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Review

Agronomic Basis and Strategies for Precision Water Management: A Review

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Abstract: Agriculture faces the challenge of feeding a growing population with limited or depleting fresh water resources. Advances in irrigation systems and technologies allow site-specific application of irrigation water within the field to improve water use efficiency or reduce water usage for sustainable crop production, especially in arid and semi-arid regions. This paper discusses recent development of variable-rate irrigation (VRI) technologies, data and information for VRI application, and impacts of VRI, including profitability using this technology, with a focus on agronomic factors in precision water management. The development in sprinkler systems enabled irrigation application with greater precision at the scale of individual nozzle control. Further research is required to evaluate VRI prescription maps integrating different soil and crop characteristics in different environments. On-farm trials and whole-field studies are needed to provide support information for practical VRI applications. Future research also needs to address the adjustment of the spatial distribution of prescription zones in response to temporal variability in soil water status and crop growing conditions, which can be evaluated by incorporating remote and proximal sensing data. Comprehensive decision support tools are required to help the user decide where to apply how much irrigation water at different crop growth stages to optimize water use and crop production based on the regional climate conditions and cropping systems.

Keywords: variable-rate irrigation; precision agriculture; irrigation scheduling

1. Introduction

Agriculture is the largest consumer of the world′s available fresh water, as plant growth largely depends on the availability of water. According to the Food and Agriculture Organization (FAO), current world irrigated area is approximately 300 million ha, and projection to 2050 suggests growing scarcities of water resources for agriculture, although water is a renewable resource. This situation has amplified the intensity of global food insecurity, climate change, and poverty. The greatest challenge to agriculture is to provide food and fiber for almost 8 billion people around the world in the advent of depleting freshwater resources [1].

The challenge is more prominent in the arid and semi-arid regions, where underground water sources, especially aquifers are used for irrigation, as rainfall provides only a portion of the total requirement for crop evapotranspiration (ET) demand [2]. Heavy irrigation has caused rapid depletion of many aquifers. For instance, comparing the water level of the Ogallala aquifer in the 1950s to that of 2013, in some wells, up to 78 m of water was depleted in the Texas High Plains area [3]. This is almost 12 times the average decline of 4.5 m for the whole area of the aquifer. Given this depletion rate, scientists have predicted that 35% of the Southern High Plains will not be able to support irrigation in 30 years. Many other water resources in the world are depleting rapidly in recent years with negligible recharge, indicating the need for water conservation solutions in agriculture [4,5]. More effective and efficient management of water is required to better conserve water and improve water use efficiency for sustainable crop production.

Conventional farming practices manage an agricultural field uniformly without incorporating the intrinsic variability in topography, soil, crop growth conditions, and other agronomic factors. This can result in nutrient leaching, environmental contamination, and reduced profitability especially when applying high inputs in low yielding areas and vice versa [6,7]. Precision agriculture can be adopted to divide the field into small management units for optimized production [8]. There are several definitions for precision agriculture, and it keeps evolving with emerging technologies and understanding of what is achievable [9]. The idea of precision agriculture or site-specific management started around the early 1980s with the development of various technologies to assess field variabilities such as soil survey, soil testing and mapping, and crop yield monitoring [10–13]. Precision agriculture depends on detailed spatial information, information technology, greater information processing capability, and better decision aids [14]. Precision agriculture is a management system that measures and responds to the spatial and temporal variability of soil and crop growth at the sub-field level with the aim to enhance profitability and reduce environmental impact [15,16]. Major technologies involved in precision agriculture include geographic information systems (GIS), remote and proximal sensing, Global Navigation Satellite System (GNSS), yield monitoring and the variable rate technology. Georeferenced information about soil and plant characteristics can be obtained efficiently using GIS, proximal sensors and remote sensors [17]. Application of yield monitors provides the capability to precisely characterize yield variability at large scales in the field. Moreover, the variable rate technology provides the ability to site-specifically apply irrigation water in the field to achieve potential water savings [18]. This enables the timely and accurate water application incorporating the spatial and temporal soil properties and plant demand at different growth stages [15]. In other words, the variable rate irrigation (VRI) technology can help to apply the right amount of water in the right area of the field at the right time resulting in water savings.

Recent research suggests site-specific management of water or VRI could be a solution to conserve water and improve water use efficiency (WUE), which is the ratio between effective water use and actual water withdrawal in the field [19]. VRI can support water and energy conservation with a positive influence on crop water productivity and the environment [20]. This is possible by applying irrigation at rates that vary to appropriately match field variability based on specific water needs of individual management zones rather than applying a uniform rate throughout the field [21]. The magnitude of soil water content (SWC) varies with time and location, but the pattern of spatial variability usually remains similar. This temporal stability of SWC is associated with properties of the field such as topography, soil texture, apparent soil electrical conductivity (EC_a) and drainage patterns that insignificantly change over time [22,23]. The feasibility and effectiveness of VRI depend on the size of the field, crop species under consideration, weather, and the underlying field properties such as elevation, slope, soil texture, and EC_a that influence soil moisture content and irrigation requirements for the crop [24,25]. Hence, understanding the influence of agronomic factors such as topography and soil properties on soil water and ultimately yield can provide a basis for application of VRI in the field to achieve potential water savings together with yield optimization.

