Opportunities for conservation with precision irrigation

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ABSTRACT: Precision agriculture has mostly emphasized variable-rate nutrients, seeding, and pesticide application, but at several research sites, variable-rate irrigation equipment has been developed to explore the potential for managing irrigation spatially. The modifications to commercial machines are relatively straightforward, but costly; thus economic analyses have not been positive at current grain price: water cost ratios. However, with increased attention to conservation of water during drought, with increased contention for environmental, recreational, municipal, and industry use, or with regulatory constraints, conclusions regarding profitability or desirability of variable-rate irrigation may change. The objectives of this paper are to: 1) define and describe site-specific irrigation, 2) discuss the opportunities for conservation using site-specific irrigation, 3) present case studies from production and research fields that illustrate these opportunities, and 4) discuss critical research needs to fully implement precision irrigation and thus realize these opportunities for conservation. The opportunities for conservation discussed include situations where non-cropped areas exist in a field for which irrigation can be turned completely off, situations where a reduced irrigation amount provides specific benefits, and finally, situations where optimizing irrigation amount to adapt to spatial productivity provides quantitative benefits. Results from the case studies provide estimates of the potential for water conservation using precision irrigation that range from marginal to nearly 50 percent in single years, and average from eight to 20 percent, depending on the previous irrigation management strategy employed. Critical research needs include improved decision support systems and real-time monitoring and feedback to irrigation control.

Keywords: Site-specific irrigation, spatial variation, water conservation

Agriculture has vaulted into the space age using remote sensing, geographic information systems (GIS) and global positioning systems (GPS) into what is being referred to as precision agriculture or site specific crop management. Precision agriculture involves aspects of remote sensing, crop protection, field sampling, precision planting, precision tillage, precision fertilizer placement, precision irrigation, on-the-go yield monitoring and other emerging applications. It has the potential to increase certain economic efficiencies of the operations by optimally matching inputs to yields in each area of a field and reducing costs. The potential economic benefit of precision farming lies in reducing the cost of inputs, but precision agriculture could increase risk. When the farmer's management tolerance for risk is low, the potential economic benefit would be smaller. Beyond economic benefits, most expect some improved environmental stewardship. Analysis of observed spatial variability and the performance of equipment indicate that methods to increase yield or reduce inputs may include variable rate herbicide application, management zones for nitrogen application based on soil characteristics, yield maps, and growers' assessment of productivity, use of multi-spectral remote sensing technology to assess nitrogen stress of the crop, and site-specific pest management. Innovative application of statistical methods and analytical methods using new or existing simulation models may prove beneficial.

Currently, agricultural production systems have reached a critical point with respect to adopting various precision technologies. Many of these tools promise a competitive advantage by enabling differential management of a number of inputs across a single field that could positively impact both the economic and environmental aspects of production. However, most of these technologies have been developed without considering the knowledge levels, skills and abilities of farmers and service providers to effectively and economically manage these tools. In addition, the equipment is often expensive and the economic returns from adopting these technologies have not been easy to consistently demonstrate. Nevertheless, the economics are improving and there is little doubt that at least some of the emerging precision agriculture technologies will be part of future crop production systems in American agriculture. The questions are how, which ones, and to what extent? We believe that precision differential irrigation under self-propelled irrigation systems will be a significant part of the future precision agriculture toolbox for many growers. Most interest in precision agriculture has focused on variable-rate, spatially variable inputs for primarily rainfed agriculture, with a high proportion of the interest in the upper Midwest. However, the potential for spatial control of inputs under moving irrigation machines prompted research to examine technical and economic feasibility of, and operation and management of, site-specific irrigation machines. Once these studies proved the performance, the machines were used for studies of site-specific crop responses to variable-rate irrigation and nutrient application.

One goal of site-specific agriculture is to apply only the optimum amount of an input. While conditions could exist for which the entire field's optimum input is greater than the amount usually applied in a conventional, whole-field mode, most participants expect a reduction in input use on at least parts of fields, if not a reduction in the value aggregated over entire fields. For the most part,

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the optimization chosen for such studies is maximum profit based on the ratio of the cost of the input and the crop response to it. This has only recently been accomplished for site-specific irrigation, and then for only a few instances. The objectives of this paper are to: 1) define and describe site-specific irrigation, 2) discuss the opportunities for conservation using site-specific irrigation, 3) present case studies from production and research fields that illustrate these opportunities, and 4) discuss critical research needs to fully implement precision irrigation and thus realize these opportunities for conservation

Definition of precision irrigation

The term precision irrigation predates site-specific agriculture. Its meaning in the irrigation industry connotes a precise amount of water applied at the correct time, but uniformly across the field (Evans et al., 2000b). In this paper, precision irrigation now includes a spatially variable capability. To achieve such capability, an otherwise conventional irrigation machine would need variable-rate sprinklers, position determination, variable-rate water supply, variable-rate nutrient injection (probably), and variable-rate pesticide application (possibly).

