PROPER IMPLEMENTATION OF PRECISION AGRICULTURAL TECHNOLOGIES FOR CONDUCTING ON-FARM RESEARCH

J.P. Fulton

Biosystems Engineering Department
Auburn University
Auburn, Alabama

M.J. Darr

Department of Agricultural and Biosystems Engineering
Iowa State University
Ames, Iowa

R.K. Taylor

Biosystems and Agricultural Engineering Department
Oklahoma State University
Stillwater, Oklahoma

S.A. Shearer

Department of Biosystems and Agricultural Engineering
University of Kentucky
Lexington, Kentucky

ABSTRACT

Precision agricultural technologies provide farmers, practitioners and researchers the ability to conduct on-farm or field-scale research to refine farm management, improve long term crop production decisions, and implement site-specific management strategies. However, the limitations of these technologies must be understood to draw accurate and meaningful conclusions from such investigations. Therefore, the objective of this paper was to outline the limitations of several precision agriculture technologies (automatic section control, variable-rate, yield monitors, on-the-go sensors and GNSS receivers) to help insure these tools are utilized properly to conduct research at the sub--field scale. Selection, calibration, maintenance, and management of precision agriculture technologies are important factors to be considered when minimizing management and data collection errors thereby maximizing benefits for practitioners adopting these technologies. Delay times for control and measurement systems exist and can vary between technologies. In some cases, delay times for control systems are long enough (several seconds) to limit management resolution such as grid or zone size. Delay times can also impact the application performance of on-the-go sensing technologies. Further, incorrect setting of the harvester delay time(s) within yield monitoring systems to account for material conveyance before arrival at measurement sensors can significantly impact the precision and accuracy of yield mapping data. In summary, users must be aware of the limitations of precision agriculture technologies such that performance expectations do not exceed systematic capabilities thereby producing data that are dubious at best. This paper provides suggestions for practitioners who design and conduct investigations that rely on precision agriculture technologies.

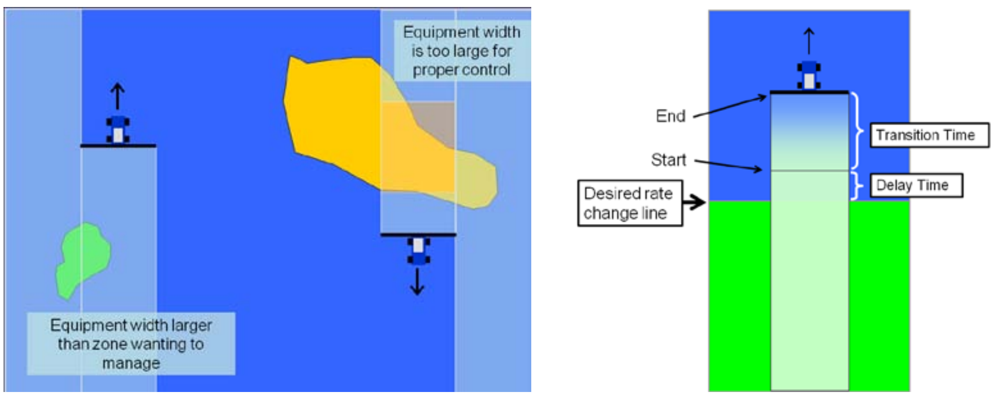
Keywords: application, GPS, RTK, site-specific management, on-farm research, variable-rate technology, yield monitoring, on-the-go sensing

INTRODUCTION

Today, the modern farmer and researcher has the ability to utilize various precision agriculture (PA) technologies such as yield monitors, variable-rate technology (VRT), automatic section control (ASC), and on-the-go sensors to enhance decision making and implement site-specific management (SSM). These technologies allow farmers to manage fields on a much finer resolution when compared with the traditional "whole field" approach. While the adoption of these innovative technologies and concepts by the agricultural community depends on cost to benefit ratio, the evaluation and measurement of benefits that accrue to the practitioners must be accurate to insure such benefits are realized by the adopters. SSM adds the spatial dimension to crop diagnostics and input management recommendations. Profitability will be a major outcome of PA (Lowenberg-DeBoer and Swinton, 1997). However, most SSM profitability assessments, presented in contemporary literature, only offer broad principles (Fairchild and Duffy, 1993). The adoption of PA hinges on several key factors which include access to information about the technology, confidence in this information, and favorable outcomes resulting from this information (Lowenberg-DeBoer and Swinton, 1997). Further, those individuals and companies implementing PA technologies often lack the technical expertise or necessary training programs to properly assemble and utilize PA systems (Leer, 2003).