Today, site-specific water management has been made easier with several precision agriculture tools, such as GNSS, GIS, yield mapping, soil survey and remote sensing [26]. Several decision support tools and strategies to reduce groundwater withdrawal without reductions in irrigated land area or crop productivity have been developed [4]. The measures to optimize the use of irrigation water in the fields include increasing weather-based irrigation scheduling, converting gravity-based irrigation to center pivot irrigation, subsurface drip irrigation, replacing high water to low water demand crops, and deficit irrigation based on evapotranspiration replacement using various water-balance models [27]. Several studies have been done to understand the possible water savings with VRI. A review on VRI across different crop and weather regimes of the world concluded that VRI could save 10%–15% of water [28]. Although the use of VRI seems to be a reasonable measure to improve water management, many producers are reluctant to adopt it because limited research is done at the field scale to understand its reliability and economic potential [25]. A better understanding of field variability and how it affects crop yield is needed for effective implementation of the new technologies. A review for site-specific sprinkler irrigation [29] focused on the technology and challenges for adoption. Another review of 20 years' research on increasing crop productivity with sprinkler and micro-irrigation discussed the importance of understanding the crop response to VRI [30]. The study emphasized the need for continuous effort towards management zone delineation based on field properties integrated with dynamic information from real-time monitoring of climatological and crop data. However, this study focused more on the technological aspect of irrigation management than the agronomic aspect of water conservation with VRI. The agricultural science behind VRI is equally crucial for the successful implementation of this technology. Hence, the objective of this paper is to review the scientific background and technologies in precision water management, with the focus on agronomic factors and strategies for site-specific water management.

2. Variable-Rate Irrigation Technologies

The irrigation system changed from gravity-based furrow irrigation in the 1950s to sprinkler irrigation in late 1990s. Initially, the high-pressure sprinkler irrigation system was available in the 1980s which later developed to low-pressure sprinklers and low-energy precision application (LEPA) in 1990s [31–33]. About 49% of total irrigated land in the United States is irrigated with center pivot systems, out of which 44% is irrigated at low pressure under 30 psi [34]. The basic requirements for the VRI technology are sensors and spatial information, prescription maps and a system to incorporate VRI prescription (e.g., LEPA, lateral irrigation, etc.) to apply in the field [35]. At present, there are several irrigation technologies for conservation irrigation, such as sprinkler, drip, and other micro-irrigation systems but limited site-specific studies have been done [30,36–38]. For example, a study of the variable-rate drip irrigation system on vineyard found up to 17% increase in yield and a 20% decrease in water consumption compared to uniform irrigation [39]. Researchers in the UK assessed the potential of hose-reel boom irrigators for precision irrigation in vegetables [40]. Automatic gravity-fed irrigation systems in Europe decreased manual labor and supported adoption by innovative farmers [41]. Variable-rate irrigation using center pivot in rice showed better performance compared to uniform flooding irrigation [42]. In this review, we will focus more on those irrigation technologies that have been used for site-specific water management more frequently around the world, such as variable-rate lateral irrigation systems and center pivot irrigation systems.

The components of a variable-rate lateral irrigation system commonly consist of a GPS or GNSS receiver, custom software-controlled relays and valves, which can apply variable water utilizing the nozzle-pulsing technique and a variable speed control system. This system can control the irrigation rate and forward speed with high accuracy [43]. Similarly, the components of a center pivot VRI system include a pivot control panel, a VRI control panel, solenoid valves, control nodes, a GNSS system, a variable frequency drive and a remote-control system [21]. The pivot control regulates the operation and speed of the pivot, while the VRI control panel regulates the irrigation application rate in response to the prescription map and the pivot location. Solenoid valves regulate the flow of sprinkler heads. The GNSS system at the end of the center pivot provides the pivot position. The control nodes along the length of the pivot determine when the valves are open or close. The variable frequency drive (VFD) helps to regulate the pressure while instantaneously changing the rate of irrigation at different positions of the field. The VFD controls the rotation speed of the pump impeller by receiving the input from a pressure switch installed on the pump outlet pipe. This keeps water pressure stable within preset maximum and minimum thresholds and thus saving water and energy. The remote control system allows to view and control the center pivot and the pump from a distance via a smartphone or a computer using the internet [21]. Further, research and development are striving to control irrigation amount with VRI controllers using real-time information from plant and soil sensors in the field [44].

Currently, several companies work on the manufacture and application of this technology. The commercially available VRI control resolution varies with the manufacturers. VRI systems can apply zero water to specific nozzles and as much as 200% of the standard application rate to other nozzles by opening or closing individual nozzles and by changing the speed of the pivot [45]. Some companies provide the ability to control zones of sprinklers, while others can control each sprinkler independently [46]. For example, Valley (Valley, Valmont Irrigation, Valley, NE, USA) provides variable speed control and variable zone control technologies for site-specific water application. The variable speed control system uses an advanced control panel that can slow down or speed up the pivot to vary water input in different areas (sectors) of the field, but the overall pivot flow rate remains constant. This system does not need additional hardware on the existing pivot irrigation system. The variable zone control system can vary the speed of the center and change the application rate along the pivot lateral. This system applies different irrigation depths to different areas of the field by turning sprinklers on and off for various amounts of time. Trimble (Trimble Navigation, Sunnyvale, CA, USA) has developed the Irrigate-IQ Variable-Rate Irrigation System. This system incorporates the VFD and variable speed drive (VSD) into the recent optimal flow VRI that works with standard pump equipment on wells with limited capacity. This system is capable of individual nozzle control, which can apply the right amount of water in the right place more accurately [47]. Currently, it is possible to achieve sector control with very small resolution, and zone control can add irrigation zones further to the sector at the small scales of lateral spans (Figure 1) [48]. A study conducted in Canada to evaluate the performance of VRI found that the accuracy of water application was up to 90% in the center pivot system [49]. However, the performance of these irrigation systems in field applications is affected by many factors, such as field attributes, the spatial resolution of the sensors used in irrigation management and temporal resolution of data inputs, as well as unexpected environmental conditions. Hence, adaptive irrigation management strategies and active research support are required to enhance the adoption and application of VRI [20,50].