During the early 1990's, interest in the potential for fully site-specific irrigation prompted research at four sites, independently at first, then with shared information as awareness developed of other work. A group at Fort Collins, Colorado, developed a four-span linear-move site-specific irrigation machine for research purposes (Fraisse et al., 1992; Duke et al., 1992). At approximately the same time, a University of Idaho group received a patent on a method and apparatus to variably apply irrigation water and chemicals (McCann and Stark, 1993). That group later described two site-specific irrigation machines (King et al., 1995). Concurrently, in Florence, South Carolina, design criteria for a site-specific center pivot irrigation machine were developed (Camp and Sadler, 1994); it was constructed in 1995 (Sadler et al., 1996; Omary et al., 1997). Starting in 1994, Washington State University began development of a custom control system on a commercially operated center pivot system (Evans et al., 1996a; Evans, 1997; Evans and Harting, 1999). Harting (1999), also in central Washington State, designed and installed programmable logic control-based control systems on three full and three partial (first span only) commercially operated center pivot systems. At all four research locations, various techniques were used to design and control their individual irrigation machines, as described in Buchleiter et al. (2000) for variable-rate sprinklers, Evans et al. (2000) for controls, and Sadler et al. (2000) for overall design considerations. Since that series of papers in 2000, Harting has expanded the commercial implementation to a large farm in Oregon (R.G. Evans, personal communication, 2004), and the research group at Tifton, Georgia, has developed a research/demonstration facility for irrigation (C. Perry, personal communication, 2004), using a modification of the Washington/Oregon methods.

Water conservation potential using precision irrigation

Potential for conservation accrues from not irrigating non-cropped areas, reducing irrigation amounts to adapt to specific problems, or fully optimizing the economic value of the water applied through irrigation. The case studies provided below are organized according to these types of potential. In some, anecdotal information is all that can be found; in one, extensive research provides much more quantitative information. Consequently, the level of detail is necessarily not uniform.

One way to conserve water using precision irrigation is to program zero irrigation amounts in non-cropped areas. The degree of conservation obviously depends on the scope of the non-cropped area, but it can often be substantial. In addition to conservation of water, there may be policy incentives or regulatory penalties if non-cropped areas are irrigated. For irrigation overspray onto roads, there is a definite potential for public relations problems, if not liability for accidents. Such costs are either so indirect as to defy calculation or so catastrophic that one cannot imagine willingly participating in the activity. Nonetheless, overspray occurs. Regulatory attention is heightened if nutrients or pesticides are injected into the irrigation water, or if animal waste is spread with the irrigation machine. Spraying chemicals onto water bodies is prohibited in some areas. Unfortunately, avoidance of water bodies is often not easily programmed into the standard commercial irrigation controllers, sometimes leaving substantial cropped areas without irrigation. Application onto rock outcrops is strongly discouraged in parts of the Pacific Northwest, with similar disadvantages for commercial controllers. Examples in case study No. 1 below illustrate this problem.

Yet another real-world problem is adapting to spatial variation in infiltration rate of the soil and in soil water storage capacity. Either, or worse yet, both of these characteristics being lower in one place than in the bulk of the field can cause runoff from that place, despite the machine being optimally designed for the bulk of the field. Runoff collecting within the irrigated area can create a pond, with aeration damage to the crop. An example in case study No. 2 below illustrates this problem. Runoff leaving the field represents waste of water. Either way, the field is also subject to sediment and nutrients moving with the runoff.

This last example illustrates potential for conservation of both soil and nutrients. Irrigation-induced erosion has been studied fairly extensively for furrow irrigation, with management options to reduce it (injection of polyacrylamide, PAM, Aase et al., 1998; Bjorneberg and Aase, 2000) that may also be possible in moving irrigation machines. However, if precision irrigation capabilities have been added to a moving irrigation machine, erosion may be addressed without adding the PAM injection. PAM has been shown to affect infiltration rates for soils (Lentz et al., 1992; Lentz and Sojka, 1994; Trout et al., 1995; Sojka and Lentz, 1997; Sojka et al., 1998a,b), but it is not clear whether all such infiltration problems can be solved in this manner, leaving producers with the primary option of reducing irrigation rate in certain areas of the field.

