MONITORING AND MODELING THE EFFECTS OF WATER AND NUTRIENT BMPS ON WATER QUALITY AND CROP PRODUCTION UNDER SHALLOW WATER TABLE ENVIRONMENTS

By

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To my wife, Katherine Elizabeth May Hendricks, and my mother, Sylvia Evadney Hendricks.

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Major: Agricultural and Biological Engineering

Relatively high nutrient and water use by vegetable production systems can create conditions for nitrogen (N) and phosphorus (P) leaching that are more likely to impair surface and groundwater quality compared to other crop systems in Florida. Best management practices (BMPs) have been developed and recommended for improving surface and ground water quality while maintaining economic viability. However, the effects of most vegetable BMPs have not been quantified. A 3-year study was conducted in southern Florida to evaluate the effects of water-nutrient BMPs on crop yield, water use, and water quality. Three water-nutrient treatments were randomly applied among six hydrologically isolated 0.24 ha plots, which were planted with tomato (fall)-watermelon (spring) rotations. The water-nutrient management strategies compared were: 1) high fertilizer rate and irrigation input (HR) with seepage irrigation, which represents the current water and nutrient input by vegetable producers in south Florida; 2) recommended fertilizer rate and irrigation input (based on soil moisture) (RR) with seepage irrigation; and 3) same as the RR but with subsurface drip irrigation (RR-SD). Response variables tested were crop yield, water use, and N and P concentrations in soil and groundwater (shallow and deep). Field data were used to modify a lumped hydrologic model (ARCU2000) to simulate water table

dynamics for plastic mulch raised bed conditions. The modified model was evaluated using measured water table depth beneath the crop bed surface.

No treatment effect on yield was detected for the entire study period, except for watermelon during a relatively wet spring 2005 crop season. The yield for spring 2005 for HR (38.7 Mg ha^{-1}) was statistically greater than the yield from RR (21.6 Mg ha^{-1}) and RR-SD (24 Mg ha^{-1}). Soil solution analysis revealed that N concentrations within and below the crop bed were significantly higher for HR compared with RR. Weekly to bi-weekly soil N concentrations in deep core (0-20 cm) soil samples were used to estimate the amount of N leached to the groundwater. Soil N leaching for HR was 60% greater than that from RR. Shallow groundwater quality data indicated that total N (TN) and P (TP) concentrations were significantly higher in HR (TN=38 mg/L, TP=3.1 mg/L) compared with RR (TN=16 mg/L, TP=2.1 mg/L) and RR-SD (TN=21 mg/L, TP=2.0 mg/L). However, no treatment effect was detected for deeper groundwater N and P concentrations. Results from the model evaluation showed that the modified model under performed (i.e., Nash-Sutcliffe coefficient = -0.67) in simulating water table depths. The model's performance was limited by its daily time step. Use of a sub-daily time step is likely to improve the model's performance.

Overall, use of recommended fertilizer and irrigation input for vegetable production in southern Florida can improve groundwater quality while maintaining crop yields under average weather conditions. Adverse impact on yield is likely under unusually wet growing conditions and may justify the application of additional fertilizer. The water table dynamics beneath these vegetable production systems can be simulated using lumped hydrological models.

CHAPTER 1
INTRODUCTION

Nitrogen and Phosphorus Loading to Surface and Groundwater

"Nitrate concentrations (as nitrogen) exceeded the U.S. Environmental Protection Agency (USEPA) drinking-water standard of 10 milligram per liter (mg/L) in more than 20 percent of groundwater samples from surficial aquifers in agricultural areas." Berndt et al. (1998) made this observation in a study conducted within the Georgia-Florida Coastal plain. Samples were collected from aquifers that overlie the Upper Floridan aquifer. Berndt et al. (1998) deduced that high levels of nitrate (NO_3^-) found in groundwater samples were most likely the result of fertilizer applied to crops, which eventually leached from the root zone into the groundwater system. Groundwater contamination from fertilizer use has serious implications for the 890 thousand hectares of agricultural land use (NASS, 2004) in south Florida that overlies the Upper Floridan Aquifer. Two million tons of fertilizer were purchased for commercial use in Florida during the July 2004 to June 2005 period; 34% of this fertilizer was applied to farms in south Florida. Of this amount, 11, 4, and 12% were nitrogen (N), phosphate (P2O5) and potash (K2O), respectively (FDACS, 2006c). Since groundwater supplies 90% of Florida's drinking water (USGS, 2003), large loading of N fertilizers is a matter of great concern. Another water quality concern in south Florida is the excess phosphorus (P) loading to surface water bodies, especially Lake-Okeechobee-Everglades ecosystem. The N and P cycling and transport mechanisms differ considerably.

Phosphate ions (PO_4^{3-}), unlike nitrate are strongly adsorbed by soil particles. Nitrate ions are water soluble and are generally not adsorbed by soil particles and, as a result, are able to flow relatively freely with water through the soil matrix (McCullum, 1996). In contrast, PO_4^{3-} typically reacts (depending on soil pH) with Al^{3+}, Fe^{3+} or Ca^{2+} ions or their oxides present in the soil (McCullum, 1996). The reaction of PO_4^{3-} with these metal ions (or their oxides) can result in insoluble phosphorus compounds that precipitate out of soil solution, or phosphate ions that become fixed to the surface of soil particles. As a consequence, dissolved P (in the form of PO_4^{3-} ions) is removed from soil solution and is not available for plant uptake or leaching. The bonds between PO_4^{3-} ions and soil particles are strengthened over time, decreasing the possibility of P leaching (McCullum, 1996). However, each soil type has a P sorption capacity beyond which additional PO_4^{3-} ions cannot be held by the soil. These additional PO_4^{3-} ions are available for leaching.

Nitrogen, as well as phosphorus (P), entering the water table also impacts surface water through groundwater discharge to streams, rivers, and lakes. Results of the National Water Quality Assessment (NAWQA) program indicate that groundwater and streams in basins with significant agricultural and/or urban development land uses almost always contain complex mixtures of nutrient and pesticide contaminants (USGS, 1999). Fertilizers and nitrates in groundwater are among the principal contaminants that can lead to drinking water well closures (USEPA, 1992). Pollution caused by fertilizer is ubiquitous, which makes it near impossible to isolate and difficult to control. Nevertheless, land use management practices are being developed and implemented at the state and national level to address the concern of nonpoint source contamination of groundwater resources.

In response to public awareness and concern for contamination of surface and ground waters, the federal government implemented the Federal Clean Water Act (FCWA) in 1972 (amended in 1987) that requires states to assess the impact of nonpoint sources of pollution on surface and ground waters. The states reported that siltation and nutrients impair more kilometers of rivers and streams than any other pollutants, affecting 45 and 37% of impaired river and stream kilometers in the states, respectively. These states also reported that agricultural runoff is the leading source of pollutants in rivers and streams.

Forty-five states identified almost 257,495 km of river impaired by agricultural sources, including non-irrigated crop production, irrigated crop production, rangeland, and animal holding areas. Furthermore, agricultural activities contribute substantially to the impairment of 72% of the impaired stream kilometers in the lower 48 states (USEPA, 1992). Fifteen percent of the samples taken from 4 of the 33 major drinking-water aquifers across the United States exceeded the drinking water standard for NO_3^-. These NO_3^- concentrations were detected in shallow groundwaters (less than 30 m below soil surface) located in the agricultural areas (USGS, 1999). To address the problem of excess nutrient transport, the FCWA requires states to develop total maximum daily loads (TMDLs) and propose Best Management Practices (BMP) to control non-point source pollution. The FCWA also requires states to develop strategies (e.g., BMPs) that reduce nutrient contamination of water resources on a watershed-by-watershed basis (USEPA, 2002). Programs such as the Chesapeake Bay Program, Great Lakes Regional Water Quality Program, California's Nonpoint Source Pollution Control Program and Florida’s Watershed Management Program are all examples of watershed protection plans dedicated to developing management practices that improve the quality of surface and groundwater in accordance with the FCWA. These management practices, developed through field research, consider several factors such as land use, local soil properties, and climatic conditions. Many field studies have been conducted (Clark et al. 1991; Hochmuth and Cordasco, 2000; Stites and Kraft, 2000; Inamdar et al., 2001; Alva et al., 2003; Grigg et al., 2003; Alva et al. 2006) throughout the nation, including Florida since 1987 to evaluate the effects of different management practices on water quality and/or production.