Many believe the use of PA practices allows for better nutrient management by applying only what is required for crop growth thereby providing agronomic, economic and environmental advantages over the traditional blanket application approach. Rawlins (1996) stated that the objective of precision agriculture is to apply chemicals, water, seeds, or other inputs to fields in quantities sufficient to meet site-specific crop requirements. Some researchers have found yield and economic benefits to PA management strategies when compared with traditional management approaches (Cambouris et al., 1999; Bongiovanni and Lowenberg-Deboer, 2000; Yang et al., 1999) although other researchers have reported the opposite (Lowenberg-Deboer and Aghib, 1999; Mallarino, 1999; Weisz et al., 2003). While yield maps quantify spatial crop performance and fertility maps provide soil nutrient levels, practitioners must realize this spatial information contains inherent errors, and if not understood or documented, these errors can impact evaluation efforts.

Increasingly, agricultural producers around the world are turning to larger and faster equipment to be timely with field operations. For example in the US, it is common to see seeding equipment with working widths up to 25 m, sprayers that exceed 35 m, and grain harvesters exceeding 10 m. This focus on ever increasing machinery size poses a serious problem when considering the capability of this equipment when it comes to addressing the inherent variability of agricultural lands (Fig. 1). While existing technologies continue to evolve much of production agriculture in the U.S. is forced into “boom-width” management. Specifically, much variable-rate management is based on varying application or seeding rate across the implement width. With this limitation come several operator problems that further degrade “metering and application accuracy.”



(a) (b)

Fig. 1. Illustration of how equipment width can impact management resolution both laterally (a) and longitudinally (b).

Applicator dynamics have an imperative effect on VRT performance. However, feed forward control can provide considerable improvements (Schueller and Wang, 1994). Cointault et al. (2003) noted that an accurate spatial fertilizer application using granular applicators requires instantaneous fertilizer flow and distribution controls. For PA technologies, a complement of components is required to successfully implement this approach. A typical complement might include a GPS receiver, rate controller, software (or firmware), and sensors to either measure a variable of interest, and/or provide the necessary feedback for closed-loop control. Error analyses suggest that each component produces some level of uncertainty which in return can then be translated into an overall system error. The overall error is a summation of individual component errors understanding that interaction effects may exist. One of the most significant, and often overlooked, sources of error for such technologies is system latency or delay time since actions, either measurement or control, cannot be executed instantaneously. As an example, rate control systems inherently have response time delays which can be characterized by 1) control system response or delay time and 2) settling or or transition time (Fig. 1b; Fulton et al., 2005). Therefore, SSM resolution is limited by the ability of existing equipment to physically implement an input management strategy within the confines of prescriptive management zones (Fig. 1). For example, variable-rate granular applicators are susceptible to several distribution and control errors that compromise their ability to effectively apply nutrients in relation to plant needs and local soil conditions.

Several studies have highlighted delay times for various application control systems (Al-Gaadi and Ayers, 1999; Anglund and Ayers, 2003; Fulton et al., 2001; Fulton et al., 2005; Molin et al. 2002; Schueller, 1989; Qiu et al., 1998). Quantifying the system latency or delay time for applicators allows the "look-ahead" feature provided in most software packages to be selected thereby adjusting the control initiation point backward or forward in time to minimize application errors. The main assumption is that an operator or manager is able to quantify the needed "look-ahead time" and enter this value within software. Further complicating this process, the delay time may vary based on the initiation of step increases or decreases (Fulton et al., 2001; Fulton et al., 2005; Molin et al., 2002). Problems with variable-rate application equipment can also include distribution pattern shifts during rate changes especially for spinner spreaders (Fulton et al., 2001; Olieslagers et al., 1997). The problem with pattern shift is not easily rectified and will require real-time adjustments to applicator hardware.

Yield monitors have become vital reference tools for grain growers in making informed management decisions in their cropping operations. Increasingly, farmers utilizing PA strategies are turning to yield monitors to obtain information on crop response to cultural practices (e.g. hybrid/variety selection, plant population, nutrient levels, etc.). More importantly the field trials normally conducted by university researchers, seed companies, or chemical companies are now being conducted by farmers using yield monitors rather than the traditional weigh wagon. While this new tool affords producers new capabilities, they are urged to remember that like most other tools the results are comparable to the user's ability to use the tool correctly. Errors in the representation of spatial data exist for yield monitoring (Arslan and Clovin, 1998; Bashford et al., 1995; Jasa et al., 2000; Kettle and Peterson, 1998; Strubbe et al., 1996).

Yield monitors, like many measurement instruments, must be calibrated. The majority of the yield monitors in use today within the US are "force impetus" devices. Force impetus devices rely on acceleration of the grain as it is turned 90 degrees at the top of the clean grain elevator. As the grain strikes the impact plate of the mass flow sensor (top of the clean grain elevator), the deflection or impact force is measured. Anything that changes the nature of this impact alters the force or displacement registered by the mass flow sensor. While every effort has been made by yield monitor manufacturers to calibrate the mass flow of grain to the magnitude of grain impact on the mass flow sensor; certain circumstances may cause this calibration to vary (i.e. sloped terrain, grain test weight variations, etc). Further, the time relationship of GPS data and associated measured yield variables is critical to ensure accurate data. Searcy et al. (1989) outlined theses time delays and transfer functions describing grain movement through grain combines.

