16 New and Future Technology

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HISTORICAL CONTEXT

Judging from archaeological evidence, irrigation has been practiced for at least eight millennia, starting in the Nile, followed by the Tigris and Euphrates in Mesopotamia, the Yellow River in China, and the Indus River in India (Hoffman et al., 1990). During this time, the experience and skill of humankind has been accumulated, improved with an eye toward future needs, and yet sometimes still lost to history. Therefore, capturing the state of the art of irrigation is clearly worthwhile. On the other hand, predicting the future is far less so clearly worthwhile. We recognize that our foresight may well in time be proven dim. Bearing in mind the context of 80 centuries, however, we attempt to describe new and predict future trends.

Equipment

There has been more innovation in irrigation and drainage technologies and practices in the last 100 yr than in all of the previous periods. This applies to every aspect of irrigation: diversion works, pumping, filtration, conveyance, distribution, application methods, drainage, power sources, scheduling, fertigation, chemigation, erosion control, land grading, and water conservation. It is most useful to consider the more recent innovations that continue to be adopted.

Conveyance probably began with small earthen ditches close to streams and rivers to move water in larger volumes for longer distances, with hand-carried containers used for smaller volumes and shorter distances. Open-channel canals can be seen in many paleo-agricultural contexts, and similar structures are still commonly used around the world. Gravity and pressurized pipe distribution systems are a more recent but still well-established method.

Except for gravity-flow distributions systems where water supplies exist at higher elevations, some method to move water up a gradient has always been a prerequisite to irrigation. Water wheels, screws, reciprocating pumps, turbines, and centrifugal pumps were all, at one time in history, new innovations. Power sources have improved with time, relying first on humans and animals, then later steam engines, internal combustion engines, and eventually highly efficient electrical motors. Today, the innovation edge is represented by variable-frequency controllers for electric motors driving pumps. Perhaps in the future, pumps can be powered by solar cells.

For millennia, standard water application methods included gravity flow into fields via wild flooding and furrows. Modern improvements in surface irrigation have included better field preparation, especially via laser-aided grading and leveling; canvas dams; better transfer from the head ditch to the furrow via siphons and aluminum and plastic gated pipe; and better management of the flow rate and infiltration using techniques such as pipe spigots, surge flow, cablegation, soil amendments, and timing.

Improvements in pressurized application include high-pressure impact sprinklers and, later, low-pressure sprinklers; bubblers, microsprinklers, and surface and subsurface drip irrigation; and low-energy precision applications (LEPA) to the soil surface. Sprinkler irrigation innovations include aluminum and plastic solid set, side-roll, and end-tow set-move systems. Several moveable irrigation systems, including traveling big guns (hose- and cable-towed), linear-move systems, and center-pivot systems have had a major impact. Innovative extensions for center pivots and linear moves allow coverage of irregular field shapes and corners with end guns and corner units.

Irrigation Scheduling

How paleo-agricultural irrigation scheduling, if any, was achieved is not well known. Since any pretechnological irrigation event was very labor and time intensive, however, schedules were probably based on visual and tactile observations, such as feeling the soil or observing wilting or rolling of leaves. These methods are still widely used, especially in developing countries, but by the time visual symptoms occur, yield reductions have already occurred. Various anticipatory methods, based on experience, time, feel of the soil, or other input, surely must have developed in prehistoric times, but no evidence is known of the specific methods used. Current scheduling methods include plant-based, soil-based, and computer-based techniques.

Plant-based methods are a logical outgrowth to scheduling based on visual observations. Innovation stems from methods capable of detecting plant water stress earlier. Methods have been reported using measurements of leaf water potential (Scholander et al., 1964, 1965), stem or fruit diameter (Brough et al., 1986; Huguet et al., 1992; Garnier and Berger, 1986), acoustic characteristics (Tyree et al., 1984; Pena and Grace, 1986), heat balances of sap flow (Braun and Schmid, 1999; Lascano et al., 1992; Green and Clothier, 1988), leaf temperature (Jackson et al., 1986; Wanjura et al., 1992), variation in leaf temperature (Aston and Van Bavel, 1972; Clawson and Blad, 1982), interpretation of leaf spectral characteristics (Hunt et al., 1987; Jackson et al., 1981, 1986), and a combination of leaf temperature, air temperature, and humidity into a crop water stress index (Idso et al., 1981; Jackson et al., 1981).