Loss of nutrients with runoff leaving the field is one way that nutrients may be lost and have off-site impacts. The other is by leaching. Collection of water into a pond within the field, or to ponds outside the cropped area, extends the amount of time that water can drain through the profile under the pond, and it concentrates much of this drainage into an area much smaller than the field. While the nutrients previously applied to the area that becomes ponded are clearly vulnerable to loss, the likelihood is that nutrients from the source area for the water will migrate with the runoff, thus exacerbating severity of the problem.

The combination of soils that are considered quite uniform from an agronomic standpoint and of uniform irrigation application systems (i.e., center pivots) can result in a considerable amount of redistribution of the applied water by surface (in-field and off-field runoff) and shallow subsurface flows (often referred to as interflow) of water to lower areas. This is often due to the terrain under self-propelled center pivots and linear move machines, which is often quite variable (Duke et al., 2000; Evans et al., 1996; James, 1982). Elevation differences cause both water pressure and flow to change along the CP lateral pipe. These problems can often be reduced with pressure regulating valves or flow control nozzles (Duke et al., 1997; Jordan, 1998). However, even with relatively uniform applications, surface runoff and ponding can still occur at the lower elevations in a field. Soil compaction may also reduce local soil water availability by reducing effective rooting depths. For any or all of these reasons, even the most careful irrigators will have areas in the same field that are either too wet or too dry. Water collected in low-lying areas from the tops and sides of hills is likely a major contributor to leaching of nutrients and tends to create unfavorable growing conditions due to water logging. The cumulative effects of early season water management undoubtedly play a large role in the emergence of wet areas within and outside of a field. Over the course of the growing season, areas of standing water will often develop in these low-lying areas even on the sandy soils. Irreversible yield damage has often occurred by the time the wet areas become visually evident. These factors combine to reduce crop quality and yields and increase the leaching of soil nutrients and other agrochemicals past the root zone. In addition, pumping energy is wasted. Thus, it is evident that the ability to more precisely manage small areas within each field will be necessary to further reduce groundwater degradation and reduce water use for irrigation.

Meisinger and Delgado (2002) presented the principles for managing nitrate (NO_3-N) leaching. One of the key principles to reduce NO_3-N leaching is water management. Delgado (1999; 2001) reported that there is a spatial variability in residual soil NO_3-N after harvest related to soil physical properties. He reported on the spatial variability of residual soil NO_3-N and NO_3-N leaching during the growing season for center-pivot irrigated systems. The residual soil NO_3-N for barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), and potato grown on a loamy sand zone was 20, 44, and 109 kg N ha^{-1}, respectively, which was lower than that measured for the sandy loam zone of 42, 51, and 136 kg N ha^{-1}, respectively. The NO_3-N leached from the irrigated barley, canola, and potato in the loamy sand zone areas of the field were 32, 39, and 91 kg N ha^{-1} respectively, higher than the 29, 13, and 72 kg N ha^{-1}, respectively, observed for these crops grown on the sandy loam zone. Bausch and Delgado (2003) reported that we can use remote sensing to manage this variability and increase nitrogen (N) use efficiencies. Delgado and Bausch (2005) reported that use of remote sensing to determine in-season N application, which cut N inputs by about 50 percent without reducing yields, reduced NO_3-N leaching losses by 85 percent. We are proposing in our paper that spatial water management can contribute to the integration of the spatial soil-plant-hydrological variability and can increase water use efficiencies and reduce potential NO_3-N leaching losses. This principle needs to be tested for commercial farm systems.

Weekly measurements of soil water and the use of passive capillary wick soil solution samplers in low areas on some sites have indicated that these low areas are the source of much of the deep percolation and leaching of nutrients in the central Columbia Basin (Evans and Han, 1994; Evans and Harting, 1999). Others (Mulla et al., 1996; Mallawatantri and Mulla, 1996) have also shown that a high proportion of the leaching often occurs in a relatively small amount of the total field area due to surface, as well as subsurface lateral transport of applied water and precipitation. These studies indicate that precise management of water and agrochemicals in relatively small areas of a field can have a large impact in reducing groundwater contamination. Extrapolation of these results indicates that an even greater reduction in groundwater contamination could be realized in fields with a larger percentage of coarse-textured soils by the use of site-specific water applications.