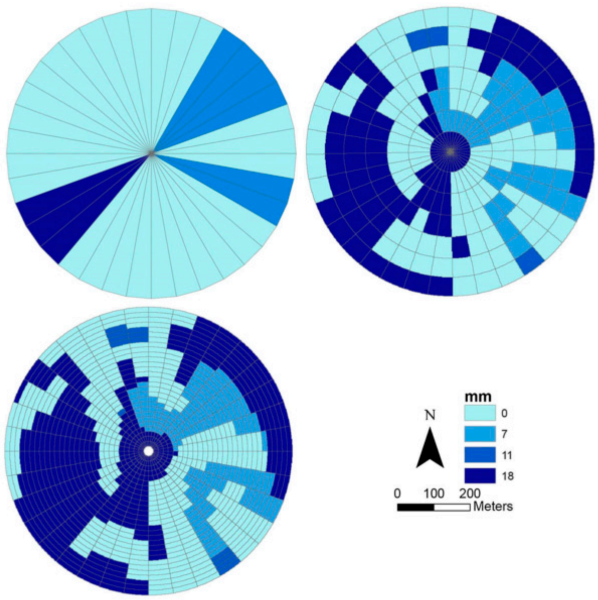

Figure 1. Prescription maps with different control scenarios for four irrigation depths ([48], reproduced with permission from Springer Nature).

3. Topographic and Soil Factors in Precision Water Management

An essential prerequisite for site-specific irrigation is the understanding of the spatial and temporal variability of soil properties and crop growth conditions that affect water availability, water requirement, water use efficiency, crop growth, and crop yield. Topography and soil properties are important factors that influence water availability for crop growth. The variability of soil and topographic properties combined can explain 28% to 85% of yield variability [51]. Hence, it is critical to quantify the variability of terrain attributes and soil properties for VRI applications.

3.1. Topography

Topographic variation is a common characteristic of large agricultural fields that result in spatial variability of soil water and ultimately crop yield [52]. Topography or terrain has two types of attributes, primary and secondary attributes [53]. Primary attributes include elevation, slope, aspect, curvature, flow length, and upslope contributing area. Secondary attributes are derived empirically from several primary attributes to characterize specific processes manifesting in the landscape, mainly including sediment transport index (STI), stream power index (SPI), flow direction, flow accumulation, distance to flow accumulation lines (DFL), and wetness index [53,54]. Topographic properties affect soil physical and chemical properties such as texture (sand, silt, and clay content), pH, $CaCO_3$, extractable Ca and Mg, available K, base saturation, organic matter, and cation exchange capacity (CEC). Topography also influences hydrologic properties and processes and can account for up to 50% of water availability differences in the same field [52]. Elevation, slope and surface curvatures directly affect infiltration and runoff as they influence the surface and subsurface flow of water in the field [55,56]. This can have a significant effect on crop growth and yield, resulting in differences in crop production of up to 69% at different positions in the field [57–59].

A study conducted in central Illinois and eastern Indiana showed that topography alone could explain about 20% of yield variability [60]. Corn yield variability was consistently correlated with elevation and slope in a three-year study in Southern Portugal [53]. This study showed that topographic indices, such as distance to flow accumulation lines (DFL), were negatively correlated with yield, hence could be used to evaluate spatial yield variability. A research conducted on a 7.4-ha field in the Southern High Plains of Texas showed cotton lint yield was negatively correlated with site elevation. The lint yield and nitrogen (N) uptake was higher in bottom slope positions than in upslope, possibly due to the accumulation of run-off water and NO_3-N eroded from the upper slope areas. However, this trend depended on weather conditions. For a wet year when there was over accumulation of water in bottom slopes, lower yield in bottom slopes and higher yield in upper slopes were observed [61]. Relative elevation explained up to 49% of water content variation in the soil and 32% of lint yield variation in the field. The negative correlation between crop yield and elevation could be in part due to the effect of erosion and topographical attributes on soil properties that influence infiltration and storage of water. Slope length also affects crop yield by influencing N denitrification, soil N, P, K, Ca and Mg distributions, soil carbon storage, and nitrate distribution, as well as the infiltration rate of water in the field [62].

The curvature of the field surface determines the concentration or dispersion of surface water in the field [55]. Concave surface with negative curvatures concentrates water flow, while convex surface with positive curvature disperses water flow [63]. For example, SWC was found strongly correlated with soil surface curvature ($r = 0.9$) [64]. Soil surface curvature can explain up to 15% of variations in the crop yield [65]. Corn yield was negatively correlated with surface curvature in another research [53]. In this study, corn yield was 14% higher in concave curvatures than convex areas. In a six-year study [55], corn yields were negatively correlated with elevation, slope, planar curvature and profile curvature for the wet years. The impact of surface curvature on crop yield also depends on weather conditions and the location to some extent. Weather factors have the largest effect on grain yield at locations with large curvature values. In some cases, surface curvature is positively related to crop yield at locations or years with higher precipitation [60]. The magnitude of curvature also has an impact on crop yield. The effect of curvature on crop yield between wet and dry years are highly different at locations with small curvature [66]. Hence, understanding and incorporating topographic attributes of the field, such as elevation, slope length and aspect, surface curvature and their influence on water dynamics can be an important input for site-specific water management to achieve potential water savings and optimized production.

3.2. Soil Properties

Soil functions as a medium for plant growth, a regulator of water flow and nutrient cycling. It is a dynamic entity where complex interactions occur among its physical, chemical and biological properties to enable these functions [67]. Soil forming factors such as parent material, biota, topography, climate, and time are variable in time and space and explain most of the soil variability besides the management induced variability [11]. Spatial variability of chemical properties including nutrients, organic matter, and pH can result in within-field variation in available water content and crop productivity [68]. Complex spatial patterns of soil physical properties also affect soil water availability and rooting of a plant, resulting in variability in crop growth and yield [69]. Soil texture, organic matter content, apparent electrical conductivity, and biological properties are relatively stable properties of the field that are usually considered for site-specific management of the field.