Modern soil-based methods derive from the conceptual need for irrigation, which is the recognition that dry soil means poor plant growth and that timely water applications to maintain soil water supply help reduce the effects of short-term drought on crop yields. The initial sensing method was almost certainly the feel of the soil, a practice that continues today, even in well-developed irrigation practice (Phipps, 2003). Clearly, one must know what soil water content should be used to trigger an irrigation. In modern practice, the manual method is correlated to soil water content measured by some sensor, allowing the method to act as a cheap surrogate for instrumentation. Soil water sensors used for irrigation encompass the entire range of technology available for measuring soil water. These include, for example, gravimetric methods, tensiometers, attenuation of radioactive sources, nuclear magnetic resonance, electrical resistance blocks, capacitance sensors, thermal conductivity, psychrometers, soil matric potential sensors, time-domain reflectometry, frequency-domain reflectometry, radio waves, eddy currents, x-rays, and microwaves.

Computer-based methods have been an outgrowth of graphical (Henggeler, 2001) and checkbook methods (e.g., Henggeler, 2002). They were made possible through the concurrent development of computers and improved theories of soil–plant–air–water interactions. The concept of plant-available water, as a simplification of the complex physical processes involved, provided a theoretical basis for establishing the soil water trigger point for irrigation. When combined with calculation of water use, it also allowed an objective forecast for when irrigation would next be needed. Development of empirical (e.g., Thornthwaite and Holzman, 1939; Thornthwaite, 1948; Blaney and Criddle, 1950; Jensen and Haise, 1963) and theoretical (e.g., Penman, 1948; Monteith, 1965; Van Bavel, 1966) methods to calculate evapotranspiration constituted a major innovation for irrigation. The near-coincident development of mainframe computers made computer-based irrigation management a logical step (e.g., Jensen, 1970; Jensen and Wright, 1978). The further development of personal computers since the late 1970s provided a means for local control (e.g., Lambert, 1980), but this technique has not caught on as broadly as initially expected, probably because of the extra time commitments by growers to fully realize the benefits.

This brief historical review sets a context within which to evaluate and recognize trends now existing in the irrigation industry.

TRENDS

The quantity and perhaps also quality of existing and future water resources for irrigation throughout the world is expected to continue to decline, while competing demands may limit water availability for irrigation expansion and energy costs are rapidly escalating. Competition for water is the dominant force for change in most regions of the world where extensive irrigation is practiced. For example, for some time in the western USA and more recently in the southeastern USA, land is being either threatened or actually taken out of irrigated production because of declining availability of water resources, soil salinity, water quality degradation, endangered species regulations, urbanization, and intense competition between users for existing fresh water resources. These issues are exacerbated during hydrological droughts and are especially severe in regions with declining aquifer levels.

Obviously, improved technologies continue to be needed to better manage energy, water, and soil resources. New and improved strategies and practices are needed to reduce surface and groundwater contamination from agricultural lands, and sustain food production for strategic, economic, and social benefits. Innovative irrigation techniques and management systems will be necessary to increase the cost-effectiveness of crop production, reduce soil erosion, and reduce energy requirements while enhancing and sustaining crop production, the environment, and water use efficiency.

Competition for water with municipalities, industries, recreation, and environmental uses appears to be a globally important issue, with water conservation mandates and related litigation increasing. The implications of these pressures will necessarily result in continued refining of water conservation measures, through improved efficiency in delivery, timing of applications, and, probably, increased use of various deficit irrigation strategies. Maintaining crop production through more efficient use of rain and irrigation is critical to overcoming these problems, which are complicated because their severity varies in both time and space. To maintain profitability, irrigators will have to apply water and agrochemicals in an efficient manner to reduce the social as well as the economic costs of diverting or pumping water across relatively long distances.

As skilled labor for irrigation becomes more limited and the farming population ages, it is expected that the conversion from other irrigation methods to center pivots and microirrigation technologies will rapidly increase. During the last decade, areas with appreciable increases in irrigated land in the USA are Nebraska and the lower Mississippi River Valley Delta (U.S. Bureau of the Census, 1988; National Agricultural Statistics Service, 1992, 1997, 2002); most of this increased area was with center pivots. Surface irrigation techniques persist as by far the dominant methods around the world; however, in the USA, they will continue to decline, as will solid set and set-move sprinkler systems in labor-short and water-short areas.

Another issue is the effect of irrigation on the environment, which is very complex and causes often-contentious public debate regarding both water quality and quantity. It is inextricably linked with the competition for water in that low water resources usually exacerbate the environmental issues being debated. The most commonly cited environmental concerns include wildlife habitat, especially pertaining to endangered or otherwise protected species, groundwater contamination, salinity (e.g., Colorado River Basin), and irrigation tailwater quality from sediments and chemicals moving off irrigated land. All of these concerns align with water conservation as mitigation measures. The water quality concerns also align with retention of agricultural inputs within fields in a manner similar to rainfed practices. Continued refinement of application methods and technologies to improve distribution and timing to address these issues will be required. Detailed documentation of both water use and conservation measures will probably gain importance as water rights and water quality litigation increases.