Case Studies for BMPs

Inamdar et al. (2001) conducted a 12-year study in Westmoreland County, VA that evaluated the effectiveness of several BMPs (e.g. conservation tilling and nutrient management) in improving water quality at the watershed scale and over the long term. The authors concluded that the BMPs adopted were effective in improving water quality at the watershed scale and that these improvements continue to be observed through a 7-year period after the BMPs were implemented. Stites and Kraft (2000) conducted a study in Wisconsin to evaluate groundwater quality under irrigated vegetable fields in the state's central sandy plain region. The authors concluded that irrigated vegetable agriculture had a direct effect on shallow groundwater quality; groundwater under vegetable fields had significantly higher concentrations of most solutes (e.g. N and K) and lower pH compared with up gradient locations. Groundwater nitrate (NO_3^-) concentrations were almost double the MCL even when the growers in the study approached BMP fertilizer inputs recommended by the University of Wisconsin. Such results present a challenge with regard to achieving water quality goals since reducing fertilizer rates beyond the research-based university recommendations has the potential to adversely impact the economic viability of agriculture in the region.

Grigg et al. (2003) conducted a study in Baton Rouge, LA, to determine the impact of water table management on surface runoff, subsurface drainage effluent, soluble nitrate losses and corn yield. Three methods of subsurface drainage were applied: 1) surface drainage only, 2) surface drainage with controlled subsurface drainage at a 1.1 m depth, 3) and surface drainage plus water table control at 0.8 m via controlled subsurface drainage and sub surface irrigation. Grigg et al. (2003) concluded that carefully managed subsurface drainage could be an effective part of integrated management to reduce runoff volume as well as sediment and nutrient loading while increasing crop yield. While the above-mentioned studies are useful for regions with similar landscape and hydrology, they have limited applicability for regions that have a unique combination of weather, topography and hydrogeology (e.g., south Florida). South Florida has a unique soil-hydrologic condition that include coarse sand texture, high hydraulic conductivity, low water holding capacities, shallow water tables, flatwoods topography, and a subtropical climate. Such unique conditions affect the dynamics of fertilizer nutrient (i.e., N-P-K) and make it imperative for Florida to conduct its own research for BMP development and evaluation.

The Need for BMPs in Florida

The development of BMPs in Florida is essential for finding a balance between the state's agricultural production, which can be linked with eutrophication of water bodies and maximizing tourism revenues that rely on a pristine ecosystem. Both industries have an enormous impact on the state's economy, generating billions of dollars each year. The crux of this dilemma rests on the fact that agricultural lands are interspersed among many of the state's ecosystems (e.g. Florida Everglades) that are of interest to tourism as well as urban developers who must meet a housing demand generated by a net influx of 1,000 people who until know immigrated to Florida per day (Penn, 2006). Consequently, the competition for the same water resources between the urban and agricultural sectors has been increasing.

Increased competition for water in Florida has resulted in a continued need to develop efficient irrigation management practices for agriculture. Groundwater accounts for 62% of Florida's water supply, and the rest is derived from surface water. Among the aquifers in Florida, the Floridan is the most important, in that it supplies 90% of drinking water and 51% of agricultural irrigation needs (USGS, 2003). Presently there is a concern regarding contamination of this vital water resource by fertilizer N and P leached from agricultural land uses. Part of any leached N and P can move laterally under shallow water table conditions to ditches and canals and eventually to the lakes and rivers, where it can be a cause of increased eutrophication.

Introduction of nitrates into the groundwater system can lead to water supplies that are not suitable for human consumption or the degradation of associated ecosystems. Limited domestic water supplies resulting from contamination will have a negative socioeconomic effect on a community or, to a larger extent, the state.

Berndt et al. (1998) reported that nitrate concentrations exceeded the USEPA's maximum contamination level (10 mg/L) in more than 20% of groundwater samples from surficial aquifers in agricultural areas within the Georgia- Florida coastal plain. For urban areas, the median nitrate concentration in groundwater samples taken from the surficial aquifer was 0.95 mg/L. This is in contrast to the median nitrate concentration of 0.05 mg/L in groundwater samples taken from the upper Floridan aquifer in urban areas (Berndt et al., 1998). Total phosphorus (TP) concentrations that were less than 0.05 mg/L in 50% of groundwater samples taken, and TP concentrations did not differ by land use. The maximum P concentration measured (1.3 mg/L) was in samples taken from groundwater located beneath forest and urban areas (Berndt et al., 1998).

McPherson et al (2000) reported that groundwater nitrate concentrations in southern Florida were low for most of the wells sampled; however, some samples occasionally had elevated nitrate concentrations in areas with agricultural land use. Phosphorus in groundwater samples taken from wells in southern Florida varied widely (0.001-0.79 mg/L). The highest P concentrations were generally found in samples taken from the deeper public supply wells of the Biscayne aquifer and in the citrus land-use area (McPherson et al., 2000). Elevated groundwater P concentrations were associated with fertilizer use and naturally occurring sources that include silt and clays (McPherson et al., 2000).

It is clear that there is a need to develop practices that can minimize the movement of contaminants (fertilizer nutrients in this case) into adjacent water bodies while maintaining the economic viability of Florida's agricultural industry. The TMDL program required by FCWA plays a critical role in finding this balance since agricultural land uses, known to be non-point sources of agricultural chemicals, cover at least 30% of land in Florida (FDACS, 2006b). One such land use is fresh market vegetable production that accounts for 88,793 hectares used for agricultural production in Florida (National Agricultural Statistic Service, NASS, 2004).

Agricultural operations such as sugarcane, citrus, and vegetable production use large amounts of N and P fertilizer. Due to the intensive nature of the production system, vegetable production has a greater potential to contribute N and P loadings to surface and groundwater compared with other crops in Florida. Unlike citrus or sugarcane production, vegetable production requires seasonal tilling for each crop cycle (at least twice a year) that results in considerable soil disturbance, which in turn promotes mineralization of mobile nutrients such as N and P and results in greater potential for sediment losses and nutrient leaching. The potential for N and P leaching in south Florida is further increased by coarse sandy soils with high water tables, which result in rapid movement of water and dissolved N and, to a much less extent, P to groundwater in a relatively short period. Leaching associated with vegetable production is increased by the common practice of seepage irrigation that requires artificially raising the water table (approx 45 to 55 cm below the surface) to depths higher than natural to supply moisture to the root zone through upflux. Therefore, regions under seepage irrigated vegetable production in Florida are likely more susceptible to shallow groundwater pollution compared with other land uses.

Florida's vegetable production is concentrated in southern Florida, where many growers use seepage irrigation with raised beds that may be covered with polyethylene film (plastic mulch). Plastic mulched raised beds (PMBs) contain all the fertilizer for the crop growing season. Plastic mulch reduces leaching by sheltering applied fertilizer granules from rainfall that can quickly dissolve and flush nutrients from the root zone of the plants into the surficial aquifer. Seepage irrigation is commonly practiced in areas where the soil contains a nearly impermeable subsurface layer (called a spodic layer) at approximately 75 cm or below. Water is supplied through large or small in-field V-shaped ditches, which results in perched water table conditions above the spodic horizon. Seepage irrigation is less efficient than other forms of irrigation systems such as drip irrigation. However, given the low cost of operation and maintenance and years of application, this system is the grower-preferred form of irrigation in south Florida. The water table is adjusted during the crop season to control moisture content of the root zone. Naturally high water table conditions (e.g. 45 cm from the top of the bed) in south Florida combined with rapid water movement in sandy soils can result in large fluctuations in water table levels as a result of rainfall or irrigation. Jaber et al. (2006) observed that for every 1 cm rainfall the water table for the Immokalee fine sand can rise up to 15-16 cm. Bonczek and McNeal (1996) noted that water table fluctuations in seepage irrigation systems could result in a significant movement of fertilizer nutrients (N, P, and K) out of the root zone. Excess nutrients from high fertilizer application may result in high N and P concentrations in groundwater, which can have an adverse effect on water quality (Stites and Kraft, 2000; Berndt et al., 1998).