3.2.1. Soil Texture

Soil texture, the relative content of sand, silt, and clay particles, is an important soil physical property that affects crop growth and yield. Soil texture determines the rate at which water drains through saturated soil and influences available water-holding capacity. Therefore, it affects the distribution of available water for plant growth and irrigation requirements in the field. Fine sandy loams and silts tend to have the highest water-holding capacity, while an increase in either clay or sand content in the soil profile decreases the water-holding capacity [70]. The matric potential of soil, which depends on soil particle size, influences the availability of soil water. For example, clay particles have higher matric potential and lower soil available water compared to sand and silt particles [71]. Soil texture also affects the spatial variability of residual NO_3-N and the leaching of N. More residual was found in sandy loam soils compared to loamy sand, and leaching was higher in loamy sand compared to sandy loam [72]. Soil texture also affects the pore sizes and porosity of the soil, which ultimately affects crop root growth and yield by limiting the water available to the plant and the growth space for the roots [73]. In general, soils with high clay content are more difficult to manage due to lack of porosity and water available for plant growth. On the other hand, well-drained soils have good soil aeration for healthy root and crop growth [74]. The clay content can also influence soil water and nutrient content and result in crop yield variability across the field [61,75]. A study showed that clay content in the soil could explain up to 17% variability in winter wheat yield by affecting the water available in the soil for crop growth [76]. A study conducted in the Southern High Plains showed that a very sandy soil (the Brownfield soil series) with high slope consistently had low yield when given the same amount of irrigation water, fertilizer, seed population, and other management practices [56]. A cross-correlation study conducted between cotton lint yield, soil water, clay, sand and elevation in a 45-ha field in Texas High Plains also showed that correlation among these factors varied between 0.72 and 0.63 and cotton crop and soil physical properties could be correlated within 60 to 80 m across the field [77]. In summary, soil texture influences variability in water availability and crop yield, and hence should be considered in VRI planning and implementation [78].

3.2.2. Soil Organic Matter (SOM)

The role of SOM in VRI lies in its influence on water-holding capacity because the affinity SOM has for water [74]. SOM has a positive influence on yield, and the influence is more prominent in soils with low organic matter content [60]. SOM distribution in the field is variable depending upon topography and other soil properties. Accumulation of SOM often occurs at the bottom of slopes, possibly due to the run-off of organic matter from higher areas and increased plant growth at low-lying wet areas of the field [60,61]. SOM generally increases with increasing clay content. The organic matter in fine-textured soils such as clay can be two to four times that of coarse-textured sandy soils under similar climatic conditions, which in turn, can influence soil water holding capacity [79]. Therefore, understanding the organic matter distribution in the field can help in estimation of irrigation requirements for the field and hence should be incorporated in developing site-specific water management.

3.2.3. Soil Biological Properties

Most site-specific studies did not consider spatial variability of soil organisms, but recent studies have shown that the spatial distribution of soil organisms influence plant growth and possibly yield [80]. Spatial and temporal distribution of microorganisms at the landscape scale is complicated by the interactions among topography, soil type and distribution of water in the field [81]. The management activity in the field can influence the distribution of soil biological components and this, in turn, affects the efficiency of agricultural management [82]. The soil has the greatest microbial diversity among all ecosystems that support soil conditioning and plant growth [83]. A study conducted in France [84] showed that microbial indicators expressed a high spatial heterogeneity at the field level, which masked the effects of several soil and crop management treatments. The results also showed that the spatial variability due to biological variables was similar in magnitude as compared to that exhibited by physicochemical parameters, which indicated the feasibility of site-specific management of biological variability in the field using management zones. Such site-specific management can be effective since organisms such as earthworms, protozoa, nematodes, bacteria, fungi, and different arthropods play a vital role in soil fertility and productivity [71].

3.2.4. Apparent Soil Electrical Conductivity (EC_a)

Obtaining accurate information about the spatial and temporal variability of SWC and irrigation requirements is one of the important challenges in site-specific water management. EC_a is a measurement of field variability that can be applied to precise water management because it is easy to measure and facilitates the spatial understanding of the soil-water-plant relationship [85]. EC_a is a function of several soil properties, such as soil salinity, texture, bulk density, ion concentration, type and amount of clay, topsoil thickness, and water content [86]. The effect of EC_a on crop yield is through its relation to soil properties, which depends on climate, crop type and other specific field conditions [87]. In general, high EC_a is associated with high clay content in the soil [88]. For example, a study conducted near Lamesa, Texas, showed that in four of the six sites, shallow EC_a measured with a Veris mapping system was positively correlated with clay content. Clay content was negatively related to shallow EC_a at one site due to the low bulk density of the calcic horizon [89]. Most of the research conducted did not consider the spatial correlation of soil characteristics when evaluating their distributions. However, spatial autocorrelation of soil properties can be more important than soil properties themselves in explaining EC_a. Therefore, future studies need to incorporate the spatial correlation of soil characteristics in evaluating the impact of EC_a on crop yield [90]. EC_a has the potential to differentiate between soils when the soils have enough water content and can be used as an indicator of SWC. In general, areas with high EC_a are associated with high water content [91]. Several studies have shown a higher correlation of crop growth characteristics and yield with EC_a [92,93]. A study showed that EC_a in combination with topographic attributes and bare soil brightness could explain up to 70.1% of the variability in cotton yield [56]. Hence, understanding the spatial and temporal variability of EC_a provides information for site-specific irrigation management for optimized yield.