For example, an interesting trend has emerged as researchers have collected site-specific data on spatial variability in potato (*Solanum tuberosum* L.) yields in the undulating topography of the Pacific Northwest (sandy soils). They have consistently shown yield to be positively correlated with elevation within a field (yields are better on the hills and hillsides) and concluded this was actually a correlation with soil moisture levels (Han et al., 1996). Research in Idaho (silt loam soils) has shown a negative correlation between yield and elevation (Ojala and Chiappini, personal communication, 1998) and has also indicated that soil moisture status is likely one of the major factors involved. The conflicting results between Washington and Idaho are due to major differences in irrigation management strategies in the two growing areas. Water is more limited in the Idaho growing areas and growers do not worry as much about yields on the tops of hills that tend to have lower yields due to stress. On the other hand, Washington growers are not as limited for water and often manage for maximum yields including the hilltops. This strategy tends to over irrigate the bottoms of the swales due to runoff and redistribution of water, which reduces harvestable yields in those areas due to waterlogging and/or the inability to harvest due to overly wet soils. Thus, increased management of irrigation water distribution could potentially improve yield and quality of potato in both of these important potato production regions.

Another problem that can be addressed by reducing irrigation amounts in selected areas is the frequent occurrence of both nozzle clogging and disease outbreaks in the first span of center pivots. Both of these problems are discussed as an example in Case Study No. 2.

The third real-world problem concerns dealing with inherent variation in soil productivity. This requires substantial quantitative, site-specific information about the response of a crop/soil/weather combination to all of the managed inputs. Extending site-specific management from nutrients to irrigation alters the response functions, which must be determined to fully optimize management.

Variable-rate recommendations for N under rainfed conditions often assumed that historical yield at a point indicated the yield potential, so that variable-rate recommendations could parallel conventional recommendations, using historical yield as a target yield (Vanotti and Bundy, 1994). This assumption is being debated (e.g., Lory and Scharf, 2003). For irrigated culture, interannual variations in rainfall are managed by providing a more-uniform water supply to the crop, but nutrient management remains a topic of research (e.g., Ferguson et al., 2002). For irrigation one cannot presume a monotonically increasing linear response function; loss of profit and even loss of yield can be easily demonstrated for over-irrigation (Sadler et al., 2002). Therefore, to properly optimize irrigation amount, one requires the response of the crop-nutrient-soil-weather-management combination to the irrigation amount for the full range of responsiveness of the soils in a field.

Assuming that response function is known beforehand (and that one can predict the weather and harvest-time commodity prices), one should be able to apply irrigation at an amount that maximizes profit. A post-experiment analysis illustrating the theoretical maximum potential for water conservation following this objective is shown in Case Study No. 3 in the following section. In practice, variations from expected weather would probably severely impact the achievable conservation.

One approach employed to hedge against rainfall is to irrigate to a planned soil deficit, or soil water content somewhat less than the optimum one would choose if no rain would come. This is termed a management allowed depletion when it is applied uniformly in space (Cuenca, 1989). Some variation of this approach would be possible with precision irrigation. Sometimes, particularly with downslope movement of surface irrigation, this deficit can be spatial—irrigation amounts at the upper end of the furrow are kept low enough that they do not extend all the way to the end of the run, leaving some soil water storage capacity for possible rainfall. While this approach would have a spatial component, it is not likely to be employed with moving irrigation machines. To a certain extent, the corner areas of center pivots could be considered a planned-deficit area. A center pivot with no end gun or corner unit leaves a little less than one fourth of a square field area unirrigated. Using rainfed culture or low-input methods such as surface or subsurface drip in these areas could be attempted, although the temptation would likely be to irrigate to maximize return on any capital investment.

Case studies to illustrate potential for conservation

Case Study 1. Avoidance of water applications within a field. There may be two reasons to not irrigate an area within a field. The first is the random occurrence of rocky outcrops or otherwise unsuitable areas for crop production. When these conditions occur under a standard commercially available machine, these areas receive the same water and agrochemicals being applied with the system as the rest of the field. This is obviously environmentally unacceptable as well as a waste of water, chemicals, and energy. The second reason is that some areas, because of soil physical or chemical differences, have repeatedly produced low yields, and the operator desires to remove them from production. One example is the southeastern U.S. Coastal Plain, where 11 to 28 percent of rainfed yield maps from southeast North Carolina showed stable, low yields (Sadler et al., 2005). These areas within fields are often depressions where many of the considerations regarding runoff and leaching apply, but even in rainfed cases, the yields are low. While rains could cause the same waterlogging, some areas appear to be low even in dry years, suggesting reasons in addition to water relations. Prevalence of these areas is similar to that in South Carolina, where 26 percent of Florence County consists of soils associated with bays. However, much of this land is left in non-cropped land uses, often forest, leaving something on the order of 10 percent under row crops. For instance, in one 24-ha (60-ac) research field, 7.5 percent of the area consisted of the two main soil map units associated with bays (Karlen et al., 1990).

