greatly. The systems using GPS speed were easier to calibrate as no speed sensor calibration was necessary. In general, calibration consisted of harvesting and weighing from one to four loads of cotton. These data were then used by the yield monitors to develop a calibration coefficient.

To prevent any inadvertent loss of data, all data cards were downloaded to a notebook computer at the end of each harvest day. Yield maps were created daily to ensure that the yield monitors were performing properly and to obtain immediate feedback and interpretation from the farmers on observed trends and variability. During harvest, the performance of each yield monitor was continuously compared to the scale weights. During 1997–1999, if a yield monitor's data began to diverge from the scale data, corrective action was taken. This action ranged from halting harvest to clean the sensors to recalibrating the system. All sensors were routinely cleaned prior to each day's harvest. During 2000, in an effort to replicate how a farmer would respond to system problems, we took corrective action only prior to the



Figure 10. Field procedure used to obtain accurate yield values for each harvested basket load during the 1998–2001 harvest seasons consisted of harvesting (a), emptying into the boll buggy (b and c), and weighing the load (d).

beginning of the next day's harvest. Calibration was done only at the beginning of harvest and not throughout the season. During 2001, the systems were recalibrated in each field.

After the season, yield monitor performance was assessed quantitatively and qualitatively. Quantitative assessment consisted of comparing load data from the yield monitors to scale data. Qualitative assessment consisted of evaluating the systems in terms of overall performance, ease of use, reliability, technical support, and adequately capturing variability within a field. This information was made available to cotton industry groups.

#### 1997 Harvest Season

In 1997 and 1998 only the Agri–Plan and Micro–Trak systems were commercially available. Agri–Plan and Micro– Trak sensors were installed on the four chutes of the UGA picker. Per the manufacturer's instructions, the Micro–Trak sensors were installed near the top of the chute while the Agri–Plan sensors were installed as low as possible on the chute. Both sensor types were installed with the light–emitting component of the sensor on the front side of the chute and the receiving component on the back side of the chute.

We harvested three fields totaling 148 ha (366 acre) but because of rain, low yields, and calibration problems, only one field produced a good data set for comparing the performance of the Micro–Trak and Agri–Plan sensors. This field was located in Worth County, was 19 ha (47 acre) in size, and was characterized by several depressions, gullies, and highly eroded areas. Limited irrigation was provided by a traveling gun system during the growing season. The average yield was 1790 kg/ha (1594 lb/acre).

We also harvested approximately 2 ha (5 acre) of cotton research plots located on a University of Georgia research farm. The 33-m (108-ft) long  $\times$  4-row wide plots totaled about 2 ha (5 acre). Weed pressure was very low, and the terrain was gently sloped. The plot test was designed to investigate the instantaneous accuracies of the Agri-Plan and Micro-Trak systems and to establish how accurately they would predict known yield levels. Plots were altered to three yield levels, (0.5x, x, 1.5x) by manually removing or adding cotton stalks to the rows. The x rate was the natural yield. The 0.5x rate was achieved by removing half the cotton stalks from the plot. The 1.5x rate was achieved by securing the cotton stalks removed from the 0.5x plots to the stalks in the 1.5x plots. Three replicates of each yield level (nine total) were established and harvested. Several x rate plots were harvested first to calibrate the systems. During the experiment, after each plot was harvested, the picker was stopped and the cotton was bagged and removed from the basket to be weighed later. Thus the actual weight of all cotton passing through the four chutes could be determined at the end of every plot and compared to the data collected by the yield monitors. A uniform theoretical yield rate was applied to the length of the plot by dividing weighed plot yield by plot area. Plot yields ranged from 1340 to 2690 kg/ha (1194 to 2396 lb/acre).

#### 1998 Harvest Season

Despite press releases by various companies announcing the availability of other yield monitoring systems, only the Agri–Plan and Micro–Trak systems were commercially available in time for the 1998 harvest season. Both companies had made significant changes to their systems since 1997. Agri–Plan's most visible changes were made to the user interface components that were consolidated to a single console similar to that shown in figure 4. A new console was purchased and installed. No changes were made to the sensors.