The association between crop yield and soil physical and chemical properties and landscape processes provide opportunities to improve water management at the landscape scale [61]. Soil properties and topography influence crop yield from microscales to watershed scales and the magnitude of complexity increases with the scale due to an increase in soil and topographical variability, as well as variability in rainfall, temperature and other climatic factors [60]. A study showed lower corn grain and stover yield in depositional and flat areas which retained water for longer periods, and high yield at well-drained summit positions [94]. In the same research for alfalfa and poplar, the results showed higher productivity at a site with a relatively steep slope and potentially erosive soils. This relationship was attributed to the above-normal rainfall in both years of study. In a six-year study to understand corn yield in relation to terrain attributes, two years with more than normal precipitation showed a positive correlation between yield and slope. For the other four years, yield was negatively correlated with slope [55]. Crop yield in relation to soil properties and topography depends on different soil management and climate conditions. The correlation was found to be stronger for dry years in degraded soils and attributed to differences in water availability. This suggests that variable-rate irrigation strategies might require adjustments in different crop seasons with different climatic and management conditions and hence more researches on VRI are needed [95].

4. Crop and Soil Monitoring for Precision Water Management

Water requirement varies with the crop and crop growth and development status, soil water status, as well as environmental conditions. Closely monitoring soil water status, crop growth conditions and their spatial and temporal patterns can aid in irrigation scheduling and precise water management. Among many tools, remote sensing can serve an effective basis by providing images with spatial and temporal variability of crop growth parameters and soil moisture status for input in precision water management.

4.1. Crop Coefficient and ET

VRI aims at increasing WUE and stabilizing yield, which can be improved by scheduling the irrigation of crops using physical and agronomic principles in irrigation management strategy. WUE (kg/m^3) can be expressed as the ratio of the amount of target product of the crop to the amount of water applied to produce that output. The amount of water used for crop production is the amount required to overcome the water lost by ET from plant and soil surface, and it varies spatiotemporally according to weather and vegetation cover conditions [96,97]. Climatological parameters such as solar radiation, air temperature, air humidity, wind speed, and crop and soil water characteristics, including management and environmental aspects, are important parameters influencing ET in agricultural fields. Since ET is difficult to measure, reference ET from a hypothetical grass reference surface is commonly calculated using the FAO Penman-Monteith equation based on meteorological parameters [98]. The equation is expressed as follows,

$$ET_0 = [0.408\ \Delta\ (R_n - G) + \gamma\ \{900/(T + 273)\}\ u_2\ (e_s - e_a)]/[\Delta + \gamma\ (1 + 0.34\ u_2)]$$

where, ET_0—Reference evapotranspiration [mm day^{-1}], R_n—Net radiation at the crop surface [MJ m^{-2} day^{-1}], G—Soil heat flux density [MJ m^{-2} day^{-1}], T—Air temperature at 2 m height [°C], u_2—Wind speed at 2 m height [m s^{-1}], e_s—Saturation vapor pressure [kPa], e_a—Actual vapor pressure [kPa], e_s—e_a saturation vapor pressure deficit [kPa], D—Slope vapor pressure curve [kPa $°C^{-1}$], γ—Psychrometric constant [kPa $°C^{-1}$].

Crop-specific evapotranspiration needs are calculated based on crop coefficients (K_c). By using the FAO Penman-Monteith definition for ET_0, crop coefficients at research sites could be calculated by relating the measured crop evapotranspiration (ET) with the calculated ET_0, i.e., $K_c = ET/ET_0$. The crop coefficient differs widely between crops and among growth stages for the same crop. This K_c factor serves as an aggregation of the physical and physiological differences among crops and averaged effects of evaporation from the soil [98]. Several spatial models have been developed for ET estimation, which showed that accurate spatial ET and water-balance models could be of great importance in VRI application [61,99,100].

4.2. Remote and Proximal Sensing

Besides crop coefficient and ET, mapping soil properties in a field, such as field capacity and root zone water availability, is also important for site-specific water management [101]. Information regarding variability of plant conditions such as water stress, growth parameters, ground cover can also provide a basis for VRI. Remote sensing using various sensors and platforms is often used to estimate several soil and crop characteristics during the growing season that can provide important information in decision support. The near-real-time information from several sensors, such as spectral reflectance sensors and infrared thermometers have been used to develop field maps for water, vegetation, and nutrient status [50,102]. Remotely sensed images can be useful in determining leaf area index and ground cover for a field and thus help in yield forecasting [103]. Remote sensing can also help estimate ET more reliably from individual fields [104]. A study in Nebraska evaluated remote-sensing-based ET and a water-balance model for irrigation management [105]. In this study, four irrigation treatment combinations were tested: VRI based on water-balance model using remote sensing, VRI based on water-balance model using neutron probe, uniform irrigation based on neutron-probe measurement and rainfed. Landsat 7 and 8 imageries were used for model input in a remote sensing-based model, which included reflectance-based crop coefficients for ET estimation. The result showed that remote sensing-based treatment had the greatest mean prescribed irrigation, which was attributed to water-balance drift. The study concluded that the remote-sensing-based model might perform better when coupled with SWC measurement. This can be helpful in site-specific management of irrigation water, as well as weedicide, pesticide and other chemicals [106–108]. Various indices derived from thermal and multispectral images, such as crop water stress index (CWSI), perpendicular vegetation index (PVI), normalized difference vegetation index (NDVI) and photochemical reflectance index (PRI), can predict soil or plant water status and drought stress as a basis for site-specific water management [109,110]. Use of digital infrared thermography to measure canopy temperature can help producers to detect early crop water stress and avoid yield declines as well as saving water with site-specific irrigation management and irrigation scheduling [111,112]. Recent improvements in remote and proximal sensing technologies such as wireless soil moisture sensors and unmanned aerial systems (UAS) have increased the efficiency for farmers to exercise site-specific irrigation management. Indices derived from high-resolution UAS imagery have shown the potential to predict crop water stress indicators such as water potential and stomatal conductance [113]. Such information can aid in improving irrigation efficiency, reducing pumping costs, and retaining groundwater. Although soil moisture sensors are found to be more profitable in the present context, with the increasing number of manufacturers and clear regulations, UAS-based sensor technology for soil moisture estimation is gaining momentum [114]. This explains the importance of remote sensing as a low-cost tool to improve water management in crops.

