Multidisciplinary Teams: A Necessity for Research in Precision Agriculture Systems

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ABSTRACT

Precision agriculture may offer great promise for the future, but extensive research is required if that promise is to be realized. The research will not be easy, for few, if any, individuals have sufficiently broad training in the many disciplines (e.g., economics, engineering, crop and soil sciences, pest management) required to design the experiments, interpret the data, and ultimately provide answers for the practical, economically oriented farm management questions being asked. We are convinced that many experiments would benefit, as ours did, from collaborative research conducted by multidisciplinary teams. From our effort, we learned much about the nature of precision agriculture, but we also learned about the nature of research and the value of expertise outside of our own areas. In the case of the former, we learned that precision agriculture is highly dependent on, and perhaps even defined by, engineering technology, but the profitable use of the technology depends on a thorough understanding of the physical and biological factors of the field and crop. It appears that much of the technology is only profitable when a producer possess very detailed field characteristic information. Unfortunately, the level of information required may be impossible to obtain for many of the proposed uses of precision agriculture technology. In the latter case, we gained an appreciation of the skills and expertise of those from other disciplines. We believe that multidisciplinary teams are a necessity for this work, and we recommend that the existing research community recognize this need and provide rewards for participation in interdisciplinary research.

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> We are drowning in information and starving for knowledge.
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> —*Rutherford D. Roger*

Perhaps this is a simplistic or at least an overly pragmatic view, but we suggest that the major difficulty facing the agricultural research community currently is not one of insufficient funding, a lack of clever and resourceful individuals, or even too little data, but rather that most of the easy questions have been answered.

Producers and other decision makers intuitively recognize the site specificity of economically optimal management practices, and they are asking the agricultural research community to provide the information necessary to capture the increased efficiency and profit that site-specific technology offers. This is an entirely appropriate request, but it is not clear that the producers or the researchers really appreciate the complexity of the question. We, the authors of this manuscript, have shared in that ignorance, but our experience has afforded us the opportunity to recognize that multidisciplinary teamwork will be necessary if researchers are to meet the challenge of providing producers with the knowledge needed to take full advantage of site-specific technology. Few, if any, individuals have sufficiently broad training in the many disciplines (e.g., economics, engineering, crop and soil sciences, pest management) required to design experiments, interpret data, and ultimately, provide answers

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for the practical, economically oriented farm management questions being asked. We are convinced that many experiments would benefit from collaborative research conducted by multidisciplinary teams, for we will show that a producer needs extensive knowledge in addition to technology in order for precision agriculture to be profitable. Further, while many of us in the agricultural arena have proclaimed to know what "systems" research is, we now perceive that our past near-sighted vision did not recognize the extent of interdisciplinary cooperation necessary to understand the complex questions well enough to answer them.

> We live on an island surrounded by a sea of
> ignorance. As our island of knowledge grows,
> so does the shore of our ignorance.
> —*John Archibald Wheeler*

This issue of the true site-specific nature of economically optimal management actions is not new. Since the dawn of crop and soil husbandry, farmers have recognized that intrafield productivity is heterogeneous and that the appropriate action for any given portion of a field depends on the characteristics of the portion. Virtually all farmers would agree that what you should do depends on where you are.

This axiom is well supported by the literature. For example, Kravchenko and Bullock (2000) showed that on large (>20 ha) fields soil properties explained about 30% of the corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] grain yield variability, with organic matter content influencing yield the most. The cumulative effect of the topographical features explained another 20% of the yield variability. Elevation had the most influence on yield, with higher yields consistently observed at lower landscape positions. Curvature, slope, and flow accumulation significantly affected yield only in certain conditions, such as extreme topographical locations (poorly drained depressions or eroded hilltops) combined with very high or low amounts of precipitation.

In another example, Sudduth et al. (1996) found that after dividing claypan soil fields into subfields using soil electrical conductivity and relative elevation, correlation coefficients between yield and soil test data (e.g., soil-test pH, P, K, Mg, and Ca) were greatly improved over correlations performed on a whole-field basis.