Case Study 2: Specific problems that can be addressed using reduced irrigation amounts. The first of two specific problems involves the development of wetland areas under an irrigation machine. Irrigation of wetlands, drainage ditches, and bodies of open water is unnecessary and also environmentally unacceptable. Wet and waterlogged areas can also develop as the season progresses, often because of irrigation. Shallow soils over bedrock can also produce areas of standing water even on fairly flat areas where applied water moves laterally and collects in low areas. An example of this occurred on a farm in northern Oregon where several center pivot irrigated fields developed areas of standing water that were as much as 30 cm deep and ranged from 0.2 ha (0.5 ac) to as much as 8 ha (20 ac) in size. Consequently, crops in these wetland areas were either totally lost or were unharvestable either due to due to poor quality or disease or physically because harvesting equipment cannot traverse the area. During the next potato-cropping season, the use of precision irrigation avoided application of water to these wetland collection areas and allowed them to produce yields that could be harvested with standard equipment.

Reports from the operator in one of these instances provide some idea of the potential for both conservation of water and improved economic benefit. In this example, the center pivot covered 60 ha (150 ac), and the irrigation-induced pond covered 8 ha (20 ac). After retrofitting the pivot with precision irrigation capabilities, the pond did not form, and the operator reported good potato yields in that area. He also reported 15 percent less water use than the prior potato crop under the pivot. The combination of 15 percent water savings and 13 percent increase in harvested potato area suggest substantial environmental and economic benefit.

The second specific problem involves the pipe span between the pivot point and the first tower, which is often problematic because of nozzle issues and disease. First, nozzles that apply the design application depth so close to the pivot point require very small orifice sizes. This often causes problems with clogging by debris and weed seeds in the water supply. Even with small orifices, over irrigation often occurs. Further, the start-stop motion of the machine, which is worst in the first span, creates severely non-uniform applications. All of these nozzle-related problems can be addressed using larger orifice-sized nozzles and pulsing them on and off to control water applications.

The second problem is increased occurrence of disease. Since the machine moves slowly in this region of the field, the foliage is constantly wet, which provides excellent conditions for fungal diseases. Often, the first occurrence of a disease is in this area, from which it spreads to other parts of the field. Especially in potato, first-span variable-rate management could decrease the area in a field susceptible to the fungal rot organism late blight (*Phytopthora infestans* L.).

Case Study 3: Site-specific irrigation response functions. This case study is a site-specific re-analysis of data published as map unit means and field means by Sadler et al. (2002b) for irrigation and Camp et al. (2002) for nitrogen production functions. Space here does not permit extensive description of the equipment used. Readers can see Camp and Sadler (1997); Omary et al. (1997); and Camp et al. (1998) for these details, and Camp and Sadler (1997), Omary et al. (1997), and Camp et al. (1998) for information on system performance. Data were obtained during 1999 to 2001 in a 396-plot irrigation by nitrogen fertilization experiment in a 6.6-ha (15-ac) field representative of the southeast U.S. Coastal Plain. Soil information as soil map units determined on a 1:1200 scale by U.S. Department of Agriculture's Soil Conservation Service in 1984 was described in Karlen et al. (1990). The treatments were irrigation amount (0 percent, 50 percent, 100 percent, and 150 percent of normal, which replaced evapotranspiration according to tensiometers in selected 100 percent plots) and nitrogen fertilizer (135 kg/ha and 225 kg/ha, which are the recommendations for rainfed and irrigated corn and correspond to target yields of 6 and 10 Mg/ha, or 120 and 200 lbs/ac for target yields of 100 and 160 Bu/ac). Conventional surface tillage was used, including disking of the surface. Corn was planted in 76-cm (30-in) rows around the circle with in-row subsoiling to 40 cm (16 in) to break up a dense eluviated horizon. Cultural operations followed regional extension guidelines. Corn was harvested using a plot combine in two-row swaths 6 m (20 ft) in length from the center 6 by 6-m (20 by 20-ft) control area of the plots. Yields were stated at 15.5 percent moisture. A preliminary re-analysis on a strictly spatial basis was conducted that ignored the soil map unit delineations (Sadler et al., 2002c). In this analysis, spatial patterns were evident in both irrigation response and the irrigation amount that produced the maximum yield. The Sadler et al. (2002c) analysis lumped nitrogen treatments to obtain an average irrigation response. That procedure interpolated spatial data for like treatments to obtain estimates at each plot position, then fit quadratic regressions to obtain a production function for each plot. The current case study removed the average across N treatments, providing separate irrigation quadratic production functions at each nitrogen level, for each plot in the field.