Calibration and proper maintenance is critical for successful implementation of precision technologies and in some cases the equipment itself, most notably, application equipment. As an example, Grisso et al. (1989) reported that only 30% of the herbicide applicators in Nebraska surveyed in their study were applying within 5% of the target rate. While these types of issues are not linked directly to PA technologies, errors could be amplified when the technology is combined with these traditional maintenance and calibration issues. Therefore, the objective of this paper is to outline potential limitations in precision agriculture technologies so practitioners can properly implement large scale research plots and draw useful information from them.

MATERIALS AND METHODS

The subject of GPS accuracy is not universally understood by end users and most manufacturers focus only on the positive attributes of their systems. To this end, it is essential to understand accuracy within the context of GPS coordinate fixes. More importantly, when GPS is deployed for field operations, what can the end users expect? In addition to position accuracy, the velocity accuracy of GPS is critical for many adopted PA systems such as hydraulic drive planters. When GPS is used as the main speed input for these systems, any delay in velocity determination from the GPS results in planting gaps within fields. The accuracy of GPS velocity has been previously studied and deemed accurate for PA systems (Vishwanathan et al., 2005), but little work has been done to document the dynamic accuracy of these systems. A series of speed step response tests were conducted to evaluate the dynamic response of a commercial RTK corrected GPS receiver and to evaluate the impact of this response for PA applications. The RTK GPS receiver speed was compared to both radar and wheel axle speeds measured directly from the test tractor's controller area network.

The recent growth in commercial and state-owned RTK network solutions has enabled a significant growth in RTK correction adoption in the past few years. Within the first year of deployment of the Iowa Department of Transportation continuously operating reference station (CORS) network over 150 agricultural users have registered and adopted this correction source for their RTK based field operations. Nearly one-third of the states within the US now have real-time, CORS based RTK correction available for agricultural use. While these systems break the availability limitations of RTK to users, they have also led to confusion surrounding the use of networked based RTK. A new term, networked RTK, has often been promoted as a higher quality RTK signal. Although different methods exist, networked RTK essentially combines information from multiple surrounding base stations in order to provide a virtual local reference location in near proximity to the in-field vehicle (Leica, 2009). A series of tests were conducted using commercially available CORS RTK equipment to evaluate the performance differences of various RTK correction messages. Specific comparisons were made between networked and single base solutions. Additional testing was completed in several geographically unique regions of Iowa to access best management practices related to connectivity and reliability of CORS based RTK solutions.

Response time of a commercially available rate controller equipped with a "fast" close valve was evaluated with two different VRT input functions. The first input function was simply a step rate change that would be common for a map based VRT application. The second input function was from a sensor based VRT application where the rate was updated every second. Various rate controller settings were tested to determine the minimal response time. The sprayer was equipped with variable orifice nozzles (TurboDrop Variable Rate –TDVR02, GreenLeaf Technologies; Covington, LA) to allow a wide range of rate changes. Details of this research were reported in Bennur and Taylor (2009). Futher, high frequency pressure transducers were mounted across the spray boom of a commercial sprayer to evaluate tip pressure/flow when using ASC technology. System flow rate was also collected simultaneously which represented the feedback flow measurement used by the spray controller to maintain the target rate. Tests were conducted with the sprayer remaining in a static position and ASC engaged to simulate typical field operating conditions (Sharda et al., 2009). Finally, as-applied maps for the application of dry fertilizer were generated using a GIS model (Fulton et al., 2007). This model utilized field application data along with distribution information to generate as-applied surfaces depicting the distribution of dry fertilizer when using map-based variable-rate application.

The effect of slope on grain yield monitor (force impetus) performance was conducted in the Yield Monitor Tests Facility (YMTF) located at the University of Kentucky, Lexington, Kentucky. A detailed description and specifications of this test facility has been provided by Burks et al. (2003). In this facility, a clean grain elevator can be mounted on a gimble permitting the positioning of a clean grain elevator to a specified slope either right/left or fore/aft. A commercially available yield monitor was calibrated for a specific range of mass flows under laboratory conditions with the clean grain elevator in its normal vertical orientation. Next, data was collected by sloping the elevator forward in increments ranging from 0 to 15% (downhill) and then backwards from 0 to 15% slope (uphill). Additional details can be reviewed in Fulton et al. (2009).

RESULTS AND DISCUSSION

GPS Sensors

Results from field testing of the dynamic velocity response of GPS receivers yielded phase shift errors typically between 1 to 2 sec. with occasional errors as high as 8 seconds when compared to radar based ground speed (Figure 2). Tests were conducted on a flat and hard surface to minimize potential errors in radar speed indication. Figure 2 also clearly indicates the overall accuracy of the GPS based speed signal when the signal reaches steady state. The physical implications of this phase shift in velocity are prominent when using GPS speed as the primary speed input for variable rate planting equipment. If a planter is stopped at the headland edge for refilling or backed into a field corner the GPS velocity will settle to zero. When the operator begins to make the next pass within the field the phase lag time must be overcome before the planter recognizes that a non-zero speed is present. This results in an unplanted zone within this phase lag area.