5. Precision Water Management Strategies

Several precision irrigation technologies have been developed to improve crop productivity under water-limited conditions. However, appropriate precision irrigation strategies are equally important for increased efficiency and profitability for site-specific technologies. The development and application of management zones using spatial and temporal information of various agronomic factors have been practiced for site-specific management for several decades. In recent years, the use of artificial intelligence in prescription map development for site-specific water management is also increasing.

5.1. Management Zones

VRI is often implemented in the field by dividing it into a number of sections, or management zones with the aim to save water and other inputs together with yield optimization [25]. A management zone is a subfield area that is relatively homogeneous in soil and topographic attributes. The use of management zones can be a convenient means to capture the spatial distribution of yield-influencing factors within the season. The information on spatial and temporal development of abiotic and biotic stresses can be linked with site-specific irrigation systems via dynamic prescription maps to help producers improve irrigation WUE, agricultural sustainability and the environment [102]. Various factors such as soil properties, landscape attributes, crop properties, sensor-based information, management practice, weed, and pest management as well as crop modeling have been considered in delineating management zones for VRI application since several years [115]. Soil properties such as soil organic matter, texture, nutrient content, pH, color, soil moisture content and water-holding capacities, EC_a, etc. have been used effectively in management zone delineation [116–119]. Landscape attributes such as elevation, slope, aspect, curvature, and others have also been an important part of management zone delineation in several studies [118,120–122]. Numerous studies have used crop properties such as yield maps and ground-based leaf area index to delineate management zones for VRI application [116,117,123,124]. The management zones delineated based on yield data from multiple years can effectively capture nutrient variability in the field [125]. However, the application of yield maps for site-specific management can be challenging because spatial and temporal variation in yield is affected by the interactions among several biotic and abiotic factors [126,127]. Information from proximal and remote sensing such as satellite and airborne imagery, normalized difference vegetation index, digital photography, etc. can be a powerful approach for delineation of relative productive areas [128–131]. The zone information together with early season environmental indicators and crop response models can also be used to determine the action decisions throughout the season [132]. Similarly, the selection of factors for management zone delineation is equally important in management zone delineation. A study was conducted to compare the site-specific irrigation with conventional uniform irrigation management for potatoes in Idaho [25]. The available water-holding capacity of soil was used to delineate a 2.9-ha field into nine management zones. The results showed that six out of nine management zones produced a higher yield with site-specific management. However, the study suggested that management zones were only based on available SWC and in some management cases, other non-measured factors unrelated to soil texture or available water content could have an impact on the yield of crops. The study pointed out the importance to take into consideration all the known factors affecting yield and include them in delineating irrigation management zones for site-specific irrigation management. The optimum number of zones for a field depends on the scale of the field, economical and logistical practicality, and agronomic response to irrigation amounts. For example, the quantity and placement of soil moisture sensors for determining irrigation amounts may vary with field size, cost of the sensors and manageability, which, in turn, can influence the number of management zones in the field [133].

There are several methods to delineate management zones, including unsupervised clustering, supervised clustering, user-defined thresholds, etc. The clustering technique groups similar data points into different classes using algorithms such as k-means, fuzzy k-means, fuzzy c-means [127,134], Ward′s method, and Jenk's optimization procedure [125]. The appropriate factors to be considered for management zone delineation could be prioritized using several methods such as principal component analysis (PCA) [118]. It is equally important to determine the number of optimum management zones for the field and their production and economic justification [20]. A software program (MZA software [135]) was developed for creating management zones using the fuzzy k-means method. This program determines the appropriate number of zones for a field by evaluating the clustering results. Many studies have used management zones for VRI and other site-specific crop management. For example, a study conducted in a 4.8-ha field in Colorado assessed the effectiveness of EC_a in characterizing the spatial distribution of soil water [136]. This study found that SWC was significantly different among different EC_a derived management zones using MZA software. This justifies the importance of characterizing management zones for site-specific water management.

5.2. Development of Site-Specific Water Management Strategies

To enable the VRI technology in practice, the irrigation management strategy is equally important. The use of technology in the field may not always be effective in terms of final yield or profitability. For example, research has shown that the use of VRI technology may not be cost effective where there is high rainfall throughout the growing season [29]. Several strategies could be applied to save water and energy in the field to gain yield benefits in the field. Some of the strategies include skipping irritation in non-cropped areas, planting different crops in the same field, rainfall harvesting in areas with high water-holding capacity, and lowering irrigation to areas with low water use (ET) [46]. New irrigation strategies such as modifying the current irrigation system for site-specific water and chemical applications are required to sustain modern irrigated agricultural cropping systems [102].