Grain quality has also been shown to be affected by field position. Kravchenko and Bullock (2002a) demonstrated not only that field characteristics account for soybean yield but also that topographical features influence protein content of soybean grain and that the characteristics could be used to demarcate areas for differential harvest (Kravchenko and Bullock, 2002b). Similarly, Martin et al. (2007) demonstrated that secondary field characteristics can be used to describe not only yield but also soybean oil quality.

In the recent past farmers have used this concept of differential management, albeit on a rather coarse scale. Farmers manage separate fields and perhaps even large sections of individual fields differently, but since the mechanization of farm equipment, it has not been practical to manage differentially small sections of individual fields. However, due to recent engineering contributions, differential management of small sections is now possible. The advent of global positioning system, geographical information systems, variable rate controllers and associated variable rate technology, and sensor technology now provide farmers the means and promise to differentially manage and acquire information from small (<500 m^2) areas of individual fields.

But how is this technology to be used if the obvious goals are to increase profit and improve environmental stewardship? Is it appropriate to simply scale down current field-based recommendation algorithms? Can we use the same base layers of testing and information? What do we need to do differently, if anything, to benefit from the technology? The question farmers are asking now is no longer whether precision technology "works" but rather whether and how they can make money from it.

The plethora of precision technologies and services available for purchase or hire in the marketplace, as well as the volume of precision technology testimonials published in the agricultural press and agricultural advertising, suggests that we know how to use precision technology. Our research indicates otherwise.

Some precision technology is certainly valuable (e.g., yield monitoring) and we have no doubt that its use will become standard practice in the near future. Nonetheless, we are equally certain that much precision technology is currently not valuable and will provide no economic benefit (Bullock et al., 1998). The forces driving these conclusions are both interesting and surprising. The main, and most important, lesson we have learned from multidisciplinary research into site-specific management of corn and soybean systems is that the optimal management decision for a given piece of ground depends not only on its location and physical characteristics but also on how much the farmer knows about these characteristics and whether the farmer knows how to use that knowledge. For we have concluded that information and site-specific management technology are *economically complementary*: value is obtained only when one possesses both (Bullock and Bullock, 2000).

Only after much discussion with team members did we realize that we all saw the problem from our own disciplines. Our ignorance of the other issues was preventing us from having a comprehensive understanding of the actual question, and thus we could not provide an appropriate answer. By working in a multidisciplinary team, we could fill the gaps in understanding we each had. We also recognize, however, that large multidisciplinary teams present a problem for reward, in that multiple authorship on manuscripts can lead to a dilution in the perceived contribution of those participating or at least a problem with understanding how much contribution was made by authors in the middle of a multiple author list (Laurance, 2006; Weltzien et al., 2006). Not everyone can be listed as the first author or the last author. We do recognize that while this is not a problem everywhere, substantial literature on the topic indicates that multiple author lists create interpretation problems in many institutions (Davidoff, 2000; Horton, 1996; Laurance, 2006; Weltzien et al., 2006); we have personally encountered the issue in our own review process. We call for increased recognition of the value of multiple, interdisciplinary authorship in the precision agriculture research community and a realization that when large teams work together, many persons make important contributions.

> It is not good to know more unless we do more with what we know.
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> —*R. K. Bergethon*

Let us elaborate on the complementary nature of information and precision technology by beginning with a simple example of soil testing. In the midwestern Corn Belt, recommendations and practices vary, but in Illinois it is common and recommended to soil test fields by pulling subsamples at approximately 1 sample per ha (1 sample per 2.5 acres) and then uniformly broadcast fertilizer and lime to the entire field based on some sort of an average value, with the median often being the measure of average preferred, due to the log normal distribution of many fertility measures (Jobbágy and Jackson, 2001). Two main points need to be understood about the recommendation of collecting a sample for each 2.5 acres. The first is that while this would seem to many an intensive and expensive sampling effort, in reality only a very small amount of the field is sampled; thus, the decision regarding how much fertilizer or lime to apply on the massive majority of the field that is not sampled is made based on a very sparse data set and one must make an assumption on how well the individual samples represent the surrounding nonsampled sites (Ruffo et al., 2005). Second, while the field is treated as a homogenous unit, no person involved in the management of the field believes this actually to be the case.