The magnitude of phase lag will vary based on GPS receiver model and firmware. Additionally, position filtering can also negatively impact the system lag. To compensate for this producers are encouraged to enter new planter passes with a rolling start which enables the GPS receiver to reach the true steady state speed before the planter enters the unplanted zone. Although this is effective in minimizing skips when entering new passes, this approach does not solve delay issues associated with backing the planter into a field corner. To achieve complete and accurate control under all scenarios additional sensors, such as external radars or wheel speed sensors, should be used in addition to GPS receivers. A select number of current variable rate control systems will allow simultaneous input of radar and GPS signals and will default to radar when experiences significant changes in velocity and will default to GPS during steady state to gain the benefits of the inherent steady state accuracy of GPS.

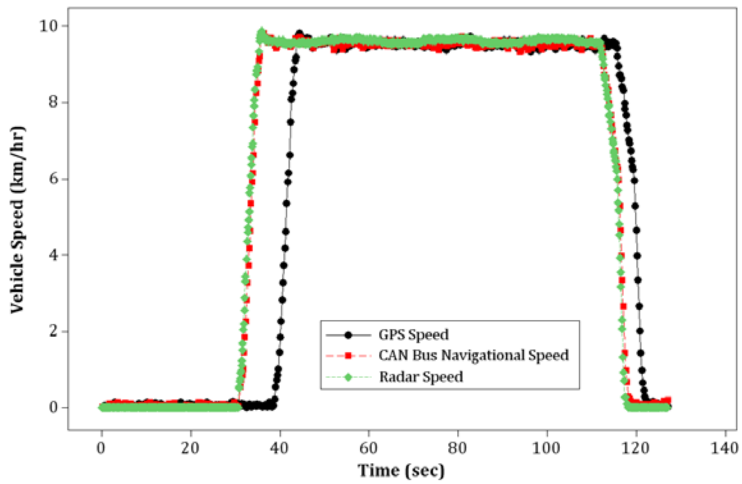


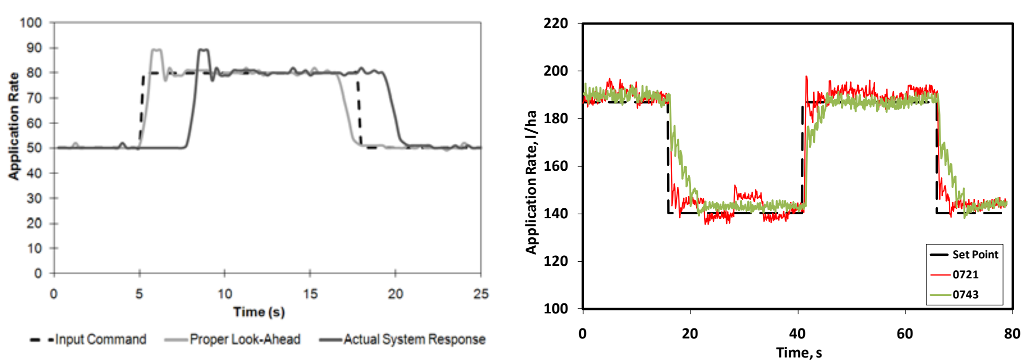
Fig. 2. Dynamic response in speed signal output from an RTK GPS receiver and tractor based radar speed sensor showing a phase shift error of 8 s.

Additional GPS based system inaccuracies can occur due to an incorrectly chosen correction type. Confusion over RTK based message corrections has been seen recently with the growing use of CORS networks for RTK solutions. The term "network" when attached to RTK can hold two very different means depending on the network configuration. Traditionally the term RTK network was used to represent a series of individual RTK base stations. Subscriptions could be purchased to gain access to the RTK network which enabled users to receive a single-base RTK correction signal from any of the available base stations. Although this approach did not guarantee RTK coverage, it did significantly enhance the likelihood of RTK service.

Tests conducted during the spring of 2010 throughout Iowa aimed to evaluate the difference between traditional single base and networked solutions both provided by the Iowa DOT CORS network. Based on the CMR+ correction message the results showed that the 2DRMS accuracy of single base correction (3.02-cm horizontal, 4.27-cm vertical) was better than the networked iMAX correction (3.68-cm horizontal, 7.14-cm vertical). Additionally, over the course of the 24 hour test the single base solution maintained an RTK fix for 99.8% of the time while the networked iMAX solution maintained an RTK fix for 98.5% of the time. These results were opposite of the hypothesis that the networked based RTK solution would provide enhanced accuracy for agricultural use. Further investigation found that many networked based solutions require common satellites between all included base stations which significantly reduced the number of satellites in the correction. Testing in central Iowa yielded an average of 9 satellites for single base corrections and only 7 satellites for networked based corrections. The lower satellite availability was also evident in the reduced RTK fix reliability of networked based solutions.