The most visible Micro–Trak changes were to the mounting brackets used for the sensors. The new design (fig. 9) allowed the sensors to be inspected and cleaned when needed. Internally, the Micro–Trak system was also upgraded to correct power supply problems that were occasionally observed during 1997. An entirely upgraded Micro–Trak system was installed prior to the 1998 harvest season. Both the Agri–Plan and Micro–Trak software packages were upgraded.

The performance of the two yield monitoring systems was compared on three fields harvested in September and October of 1998. To monitor the performance of the yield monitors on a per–load basis, each basket–load harvested by the cotton picker was weighed in the boll buggy with the wheel load scales (fig. 10).

The first field [24 ha (59 acre)], located in Cook County, was harvested in late September, and the harvest required three days. Average yield was 2703 kg/ha (2408 lb/acre). This harvest was the first operation of the yield monitors, hence, no prior calibration information was available. For the Micro–Trak system, the calibration coefficient was set to a value used in the previous year's harvest. The Agri–Plan coefficient was not changed from the factory default. A full basket was harvested for calibration, and the Micro–Trak coefficient was adjusted according to the load weight as indicated by the truck scales. The calibration procedure described by the Agri–Plan documentation could not be implemented — the console could not perform the procedure listed in the manual. Consequently, the calibration coefficient was not changed from the default value.

The second field [17 ha (42 acre)] located in Worth County, was harvested over four days in early October. Average yield was 2119 kg/ha (1887 lb/acre). In this harvest, the calibration problems of the Agri–Plan were circumvented by changing the calibration coefficient directly. The calibration information from the first field harvested was used to begin harvesting the second. Again, a calibration load was harvested and the coefficients were changed. Thirty–one loads were harvested from this field, and 22 loads were weighed for comparison with the yield monitor readings.

The third field [42 ha (104 acre)], also located in Worth County, was harvested in late October. Average yield was 2709 kg/ha (2413 lb/acre). Both yield monitors were calibrated to the best of our abilities. A six-day harvest resulted in 62 loads, all were weighed for comparison with the yield monitors.

## **1999 Harvest Season**

During the 1999 season, the FarmScan yield monitor was added to the UGA cotton picker. Although the FarmScan was officially commercially available, in reality it was still a beta-test version of the system. Based on testing in Australia, the manufacturer claimed that two sensors rather than four would adequately characterize yield. As a result, sensors were mounted only on the exterior chutes of the picker between the Agri–Plan and Micro–Trak systems. The FarmScan sensors, however, were installed from side to side on the chutes rather than front to back in order to minimize the possibility of interference among the three sets of sensors.

A commercial supplier of precision agriculture tools contacted us about evaluating a hybrid system they were using which consisted of the Micro–Trak sensor and a Rockwell Vision user interface console. They claimed that this system had been extensively and successfully tested in Mississippi during 1998. We agreed to evaluate this new system because no improvements to the Micro–Trak system were offered by the manufacturer. We were never able to obtain good results from the hybrid system despite numerous calibrations during the season. We continued to use the Agri–Plan system to ensure that we obtained yield maps of the harvested fields because we considered the FarmScan and the hybrid Micro–Trak/Rockwell system somewhat experimental with no guarantee of success.

Approximately 62 ha (153 acres) were harvested and mapped with the three systems. Although good quality data were collected with the Agri–Plan system, the problems encountered with the other two systems did not allow us to create a database suitable for comparison of yield monitor performance. Consequently, results are not presented for the 1999 season.

## 2000 Harvest Season

Prior to the 2000 harvest season Agri-Plan and FarmScan upgraded their systems. The 2000 FarmScan flow sensors appeared vastly improved over the 1999 models. They were easy to install and appeared robust. No changes were made to the Micro-Trak system by the manufacturer since it was last upgraded in 1998 so we chose to remove the Micro-Trak system from the UGA picker and replace it with the newly available AgLeader yield monitoring system. Because of licensing restrictions, AgLeader was only available for commercial use on Case cotton pickers. However, we were able to purchase a system from AgLeader for research purposes. This system, like the FarmScan, required sensors on only two of the four air chutes. It was installed on chutes 1 and 3. Agri-Plan offered upgraded sensors for 2000, which we purchased and installed on two chutes. So, for the 2000 harvest season, the UGA picker was equipped with two Agri-Plan sensors (chutes 2 and 4), and two AgLeader and two FarmScan sensors both installed on chutes 1 and 3 (fig. 11). All sensors were installed front-to-back on the chutes.