Less commonly cited, but increasingly raised by irrigation practitioners and advocates, are the environmental benefits of irrigation. For instance, higher production on irrigated land allows the same amount of food to be produced on less land area. Less land area used may allow protection of land more susceptible to erosion or other degradation. Under many agricultural practices, fossil fuel use is more related to land area than production, thus irrigation might reduce fuel use, depending on the power requirements for pumping. Advocates have also postulated benefits to carbon sequestration, habitat preservation, and moderating climate at the regional scale. Quantifying these effects remains beyond our capability at our present level of knowledge about ecological interactions at and above the landscape scale. Thus, debate between irrigation interests and environmentalists is expected to continue.

A third, perhaps less contentious, trend is toward a growing awareness of spatial variation within irrigation management units. This is a logical outgrowth of a similar awareness in rainfed culture, which led to precision agriculture. On-farm application of precision agriculture took its first major step when equipment became available to spread dry granular fertilizer according to a map of site-specific recommendations (Ortlip, 1986). Given the fertilizer industry's reliance on soil tests, grid or map-based soil sampling was used to develop recommendation maps. On-the-go crop yield monitors and sensors for organic matter and other characteristics followed quickly. Two conclusions soon became apparent from these spatial data. First, there was much more variation than expected, and it was more extreme than expected. Second, fertility alone could neither explain nor manage or compensate for the observed variability. By the mid-1990s, many researchers were also including water relations as a partial, but major, causal factor for, and a way to manage, spatial variation in crop yield (Mallawatantri and Mulla, 1996; Mulla et al., 1996; Evans et al., 1995).

The case for variation in soil water characteristics as a key cause for spatial variation in crop yield can be made from several rationales. Common experience indicates and climatological records show that seasonal rain is the primary correlate to crop yield, which suggests a mechanism capable of causing the magnitude observed in spatial crop yield variation. Spatial yield patterns often correlate to topography and soil texture, with low areas yielding higher in dry seasons and less in wet seasons. This suggests collection of runoff as a mechanism for higher water supplies in those areas explaining deficit reduction as well as waterlogging and salinity effects. Spatial variation in canopy temperature related to soil water status has been observed via thermal infrared remote sensing (Moran and Jackson, 1991) and close-range infrared thermometer sensing (Sadler et al., 2002b; Upchurch et al., personal communication, 1998). The close physical link between canopy temperature and energy balance and the dominance of the energy balance by the water flow term together suggest that extreme spatial variation in water flow is quite common. These observations, given there is no prime candidate other than water, make a convincing case.

Ensuring the success of irrigated farming enterprises will require the development of reliable and more-timely information on field and plant status to support the decision-making processes. Research is needed to focus on the development of spatial and temporal management approaches that address site-specific crop water, nutrient, and pest management requirements in real time. Advancement of spatial-temporal modeling is needed also to guide management innovation and as a component of on-farm decision aids.

Plant models capable of calculating the physiological needs of a crop across space and time tend to be complex and impractical for real-time on-farm management. Furthermore, most of these models are point models that lack sensitivity to adequately calculate site-specific plant needs across a field in a timely fashion. Simpler, more appropriate models might be used but will probably need frequent updating via automated, field-based sensor systems to readjust model parameters to help ensure reasonable tracking and spatial calculations of field conditions. Such sensor systems could include canopy microclimate monitoring, soil water status, plant reflectance characteristics, video cameras with pattern recognition, and other remote sensing technologies. More robust and more accurate methods are needed to estimate or indirectly measure missing model parameters. The ultimate goal of this research area is to use sensor systems, models, and other techniques to provide data products that reduce time requirements for busy decision makers while improving their management capacity.

Remote sensing is a possible information source that could improve spatial-temporal modeling and farm management. Better ground, airborne, and satellite systems capable of precisely measuring specific plant parameters (e.g., nutrient status, water status, disease, and competing weeds) are needed to improve crop modeling and thus improve within-season management. While rapidly changing technology has resulted in many promising advances in related sensors, techniques, and procedures, there has been little scientific assessment of the advantages and limitations of these systems, other than difficulties providing information rapidly enough to use it during a season. Therefore, considerably more work is needed to adequately evaluate some of these different information sources to determine their usefulness in real-time and spatially sensitive crop modeling and management applications.