Application of BMPs in Florida

Surface and groundwater quality can be preserved by a number of methods. Bottcher et al. (1995) considered three methods of reducing P concentrations in farm discharge waters. These methods can be applied to minimizing both N and P concentrations in surface runoff discharged from a farm. The methods are as follows: 1) reduce the amount of nutrients on the farm by minimizing the nutrient imports to the farm and maximize non-runoff nutrient export from the farm; 2) reduce the hydraulic mobility of nutrients by limiting the water contact and/or reducing the solubility of the nutrient materials; and 3) apply edge of field pre-discharged treatment using uptake, adsorption, deposition, or precipitation technologies, such as wetlands and/or chemical additives. A variety of BMPs have been proposed based on these concepts for several land uses (e.g. vegetable production), some of which are evaluated for their performance with regards to water quality (Clark et al. 1991; Bottcher et al. 1995; Sheffield et al. 1997; Hochmuth and Cordasco, 2000, Alva et al., 2003).

One of the more commonly used BMPs for vegetable production is the application of reduced fertilizer rates for achieving optimum yield. Hochmuth and Cordasco (2000) summarized tomato fertilization research based on reduced fertilizer inputs, which led to the development of University of Florida (UF) tomato fertilization recommendations. The authors were able to conclude that the recommended fertilizer rates did not adversely affect crop yield when compared with higher fertilizer rates used by growers. Similar studies were conducted for several varieties of vegetables; Hochmuth and Cordasco (2000) outlined N, P and K management practice for tomato, determined by field studies and grower experience, that can be used for vegetable production in Florida without adversely affecting crop yield while reducing the potential negative environmental impact.

While fertilizer inputs are critical for crop growth, water has an equal if not more important role in crop growth and development. Water is the vehicle responsible for transporting nutrients from soil to plant roots; it can also carry nutrients from the plant root zone to groundwater. Therefore, careful water management is essential to sustain crop yield while reducing water wastage and off-site nutrient transport to water bodies. Hence, the need to provide optimal moisture content in the root zone must be balanced against moisture levels that promote nutrient leaching out of the root zone. Such a balance often requires field scale experiments that are necessary to develop and evaluate water and nutrient management strategies, which consider different nutrient and moisture content combinations that sustain current yields while minimizing nutrient leaching. One such study conducted by Clark et al. (1991) in Bradenton, Florida, evaluated the effects of different water management strategies (microirrigated) and applied fertilizer (N and K) rates on the production of fresh market tomatoes in sandy soils. High fertilizer rates (336 kg N/ha and 558 kg K/ha) were compared with lower fertilizer rates (224 kg N/ha and 372 kg K/ha). The authors observed that their reduced fertilizer rates did not adversely affect fruit yield and quality and using micro irrigation did not necessarily reduce nor enhance tomato yield and quality. The authors concluded that reducing the fertilizer application rates in conjunction with precision water application control using microirrigation resulted in reduced fertilizer cost and reduced potential for N fertilizer leaching to the groundwater. However, the study did not specifically measure the water quality impacts.

While valuable, the results from vegetable BMP studies conducted in south Florida are typically limited with regard to their scope in quantifying treatment effects only on crop yield. However, the definition of a BMP as stated by FDAC (2005) is: “a practice or combination of practices determined by the coordinating agencies, based on research, field-testing, and expert review, to be the most effective and practicable on-location means, including economic and technological considerations, for improving water quality in agricultural and urban discharges.” It is clear that water quality, crop yield, and economic evaluation are needed of a BMP to meet the legal criterion (of a BMP) in the state of Florida. Most studies that evaluate vegetable BMPs are based on either different nutrient treatments or different water management strategies and their effect on water quality and crop yield, but rarely on both. These studies often assume that the adopted management strategy will improve the quality of edge-of-field discharges into adjacent surface water bodies or groundwater based on reduction of nutrient and water inputs; however, in most cases, water quality sampling was not conducted for the analysis of N or P. Alva et al. (2003) expressed similar concerns for Florida by stating that: “Most fertilizer response studies conducted in the past, on Entisols, were focused on the crop production and quality responses; therefore, information is extremely limited on the fate of applied N which could contribute to potential NO_3^- contamination of groundwater.” Therefore, to address the effectiveness of a BMP, field experiments should be designed to simultaneously evaluate the effect of fertilizer reduction on crop yield and water quality. Such an approach would be prudent since it accounts for possible interaction effects that occur between treatment parameters within a field experiment (e.g. nutrient and water input combinations).

Field experiments can be conducted on either a small or large plot scale. In the context of water quality effects of BMP, small plot research has limited usefulness under the high water table conditions of Florida due to extensive mixing of ground water beneath the treatment areas. Large plot studies are more susceptible to uncertainties resulting from increased variations in field parameters (e.g. hydrologic conductivity and nutrient pools). Furthermore, it is difficult to simultaneously evaluate the effects of different nutrient and irrigation practices on groundwater level and quality within an open field. Consider, for example, an experiment conducted to determine the effects of maintaining a higher, lower, and optimum water table depth for a seepage irrigated vegetable production system on water quality and yield. To reduce the variability due to the soil type, hydrogeology of the site and neighboring land use, such a study will require side-by-side comparison of crop production and water quality. However, differences in the hydraulic head of the water table in such a study will result in the mixing of groundwater as well as dissolved nutrients from one plot to another. Due to very sandy soils, this mixing is extensive in south Florida and may mask the effects of individual treatments on groundwater quality. Therefore, these studies must be conducted so that hydrologic isolation is achieved between the BMP treatments to contain the nutrients in the groundwater within each treatment area. Furthermore, these studies must be conducted for multiple years to increase the chance of documenting the water quality effects that may be masked by year-to-year variations in nutrient concentrations in the groundwater due to factors such as rainfall, plant uptake, and background soil nutrient concentrations. Such BMP studies are feasible and require innovative monitoring design.

Lombardo et al. (2000) recommended appropriate experimental designs (at the watershed scale) that would ease the difficulty of evaluating the effectiveness of nonpoint source pollution controls. These recommendations included designs such as paired watersheds, upstream/downstream monitored before, during and after land treatment; or multiple watershed monitoring. The authors stated that the best method for documenting BMP effectiveness in a limited number of years (3 to 5) is the paired watershed design. However, the authors point out that one of the key challenges with this design is the ability to control the land use in the control watershed, as well as the treatment watershed. Another challenge with any of these designs is to control the amount of groundwater mixing that occurs between adjacent study areas. These challenges are likely to affect all experimental designs for evaluating the effectiveness of BMPs on water quality.

The hydrological and geochemical properties of an aquifer depend mainly on the texture, structure and composition of aquifer. The hydrological properties of the soil determine how water is distributed within the soil and how quickly it moves through the soil. In general, the water table of an aquifer is continuous and its groundwater movement follows the hydrologic gradient, transporting all soluble chemicals such as NO_3^- with it. Nutrients naturally occurring in an aquifer depend on the chemical composition of the parent geologic material. The concentration and mobility of nutrients in a surficial aquifer depend on soil properties such as soil texture, moisture content at various depths, soil cation exchange capacity (CEC), and soil pH.

Nutrients in a soil can be transported by three mechanisms: diffusion, dispersion and advection. Diffusion is the movement of soluble nutrients from areas of high concentration to areas of low concentrations. Dispersion is the spontaneous expansion of a nutrient plume as it moves through the soil. Advection is the transportation of the nutrient plume by a flux of water. Therefore, mobile nutrients within the saturated zone are free to move throughout so long as there are no impermeable barriers impeding their movement; nutrient concentrations will adjust to meet any physical or chemical equilibrium requirements in the aquifer. Consequently, such mobility and transport of water and nutrients within the saturated zone is likely to create large uncertainties in a study that compares groundwater quality beneath fields even when they are located close to each other. Some of these uncertainties can be mitigated by the implementation of a physical barrier within the soil. The presence of a physical barrier will minimize the amount of groundwater mixing that can occur between treatments in a comparative field study that evaluates the effectiveness of BMPs. However, the cost and implementation of such a barrier is very expensive, which limits its use in large scale field studies such as BMP evaluations.