Five fields were harvested to assess the performance of the yield monitors under a wide variety of conditions (table 2). All the fields except the fifth field were defoliated prior to harvest. To save on defoliant costs, the grower allowed frost to kill the leaves in this field. At harvest, many leaves remained on the plants that caused dried plant material to blow around and to accumulate on and around the picker during harvest. It is possible that this plant material in the airstream flowing past the sensors may have affected their performance.

Because we have worked closely with Georgia farmers, we have gained much insight on how and when they would use cotton yield monitors. It is clear that farmers are very reluctant to calibrate systems several times during the season because of the time required and difficulty in locating



Figure 11. Configuration of the three sensors mounted on chutes 3 and 4 of the UGA John Deere 9965 cotton picker during the 2000 harvest season.

certified scales in close proximity to the fields. Furthermore, the cotton pickers are often operated by farm hands that are unable to perform the calibration without assistance. Yet, manufacturers recommend that their systems be calibrated whenever field conditions change or a new variety is encountered. For some farmers who plant more than one variety in a field or who farm many small fields [<15 ha (37 acre)], daily calibrations could be required.

Our 2000 harvest strategy was to assess yield monitor performance when used as a farmer would prefer to — that is, with minimal intervention. This strategy involved calibrating at the beginning of harvest and then using that calibration for the rest of the harvest. All three systems recommended harvesting a minimum of one full picker load for calibration and additional loads to check the calibration. Prior to beginning our assessments, a small field was harvested for another project and used to calibrate the Agri–Plan system. Once harvest began in the first field (table 2), the first four loads were used to calibrate the AgLeader and FarmScan systems.

#### 2001 Harvest Season

During the 2001 season, we evaluated two sensors — AgLeader and the prototype MSU sensor. The AgLeader

Table 2. Fields harvested during the 2000 season.

		Size				Averag	ge Yield
Field	County	(ha)	(acre)	Dates	Irrigation	(kg/ha)	(lb/acre)
1	Colquitt	14	35	1-2 Nov	Irrigated	2923	2601
2	Colquitt	10	25	2–6 Nov	Irrigated	2030	1807
3	Tifton	9	22	13–15 Nov	Dry land	1882	1675
4	Coffee	10	25	28 Nov	Dry land	1556	1385
5	Coffee	19	47	29–30 Nov	Dry land	1017	905

system was identical to the one evaluated in 2000 while the configuration of the MSU sensor was as described earlier. We also operated a FarmScan system during the season for the purpose of field-testing two types of new sensors designed by FarmScan to overcome dust accumulation problems encountered during 2000 (discussed in the Results section). The FarmScan Can–Link 3000 user interface was externally the same but firmware had been updated to communicate with the new sensors. The AgLeader and FarmScan sensors were mounted on chutes 1 and 3 and the MSU sensor on chutes 2 and 4.

Three non-irrigated fields were harvested during November: a 17-ha (42-acre) field in Brooks County, and 15- and 19-ha (37- and 47-acre) fields in Coffee County. Average yields were 2879, 1992, and 1870 kg/ha (2564, 1774, and 1666 lb/acre), respectively. Because of timely rains during the growing season, yields were good in all three fields despite the lack of irrigation. In contrast to the 2000 season, the three systems were calibrated in each field and sensors cleaned at the beginning of each harvest day. No operational problems were encountered.

The Brooks County field was part of a variety trial. Twenty-nine varieties were planted in four-row strips across the field. During harvest, the cotton harvested from each cotton picker pass (four rows) was emptied into a boll buggy instrumented with load cells and weighed. That value was compared to the corresponding yield value from each of the yield monitors. The Coffee County fields were harvested with the procedures used during the previous seasons.

## RESULTS

A quantitative and qualitative assessment of the five tested systems is presented below. Quantitative performance comparisons are presented for each harvest season. The qualitative performance of the yield monitors is described only with respect to their most recent release.