Until very recently, there was virtually no suggestion that samples should be collected at considerably greater density (e.g., 2 or more samples per ha) if the field was treated as a homogenous unit. The simple fact is that the improvement in the estimate of the field median is asymptotic and thus improves only slightly with dense sampling on the typical midwestern field. This relationship is demonstrated in Table 1 for soil fertility data from a full section (~259 ha) in central Illinois for which a total of 1752 individual soil samples were obtained. The data presented in Table 1 are values for P determination from subsets on approximate 50-, 100-, and 200-m grids. Note that as the grid spacing decreases, there are changes in the variance and range but no change in the median P value and thus no change in recommended fertilization if the field is treated as a single unit.

Table 1. Soil P analysis results from a full section (~259 ha field) field in central Illinois.

Approximate grid spacing	Number of samples	Median P	Minimum P	Maximum P	Variance
m			mg L^{-1}		
50	1018	24	2	125	359
100	254	24	5	125	322
200	64	24	10	73	160

If acquisition of additional information is to be economically profitable, any revenue increases that are made possible by the acquisition must be greater than the additional cost associated with the acquisition. In this example, acquiring additional information only has a chance of increasing profit when the producer acquires the ability to differentially apply the fertilizer and liming materials (i.e., purchases or hires site-specific management technology). The differential application might be done crudely and inexpensively simply by manually flagging out large areas of the field and spreading those subareas separately, or one might go to the other extreme and hire the services of a computer-assisted variable rate application truck. The point is that the profit cannot be gained from variability unless one can react to, and manage for, that variability. Simply recognizing that variability exists does not provide for profit. It is important to note, however, that although the acquisition of the technology makes information more valuable, it does not guarantee that the use of precision technology will be profitable. Let us look at this key point in more depth with a goal of providing an outline of what must be known to benefit from site-specific agriculture.

> The essence of knowledge is, having it, to apply it; not having it, to confess your ignorance.
>
> —*Confucius*

The factors that affect crop yield may be placed into three broad categories. The first category is made up of factors not controlled by the farmer but remaining constant over the course of the growing period. We will call these factors *site characteristics*. Examples of characteristics are soil texture and slope. Clearly, characteristics can vary among different sections of a field. Let us divide a field we call L into I sections called $L_1, L_2,..., L_I$, where we make these sections small enough such that characteristics are considered uniform throughout the section. Every section L_i is then characterized by a vector of characteristics $c_i = (c_{i1}, c_{i2},..., c_{iM})$. So, for example, c_{i1} may describe the soil structure of section L_i, c_{i2} may describe the slope of section L_i, and so on.

The second category of factors that affect yield consists of factors controlled by the producer. These are most easily thought of as application rates of inputs to production, such as seed, fertilizers, and pesticides, although other management actions such as tillage intensity would be applicable. The essence of precision farming is to apply these controlled inputs at different rates on different sections of the field. For $i = 1,..., I$, in every section L_i, we denote these controlled inputs to production by the vector of variables $x_i = (x_{i1}, x_{i2},..., x_{iJ})$. For example, x_{i1} could be any seeding rate chosen by the farmer for section L_i, x_{i2} could be the fertilizer application rate chosen by the farmer for section L_i, and so on.

The third category of factors that affect yield are uncontrolled stochastic factors, which we denote by a vector $z = (z_1, z_2,..., z_K)$. These factors are uncontrolled because the farmer cannot choose them, and they are stochastic because their values may vary over time in a random fashion. Examples of uncontrolled stochastic factors are weather variables, such as rainfall or the first autumn frost date. The values that these uncontrolled stochastic variables will take on are not known for certain by the farmer at planting time.

In every section L_i, the response of yield to site characteristics, input application rates, and weather may be described by a function $f(c_i, x_i, z)$. To estimate economically optimal input application rates, it is first necessary to estimate this function f, for we cannot know how farm profits respond to input application rates unless we know how yield responds. To use a single response function for all sites within a field ignores a very large portion of the site specificity present.

Ideally, a farmer would be able to measure and map out the characteristics c_i of many small sections of field and then know the economically optimal input application rates for each section. We are currently a very long way from this type of knowledge, and perhaps we will never obtain it.