The experimental verification of different BMP combinations (e.g. use of recommended nutrient rates and different water table depths) is a costly proposition; hence, the use of hydrologic/water quality simulation models that have been tested using field data is an economically viable alternative for evaluating BMPs. However, a review of the literature indicated that PMB production systems for vegetable crops are not represented in currently available hydrologic and nutrient models. PMBs should be considered in model-based evaluations of BMPs for vegetable production under high water table environments of south Florida. The PMBs used for vegetable production in south Florida improve crop yield by maintaining optimum soil temperatures, minimizing nutrient losses and soil evaporation. PMBs affect surface and subsurface hydrologic processes including runoff, infiltration and evaporation.

The processes of infiltration and evaporation play an important role in the movement of nutrient and water within and out of the crop root zone sheltered within the PMB. Soils within a PMB are shielded from rainfall, limiting infiltration and soil evaporation from the PMB to only a fraction of that from an open field. Holes punched into the plastic sheet on top of the PMB provide an avenue of water flux in or out of the PMB. The number of holes varies according to the crop type. However, irrespective of crop type, all PMBs have plant holes. For some crops such as tomato, additional holes are punched into the PMBs to drive wooden stakes that provide structural support for mature plants. As the crop season progresses, the number and size of plant and/or stake holes in the plastic may increase depending on the type of crop management associated with this increase is a change in the canopy interception, infiltration and evaporation from the PMB throughout the crop season. The presence of impervious plastic sheets with plant holes creates a hydrologic condition that is considerably different from open field production systems. Therefore, it is important for hydrologic water quality models to simulate PMB environments if they are to accurately represent vegetable production systems in south Florida and other regions and states where PMB is used. Unless an effort is made to build a new model to include a PMB component or modify an existing model to include a PMB component, simulation of water and nutrient movement from a PMB system is likely to generate erroneous predictions. Consequently, these errors will limit a model's ability to meet the needs of BMP evaluations for PMBs.

Simulated Hydrological Processes Associated with Floridian BMPs

Borah et al. (2006) conducted a critical review of 25 models that simulate sediment and nutrient transport and have been used or have the potential for use in TMDL development and implementation. The authors observed that while tremendous advancements have been made with modeling the hydrology and transport of sediment and nutrient, simulations have not always been consistent with the needs of the TMDL program. This is the case with vegetable production systems that use seepage irrigation and PMBs in high water table conditions. Borah et al. (2006) concluded that benefits to the TMDL program, using models, will only increase when existing models are enhanced for representing field conditions such as PMBs.

Currently, some field scale hydrologic/water quality models exist that can simulate hydrologic and nutrient processes in exposed soils under high water table conditions in south Florida. There are two models, FHANTM 2.0 (Fraisse and Campbell, 1997) and EAAMOD-FIELD (Bottcher et al., 1998) that have been tested for hydrologic conditions in south Florida. However, a new model ACRU2000 (Smithers and Shulze, 1995) recently became available and offers several advantages compared with other models with regard to its structure.

The Agrohydrological Model of the Agricultural Catchments Research Unit [ACRU, (Smithers and Schulze, 1995)] was developed to simulate the hydrological processes (Fig. 1-1) of various land uses in the Republic of South Africa (Kiker et al. 2006). Like several previous models, ARCU was developed using FORTRAN 77, which made the structure of the model's program relatively difficult to expand.

ACRU was restructured to create ACRU2000, making it more extensible and better to represent the individual spatial elements of the model. Campbell et al. (2001) added a nutrient module that permits ACRU2000 to simulate N and P dynamics within the soil. Kiker et al. (2006) evaluated the Java-based, object-orientated modeling system (ACRU2000) for Southern African hydrology. The authors concluded that the extensible, flexible and modular nature of ACRU2000 allows model developers to independently adapt the model to their specific requirements without changing the existing source code; this allows the model to evolve with modeling needs and approaches.

Both Clark et al. (2001) and Campbell et al. (2001) applied the object-oriented methodology in the development/modification of ACRU2000. For this methodology, an object is defined as any material that possesses attributes and behavior (e.g. Immokalee fine sand). Attributes describe the physical characteristics or structure of an object (e.g. soil texture, structure, or composition), and the behavior (e.g. soil infiltration, percolation, or capillarity) describes how objects interact with other objects (Clark et al. 2001). Objects with similar attributes, behavior, and relationships are classified into groups or classes of objects; e.g. Immokalee fine sand (object) is one of many soils (class).

There are seven main types of objects in ACRU2000 described by Clark et al. (2001). Only three of these main objects are used for modeling hydrology (i.e., Component, Processes and Data). ACRU2000 adopted a convention that all class names should start with a letter indicating the class type, names of all Component class start with C, Process classes start with P and Data classes start with D. The Component objects/classes in ACRU2000 represent the physical components of the hydrological system being simulated (Fig. 1-1). The Process objects/classes in ACRU2000 represent the behavior of water and other related resources (e.g. sediments, nutrients and plants) in the model domain. The Data objects/classes in ACRU2000 represent Component attributes such as a soil's texture (DTexture) or area (DArea). The Unified Modeling Language

(UML) was used by Clark et al. (2001) and Campbell et al. (2001) to specify, visualize, construct and document ACRU2000.

In summary, a review of the literature revealed several research needs in the area of vegetable BMP evaluation which include: 1) field-scale vegetable BMP studies conducted at relatively large-scale; 2) experimental studies designed and conducted under hydrologically isolated conditions to minimize the transport of water and nutrients between treatments; 3) simultaneous quantification of the effectiveness of vegetable BMPs with regard to water quality, water quantity and crop yield on plastic mulched raised beds (PMBs) under shallow water table conditions; and 4) the representation of a plastic mulched raised bed environment within hydrological models for facilitating future BMP studies in Florida. Many studies conducted in Florida often focus on vegetable production since vegetables are a high cash crop. Nationally, Florida ranked number one in value of production of vegetables and watermelon during 2006. Tomato and watermelon ranked one and six, respectively, for cash receipts during 2006. Hence, this study will focus on tomato and watermelon production with regard to the effect of water and nutrient BMPs on groundwater quality.

Goals and Objectives

The goal of this study is to evaluate the effectiveness of nutrient and water management BMPs on crop yield, water use and groundwater quality. Specific objectives include: 1) Design a monitoring system to perform side-by-side comparisons of water and nutrient BMPs under hydrologically isolated conditions; 2) Evaluate the effectiveness of nutrient and water table management strategies with regard to N and P leaching to groundwater, water use and crop yield; and 3) Modify an existing model to represent plastic mulched raised beds for crops grown under high water table conditions to evaluate BMPs.

The objectives were achieved by completing the following tasks: 1) Evaluation of watermelon yield and production economics affected by water and nutrient BMPs, 2) Evaluation of tomato yield and production economics affected by water and nutrient BMPs, 3) Evaluation of water use, N and P leaching and groundwater quality affected and water and nutrient BMPs, 4) Modification of an existing model to represent plastic mulched raised beds for crops grown under high water table conditions to evaluate BMPs. The methodology and results for these tasks are discussed in chapters 2 through 5.

For this study, only hydrological processes in the ACRU2000 model will be modified. The processes identified for application in the PMB module of the model are evaporation, infiltration, percolation, runoff and upflux (Fig. 1-2). Based on the methodology discussed by Clark et al. (2001), the PMB module will be a part of ACRU2000's soil horizon component.