Management strategies including placement and timing are crucial in optimizing irrigation throughout the growing season. About 9%−19% of irrigation water savings were achieved with VRI compared to the uniform application in a research conducted in variable soil, which was possible with several strategies such as withholding irrigation during specific growth stages and in particular, non-cropped areas of the field [137]. Further, the study suggests that areas where the optimized or increased irrigation does not produce an increase in yield, less water can be applied while the areas with high yield potential can be applied optimum irrigation and gain higher returns. A study showed that restricting irrigation during the peak water-demand time of cotton (80−100 days after planting) from 100% to 60% of potential ET conserves 2.6 inches of water [138]. The VRI trial was conducted in three farms in New Zealand to compare the VRI to uniform rate irrigation (URI) [139]. The URI treatments were provided with the same level of irrigation at the same time as the most drought-prone soil zone, but VRI treatment was achieved by either delaying the irrigation or reducing the amount and intensity of irrigation comparing to that with a drought-prone area. The results showed that there was a two to three-fold difference in total available water-holding capacity at each site, which justified the decision to use VRI systems. Although the study found no significant impact of VRI on crop yield, water savings of 8 to 36% were achieved in three sites with less drainage. Hence, critical management strategies adopted in a decision support system that uses real-time monitoring and feedback to irrigation control make water conversation possible [28]. Deficit irrigation (DI) is a complementary method that uses irrigation scheduling at strategic times of less critical growth for irrigation water conservation. In this method, irrigation is applied during the drought-sensitive growth stages of a crop. During less drought-sensitive stages, irrigation is applied based on rainfall and availability of water for maintenance [140].

The use of technology and strategies can also affect the level of profit achieved from the VRI technology itself. A study was conducted in a 20-ha wheat field in Southern Alberta, Canada on modeling economic returns at different levels of control [141]. A total of 62 management scenarios were studied, including (1) no irrigation, (2) uniform irrigation management, (3) speed control with two angular increments of 2 and 10 degrees, and (4) zone control with a combination of two angular increments and a different number of independent irrigation zones, ranging from 2 to 30. The study concluded that the highest profit was obtained with 30 control zones. However, considering the cost of the technology, the case of ten control zones along the central pivot system was found to be the most profitable. Hence, it is essential to set forth effective site-specific water management strategies for increased agricultural sustainability and profitability.

5.3. Artificial Intelligence and Deep Learning

Existing site-specific management utilizes several control strategies such mathematical modeling of crop yield or the plant-soil-atmosphere environment, optimizing irrigation application timing, learning sensor feedback to control the site-specific flow of water as well as using predictive model control that executes a model repeatedly to determine optimum input. The use of artificial intelligence or neuro-dynamic programming that integrates machine learning to determine the water application parameter for optimized irrigation is also increasing [50,142–145]. Hyperspectral remote sensing imaging along with machine learning has been in use in agricultural industry, and it is estimated that machine learning/deep learning-based classification has a significant potential for high-dimensional big data produced in agriculture [146].

6. Impact of Variable-Rate Irrigation

VRI can be highly effective in reducing water use and increasing water use efficiency (WUE) of crops [147]. A review on VRI across different crop and weather regimes of the world concluded that

VRI could save 10%−15% of water [28]. A study in a 7-ha sugar beet field in Germany reported that 13% of water was saved compared to the uniform application [15]. This was achieved by utilizing stored soil moisture and in-season precipitation. In a study in New Zealand comparing VRI with conventional irrigation system, 9%−19% irrigation water was saved with VRI in pasture and corn fields, which in turn reduced nitrogen leaching [137]. Similarly, the application of VRI by manipulating its several components can reduce water runoff by avoiding excess water application in the field [28]. At a large scale, water pumpage and use can be reduced by adopting VRI. A geospatial method has been provided for potential VRI technology adopters to achieve potential water savings in the field using freely available datasets such as soil survey data from the Natural Resources Conservation Service (NRCS) [48]. In this study, the difference in application depth between conventional irrigation and VRI was estimated based on root zone available water capacity. The undepleted soil water from each management zone was mined using prescription maps allowing 50% depletion. VRI in this study resulted in a reduction in irrigation depth of up to 18 mm, pumping reductions, and improved water distribution throughout the field. In addition, higher VRI control resolution increased energy savings. VRI was found to reduce pumpage in more than 13% of center pivot irrigated fields by 25 mm per year compared to the conventional irrigation system in Nebraska [99]. Another study for VRI management based on soil water spatial variation was conducted in a 1.64-ha field with center pivot to understand the yield and water-saving effects of VRI [148]. In this study, the field was divided into four management zones based on available water-holding capacity and each management zone was further divided into two sections for VRI and URI management. The results from this study indicated that the impact of VRI on water savings within zones depended on weather conditions. Water savings with VRI management was higher for summer maize when the rainfall was high compared to winter wheat grown in no-rainfall weather. The study suggests that although VRI management had no significant influence on crop growth parameters and yield within a management zone, managing the zones with different available water-holding capacity might improve the uniformity of crop growth, maximize crop yield and gain potential water savings.

Compared to the uniform application, VRI increases crop productivity. The results comparing the water productivity of sorghum and corn showed that there was more than 20% increase in water productivity for both crops using VRI [35]. Another study conducted in a 4-ha field, VRI resulted in a significant difference in corn yield in a dry year. However, the results were not significant for the year when the rain was sufficient [100]. Another study was conducted in New Zealand to understand the impact of variable-rate irrigation based on soil moisture status [139]. This study showed that although the yield was not significantly different among different irrigation treatments, water savings of 27–55 mm was achieved by limiting irrigation in soil with adequate plant available water and non-irrigating poorly drained, wet soil zones. VRI has been found effective to reduce water and energy use even in humid areas of the world with uncertain and unpredictable rainfall [40]. This study showed that potential water savings of 20mm/year could be achieved using VRI in these regions. However, the feasibility and effectiveness of VRI depend on the magnitude of the field, crop under consideration, weather and the underlying field properties [24,25,40]. The accurate determination of water requirement and its management is crucial for crop yield stabilization and improved average yield [53]. Several VRI research projects attempt to enhance the control scenarios as well as model and production function to improve water savings and reduce pumpage [40,99,141,149,150]. Further, it is necessary to understand the impact of soil water availability on crop growth to manage irrigation in spatial and temporal scales using variable-rate irrigation technologies and appropriate strategies.