Application Technology

Figure 3a illustrates how the proper look-ahead time can reduce application errors. This example highlights 1) a typical 2nd order system response in which the system actually overshoots and then finally settles to the intended target rate when increasing the rate and 2) a delay time exists when changing the rate. Further, rate controllers can be adjusted to minimize response time. Figure 3b shows the set-point and measured rates for two different controller settings. The 0721 setting was the optimum and the 0743 was the recommended controller setting. The recommended setting results in a much slower response, but provides a stable flow rate whereas the optimum setting responds quicker but exhibits a little instability. In most cases the operator would prefer a stable response, but in a VRT application the operator should be willing to trade some stability for a quick response. To a significant degree, uniformity is still the default calibration on many farm equipment technology; a reality that can prove costly to farmers, especially relative newcomers to precision agriculture practices. Most rate controllers, for example, are setup to apply a uniform rate so even when one tries to vary that rate, many of them will react so slowly that they never reach the target rate. Practitioners may think they are doing a good job, but in reality, the rate controller is not maintaining close to the preferred rate. Older, map-based variable-rate systems, spray controllers are typically provided a new rate every 107 m or even longer in some cases. However, in sensor-based systems, the controller is communicated a new rate every second thereby updating constantly never allowing the system to stabilize to the desired rate (Figure 4). A 12.3 l/ha application could increase to 18.4 l/ha in only a couple of seconds. This response accounts for why using technology not setup to provide this type of optimal performance presents a critical challenge to a producer's success with precision agriculture. Bennur and Taylor (2009) reported similar response times for sensor and map based inputs to a rate controller.



(a) (b)

Fig. 3. Illustration of how a "look-ahead" feature can be set to minimize application errors (a). Step function and measured application rates for the optimum (0721) and recommended (0743) controller settings for a commercially available spray controller using a "fast" valve (b).

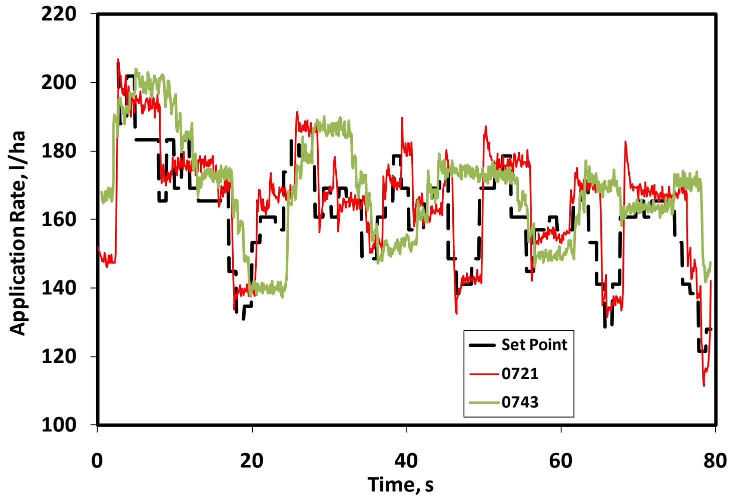


Fig. 4. Controller response to a typical 1 Hz update from a sensor-based (on-the-go) variable-rate system indicating the inability of the controller to maintain the target rate at this update rate. These results also indicate how the selection of the controller setting (valve control number) is important to minimize off-rate errors.

The ASC evaluations demonstrated that a difference in system flow rate and tip flow can exist (Figure 5). In this example, the control valve adjusted to the target flow rate in approximately 2 s but it took several seconds after this adjustment before the tip pressure finally stabilized. Further, both section control using boom valves (auto-boom) and nozzle level control (auto-nozzle) exhibited off-rate errors but were distinctly different. At times, especially when a majority of the sections or turned off, those nozzles which remain on can be impacted for extended times when more or less section are turned on or off. These tests also highlighted that the controller settings for the control valve including the look-ahead time were critical to minimize off-rate errors when using ASC technology on sprayers. Another result of these evaluations showed control issues when moving in and out of point row scenarios. In these cases, the timing of section being turned on and off occurred too quickly for the spray controller to properly respond to maintain the target rate. In fact, the controller at times appeared to respond in a way suggesting it was unable to process the feedback information and required timing to adjust the control valve. This response was most apparent as the sprayer boom was turned back on or moving back into parts of the field that have not been sprayed. In this case, it took several seconds once the entire boom was turned completely on before the controller was able to respond and adjust to the target rate generating off-rate errors over 10% during this period. These situations are dependent upon ground speed into and out of these situations, control width resolution (e.g. section versus individual nozzle control), and angle of incidence between the sprayer and headland or area previously sprayed which ultimately controls the timing of on and off sections or individual nozzles.