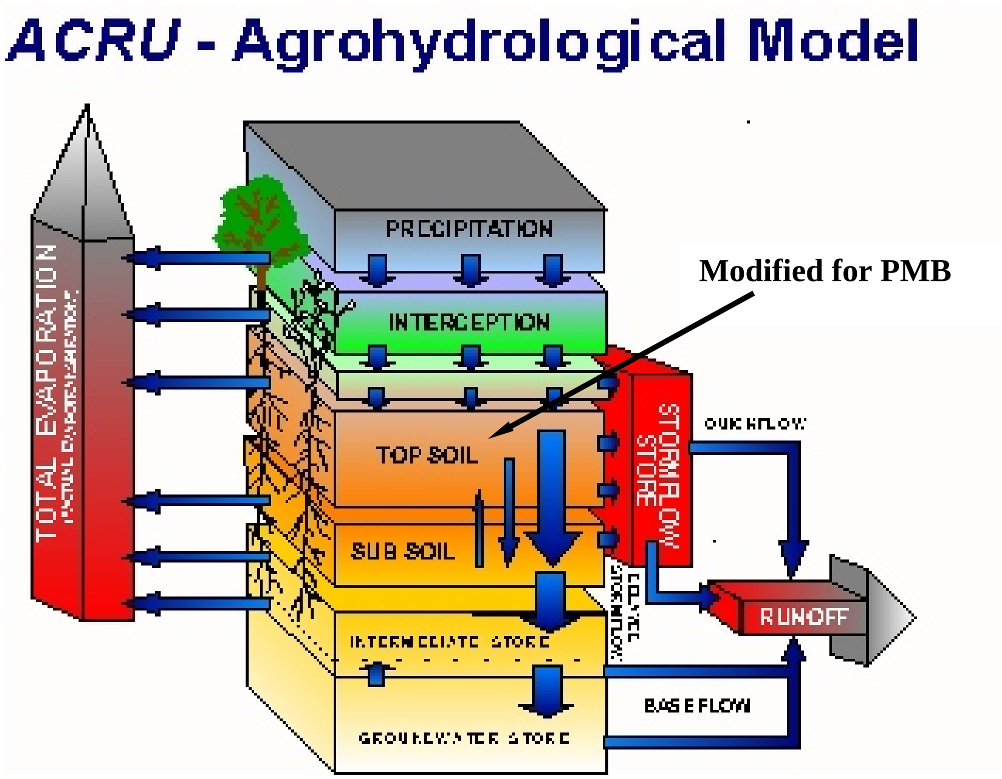

Figure 1-1. The ACRU agrohydrological modeling system: General structure (Smithers and Schulze, 1995). The top soil shown in the figure was modified to represent plastic mulched beds (PMB).

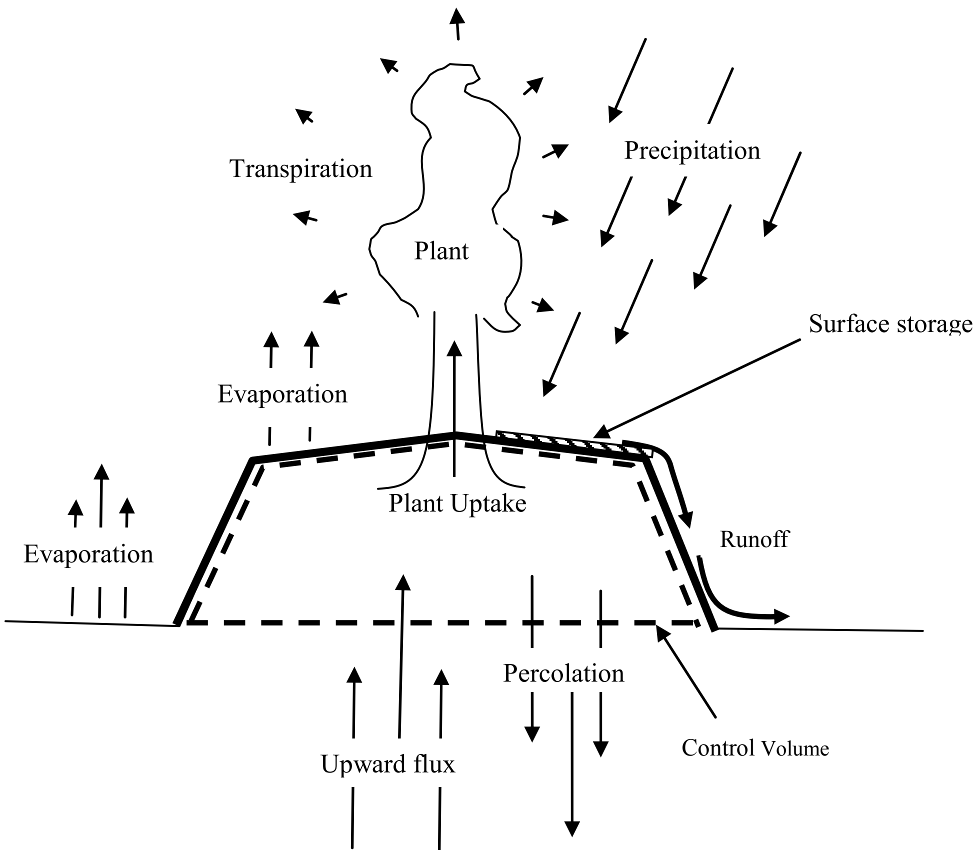

Figure 1-2. Proposed hydrological processes for the plastic mulched raised bed (PMB) module.

CHAPTER 2
FLORIDA WATERMELON PRODUCTION AFFECTED BY WATER AND NUTRIENT MANAGEMENT[1]

Introduction

Florida ranks second in the United States in hectarage and value of fresh market vegetables with almost 117,359 hectares in production (Florida Department of Agriculture and Consumer Services, FDACS, 2006 b) and more than $2 billion U.S. in farm gate value. Florida is also a leader in watermelon production, ranking first during 2005 among the top five leading states in the country along with Texas, California, Georgia, and Arizona for production and value (USDA, 2006). Watermelon production is concentrated in southern Florida, where many growers use seepage irrigation with or without raised beds and plastic mulch. Seepage irrigation involves raising the water table to provide moisture to the root zone via upflux. The water table is adjusted during the crop season to control moisture content in the crop root zone. High water table conditions (e.g. 46 cm from the top of the bed) combined with rapid water movement in sandy soils in southern Florida can result in large fluctuations in water table levels in response to rainfall and irrigation. Bonczek and McNeal (1996) noted that water table fluctuations in seepage irrigation systems could result in a significant movement of fertilizer out of the root zone. Water table management has a direct and profound impact on soil moisture and nutrient concentrations in the root zone. Either too wet or too dry soil conditions can adversely impact crop yield, but water management can also cause low or high nutrient concentrations in the root zone. Therefore, water and nutrients have to be managed simultaneously to optimize yield and minimize nutrient losses to groundwater.

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[1] This chapter was published in the July -September 2007 17(3) edition of HortTechnology. Authors include: Gregory S Hendricks, Sanjay Shukla, Kent E. Cushman, Thomas A. Obreza, Fritz M. Roka, Kenneth M. Portier, and Eugene J. McAvoy

Irrigation management practices used by watermelon growers vary from simple to complex. Some growers rely on experience and personal judgment to assess soil moisture for irrigation management. Other growers use sophisticated moisture monitoring devices and/or evapotranspiration data to schedule irrigation. Likewise, N, P and K applied to watermelon crops vary according to grower preference and site-specific conditions such as soil characteristics. According to a survey of southwestern Florida watermelon growers, the average N, P, and K rates were 297, 83, and 427 kg ha^{-1}, respectively (Shukla et al., 2004). Fertilizer recommendations developed by UF-IFAS for watermelon are 168 kg ha^{-1} N along with P and K application rates determined by soil testing and laboratory recommendations (Maynard et al., 2001). Recommendations for managing irrigation, although less specific than for fertilizer, include managing soil water between field capacity and 50% depletion of the plant's available water to avoid plant water stress (Natural Resources Conservation Service, 1993).

Florida's vegetable industry is faced with environmental issues such as the development of total maximum daily load (TMDL) for nutrients of concern such as N and P. To achieve water quality goals, state agencies are promoting the use of best management practices (BMPs). BMPs are a practice or combination of practices based on research, field-testing, and expert review deemed to be effective and practicable for producers and for improving water quality in agricultural discharges (FDACS, 2005). BMPs are required to be economical and technologically feasible. To maximize yields, fertilizer and water inputs for watermelon production in southern Florida often exceed the recommended inputs. To promote the use of recommended inputs, current production practices need to be compared with the recommended practices with special emphasis on yield performance and farm profitability.

Objective

This study evaluated three water and nutrient management systems for watermelon production in southern Florida with regards to watermelon yield, fruit quality, and farm income. The first system involved typical water and nutrient management practices encountered in southern Florida. The second and third systems involved soil moisture-based water table management systems with recommended fertilizer rates (Maynard et al., 2001).