In addition to these theoretical considerations, several additional trends provided motivation for research in this spatially variable irrigation. The first was the continued refinement of irrigation scheduling, especially with computer-based procedures. As available water holding capacity was being evaluated, it became immediately apparent that substantial differences existed within fields, with patches of soils with different textures or other soil characteristics. In these situations, the management could not be simultaneously optimized for each subfield area. A second consideration was the growing concern about irrigating uncropped areas. Aside from inefficiencies, in many cases the practice is strongly discouraged or regulated, especially if nutrients, animal waste, or other chemicals are injected or applied concurrently. These include rock outcrops and, in many areas, water bodies. In other cases, overspray into uncropped areas, such as roads or ditches, poses a significant public relations and safety problem as well as wasteful use.

PRECISION IRRIGATION

General Issues

During the past 50 yr, the goal of center-pivot and linear-move irrigation design engineers has been to have the most uniform water application pattern possible along the entire length of the center pivot or linear move, and they have been relatively successful. Soil water holding capacity, however, is not uniform and field heterogeneity has been reported in many studies (e.g., Burden and Selim, 1989; Agbu and Olson, 1990). Furthermore, the terrain under center-pivot and linear-move irrigation systems is often quite variable, causing runoff, channeling, and run-on, which can profoundly affect the crop stand and crop yield.

Terrain variation can also change the system pressure distribution along the lateral pipeline. Intermittent end-gun operation can also cause system pressure fluctuations. System pressure changes, in turn, alter the amount of water applied as water pressure varies with applicator orientation and position in the field. While engineering solutions such as flow control nozzles or pressure regulators at each head have somewhat helped this situation, they are still not able to fully compensate for the effects of system pressure changes (Evans et al., 1995; James, 1982; Duke et al., 1997; Duke et al., 2000). Other factors contributing to inconsistent applications include the types, spacings, and locations of installed nozzles. These factors not only affect the amount of water applied to a given area within the field, but they also compound the problem when applying nutrients across a field. If fertigation is used or if the water supply contains significant nutrients, the nutrient distribution will also not be uniformly distributed across the field (Evans et al., 1995; Duke et al., 2000). As a result of these and other factors, considerable crop yield and leaching variations can occur throughout the field.

The development of control and management technologies that can spatially and temporally direct the amount and frequency of water (and appropriate agrochemical) applications by "precision" self-propelled irrigation systems would be a very powerful tool that would increase productivity and minimize adverse water quality impacts. There is also a need to develop more efficient methods of applying crop amendments (e.g., nutrients and pesticides) that will reduce usage, improve profit margins, and reduce environmental impacts.

Center-pivot and linear-move irrigation systems are particularly amenable to site-specific approaches because of their current level of automation and large area coverage with a single lateral pipe. Microprocessor-controlled center-pivot and linear-move irrigation systems also provide a unique control and sensor platform for economical and effective precision-irrigated crop management. These technologies make it potentially possible to vary agrichemical and water applications to meet the specific needs of a crop in each unique zone within a field to optimize crop yield and quality goals while maintaining environmental health (reduced water and agrichemical use) and reduced leaching.

Specific Examples

Somewhat before the widespread recognition of water as the key spatial variable, researchers in four groups embarked on research to develop site-specific irrigation machines. These were in Fort Collins, CO (Fraisse et al., 1992; Duke et al., 1992), Aberdeen, ID (McCann and Stark, 1993; King et al., 1995, 1996; McCann et al., 1997), Prosser, WA (Evans et al., 1996a), and Florence, SC (Camp and Sadler, 1994; Sadler and Camp, 2002; Camp et al., 2002). The methods developed in Prosser, WA, were installed on a three-pivot cluster in a commercial farm in south-central Washington and north-central Oregon (Harting 1999).

Other research groups have since built similar equipment and capabilities. Early work on LEPA in Lubbock-Halfway, TX (Lyle and Bordovsky, 1981, 1983), used to conduct nonspatial irrigation research on cotton (*Gossypium hirsutum* L.; Bordovsky et al., 1992), corn (*Zea mays* L.; Lyle and Bordovsky, 1995) and sorghum [*Sorghum bicolor* (L.) Moench; Bordovsky and Lyle, 1996) was extended into variable-rate irrigation (Bordovsky and Lascano, 2003). Several center pivots at a new irrigation research center near Tifton, GA, were outfitted with a modification of the Washington design (Perry et al., 2002a, 2002b, 2003). Work in Germany was described at a recent conference (Sourell and Al-Karadsheh, 2003). Other research is underway but too preliminary to describe here (Pierce, personal communication, 2003).