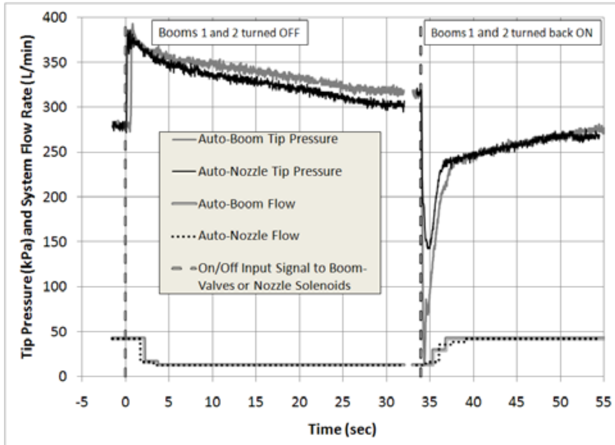


Fig. 5. Results demonstrating the potential difference between the spray system flow meter (feedback to controller) and actual tip application when using automatic section control (ASC) technology. Example represents turning off 2 out of 3 boom sections then turning them back on.

The combination of the above note errors (Figs. 3-4) can result in VRT not performing as expected (Fig. 6). This as-applied data suggested that the spreader equipped with VRT did not perform as expected which could be contributed to distribution errors, delay errors in the control and mechanical conveying system, irregular shaped management zones around the field borders leading to resolution (lateral) issues, and possibly the applicator operating outside its capabilities to maintain the target rate. While the operator's ability to maintain the set pass-to-pass width could contribute as well, it was not the foremost application error in this field. Please note the application in 0.0-kg/ha zones in this map which illustrate the time delay associated with changing rates in this case time to shut-off the spreader as it traverses this management zone. The application in the 0.0-kg/ha zones also highlights how the lateral resolution (spread width of 34.7-m in this case) so these zones received product when the spreader was actually within an adjacent zone requiring product. Therefore, size and shape of management zones must be made with the equipment lateral (spread width in this example) and longitudinal resolution in mind to minimize application errors.

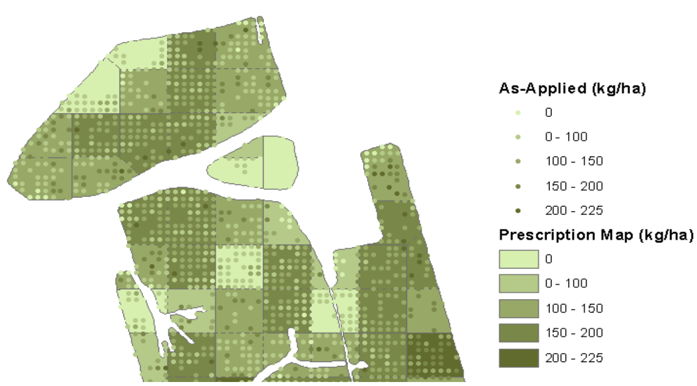


Fig. 6. As-applied map overlaid onto the prescription map with visible points indicating deviation from the target rate within each zone.

Yield Monitors

Data collected at the University of Kentucky's yield monitor test facility confirmed the impact of slope on mass flow measurements; depending on elevator inclination, the apparent mass flow rates can vary from actual by as much as 12%. Couple this error with the fact that some farmers may plant field trials in strips across a field, and that they harvest in rounds – side by side hybrid trials may exhibit an apparent 123 to 154 kg/ha difference when in reality this difference was created by harvesting different hybrids in opposite directions (uphill for Hybrid A and downhill for Hybrid B). Further, the effect of system delays also impacts yield monitoring systems since time differences exist between when the crop is initially harvested and when it arrives at the sensing mechanisms. Results are not included but can have a profound impact on resulting yield data used for field investigations. Does this suggest that yield monitors cannot be used to assess crop response when performing research? Not in the least – providing users put some thought into harvest practices. The simple solution is to harvest Hybrid A and B while traveling in the same direction. When used correctly, the yield monitor is an excellent investigative tool that everyone can use to increase their understanding of the factors affecting the profitability of farming operations.

CONCLUSIONS

The practical implications reported in this paper are that technology limitations exist and that user expectations must equal realistic performance of these technologies. With these limitations understood, good field scale investigations can be performed providing valuable information to improve crop production using PA technologies. The following recommendations are provided to stimulate thought on how best to implement PA technologies for field investigations.

1. A critical factor for anyone interested in utilizing precision agriculture technologies involves assessing your equipment and determining whether it is capable of providing the levels of accuracy essential for deriving the best results; this step includes not only understanding the capabilities but also limitations of the equipment and technology.
2. To maximize the performance of CORS based RTK systems in agriculture:
    a. Single-based RTK solutions from the nearest base station is the most desirable RTK correction to maximize GPS accuracy.
    b. Cellular data modem connectivity can be enhanced with the addition of an external cell phone booster and high gain antenna.
    c. Satellite availability is still the prime driver in overall GPS accuracy. The addition of GLONASS or other satellite constellations will increase reliability and accuracy GPS locations.
3. Need to ensure all equipment and technology is in good working order prior to any field operation. This aspect includes making sure conveying, sensing mechanisms, and other mechanical components are not worn, damaged or not is good operating condition. Visually inspect all sensor

cables to make certain they are intact and not worn from being in contact with rotating or moving parts. For yield monitors, clean the impact plate and moisture sensor. Check for material lodged behind or to either side of the impact plate.