#### QUANTITATIVE PERFORMANCE 1997 Harvest Season

Data from the third field [19 ha (47 acre)] was used to create yield maps (fig. 12) and assess the Agri-Plan and Micro-Trak systems. The Agri-Plan system had few operational problems while harvesting this field. Daily errors were small and their absolute values averaged 1.7%. The percent difference in total actual yield and total Agri-Plan estimated yield was -0.9% (table 3). Actual yield data were collected by weighing unloaded and loaded cotton trailers at a nearby peanut buying point equipped with certified scales. Consequently, we were not able to segregate the cotton into basket loads for weighing. Yield variability was visually observed prior to harvest and appeared related to soil type, drainage, and topography. The Agri–Plan map (fig. 12) seems to better represent the observed variability. In addition, the patterns shown in the yield map were also observed in a bare-soil photograph of the field in which soil types are easily distinguished.

Summarized over a day's harvest, the Micro–Trak system consistently overestimated yield (table 3). The average daily error was 17.5% with the majority of this error attributed to



Figure 12. Agri-Plan and Micro-Trak yield maps from the third field [19 ha (47 acre)] harvested during 1997.

sensor errors. During the entire season, the Micro-Trak occasionally experienced problems with one or more of the eight emitter-receiver pairs on the sensors reading continuously high. These problems were caused either by a system malfunction, or more frequently, by cotton lint getting caught on the sensor housing and continuously attenuating the signal between the emitter-receiver pair (fig. 9). Although it was possible to determine when this happened by looking at the system diagnostics on the Micro-Trak console during unloading, it caused artificially high yield readings until corrected. Artificially high yields are seen as the dark (high yield) streaks of the Micro-Trak yield map (fig. 12). The problem could be resolved by nulling the system from the console when the cause was a system malfunction or by cleaning the sensor housing when cotton was interfering. System errors may have been exacerbated by the fact that Micro-Trak stored a 3-second average whereas the Agri-Plan stored data once per second. Finally, the Micro-Trak

sensors also had problems with dust/trash collecting on the sensor photo detectors after several rounds of harvest. When this happened, a soft cloth was used to clean the photo detectors. The field was poorly defoliated so the amount of trash passing through the chutes was probably uncharacteristically high. Agri–Plan's recessed sensor mounts prevented problematic dust and trash from building on the lenses during harvest.

Under low-yielding conditions, neither system performed well. We theorized that not enough cotton was passing before the sensors to overcome some manufacturer-set threshold for recording yield – a common strategy for eliminating background noise.

The small plot data were surprising. Data showed that both systems underestimated the weighed plot yields except for one outlying data point associated with Agri–Plan (fig. 13). On the average, the Micro–Trak and the Agri–Plan systems

 Table 3. Yield monitor performance in the third field 19 ha (47 acre) harvested in 1997.

				Micro–Trak					A	gri–Plan		
Harvest	Scale	Yield	Yi	eld	Error	A	rea	Yi	eld	Error	А	rea
Date	(kg)	(lb)	(kg)	(lb)	(%)	(ha)	(acre)	(kg)	(lb)	(%)	(ha)	(acre)
25 Nov 97	17,636	38,799	20,854	45,879	18.2	9.3	23	17,295	38,049	-1.9	9.7	24
26 Nov 97	11,839	26,046	15,130	33,286	27.8	6.1	15.1	11,745	25,839	-0.8	6.5	16.1
05 Dec 97	4,390	9,658	4,676	10,287	6.5	3.2	7.9	4,506	9,913	2.6	3.3	8.15
Total	33,865	74,503	40,660	89,452	20.1	18.6	45.9	33,546	73,801	-0.9	19.4	47.9



Figure 13. Comparison of yield monitor data to yield measured by weighing bagged cotton in field plots. The diagonal line represents 1:1 agreement (conversion: multiply kg by 2.2 for lb).

underestimated yields by 22.8 and 22.4%, respectively. Because the plots were only 33 m (108 ft) long, the data may have been overly impacted by an edge effect caused by systems' data smoothing algorithms — both during calibration and during harvest. An additional reason to suspect edge effects is the high correlation between the yield monitor data and bagged cotton weights – 99% for Micro–Trak and 95% for Agri–Plan (without the outlier). The edge–effect explanation could not be verified as the algorithms used by the manufacturers to estimate yield are proprietary. Overall, the plot experiment did not provide the anticipated assessment on instantaneous accuracy of the systems.