Materials and Methods

The study was conducted during the winter-to-spring growing seasons of 2004 and 2005 and was located at the Southwest Florida Research and Education Center (SWFREC) in Immokalee, Fla. The center is located in Collier County at an elevation of 10.7 m above mean sea level. The soil at the site is Immokalee fine sand (sandy, siliceous, hyperthermic, Spodic Psammaquents) with CEC of 12 Cmol/kg and pH of 5.6 (Carlisle et al., 1989), and 49 mg kg^{-1} and 60 mg kg^{-1} of Mehlich-1 extractable P and K, respectively. This soil is common in the flatwood regions of southern Florida. Immokalee fine sand is characterized by poor drainage, nearly level surfaces (slopes less than 2%), and a poorly drained spodic layer situated approximately 0.9 to 1.2 m below the soil surface. This soil also has a moderately rapid permeability (5.1 to 15.2 cm/h) and low available water capacity (5-7%). The average annual rainfall for the region is approximately 137 cm (Fernald and Purdum, 1998). A field of approximately 1.5 ha was divided into six main plots of 0.24 ha each. Each plot was 0.1 ha of bedded area. Crop beds were 20 to 25 cm high and spaced 1.8 m apart.

This study considered three nutrient and water management systems: HR, RR, and RR-SD. The HR fertilizer rate, based on the results of a grower survey, was 297, 83, and 427 lb/acre N, P, and K, respectively, and the moisture level was held in the range of 16 to 20%. The moisture content range was based on a survey of watermelon producers in southwestern Florida (Shukla et al., 2004). The fertilizer rate for RR and RR-SD treatments was 168, 49, and 140 kg ha^{-1} N, P, and K, respectively, and the moisture level was held in the range of 8 to 12%. This moisture content range was considered suitable based on the reported field capacity of this soil, which ranges from 8.5 to 12% and the wilting point, which is about 4% (Carlisle et al., 1989). Water tables in HR and RR were managed by water supplied to shallow irrigation ditches placed parallel to each set of three rows of plant beds. The water table in RR-SD was managed by water supplied to subsurface drip tubing (UniRam RC; Netafim Irrigation, Inc., Fresno, Calif.) that was installed approximately 46 cm beneath the soil surface and perpendicular to the plant beds. Drip tubing was operated at 20 psi and emitter spacing was 0.9 m. Each emitter had a maximum flow rate of 3.5 L/h.

The three treatments in this study involved two levels of water table management. The water table for HR was higher than that of RR or RR-SD. However, maintaining two different water table regimes in neighboring fields is difficult due to exchanges of groundwater between HR, RR, and RR-SD. To maintain different water table depths for different treatments, main plots were separated from each other by a vertical polyethylene plastic barrier to prevent lateral flow of water and nutrients between plots. The polyethylene barrier extended from the soil surface to the average depth of the spodic layer (0.9 m). An external drainage canal bordered most of the field's perimeter to convey runoff or drainage from the field (Fig. 2-1). Soil samples were taken at regular intervals throughout the field to characterize the soil, especially depth to the spodic layer. Soil characterization data obtained from the samples indicated that the depth of the spodic layer, on average, was lower on the east section relative to the west section of the field. To account for possible hydrologic differences introduced by a variable spodic layer, the field was divided into two statistical blocks to account for this variation. It was assumed that hydrological characteristics within each block were uniform.

Fertilizer was applied as 10N–0P–8.3K (4.1% nitrate nitrogen, 3.2% ammoniacal nitrogen, 2.7% other water soluble N and 10% soluble potassium as K_2O derived from potassium nitrate), 0N–20.2P–0K (concentrated superphosphate), and 0N–0P–49.8K (potassium chloride). Twenty percent of the N and K and 100% of the P fertilizer was incorporated into the bed. The remainder of the N and K was applied in two shallow grooves (5.1 to 6.4 cm deep) at the top left and right sides of the bed.

Soil moisture levels within each treatment plot were monitored on a daily basis by capacitance probes (EasyAg®, Sentek Sensor Technologies, Stepney, South Australia.), each having sensors at depths 10, 20, 30, and 50 cm. Moisture content measurements were recorded as percent (volumetric, v/v). The grower survey indicated that growers in southwestern Florida often maintain soil moisture levels higher than the field capacity in the top 12 cm of a raised bed. To emulate this style of water management, soil moisture in the bed was maintained at a level that was higher than field capacity.

For 2004, seedlings of diploid watermelon cv. Mardi Gras and triploid watermelon cv. Tri-X 313 were obtained from a commercial transplant production facility and transplanted on 8 Mar. A row of diploid seedlings was transplanted between every two rows of triploid plants. For 2005, seedlings of ‘Tri-X 313’ were transplanted in all rows on 21 Feb. and then the dedicated pollinizer ‘SP-1’ was interplanted between each third and fourth triploid plant. The study was replanted on 15 Mar. due to poor growth of the first planting and variability in seedling uniformity. In addition, more than 10.2 cm of rainfall occurred during the week of 21 Feb. and additional N and K fertilizer was applied manually at the rate of 33.6 kg ha^{-1} and 26.9 kg ha^{-1}, respectively, to compensate for leaching. The compensatory N and K application was based on Florida extension recommendations (Maynard et al., 2001a). The second planting performed well and the study was brought to completion. Crop yield was recorded from three subsample areas within each plot. Subsample areas were 6.1 m long by six beds wide. An industry cooperator with experience in watermelon production determined when fruits were harvestable and experienced pickers selected marketable fruit at each harvest. Fruit from each subsample area were counted and weighed, and five fruits from each subsample area were selected for internal evaluations. Soluble solids content was measured with a handheld refractometer. Hollowheart was measured at the widest point with a micrometer gauge. Watermelons located outside the subsample areas were harvested, counted, and weighed using an industrial scale. Weights were recorded by treatment, with blocks 1 and 2 combined, to provide adequate tonnage for the scale.

Samples for leaf tissue and petiole sap analyses were collected biweekly at about 10:00 AM at each sample date. The most recently matured leaf (MRML) was removed for leaf tissue analysis. Two sets of six to eight MRMLs were collected from each plot. Composite samples were dried, ground and then sent to a commercial lab for analysis of N and K. Petioles from two sets of six to eight MRMLs were also selected from each plot. Each composite sample was chopped and mixed; a subsample was taken for petiole sap analysis using a specific ion meter (Cardy, Spectrum Technologies, Inc., Plainfield, Ill.). Each meter was calibrated biweekly according to the user manual specifications for nutrients N and K (Spectrum Technologies, 2006a, 2006b).

The experimental design was a randomized complete block design with two replications and three subsample areas within each experimental unit. Initially, the study was evaluated as a nested design, accounting for block, experimental treatment, and crop season (or year) as fixed effects and estimation of replication (block by treatment interaction) and subsampling variability. Test for treatments, however, had low power due to low replication. Wald's test was then used to compare replication and subsampling variance component estimates, and in all cases the two estimates were not statistically different. A second analysis model was used that pooled replication and subsampling variability for the test of treatment effects. Results are reported using this second analysis model, which typically had a pooled variance estimate that was larger than the replication residual variance but also more denominator degrees of freedom for the statistical tests (and hence more powerful tests). Pooling variance estimates for testing of main plot effects is typically not a valid substitute for increased main plot replication but in this case increasing main plot replication was not feasible. Estimation and test computations were performed using SAS (SAS Institute Inc., 2004), general linear model (GLM), and linear mixed model (MIXED) procedures for yield, soluble solids content, and hollowheart responses. Yields were calculated and analyzed based on watermelon fruit weights greater than or equal to 4.5 kg. Significance of statistical tests is indicated at P-values less than 0.05 and means separation was performed using Tukey's test.