In an attempt to overcome this characterization requirement, many, including the authors, have either implicitly or explicitly suggested that some measure or estimation of section "quality" could be a useful proxy for the information provided by a section's characteristics c_i (Bullock and Bullock, 2000). This suggestion is consistent with the fact that many, if not most, recommendation algorithms for determining rates of input application are based on simple mathematical formulas that depend on an estimate of potential yield (Ruffo et al., 2006). Using a measure of section quality as a proxy for the characteristics vector avoids the difficult question of how economically optimal input application rates vary with soil structure, slope, and so on. Instead, it is simpler to ask how economically optimal input application rates vary with section quality. This is exactly what is being done when a soil map or even a yield map is used as the basis for some sort of an input application-guidance map.

Many researchers have assumed that this "site-quality-as-proxy-for-site-characteristics" approach is correct and efficient. But as recent research is making increasingly clear, often it is not. For example, Bullock et al. (1998) reported that site-specific economically optimal corn plant densities were correlated to site yield potential, but only poorly ($R = 0.27$, $P > |R| = 0.0002$). Simulations based on these field data indicated that if a producer actually knew the production function showing the relationship between grain yield and seeding rate for every small section of a field, the use of variable rate seeding technology could increase revenues minus seed costs by \$12.83 ha^{-1}. Note, however, that a producer simply does not know the actual production functions for the different areas of the field. Therefore, producers are forced to find a proxy for those production functions. In our research, we used the above-mentioned site yield potential as our estimate of quality and then assumed a general relationship between yield and seeding rate. This sort of information could be obtained by farmers via a series of yield maps and the assumption of a general production function for seeding rate. Our use of this productivity proxy for the true production functions only increased revenues minus seed cost by \$0.55 ha^{-1} when compared with uniform rate seeding. The only difference between these two scenarios is the quality of the information (i.e., the level of our ignorance). Farmers who knew every site's production function could increase revenues minus seed costs by \$12.83 ha^{-1}. Farmers who had to use the site "quality" proxy could increase revenues minus seed costs by only \$0.55 ha^{-1}—certainly nowhere near enough to pay for the cost of hiring variable rate seeding equipment. It is clear that variable rate seeding technology requires very detailed information to provide profit.

Along a similar vein, we looked at a scenario for which the production functions were known but the producer only had the ability to use a uniform-rate seeding. As might be expected, the improvement was minimal (~ \$0.06 ha^{-1}). Thus, without variable rate seeding technology, information about yield response to plant density in every section is of little value to the farmer. With this insight, it is not surprising that not much research has been done on how optimal input application rates differ with fields or among fields; before the recent arrival of precision technology, such information simply was not worth much. The implication of the results of our research is that site-specific technology and information about yield response are highly complementary; a farmer has no incentive to adopt the new technology without the information necessary to make it economically viable, and a farmer has no incentive to acquire the information unless the technology is available.

> Man will occasionally stumble over the truth, but usually manages to pick himself up, walk over or around it, and carry on.
>
> —*Winston Churchill*

Is this relationship between technology and information unique to variable rate seeding, or is it a general event?

Unfortunately, the latter is correct, but the resulting scenario is not quite as bleak as one might suspect on first introduction. Site-specific technology and information will always be economic complements. Fortunately, the expense required to obtain the necessary information can be lowered. Great advances in information-gathering technology are now needed to accompany the recent great advances in crop production technology. We believe that technology offers great promise in delivering dense data sets, which inexpensively and accurately lead to site characterization. The list is long and certainly incomplete but includes digital terrain maps; land-, air-, and space-based imagery; and a multitude of other sensors. How these new technologies will be used to gather information more cheaply is not currently completely clear, and the problems in developing new information-gathering technologies are far from trivial. But now that precision technology is a physical reality, economic incentives exist for the development of better and cheaper information-gathering technology. Our feeling is that these incentives will lead to the development of cheaper ways to gather information, which will lead to wider use of much of the existing precision agriculture technology in the near future. We also believe that the wider use of precision agriculture technology will make it more important than ever for the academic community to develop and work within multidisciplinary research teams. For it is only through such teams that we will be able to provide producers with the insight necessary to determine how economically optimal management decisions vary within fields.

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