#### **1998 Harvest Season**

The Micro–Trak and Agri–Plan yield monitoring systems were compared on three fields harvested in September and October. Because of the 1997 experience, we collected good data from both yield–monitoring systems in all three fields. Although we were not able to calibrate the Agri–Plan system until the second field, the data from the first field were adjusted, post–process, with a calibration coefficient developed from the data. The most extensive data set came from the third field that resulted in 62 load–by–load comparisons of the two systems. Table 4 shows the results from the second and third fields. Load errors reported in table 4 were determined from the absolute values of the individually calculated load errors.

Without question, on a load–by–load basis, Agri–Plan was more accurate during the 1998 season. Although we do not have data on instantaneous accuracy, we were impressed by the Agri–Plan's response to yield changes. This response is exemplified by Agri–Plan's ability to map the wheel tracks of the center pivot irrigation system in the yield map of Field 3 and to map several  $3- \times 3-m(10- \times 10-ft)$  plots within the field that were hand–harvested prior to the mechanical harvest (fig. 14). Once we established a method for entering a calibration coefficient, the system performed well and required little maintenance.

The Micro–Trak again experienced the problem of emitter/receiver pairs continuously reading high which resulted in load errors approaching or exceeding 100% on occasion. The artificially high–yielding streaks discussed in figure 12 are also apparent in the 1998 Micro–Trak yield map of Field 3 (fig. 14). Nevertheless, the Micro–Trak yield map was similar to the Agri–Plan map and was able to identify yield variability within the field. The yield maps matched the known features of this field.

Figure 15 presents the load errors in percent for each of the 62 loads harvested from Field 3 over a 6-day period. Agri-Plan errors oscillated around zero with 53 of 62 error measurements (85%) within  $\pm$ 5% and only two exceeding  $\pm$ 10%. Micro-Trak, on the other hand, was biased towards overestimating loads and had 15 error measurements exceeding  $\pm$ 10%. Three Micro-Trak load errors exceeded 60% and they coincided with blocked photo detectors. These loads correspond to the high-yield streaks in figure 14.

The 62 loads of Field 3 were separated into three categories [less than 1500, 1500–2000, and above 2000 kg (less than 3300, 3300–4400, and above 4400 lb)], to determine if yield monitor performance was affected by load size. One would expect that mean absolute load error would decrease with increasing load size as larger loads allow for smoothing of the data. The results (table 5) show that Agri–Plan responded as expected while Micro–Trak values did not exhibit a trend.

## 2000 Harvest Season

Accuracy of the AgLeader, FarmScan, and Agri–Plan systems was evaluated by comparing yield monitor data to wheel scale data and calculating percent load error. Unlike 1998 and 1999, when Agri–Plan performed consistently throughout the season, the yield monitor responses during 2000 were somewhat unpredictable. None of the systems were consistently accurate throughout the season. Percent error for each load harvested is presented in figure 16. The first four loads of AgLeader and FarmScan are very accurate because their loads were recalculated by each system

Table 4. Summary of	of 1998 Field 2 and 3	yield data.[a]
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	Field	2 <sup>[b]</sup>	Field	3[c]
Parameter	Micro-Trak	Agri–Plan	Micro-Trak	Agri–Plan
Total yield (kg)	39,808	36,767	120,954	115,075
Total yield (lb)	87,578	80,887	266,099	253,165
Area harvested (ha)	12.6	13.4	39.8	42.2
Area harvested (acre)	31.1	33.1	98.3	104.2
Mean yield (kg/ha)	3166	2745	3036	2728
Mean yield (lb/acre)	2818	2443	2702	2428
Mean absolute load error (%)	16.2	3.6	11.3	2.9
Max absolute load error (%)	46.7	10.6	118.9	18.2
Min absolute load error (%)	1.3	0.2	0.3	0.1
Standard dev. of error (%)	12.7	2.9	16.55	3.11

<sup>[a]</sup> In Field 2, 22 of 31 loads were weighed and in Field 3, all 62 loads were weighed.

<sup>[b]</sup> 22 loads — 36,023 kg (79,250 lb).

<sup>[c]</sup> 62 loads — 114,065 kg (250,943 lb).