Most of these systems were summarized in a presentation at the fourth Decennial National Irrigation Symposium in 2000 (Buchleiter et al., 2000; Evans et al., 2000b; Sadler et al., 2000b). Sadler et al. (2000c) provides an overview for general audiences. Another general overview of research in precision irrigation was reported by Camp et al. (2002), with extensive descriptions of the various components used in the equipment, plus discussion of identified trends in the equipment marketplace and the global agricultural sector related to precision water management.

SYSTEM COMPONENTS

The system components required to apply variable-rate irrigation include the means to achieve variable-rate applications and the ability to have a variable-demand water supply, a control system, and location determination. Enhancements could include the ability to have variable-rate nutrient application and, possibly, variable-rate pesticide application. The above-mentioned research and commercial systems provide examples of several approaches, all of which worked for their design application. Physical descriptions of the components are listed in Table 16–1.

Variable-Rate Nozzles

There have been three methods used to implement variable-rate nozzles: pulsing on and off, stepwise multiple nozzles, and varying orifice size. The Fort Collins linear system (Fraisse et al., 1992; Duke et al., 1992), the first Aberdeen pivot (King et al., 1995), the Prosser pivot (Evans et al., 1996a), and the commercial pivots modeled after Prosser's (Harting, 1999) used pulsed sprinklers, either individually, in banks of two to four, or for a half-span additional manifold hung under the span. Designed for this application, but not yet implemented, is a pulsed metering device (Sadler et al., 2001; Camp et al., 2000b). The modified center pivots near Tifton, GA (Perry et al., 2002ab, 2003), use pulsed sprinklers in banks of two to four, similar to the Prosser designs. The other Aberdeen systems (King et al., 1999) and the Florence systems (Camp and Sadler, 1994) used multiple nozzles or multiple manifolds of nozzles. The multiple-nozzle system in Texas (Lyle and Bordovsky, 1981, 1983; Bordovsky and Lascano, 2003) used multiple orifice plates, individually controlled by solenoids and gathered into a drop tube, instead of separate nozzles.

The third, the variable-orifice method, is actually a combination of pulsing and variable-orifice size (King and Kincaid, 1996). In it, a solenoid-actuated pin is inserted and withdrawn from the nozzle orifice. When inserted, the area is reduced from the entire disk to the annulus around the pin, reducing the flow rate by 60%. Varying the frequency of the insertion–extraction cycle allows near-continuous control of flow rate from 100 to 40%. A separate solenoid turns the water flow completely off. These techniques need clean filtered water to prevent plugging problems.

Variable-Demand Water Supplies

Providing a water supply to a variable-rate irrigation machine requires some method to maintain a relatively constant pressure at the supply or the nozzles, or else the flow rate and wetted radius of the sprinklers will be affected by pressure variations as the aggregate flow rate varies when sections of the machine turn on or off. Achieving a sufficiently constant pressure can be done by variable-rate pump controls (Wall et al., 1996), by staged multiple pumps (Camp and Sadler, 1994), by system-level pressure regulators (Fraisse et al., 1992; Duke et al., 1992), or by having a sufficiently flat pump curve that the pressure variation does not adversely affect the sprinklers (King et al., 1995, 1996). Distributed pressure regulators at the nozzle or manifold level would simplify the demands on the water supply (Camp and Sadler, 1994). Gravity-pressurized pipelines, where excess water stays in the canal or reservoir when not needed, also work well in variable-demand situations. It has been proposed that bypass water could be used to supply solid set, drip, or subsurface drip irrigation systems in corners or other areas, perhaps in deficit irrigation mode, thus leveling the water demand. If done on a series of irrigation systems, this approach might be used to stage delivery with a similar dampening of fluctuations in demand.

Controls

The large number of solenoids employed in all of the above systems requires additional controls for irrigation systems. In some cases (Fraisse et al., 1992, Duke et al., 1992; Camp and Sadler, 1994; Harting, 1999; Bordovsky and Lascano, 2003), this was done by industrial programmable logic controllers in communication with a personal computer that held the prescribed application map. Wiring in these applications was typically extensive. In the other cases, the control system used a communication bus with addressable solenoids. This method reduces the amount of wiring, but requires addressable solenoids at the multiple nozzle or manifold control points. All of the above systems used general-purpose controllers or equipment custom built by the research group. The group in Georgia (Perry et al., 2002a, 2002b, 2003) worked with an industrial firm to provide a specific controller for variable-rate irrigation, with the intent to deliver commercially. Building a specific controller has the potential to reduce cost because the controller design can be simplified by removing excess capability and capacity needed in general-purpose controllers. Their system uses addressable solenoids on a bus to reduce wiring costs as well.