Once these equations were determined, they were solved algebraically for economically important points on the curves. The maximum yield and the irrigation amount that produced it were needed for this analysis because the maximum yield and the irrigation value to obtain it are generally considered to approximate the optimum in the land-limited case (Martin et al., 1990). These equations were also solved for the point of diminishing marginal returns (Lu et al., 2004) providing the profit-maximizing yield and the irrigation amount to provide that yield. This required the estimated cost of irrigation water ($0.40 ha^{-1} mm or $4.11ac^{-1} in, Clemson Extension Service, 2002) and local corn prices ($97.4 Mg^{-1} or $2.48 bu^{-1} on 8/28/02).

Table 1. Crop season rainfall, actual irrigation, calculated water use of irrigated corn, irrigation to obtain maximum corn yield, irrigation to obtain maximum profit, and the amount of water conserved had the profit-maximizing strategy been employed, at Florence, South Carolina.

Year	April-July rain, (mm)	Actual 100% irrigation, (mm)	Calculated irrigated corn ET*, (mm)	Irrigation at maximum yield, (mm)	Irrigation at maximum profit, (mm)
1999	288	218	253	278	228
2000	371	203	212	252	212
2001	334	200	240	189	130
mean	331	207	235	240	190

	Actual – max profit		Calc ET – max profit		Max yield – max profit	
	(mm)	%	(mm)	%	(mm)	%
1999	-10	-5	25	10	50	18
2000	-9	-4	0	0	40	16
2001	70	35	110	46	59	31
mean	17	8	45	19	50	21

* evapotranspiration

The opportunity for conservation of irrigation water implies two scenarios—some previous practice, and some possible future practice—so that the difference between them represents a potential savings. In this case study, there are three contrasts of interest. The first is the possible savings from the actual practice, the second is the possible savings from the same practice performed perfectly, and the third is the possible savings from the theoretical maximum yield case. Common to all three comparisons is the theoretical profit-maximizing case, so that savings in all three contrasts are from one of the three scenarios listed to the profit-maximizing case. Table 1 lists the irrigation amounts in all cases.

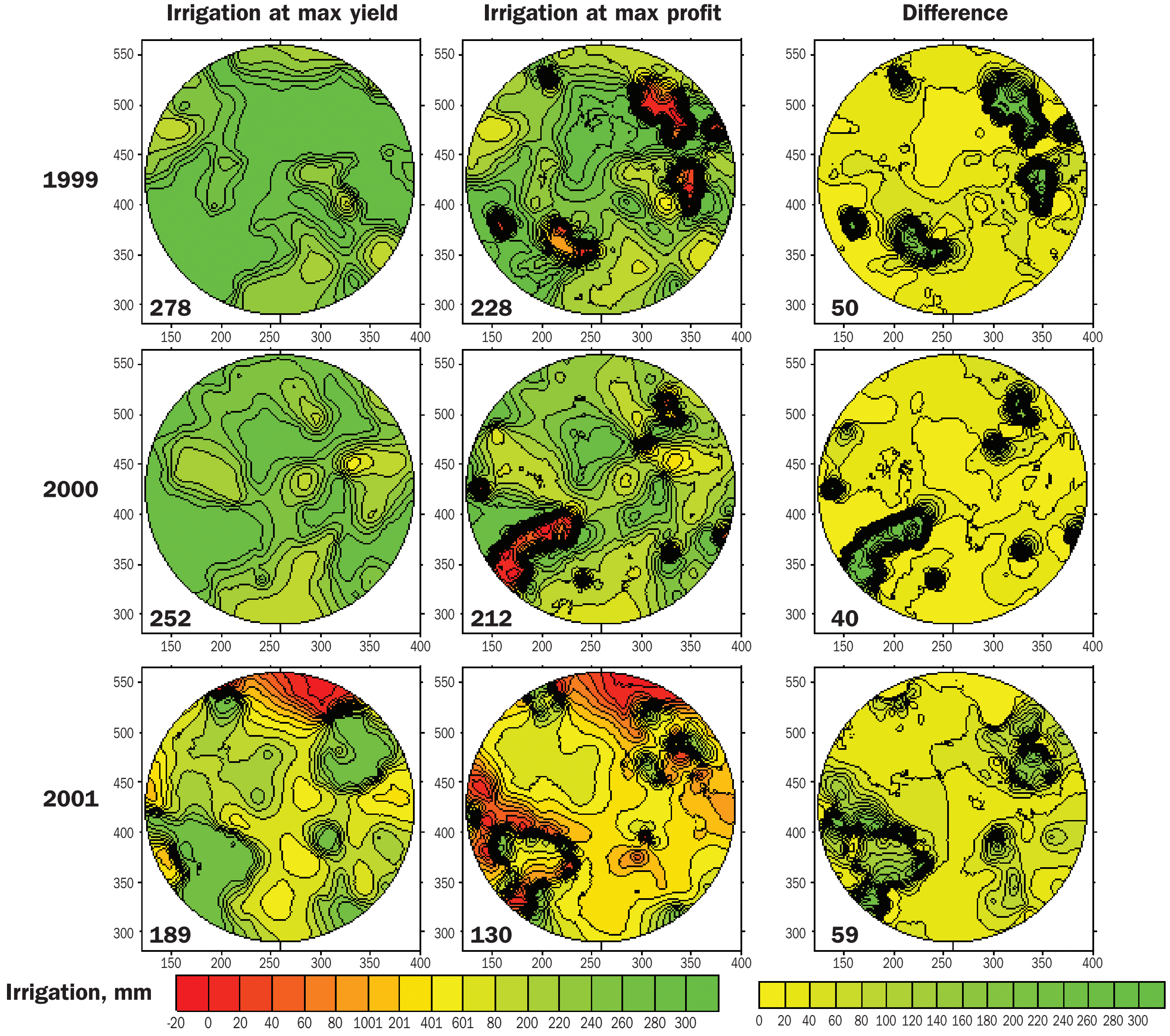
The 100 percent irrigation treatment represented the actual practice, which was intended to hold tensiometers constant in selected plots. As mentioned in Sadler et al. (2002b), irrigation amounts fell behind calculated evapotranspiration for irrigated corn (Allen et al., 1998). Thus, one could presume that had we exactly matched the evapotranspiration, we would have applied slightly more irrigation. This amount is reflected in Table 1. Both these amounts represent whole-field practice, and are thus constant over the field. The values derived from the site-specific analysis are spatially variable and are shown in Figure 1. Even more distinct spatial patterns existed in the difference, so the values were integrated over the area under the pivot for comparison to the whole-field practice.