Figure 14. Yield map of the third field [42 ha (104 acre)] harvested during 1998 created with the Agri–Plan (left) and Micro–Trak (right) system data. The semicircular patterns in the Agri–Plan map were caused by tracks of the field's center pivot irrigation system.

following calibration after the fourth load. Within a few loads after calibration, however, errors began increasing. By load 16, FarmScan errors were consistently greater than 5% so the system was recalibrated. Over this period, Agri–Plan was very inconsistent with some errors above 20%. It was also recalibrated after load 16. Despite this recalibration, performance of all three systems continued to degrade. It was probably aggravated by variety changes (fig. 16) and possibly moisture content changes in the crop. In general, AgLeader tended to over predict, FarmScan tended to under predict, and Agri–Plan's response was mixed. In past years, low yields sometimes resulted in poor yield monitor performance. By chance, the five fields were harvested from



Figure 15. Percent errors of the load-by-load comparisons from the third field harvested during 1998.

highest to lowest yielding (table 2), so, decreasing performance may also be related to decreasing yields.

All sensors were cleaned prior to beginning each field but were only cleaned during harvest if a system's user interface indicated a problem. Problems occurred twice with Farm-Scan, once in the first field and once in the third field. In both instances, dust accumulation on the FarmScan sensor resulted in a blocked sensor. Electrostatic charges on the FarmScan sensor housing caused dust to accumulate on the sensor surfaces (fig. 7). Close evaluation of the Agri-Plan sensors after the season showed that one of the emitter-receiver pairs was operating intermittently. It is likely that this problem resulted in Agri-Plan's inconsistent performance although it is difficult to explain why the Agri-Plan sensor performed well for a few loads in field 4. A field-by-field and seasonal summary of the performance of each system is given in table 6. Mean load errors and standard deviations were determined from the absolute values of the individually calculated load errors.

Table 5. Mean error	: of 1998	harvest	loads
segregated int	o load ca	ategories	

Load	Range	No. of	Mean Absolute	e Load Error (%)
(kg)	(lb)	Loads	Agri–Plan	Micro–Trak
<1500	< 3300	14	4.7	3.0
1500-2000	3300-4400	26	2.8	15.4
> 2000	> 4400	22	2.0	10.6



Figure 16. Percent load error of each load measured for the three yield monitoring systems used during the 2000 harvest season.

Yield maps were used to assess the sensors' ability to capture spatial variability. The yield maps were created from the harvest data by using each yield monitor's respective software package. As such, the plotting techniques used to create each map are different. The yield maps of field 1 in figure 17 were recreated by distributing the data points equally amongst four yield categories. Thus, the categories presented in the legend of each map are not the same. This process is a normalization technique that allows us to assess if the yield monitoring systems were able to map the same spatial patterns regardless of yield magnitude. It is a measure of precision rather than accuracy. Clearly, all three systems were able to detect some of the same spatial patterns.

Table 6. Statistical summary of the 2000 harvest.

No of	Mean Absolute I	load Error (%) (Sta	ndard Deviation)
Loads	AgLeader	FarmScan	Agri–Plan
20	3.78 (3.12)	1.64 (1.66)	7.79 (7.41)
13	12.36 (4.43)	7.25 (3.06)	16.28 (9.68)
5	9.02 (2.03)	3.19 (0.95)	2.19 (1.59)
9	11.56 (3.79)	14.16 (3.81)	4.98 (6.11)
12	14.34 (6.34)	24.78 (4.50)	8.94 (5.00)
59	9.39 (6.01)	9.90 (9.51)	8.62 (7.87)
	No. of Loads 20 13 5 9 12 59	No. of Loads         Mean Absolute I AgLeader           20         3.78 (3.12)           13         12.36 (4.43)           5         9.02 (2.03)           9         11.56 (3.79)           12         14.34 (6.34)           59         9.39 (6.01)	No. of Loads         Mean Absolute Load Error (%) (State AgLeader         FarmScan           20         3.78 (3.12)         1.64 (1.66)           13         12.36 (4.43)         7.25 (3.06)           5         9.02 (2.03)         3.19 (0.95)           9         11.56 (3.79)         14.16 (3.81)           12         14.34 (6.34)         24.78 (4.50)           59         9.39 (6.01)         9.90 (9.51)

Pivot tracks are visible in both the Agri-Plan and AgLeader maps. FarmScan was not as responsive, perhaps as a result of more smoothing algorithms. The FarmScan map also appears slightly distorted. Although we were not able to identify the cause of the distortion, we suspect it is a function of the software code that processes and plots the GPS coordinates. The changes in accuracy evident in each of the three systems could be the unique response of each system's sensors to an ever-changing environment. Our results suggest that all three systems might have benefitted from re-calibration in fields where the cotton crop was substantially different from the crop that was used for initial calibration. These differences could be variety, irrigation, yield levels, defoliation quality, etc. all of which change frequently in most areas of the Cotton Belt. Nevertheless, the maps still displayed spatial yield trends. It must be made clear to farmers that yield monitor performance is directly related to frequency of calibration and maintenance.