Position Determination

As with the general field of precision agriculture, locating position within the field is critical. The requirements for linear and pivot systems differ, but the trend is toward differential GPS (global positioning system) devices. Historically, shorter center pivots have used the pivot's built-in resolver, but even for short pivots, frequent calibration may be necessary, depending on the accuracy required (e.g., Sadler and Camp, 2002). For longer pivots, either the accumulated bend in the system across multiple joints between spans, or simply the resolver error magnified at the end, can require end-tower determination. This can be done with electronic compasses (Evans et al., 1996) or a GPS unit on the outer end tower (Evans and Harting, 1999). Corner systems can present some challenges when determining their position relative to the main lateral. On the other hand, linear systems, which travel nominally in one dimension but practically in two, require additional considerations. Newer linear-move systems follow buried wires using a long guidance antenna in the center of the machine, and a single GPS unit near this center point is usually sufficient. Older systems that wander laterally could still be handled by a single GPS unit, but systems that get out of line or have the capability to rotate at the end would benefit from having GPS units on both ends.

Nutrient Injection

In all cases where nutrient injection was done, it was achieved by injecting a liquid nutrient at a rate proportional to either the design or measured flow rate. This technique attempts to hold the nutrient concentration constant, so that variable nutrient application is achieved by varying the water applied in a minimal irrigation (Table 16–1).

Pesticide Application

In the only system with variable-rate pesticide application, some separate-path low-flow system was added to the irrigation machine. This essentially makes the moving machine a ground delivery rig, thus avoiding the problems that would accompany injecting pesticides into the water supply. Since fewer pesticides are

Table 16–1. Summary of characteristics of precision irrigation systems developed by different groups across the USA.

Location	Type, no.	Length (no. of spans) × travel (linear)	Control element size along boom, then along travel	Nozzle type (no. for multiple)	Wetted radius	Water supply method	Control type	Nutrient injection	Pesticides
Ft Collins, CO (Fraisse et al., 1992; Duke et al., 1992)	linear (1)	176 m (4) × 640 m	22 m × 53 m	pulsed	3.8 m	single turbine pump, pressure regulator	PLC†		
Aberdeen, ID (King et al., 1995)	linear (1)	100 m × 180 m	9.1 × 9.1 m, then 18.2 × 18.2 m	multiple (2) stepwise	9 m	single turbine pump	bus	yes	
Aberdeen, ID (King et al., 1995)	pivot (1)	210 m (7)	28.7 m × 5.6°	on/off	9.1 m	single turbine pump	bus		
Aberdeen, ID (King et al., 1996)	pivot (1)	354 m (9)	38.1 m × 6° (more for inner rings)	multiple (2) stepwise	9 m	single turbine pump	bus	yes	
Aberdeen, ID (Wall et al., 1996)	pivot (1)	392 m (10)	38 m × 1°	multiple (2) stepwise	10 m	variable-rate pump	bus	yes	
Florence, SC (Camp and Sadler, 1994)	pivot (2)	140 m (3)	9.1 m × 7.5° (no. 1), 4–16° (no. 2)	multiple (3) stepwise	2.5 m	multiple pumps	PLC	yes	
Prosser, WA (Evans et al., 1996a)	pivot (1)	390 m (8)	6–12 m × 0.5°	pulsed	9 m	pressurized system main line	RS-485 custom	yes	
Paterson, WA (Harting, 1999)	pivots (3 full, 3 part)	360 m (7)	12 m × 0.13° ctrl (GPS‡)	pulsed	9 m	pressurized system main line	PLC	yes	yes
Tifton, GA (Perry et al., 2002a, 2002b, 2003)	pivot (1)	173 m (3)	13.7 m × 2° (GPS)	pulsed	9.1 m	single turbine, regulator, electric	RS-485 Canlink3000	no	no
Tifton, GA (Perry et al., 2002a, 2002b, 2003)	pivot (1)	186 m (3)	10.9 m × 2° (GPS)	pulsed	15.2 m	single turbine, regulator, electric	RS-485 Canlink3000	no	no
Tifton, GA (Perry et al., 2002a, 2002b, 2003)	pivot (1)	303 m (5)	12.8 m × 2° (GPS)	pulsed	6.1 m	single turbine, regulator, diesel	RS-485 Canlink3000	no	no
Tifton, GA (Perry et al., 2002a, 2002b, 2003)	pivot (1)	429 m (last span plus gun)	11.0 m × 2° (GPS)	pulsed	12.2 m	centrifugal, electric	RS-485 Canlink3000	no	no
Tifton, GA (Perry et al., 2002a, 2002b, 2003)	pivot (1)	186 m (4)	12.2 m × 2° (GPS)	pulsed	8.5 m	centrifugal, regulator, electric	RS-485 Canlink3000	no	no
Tifton, GA (Perry et al., 2002a, 2002b, 2003)	pivot (1)	187 m (4)	10.7 m × 2° (GPS)	pulsed	9.1 m	pressurized system, regulator, electric	RS-485 Canlink3000	no	no
Lubbock, TX (Bordovsky and Lascano, 2003)	pivot (1)	410 m (last 4 spans)	16.1 m × 3°	multiple (3) stepwise		regulated valves at pumps	RS-485 PLC	yes	yes (testing)
Lubbock-Halfway, TX (Bordovsky and Lascano, 2003)	linear (1)	189 (5 spans)	18.3 × 18.3 m	multiple (3) stepwise		regulated valves at pump	PLC	no	no