As seen in Table 1, in the two drier years, the profit-maximizing amount actually would have applied four to five percent more irrigation than the actual irrigation practice. This is consistent with the calculated water use exceeding the actual irrigation amount. In the third year, the profit-maximizing strategy would have saved 35 percent of the actual irrigation amount. The savings from the calculated water use of well-watered corn were from 0 to 46 percent. The savings from the yield-maximizing strategy ranged from 40 to 59 mm, or 16 to 31 percent. Three-year mean savings from the three strategies were eight percent from actual practice, 19 percent from calculated perfect practice, and 21 percent from the yield-maximizing strategy.

Interpreting these values requires some additional information about the rainfed yields in the area. Rainfall totals during all seasons were below the 410 mm normal rainfall for April to July. However, rainfall distributions differed, resulting in inter-annual yield differences. The weather years 1999 and 2000 were very similar for corn production, while 2001 had substantially higher regional yields. Despite being the intermediate rainfall year and being well below the normal April to July rainfall, state average yield set a record and was more than 2.4 Mg ha^{-1} (38 bu ac^{-1}) higher than for the prior two years (http://www.nass.usda.gov/QuickStats/). These conditions affected the estimated maximum yields, as derived from the production functions, with maxima for the three years of 10.9, 11.1, and 12.3 Mg ha^{-1} (173, 176, and 196 bu ac^{-1}). For reference, the state average rainfed yield was 6.8

Figure 1

Spatial maps of derived values for irrigation that would have achieved maximum yield, irrigation that would have achieved maximum profit, and the difference, for 1999-2001 at Florence, South Carolina.



Mg ha^{-1} (108 bu ac^{-1}), which is close to the unirrigated treatment mean. It would be difficult to estimate amounts that could be conserved during more-favorable weather years.

Similarities between the first two years and differences between those two and the last year are visible in spatial patterns of yield-maximizing and profit-maximizing irrigation amounts (Figure 1). Distinct spatial patterns existed in the amount that could be conserved, some of which were stable across years and some of which were not. The stable ones would be relatively simple to program into an irrigation strategy. Those not recurring would be quite difficult to capture in a real-time management mode without significant new knowledge.

For a surprisingly large area in the field for the first two years, the maximum yield was at the highest irrigation treatment, despite it being 150 percent of normal. Very little of the field needed higher irrigation amounts in 2001. For most of the field during all years, the profit-maximizing irrigation amount was within the treatment range. The implication for 1999 and 2000 is that the results obtained represent a conservative estimate of the potential for water savings between these two strategies.

Case studies such as this one represent only the conditions of the test, and until independent support for such results can be obtained in other regions, with other soils, weather, crops, and management, the reader is cautioned against accepting these results as representative of the potential for conservation in other situations.