#### 2001 Harvest Season

AgLeader and the MSU prototype sensor performed well during the season with comparable accuracies (table 7). Mean field load errors ranged from 4.24 to 9.54% for AgLeader and 5.73 to 8.67% for the MSU system. Mean load errors and standard deviations were determined from the absolute values of the individually calculated load errors. Yield maps from the two systems were quite similar, exhibiting the same features. The yield maps from the Brooks



2000 Cotton Yield Maps, First Field – 14 ha (35 ac), Colquitt Co., Georgia

Figure 17. AgLeader (left), Agri-Plan (center), and FarmScan (right) yield maps of the first field [14 ha (35 acre)] harvested during 2000.

Table 7. Statistical summary of the 2001 harve	Table 7.	Statistical	summary	of the	2001	harves
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	No. of	Mean Absolute Loa	d Error (%) (Standard Deviation)
Field	Loads	AgLeader	Mississippi State Prototype
1	88 <sup>[a]</sup>	9.54 (4.87)	8.67 (6.15)
2	17	3.36 (2.64)	5.73 (5.40)
3	16	4.24 (3.85)	6.33 (4.88)
Season	121	7.93 (5.16)	7.93 (5.97)

[a] Each load consisted of a single pass (4 rows) through the field.

Co. field (fig. 18) are particularly interesting because in addition to areas of low yield caused by erosion, yield difference resulting from the variety trials are also clearly visible as streaks of higher or lower yield.

Data from the FarmScan sensors were limited because of communication difficulties between the new sensors and the Can–Link 3000. As a result, FarmScan was not included in the performance evaluation. However, one of the two FarmScan sensor types tested showed great promise and it is anticipated that the sensor will be further tested during the 2002 season.

#### **QUALITATIVE PERFORMANCE**

The next few paragraphs summarize the authors' qualitative assessment of the four commercially–available cotton yield monitoring systems tested between 1997 and 2001. Each system has strengths and weaknesses. Of the four, the AgLeader is the most recent to come on the market (during 2000) after considerable university and private testing. The AgLeader Company has been producing grain yield monitors for many years and obviously put their experience behind their cotton product. Many growers favor the concept of having a yield monitor console that will work with both cotton and grain crops and can also be used for other functions such as control of a variable rate applicator.

The AgLeader console and sensors are of a quality that surpasses the other three systems. However, like the other systems tested, the AgLeader had some drawbacks. Installation of the AgLeader system was the most involved as both the head height and ground speed sensors required calibration. Early versions of the console require the manufacturer to modify the firmware before the PF3000 can be used for a different crop. Newer versions allow the user to update the firmware. Finally, AgLeader mapping software is expensive (USD 500) and not provided with the yield monitoring system. It must be purchased separately. AgLeader has several advantages. The PF3000 console has a logical layout of functions, offers diagnostic functions, and can display many different parameters. Yield calibration is much simpler than with the other systems. The console allows the user to divide a harvest into one or more loads as well as fields. The system stores data on commonly available Flash memory cards that come in many different capacities. Although the sensors were checked and cleaned at various times throughout the harvest season, they never had any significant foreign material build-up. Documentation is very thorough and technical support for the system is readily available and responsive.

The Agri–Plan yield monitor has been on the market the longest (since 1997). The Agri–Plan had the least – user–friendly – interface console and its documentation was barely adequate. Selecting options on the console with up/down and left/right toggle switches was inconvenient and sometimes exasperating. Quite often a section of the LEDs on the console failed to work and required cycling power multiple times to remedy. Additional drawbacks for Agri– Plan include not having a straightforward method of calibration, occasional failure of sensor photo detectors, lack of a "load" parameter, and having to provide a separate RTCM correction signal for the Agri–Plan GPS unit. The biggest drawback to the Agri–Plan system over the 4 years that we used it was poor quality control of the hardware



Figure 18. 2001 yield maps of the Brooks Co. field [17 ha (42 acre)] created by the AgLeader and prototype Mississippi State University yield monitors. The field was used for variety trials with 29 varieties planted in four-row strips across the field.

shipped by the manufacturer. Almost inevitably, some piece of hardware received after upgrades was defective and had to be returned to the manufacturer. In 2000, it appears that at least one of the new sensor pairs was not operating properly. Unfortunately, we did not discover this until after the season. Technical support for the system is quite limited.