Economic data were collected on fertilizer and triploid watermelon prices, as well as costs on fertilizer application, harvesting, and marketing costs. Fertilizer prices were estimated to be \$0.99/kg, \$1.50/kg, and \$0.40/kg for N, P, and K, respectively, (Economic Research Service, 2006). Season average prices for triploids ranged from \$0.18/kg in 2004 to \$0.34/kg in 2005 (FDACS, 2006 a). Fertilizer application costs were estimated to be \$62/ha (Smith and Taylor, 2005). Harvesting and marketing costs were estimated to be \$0.065/kg (Smith and Taylor, 2005). The HR treatment incurred more fertilizer costs. An economic analysis was necessary only so long as HR produced more yield than the treatments with lower fertilizer rates. If the HR treatment produced significantly higher yields of triploid watermelons, a partial budget analysis would determine the costs of the HR treatment, the value of the yield difference, and the break-even price necessary to cover all grower costs associated with the HR treatment. Grower costs consisted of two components: 1) higher costs from using more fertilizer, and 2) higher harvesting and marketing costs associated with higher yields from the HR plots.

Results and Discussion

Despite large numerical differences, HR did not produce significantly higher yields (no. /ha and kg/ha) of diploid or triploid watermelons during 2004 compared with RR or RR-SD (Table 2-1). In contrast, HR produced significantly higher yields (no. /ha and kg/ha) of triploid watermelons during 2005 compared with RR or RR-SD, with HR producing about 60 and 80% higher yields (kg ha^{-1}) than RR and RR-SD, respectively. Compared with RR and RR-SD, watermelons from HR were larger, but this difference was significant only for triploids during 2005 (Table 2-1). Soluble solids content and hollowheart ratings were not affected by treatments. Soluble solids content ranged from 9.6 to 11.1% for diploids during 2004 and from 11.7 to 12.5% for triploids during 2004 and 2005 (Table 2-1). Hollowheart ratings were low for diploids and ranged from 7 mm to 17 mm in width for triploids (Table 2-1).

Total plant biomass during 2005 followed a similar trend as yield, with HR producing 105 and 125% greater total dry weight than RR and RR-SD, respectively (Table 2-2). The N, P, and K uptake by plant biomass of HR was 56, 29, and 120% higher than that of RR, respectively. Similarly, the N, P, and K uptake by plant biomass of HR was 56, 50, and 108% higher than that of RR-SD, respectively. Leaf tissue (N and K) and petiole sap (K only) data for 2005 exhibited declining trends, beginning at or above sufficiency levels and declining steadily with time until after second harvest (Fig. 2-2). This occurrence is a common occurrence for seepage-irrigated crops where most fertilizer applications occur before planting (Simonne and Hochmuth, 2005).

However, HR frequently exhibited higher N and K concentrations than RR and RR-SD. Higher values for HR were clearly evident for K content whereas differences for N content were not as large. The N content from leaf tissue analyses was at or above sufficiency ranges for each of the three treatments throughout the study. The K content from leaf tissue analysis was at or above sufficiency ranges until week 9 for HR and week 7 for RR and RR-SD. The K content from petiole sap analysis was within sufficiency ranges for HR for the duration of the study but mostly below sufficiency ranges for RR and RR-SD (Fig. 2-2). Values for leaf petiole sap N content produced a similar trend as that of leaf tissue N content but were significantly lower than expected and thought to be too low to be accurate (data not shown).

During 2005, yields of triploid watermelon ranged between 14683 and 17037 kg/ha higher for HR than for RR-SD and RR, respectively (Table 2-1). In addition, total large-plot yield data, as provided by the commercial cooperator, indicated HR produced at least 10088 kg/ha more triploids than RR or RR-SD (data not shown). Therefore, partial budgeting analysis was used (Table 2-3) to consider a matrix of costs and benefits of HR associated with yield increases from 14571 to 16813 kg/ha. The lower end of the yield range, 14571 kg/ha, represented a conservative estimate of yield gain from HR, while the upper end of the yield range, 16813 kg/ha, allowed more optimistic gains. Low ($0.18/kg) and high ($0.34/kg) watermelon prices were used to span a range of market conditions that existed during the 2004 and 2005 seasons.

Additional fertilizer used in HR cost $294/ha. Accounting for higher harvesting and marketing costs associated with higher yields, total costs of higher fertilization rates (HR) were between $949/ha and $1386/ha, depending on the actual yield increase. At a lower yield increase (14571 kg/ha), $0.085/kg was the “break-even” fruit price necessary to cover the total costs of the HR. As yield increased to 16813 kg/ha, the break-even price fell to $0.082/kg. During 2004 and 2005, average season prices for triploids were higher than break-even values, ranging between a low of $0.18/kg in 2004 to $0.34/kg in 2005. Under conservative yield increase expectations and low market prices, HR increased grower net returns by $1458/ha. Under higher yield and price expectations, the gain in grower net return increased by $4359/ha.

Values for yield (kg/ha and no. /ha), average fruit weight (kg/melon), and N, NO_3^-, and K content of leaf and petiole tissue were almost always higher for HR than for RR or RR-SD. The data show a trend of increased plant performance with increased fertilization and soil moisture content, but only a few of these values were statistically significant. The combined effects of limited treatment replication and variable soil properties resulted in variability that made it difficult to detect significant differences among treatments during 2004. Leaf tissue data during 2005 indicated that all treatments were above or within the N sufficiency levels throughout the duration of the study until second harvest. Leaf tissue and petiole sap data showed a rather steady decline from sufficient to insufficient concentrations of K throughout the duration of the study.

Rainfall during the two growing seasons was another source of variation, with three times more rainfall during 2005 than 2004 (Table 2-4). Higher than normal rainfall conditions in 2005 made maintenance of target soil water content difficult. Spring in southern Florida is normally dry compared with summer, fall, and winter seasons (Fernald and Purdum, 1998). Rainfall during spring 2005 was above normal. Soil moisture content varied over the duration of the study, but despite these variations, the average moisture level in HR was numerically higher than that of RR during both years. This was consistent with one of the aims of the study, to maintain greater soil moisture content in HR. Soil moisture content of RR-SD was consistently higher than RR and varied higher or lower compared with HR (Table 2-4). Moisture levels in this study were difficult to maintain using water table management for several reasons: 1) water percolation through the soil profile was affected by unpredictable fluctuations in the regional water table; 2) spodic layer (restrictive soil layer) depth and continuity varied in the experimental area; 3) irrigation was at times interrupted in response to actual and anticipated rainfall events and; 4) evapotranspiration (ET) varied in response to crop vigor (treatment) and variable soil characteristics in the experimental area. The thickness of the spodic layer can be highly variable and can vary in thickness from a few centimeters to more than 0.6 m within horizontal distances of a few inches (Jaber et al., 2005). Such differences can cause variability in water table depths and result in variable soil moisture content in the root zone of the crop.

Wet soil conditions during 2005 probably enhanced nitrate (NO_3^-) and K leaching especially during the early part of the season. This inference is supported by trends in plant N and K nutrient status that were above the sufficiency range at first measurement and then declined to either the lower limit of sufficiency ranges (N) or well below it (K) during the course of the experiment (Fig. 2-2). Plant nutrient status indicated a likely soil K deficiency for optimum plant growth and fruit production. Deficiency for N, if any, was small and occurred at the end of the study period (Fig. 2-2). Rainfall data showed 6.4 cm of rain fell on 17 Mar., just 2 d after transplant. Jaber et al. (2006) observed that for every 1 cm rainfall the water table for the Immokalee fine sand can rise up to 15-16 cm. In response to this large rainfall, water tables in all six plots rose to the surface and likely resulted in higher rates of fertilizer dissolution. In an effort to minimize stress on the transplants due to excessively high moisture conditions, riser boards installed in each plot were removed to facilitate drainage that allowed the water table to drop. The falling water table may have carried some of the dissolved fertilizer (N and K) with it thereby reducing the amount of N and K left in the plant bed. This contributed to fertilizer loss by the phenomenon called “dropout” (Bonczek and McNeal, 1996). Dropout is the downward movement of dissolved nutrients resulting from density differences in the soil solution created by high nutrient concentration in the upper regions of the soil profile relative to the lower regions.

Higher yields of HR were likely the result of higher fertilizer rates and higher soil moisture content compared with RR and RR-SD. However, our data support the conclusion that soil moisture for RR and RR-SD was above optimum levels for each year. This result suggests that differences among treatments were likely due to differences in fertilizer and not differences in soil moisture content. Periods of excessive moisture at times in HR did not adversely affect crop yield which again appears to indicate that the main factor affecting crop yield in this study was fertilization. It appears that under wet conditions, the RR approach may not be sufficient to sustain the optimum yield compared with the HR due to excessive K (and possibly N) leaching.