7. Challenges and Research Requirements

Data collection and management tools, such as yield monitors, sensors and sensing systems, GIS, GNSS, and decision support systems are available today to enable site-specific management of irrigation water for optimized crop production. Steady development in irrigation control systems provides the user with various options to implement VRI. Many studies have investigated and developed irrigation strategies, prescription methodologies, and profitability optimization involved in VRI. However, there are some challenges in the implementation and application of this technology. Further research and development are required to improve the understanding, implementation, and adoption of precision water management strategies and technologies.

(1) Research is required on the integration of technology, agronomy, and profitability with VRI

Although several studies have reported the potential of adopting VRI system to optimize crop production and profitability [29,70], some studies conducted in experimental fields have concluded that the VRI technology may not be economically viable for all crops under all growing conditions and environments [24]. This is not because of the yield-related benefit, but due to the cost of the technology itself. For example, research conducted in a 12.6-ha field in southwest Georgia showed that VRI generated $16/ha more return than URI. Although this return is not significant for this small field, the study suggested that profits could be amplified for large fields and benefit farmers [151]. From the agronomic perspective, a better understanding of the extremities of field variability and how it affects crop yield is needed for the effective implementation of new technologies [152]. In an experiment conducted in Tennessee, the same level of irrigation did not result in the same cotton lint yield in all parts of the field due to differences in texture and available water-holding capacity [153]. In some cases, the incorporation of other crops in a rotation in VRI can make this technology economically viable [25]. Additionally, most of the VRI studies are concentrated on the control scenarios of VRI [149,150]. Although a few studies [40,99,141] determined water and energy savings using VRI due to managerial limitations, they were either based on some model and production functions or arbitrary in irrigation rate determination. Hence, there is a need for a comprehensive study on VRI integrating the agronomic, technical and managerial aspects of VRI to determine its profitability, sustainability, and adoptability for various conditions.

(2) On-farm and whole-field research

Producers are more likely to adopt VRI if the benefits are shown on a "real farm." Most of the previous studies on VRI were conducted in experimental fields or in small fields that cannot represent the commercial farming practice [28]. Experimental design and implementation in large fields are challenging. This type of research requires close communication and collaborative management between the researcher and the farm owner to ensure the alignment of management practices and study goals. Acquiring data and information from large fields is costly and time-consuming. In addition, the statistical analysis of on-farm data is challenging due to the lack of adequate tools that integrates classical statistical methods and spatial analysis. This creates challenges in the understanding of the relationship between crop growth and its environment in site-specific irrigation. More on-farm studies are needed to provide information for practical VRI applications. In addition, insufficient recognition of temporal variation and environmental impact are several other factors that hinder the adoption of precision agriculture technology [9].

(3) Prescription map development

The majority of previous studies for prescription maps (management zone delineation) are for variable-rate application of fertilizers and seeds and are static [20,133]. Limited research has addressed the need for dynamic prescription map development that could incorporate seasonal changes in crop growth and conditions [133]. More research is required to evaluate VRI prescription maps or management zone development integrating different soil and crop characteristics under different environments. Use of remote and proximal sensing such as infrared sensors, near-infrared and thermal images, along with weather data can provide information on crop, soil, and environmental conditions in irrigation scheduling and developing dynamic prescription maps [97]. Further research needs to investigate how to integrate such data and information to evaluate the effectiveness of such prescription maps during the growing season.

(4) Optimal spatial and temporal scale

Few studies have evaluated the appropriate spatial and temporal scales for VRI application. Many studies have explored the use of sensors in acquiring information for modeling crop evapotranspiration, SWC, irrigation needs including the nutrient requirements [97,105,152,154,155]. Most of these studies indicated the high potential of remote and proximal sensing technologies in understanding spatial and temporal variations in crop growth conditions in the field. Temporal variability in soil water status and crop growing conditions require dynamic adjustment of irrigation amount and spatial distribution. Therefore, simulation models or on-farm studies might be considered to assess the effectiveness of VRI at different spatial and temporal scales.

(5) Comprehensive decision support tools

Precision irrigation management requires data and information from crop growth conditions, soil physical and chemical properties, weather factors, and the interaction among these factors. Effective implementation of precision irrigation requires a comprehensive decision support system to process and integrate different layers of data and information [48]. The challenge for the application of VRI still exists in the lack of user-friendly decision support tools such as for developing dynamic prescription maps [105]. Several decision support systems such as AgriDSS are available [16,156], but producers are reluctant to use them to their full potential due to their complexity. Also, these tools are based on what scientists and developers consider as necessary knowledge that should be implemented in the decision support system. However, in a real-world situation, they fail to utilize the implicit knowledge of farmers and address their needs. The complexity, lack of observability and confidence, poor user interface design, lack of incentive to learn are some of the other reasons behind the hindrance of adoption of different decision support tools [16]. The system or tool should help the user decide where to apply how much irrigation water at various crop growth stages to achieve the highest profit based on the regional climate conditions and cropping systems.

(6) Integrating VRI with other inputs

Few studies have integrated variable-rate application of nutrients with water. Crop yield response to water and N are not the same at different parts of the field [157], indicating the need for studying the interaction of water and fertilizer in variable-rate irrigation. Site-specific application of N together with irrigation using remote sensing can help reduce N inputs by 50% and leaching by 85% without reducing yields [155]. Further studies are needed to investigate the interaction between VRI fertilizers and other inputs to improve the efficiencies of water and fertilizers while reducing the environmental impact of fertilizer application and enhancing production sustainability.

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