4. Calibrate all equipment and technology on at least an annual basis if not more frequently. Calibration is critical for maximum performance of technology and probably the number one reason for errors. For yield monitors, double-check the most current calibration, by running the combine in a location that is similar in maturity and condition to the test plots to be harvested. If necessary, recalibrate!
5. Keep good and thorough field notes. Provide sketches and record observations such as areas with poor weed control or poor stands. This information is essential when summarizing field data and drawing conclusions from results.
6. Consider the size and shape of management zones in relation to equipment resolution (both lateral and longitudinal). However, reducing the control resolution on equipment (e.g. full width versus individual row control) places further demand on control system in terms of processing and requiring to respond even quicker which may be unrealistic for some technology. Do not assume increasing the control resolution to minimize know control errors; it may or may not.
7. For rate controllers, select the proper valve control numbers which provide quick response but also control when changing rates or flows.
8. Application controller setup (i.e. VRT, ASC and on-the-go sensing) is critical to minimize off-rate errors this includes utilizing the “look-ahead” features to properly adjust rate or flow changes in time.
9. Harvest side-by-side comparison plots in the same direction to minimize the effect of harvest errors when comparing yield results.
10. Operate harvesters under conditions that are similar to the conditions used when calibrating the yield monitor. Calibration can be flow sensitive.
11. Avoid stopping in the middle of the plots. This may be difficult when doing N application comparisons where the crop in some plots may be lodged. The best solution may be to calibrate at a lower harvest rate in anticipation of harvesting lodged crops.
12. Avoid unloading the combine on-the-go while harvesting plots. This activity diverts the operator’s attention from the task at hand causing mistakes and changes in harvest rates.
13. When possible, utilize a weigh wagon or system (e.g. grain cart) for comparison of harvested weights. This approach should serve to increase confidence in yield monitor results and as a backup to identify errors early on during the harvest of study sites.

In conclusion, precision agriculture technologies can be powerful tools for conducting field scale research. However like any tool, misuse can lead to issues and possibly incorrect conclusions. Understanding the limitations and operational constraints of these technologies will aid in obtaining quality research results.

REFERENCES

Al-Gaadi, K.A., and P.D. Ayers. 1999. Integrating GIS and GPS into a spatially variable rate herbicide application system. *Appl. Engr. Agr*. 15(4): 255-262.

Anglund, E.A. and P.D. Ayers. 2003. Field evaluation of response times for a variable-rate (pressure-based and injection) liquid chemical applicator. *Appl. Eng. in Agri*.19(3): 273-282.

Arslan, S. and T.S. Colvin. 1998. Laboratory test stand for combine grain yield monitors. *Appl. Engr. Agr*. 14(4): 369-371.

Bashford, L.L., S. Al-Hames, M. Schroeder, and M. Ismail. 1995. Mapping corn and soybean yields using a yield monitor and GPS. In Site-Specific Management for Agricultural Systems, ASA, CSSA, and SSSA, Madison, WI. 691-707.

Bennur, P.J., and R.K. Taylor. 2009. Response time evaluation of real-time sensor based variable rate technology equipment. ASABE Meeting Paper No. 096605. St. Joseph, MI: ASABE.

Bongiovanni, R. and J. Lowenberg-DeBoer. 2000. Economics of variable-rate lime in Indiana. *Prec. Agr*. 2:55-70.

Burks, T.F., S.A. Shearer, J.P. Fulton, and C.J. Sobolik. 2003. Combine Yield Monitor Tests Facility Development. *Applied Engr. in Agr*. 19(1): 5-12.

Cambouris, A.N., M.C. Nolin, and R.R. Simard. 1999. Precision management of fertilizer phosphorous and potassium for potato in Quebec, Canada. In P.C. Robert et al. (ed.) Proceeding of the 4th International Conference on Precision Agriculture, ASA, CSSA, and SSSA, Madison, WI. 847-857.

Cointault, F., P. Sarrazin, and M. Paindavoine. 2003. Measurement of the motion of fertilizer particles leaving a centrifugal spreader using a fast imaging system. *Prec. Agr*. 4(2003): 279-295.

Fairchild, D., and M. Duffy. 1993. Working group report on profitability. In P.C. Robert et al. (ed.) Soil Specific Crop Management, ASA Misc. Publ, CSSA, and SSSA, Madison, WI. pp 245-253.

Fulton, J.P., C.J. Sobolik, S.A. Shearer, S.F. Higgins, and T.F. Burks. 2009. Grain Yield Monitor Flow Sensor Accuracy for Simulated Varying Field Slopes. *Applied Engr. in Agr*. 25(1):15-21.