† Programmable logic controller.

being labeled for direct injection, most future systems are expected to use this approach; however, it may also be possible to inject agrochemicals directly at the sprinkler head or other water application device and still be considered a ground application rig. A commercial irrigation manufacturer markets a separate low-flow system mounted on the center-pivot or linear-move truss support structures that has been modified to provide spatial control at the same resolution as the irrigation machine (LaRue, personal communication, 2002).

Sensors

Prior research on scheduling irrigation with infrared thermometers (IRTs) suggested that some form of spatial IRT-based irrigation control system would be useful. Wanjura et al. (1992) reported preliminary information and Upchurch et al. (personal communication, 1998) filed for a patent on an IRT-based irrigation control system. Evans et al. (2000a) and Sadler et al. (2002b) demonstrated that an array of inexpensive IRTs mounted on a center pivot could detect the canopy temperatures with sufficient accuracy to be considered as an irrigation control system in the humid Southeast. That environment, with highly variable irradiance caused by cumulus clouds, posed a substantial obstacle, however, so implementing IRTs into a control system under these conditions remains a research topic. Barnes et al. (2000) described an instrumentation package that moves on a rail mounted on a linear irrigation machine. This machine is run dry through the field, with the instruments traversing back and forth, collecting nadir views of canopy temperature, which are later interpolated to correct for the effect of the lateral movement of the sensors and the longitudinal movement of the irrigation machine.

The trend in sensor use is toward integrating multiple sensor systems (and probably computer-based water balance methods), to build on strengths and minimize individual sensor weaknesses. The extension of soil-based irrigation scheduling into the spatial domain simply requires distributed soil sensors (and limited micrometeorologic instrumentation to assist in pest management), plus some means to transmit and integrate the information into the irrigation machine control system. Preliminary research toward such systems is underway (Evans, personal communication, 2003; Pierce, personal communication, 2003). The per-unit cost of multiple-site distributed systems is a key design criterion for these systems.

Management

As in the general discipline of precision agriculture, the ability to control inputs on a spatial scale is ahead of the ability to recommend the input rates. While most site-specific recommendations are conversions of whole-field recommendations on a more spatially precise scale, there exist some questions about whether whole-field recommendations can be properly applied at scales other than those for which the data underlying the recommendations were collected (Hergert et al. [1997] for fertilizers; Sadler et al. [2002c] for water). Whole-field recommendations were derived from experiments in which blocking was used to account for spatial variation, and the results are typically both temporal and spatial averages. For the present, until more-resolved data are available that properly account for spatial resolution, most practitioners will continue to adapt whole-field management to site-specific uses.

A significant obstacle to adoption of any information-intensive technology is that most or all such technologies require substantial additional investment of time by operators. Recent workshops of researchers in these fields have emphasized the need to reduce, not increase, the time needed. Achieving this will require decision support systems that are paradoxically much more powerful and yet much easier to operate if they are to be adopted by busy growers and producers.

Economics

There have been very few economic analyses conducted of site-specific irrigation, for the simple reason that the spatial production data needed for them have not been available. The equipment, described above, needed to conduct research to produce these data has been available only recently. Before that availability, analyses such as Watkins et al. (1999) relied on experience or computer simulation. Economic analyses based on empirical data from the Florence site (Sadler et al., 2002c) have been conducted (Camp et al., 2002; Lu et al., 2003, 2004), but as with many early economic analyses, the results were mixed.