A need for decision-making support

Although prototype systems for variable-rate application have been developed, decision support systems have not. To increase both the acceptance and feasibility of precision agriculture, research is needed to develop decision support systems to vary inputs that are cost effective. To this end, using measurements that either are relatively static, thus not necessitating costly annual testing, or are dynamic but inexpensive to measure, will increase the utility of precision agricultural practices, particularly on smaller farms.

In a recent review article on precision agriculture, Pierce and Nowak (1999) conclude that efforts are needed to develop both tools and management systems that are "…based on the emerging science of precision agriculture while not forcing new enabling technologies to operate under traditional crop management strategies and guidelines."

As mentioned earlier, irrigation control systems that can be used to manage spatially and temporally variable demand through GIS are currently being commercially developed. The limiting factors to this approach are the availability of cost effective support tools and instrumentation for decision-making. Decision support systems for precision agriculture systems are needed to determine management zones for differential management practices. Thus, the factors required to determine specific differential management zones need to be established. Zones for differential irrigation water management may differ from zones for differential herbicide management and the factors used to establish the management zones are unlikely to be identical.

Soil moisture and crop water requirement, likely two of the most important factors for any decision-making system, can be monitored by a variety of methods. For example, weather station data can be used to estimate potential evapotranspiration. The evapotranspiration approach is useful for making decisions on a large scale but does not address spatial variability across a single field; therefore, non-site-specific evapotranspiration is a poor source of feedback for making decisions on variable rate applications of water. Consequently, a major key to the success of precision agriculture is the measurement and monitoring of system components including the operational aspects (pressures, flow rates, position) as well as field conditions such as soil moisture, temperature, rainfall and actual applied irrigation depths.

Real time monitoring

Ultimately, because of the vagaries of "real" field conditions, we will probably need to use strategically placed, real-time soil water and micro-meteorological sensors. These could be distributed in fixed locations or moved across a field to provide continuous feedback to re-initialize and adjust various model parameters in a decision support framework. There is a real need to improve these re-initialization procedures so that the fewest number of various soil water sensors and sensor systems would be required for maximum impact on water quality.

Current soil moisture monitoring technologies are divergent in their ability to measure soil moisture. Low cost tools (e.g., tensiometers) do not provide consistently precise and accurate data on soil moisture status or require considerable maintenance. Tools that provide precise and relatively accurate measurements of soil moisture (e.g. Time Domain Reflectometry,TDR) are generally too expensive for a grower to utilize in multiple locations at multiple depths across a field.

One way to achieve the desired level of control would be the use of real-time soil water and micrometeorological sensors distributed across a field for continuously re-initializing various decision-making model parameters during irrigation events. This type of integrated feedback is necessary because of the tremendous complexities and time constraints involved in solving real-time three-dimensional modeling of the systems. Simplified assumptions may be used to increase computational speed and the predictive decision support models do not have the opportunity to drift very far from actual conditions since operating parameters are frequently re-initialized and the models rerun from more accurate baselines. Coupling real-time micro-weather stations, plant-based sensors (e.g., reflectance, infrared temperatures or video) and numerous real-time soil water sensors scattered around the field at critical locations with a set of good predictive models into a decision support system also minimizes the need for continuous and expensive agronomic oversight. Assessment of the environmental impacts of best management or "normal" irrigation practices from the integrated set of models in this configuration with real-time feedback will be more realistic and acceptable to both producers and regulators.

Wireless transmission of soil water status and other site specific parameters to a base control computer will allow real-time water applications that precisely match the water needs in each area of a field without leaching of agrichemicals or surface runoff. The development of wireless soil water, microclimatic and other sensor networks along with existing precision center pivot irrigation systems tied to a base computer equipped with special management and control software will provide economical, ecologically sound real-time management.

Summary and Conclusion

Extending the concept of precision irrigation to include spatially precise irrigation appears to have several potential opportunities for conservation of water and nutrients. The history of research confirms that precision irrigation is technologically feasible, if not yet economically advantageous. The considerations that might change this conclusion include increased awareness of need for water conservation because of drought, increased contention for short water supplies, and possible future regulatory actions. The amount of water that could be conserved using precision irrigation remains a research topic. In specific examples where quantitative estimates of water savings could be made, it appeared that precision irrigation could save from 10 to15 percent of the water used in conventional irrigation practice. In several examples, there were benefits beyond the saving of water, such as increased harvestable area, decreased incidence of disease, and in some cases, reduced leaching, or at least risk of leaching. While the potential will likely be debated academically for some time, these examples suggest that practical and important opportunities for conservation of water can indeed be realized. Improved decision support systems and technology for real-time monitoring and control would increase the utility of precision irrigation.

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