Fulton, J. P., S.A. Shearer, G. Chabra, and S. F. Higgins. 2001. Performance assessment and model development of a variable-rate, spinner fertilizer disc applicator. *Trans. ASAE*. 44(5): 1071-1081.

Fulton, J.P., S.A. Shearer, S.F. Higgins, M.J. Darr, and T.S. Stombaugh. 2005. Rate response assessment from various granular VRT applicators. *Trans. ASAE*. 48(6): 2095-2103.

Fulton, J.P., S.A. Shearer, S.F. Higgins, T.P. McDonald, C. Dillon, and T.S. Stombaugh. 2007. Variable-Rate Fertilizer Application Assessment Using an As-Applied Methodology. In J.V. Stafford, ed., Proc. of the Sixth European Conference on Precision Agriculture, Precision Agriculture '07. pp. 681-688. Skiathos, Greece, 3-6 June.

Grisso, R.D., E.C. Dickey, and LD. Schulze. 1989. The cost of Misapplication of herbicides. *Applied Eng. in Agric*. 5(3): 344-347.

Jasa, P.J., R.D. Grisso, and J.C. Wilcox. 2000. Yield monitor accuracy at reduced flow rates. ASAE Paper No. 001085. St Joseph, MI: ASAE.

Kettle, L.Y. and C.L. Peterson. 1998. An evaluation of yield monitors and GPS systems on hillside combines operating on the steep slopes in the Palouse. ASAE Paper No. 981046. St Joseph, MI: ASAE.

Leica Geosystems. 2009. RTK Networks – Different Methods. System 1200 Newsletter No. 53. Heerbrugg, Switzerland.

Lowenberg-DeBoer, J. and A. Aghib. 1999. Average returns and risk characteristics of site-specific P and K management: Eastern Corn Belt on-farm trial results. *J. Prod. Agr*. 12: 276-282.

Lowenberg-DeBoer, J. and S.M. Swinton. 1997. Economics of site-specific management in agronomic crops. In Site-Specific Management for Agricultural Systems, ASA, CSSA, and SSSA, Madison, WI. 369-396.

Mallarino, A.P., D.J. Wittry, D. Dousa, and P.N. Hinz. 1999. Variable-rate phosphorus fertilization: on-farm research mehotds and evaluation for corn and soybean. In P.C. Robert et al. (ed.) Proceeding of the 4th International Conference on Precision Agriculture, ASA, CSSA, and SSSA, Madison, WI. 687-696.

Molin, J.P., L.A.A. Menegatti, L.L. Pereira, L.C. Cremonini, and M. Evangelista. 2002. Testing a fertilizer spreader with VRT. In F.S. Zazuets and J. Xin (eds.) Proceeedings of the World Congress of Computers in Agriculture and Natural Resources. 13-15, March 2002. ASAE publication No. 701P0301. pp. 232-237.

Olieslagers, R., H. Ramon, and J. De Baerdemaeker. 1997. Performance of a continuously controlled spinning disc spreader for precision application of fertilizer. In Precision Agriculture 1997, papers presented at the first European Conference on Precision Agriculture, Warwick University Conference Centre, UK, 7-10 September 1997 / European Conference on Precision Agriculture. Oxford ; Herndon, VA : BIOS Scientific Pub., c1997. 661-668.

Qui, W., G.A. Watkins, C.J. Sobolik and S.A. Shearer. 1998. A feasibility study of direct injection for variable-rate herbicide application, Trans ASAE. 41(2): 291–299.

Schueller, J. K. 1989. Spatially variable fluid fertilizer applicator design concepts. J. Fert. Issues 6(4): 100-102.

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

Sharda, A., J.P. Fulton, T.P. McDonald, and M.J. Darr. 2008. Real-time boom pressure and flow response for swath control technology. ASABE Meeting Paper No. 085256. St. Joseph, MI: ASABE.

Strubbe, G., B. Missotten, and J. DeBaerdemaeker. 1996. Mass flow measurement with a curved plate at the exit of an elevator. *In: Precision Agriculture, Proceedings of the 3rd International Conference on Precision Agriculture*, edited by P. C. Robert, R. H. Rust and W. E. Larson (MN, USA), p. 703–712.

Vishwanathan, R., P. Weckler, J. Solie, and M. Stone. 2005. Evaluation of Ground Speed Sensing Devices under Various Ground Surface Conditions. ASABE Meeting Paper No. 051087. St. Joseph, MI: ASABE.

Weisz, R., R. Heiniger, J.G. White, B. Knox., and L. Reed. 2003. Long-term variable-rate lime and phosphorous application for piedmont no-till field crops. *Prec. Agr*. 4(2003): 311-330.

Yang, C., G.L. Anderson, J.H. King, Jr., and E.K. Chandler. 1999. Comparison of uniform and variable-rate fertilization strategies using grid soil sampling, variable-rate technology, and yield monitoring. In P.C. Robert et al. (ed.) Proc. of the 4th International Conference on Precision Agriculture, ASA, CSSA, and SSSA, Madison, WI. 675-686.