The strengths of Agri–Plan include simple installation and no requirement for head height, fan, and ground speed sensors and use of standard linear Flash memory cards. Agri–Plan's greatest strength is its ability to map spatial yield differences of very small areal extent – like pivot tracks or hand harvested plots – something that always impressed both our farmer partners and us. With the exception of the 2000 season, Agri–Plan has been the most accurate system evaluated.

The FarmScan used in 2000 was a second generation system. It was the simplest to install. The documentation provided was adequate for most users. Nevertheless, the FarmScan system had several drawbacks. Minor problems included the lack of an automated calibration procedure, inconsistent trip/file naming, having to "configure" the sensors, lack of "load" feature, and an annoying "load alarm." Other, more important problems included use of small capacity non-mainstream memory cards, the "auto hold" feature not working properly (causing incorrect measurement of area harvested), and sensors getting blocked by dust and trash. However, FarmScan self checks were able to alert the user when this problem occurred. Although technical support for the system was available, the time difference between the United States and Australia forced to communicate mostly by email. Overall, the FarmScan was more consistent (when in clean, high-yielding cotton) than the previous version and was able to map yield trends effectively.

Our evaluation of the Micro–Trak system is based on our experiences in 1998. At that time, the system was still experiencing problems with artificially high yields caused by sensors being occasionally blocked by cotton lint catching on the sensors or sensor brackets. Technical support was limited. The PCMCIA memory cards used to store data were not compatible with some personal computers thus making it inconvenient to download data. Installation was complicated as Micro–Trak required head–height and ground speed sensors and an interface box beneath the picker cab. Despite these problems, Micro–Trak yield maps were able to capture yield trends. The Grain–Trak console was quite flexible, easy to read, and was able to maintain individual load, field, and season counters. Its mounting bracket was the best we encountered.

During one evaluation season, the Mississippi State University prototype system performed well. Its sensors are easier to install as they contain both the emitter and receiver pair in one housing and thus require only one hole to be cut in the chute. The user interface and data management aspects of this system are still in the research phase.

Installation of the yield sensors where they can be affected by stray light entering through the top of the chutes or through holes in the chutes seems to have an adverse effect on performance. We particularly noticed this phenomenon with the Micro–Trak sensors that were installed near the top of the chutes (per the manufacturer's instructions). We recommend that sensors be mounted as low as possible on the chutes and that all holes through which ambient light may enter the chutes be sealed.

# **CONCLUSIONS**

Overall ease of use and reliability of cotton yield monitors has greatly improved since they were introduced to the market in 1997. Accuracy of the systems does not appear to have improved with time although the precision of some systems does appear to have improved. Each of the yield monitoring systems we assessed has something to offer the grower interested in creating yield maps. All the systems are capable of producing an adequate yield map provided the system is properly calibrated, operated, and maintained. The issue appears to be how much calibration and maintenance is required for good performance. Clearly, a discrepancy exists between manufacturers' expectations and farmers' ability to meet these expectations. Furthermore, there are discrepancies between the true accuracy and promoted accuracy of the systems and the expectations of farmers who purchase these systems. We believe that farmers should be informed upon purchasing a new cotton yield monitoring system that accuracy of the system is directly proportional to the amount of time and effort they put into calibrating, operating, and maintaining their system. A system that is calibrated frequently and whose photo detectors are cleaned regularly may predict basket loads to within  $\pm 5\%$  and will likely create a good yield map. A system that is installed and forgotten may produce maps that show yield trends but its accuracy will be poor. All systems require operators that can understand and operate the user interface consoles for optimal results.

All potential users should carefully research prospective cotton yield monitoring systems for the following attributes before purchase: quality of the product, "user–friendliness," ease of installation, GPS requirements, availability and responsiveness of technical support, skill level required of the picker operator, and time available for downloading data files.

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