Ultimately, economic analyses will probably require consideration of many more terms in the optimization equation. For instance, policy might be written to require assessments for environmental effects related to leaching, runoff, or possibly greenhouse gas release, or to provide incentives for their prevention.

Results from Research Systems

The most complete information about spatial variation in crop response to irrigation comes from the Florence site (Sadler et al., 2002b, 2002c), which represents the highly variable soils and humid climate of the U.S. southeastern Coastal Plains. The information is presented as means within soil map units on a 1:1200 scale. Rigorous statistical analyses on a strictly spatial basis remain a matter of somewhat contentious debate in the scientific community. Preliminary results from full spatial analyses of these data (Sadler et al., 2002a; Camp et al., 2002) indicated that the spatial structure of the variation in canopy temperature and crop yield is not simply explained. The magnitude and the spatial extent of the variation observed were beyond expectations. In fact, expectations based on classical production functions were met only after averaging in both space and time for these data. This is perhaps reasonable, given that the classical production functions were developed as spatiotemporal averages; nonetheless, it brings into serious question whether classical production functions can be simply adapted to guide precision irrigation.

INTO THE UNKNOWN

Predicting very far into the future requires, paradoxically, either a very bold or a very cautious author. We fall squarely into the latter category. Nonetheless, an examination of some long-term global trends may provide a context for the reader to consider possible future directions for the irrigation industry. The main trends discussed so far that represent pressures on the water supply include a growing human population, an increasing contention for water, and increasing environmental awareness on the part of the population. In addition, there has been a continual, incremental improvement in motor efficiency, in solar conversion efficiency, and in integrated circuit and computer performance, which are technologies that are or can be exploited to improve irrigation equipment. Perhaps a breakthrough in hydrogen fuel cells could render the power requirement affordable for pumping or even desalinization.

There is a trend toward warming of the earth, which would appear to make irrigation more critical, and could possibly shift its use toward regions historically unirrigated. If rainfall patterns become more variable, or shift regionally, irrigation would probably be impacted, but predicting exactly how would be beyond the scope of this chapter. If widespread instances of famine, bioterrorism, or political chaos cause a precipitous drop in world or even regional food supplies, altered economics of food production might impact irrigation, or require increased irrigation to offset the shortages.

One outcome of such dramatic impacts on world food production could be a major shift in the cost of food as a portion of income, e.g., food scarcity causes food prices to drastically increase. Another could be a shift to controlled-environment food production, i.e., greenhouses. The first could severely impact the economics of irrigation, and the latter could impact the type of irrigation equipment as well as food prices and production costs. Which, if any, of these scenarios might occur, and their ultimate consequences, will certainly be up for debate.

CONCLUSIONS

Irrigation in the future will be dominated by increasing pressure on diminishing water supplies, with local short-term decisions diverting water to uses deemed by society to be higher in value than irrigation. Concurrently, increasing public pressure on water quality will interact with pressure for conservation to increase the demand for higher postirrigation water quality. If these two pressures can be demonstrably addressed using precision irrigation, there would appear to be potential for both irrigation and for precision irrigation.

Variable-rate applications and other precision farming technologies have been used to help reduce leaching of agrochemicals from certain areas of a field by applying lower rates in those locations; however, because of the complexity and interrelationships of crop, soil, climatic, and other factors, as well as the different management capabilities of producers, there is not a single correct answer about whether adopting precision farming makes good economic sense (Lark and Stafford, 1996; Sudduth et al., 1996). Likewise, there is little information examining the environmental implications and benefits of adopting various site-specific precision farming practices (Evans et al., 1995; Mallawatantri and Mulla, 1996; Mulla et al., 1996; Omary et al., 1997; Bruckler et al., 1997; Morton, 1998). Therefore, basic research on crop- and soil-specific precision farming technologies in addition to precision irrigation practices are needed to validate the procedures as being effective in maintaining crop quantity and quality, as well as reducing chemical contaminants entering the regional hydrologic system.

Advanced technologies, such as precision irrigation, site-specific management, remote sensing, within-field real-time sensor systems, and decision support systems collectively have great potential to facilitate the reduction of water quantity and quality problems in irrigated agriculture. The use of real-time irrigation scheduling techniques (sensor based) and precision applications of water through center-pivot machines is the next step in the evolution of this technology. This should both result in substantial labor, water, and energy savings and minimize losses to groundwater. These savings and potential environmental benefits accrue both to the irrigation manager and, ultimately, the general populace. In the future, both groups will probably perceive these benefits as increasingly critical.

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