A partial budget analysis of costs and benefits of the HR treatment indicates a strong economic motivation for higher fertilization rates. Even under conservative yield and price expectations, the value of yield increases observed during 2005 covered the additional total cost for both the 2004 and 2005 season.

Summary and Conclusion

In summary, this study evaluated the performance of three nutrient and water management systems for seepage-irrigated watermelon in southern Florida. Trends in the data showed greater plant performance with higher rates of fertilizer and higher soil moisture content in 2005 but not in 2004. Our ability to detect significant differences was enhanced by higher rainfall in the 2005 season compared with 2004, indicating again the importance of maintaining adequate levels of nutrients in the root zone of a seepage irrigated crop. This study suggests that growers may need to apply higher fertilizer rates particularly during wet years; however, because of the lack of statistical differences in 2004, more study is warranted.

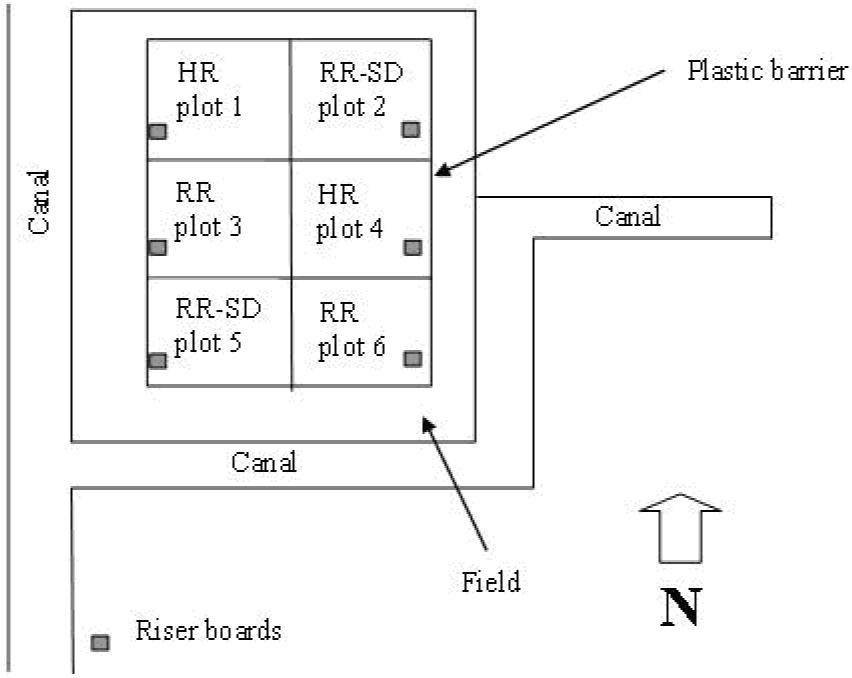

Figure 2-1. Layout of experimental design for watermelon production with plastic mulched raised beds and seepage irrigation. Total experimental area was 3.6 acres.

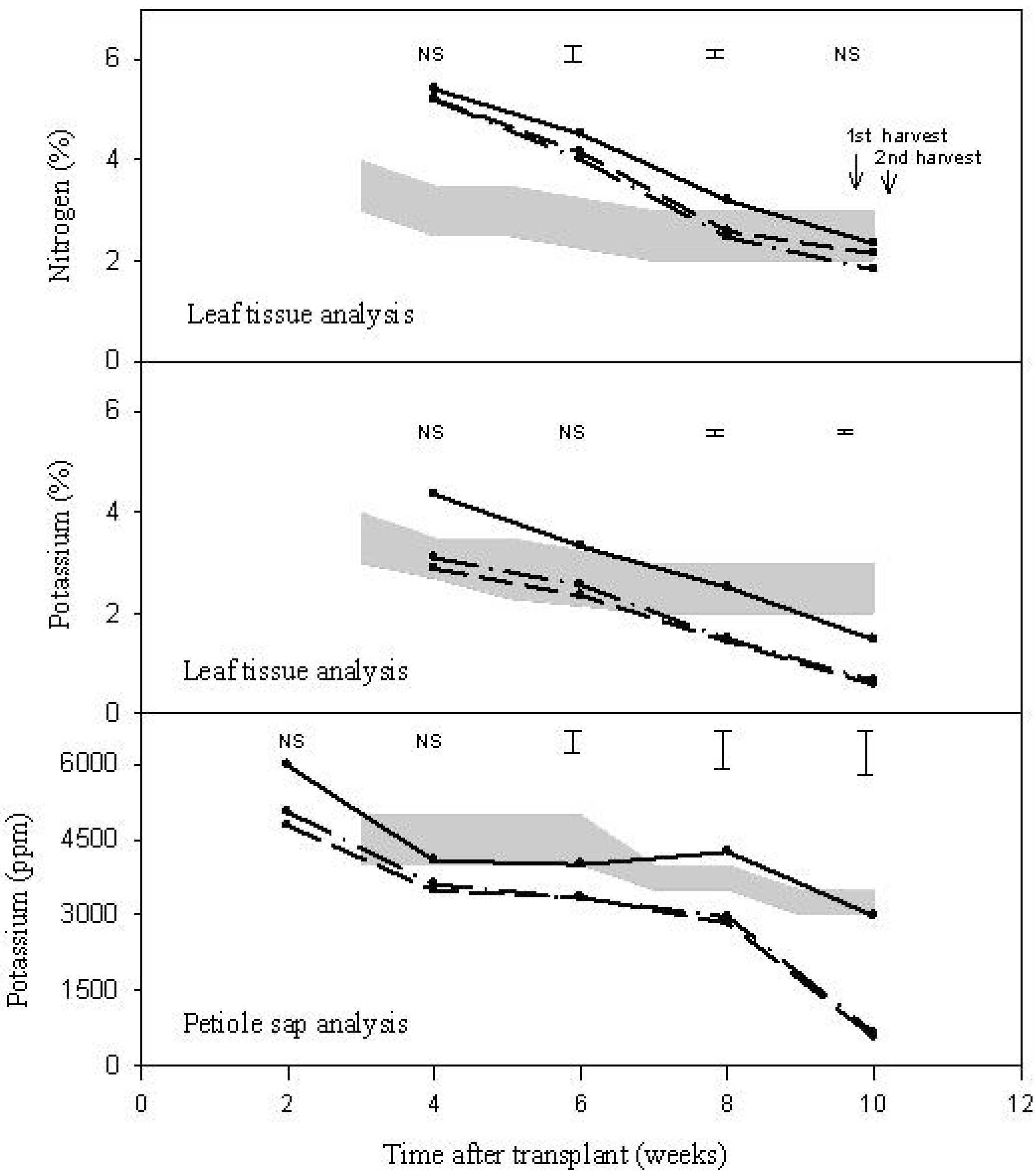

Figure 2-2. Leaf tissue analyses (nitrogen and potassium) and petiole sap concentrations (potassium) from watermelon plants during 2005. High rate (HR) treatment (solid line) is high fertilizer rate and soil water content. Recommended rate (RR) treatment (dashed line) is recommended fertilizer rate and soil water content. Recommended rate with subsurface irrigation (RR-S) treatment (dash-dot-dash line) is same as RR but with subsurface drip irrigation. Grayed areas depict sufficiency ranges (Hochmuth et al., 2004).

Table 2-1. Yield, average weight (Avg. wt.), soluble solids content (SSC), and severity of hollowheart (HH) for watermelon grown under three different water and fertilizer management strategies during spring 2004 and 2005

Year	Treatment	Diploid					Triploid				
		Yield		Avg. wt.	SSC	HH	Yield[y]		Avg. wt.[y]	SSC	HH
		(melons/ha)	(kg ha^{-1})	(kg)	(%)	(mm)	(melons/ha)	(kg ha^{-1})	(kg)	(%)	(mm)
2004	HR	9867	84961	8.6	10.7	1	7253	49766	6.8	12.2	17
	RR	7401	60302	8.2	9.6	0	4337	29254	6.8	11.7	10
	RR-SD	6578	53240	8.1	11.1	0	5983	39118	6.5	12.2	10
Significance											
	P	0.331	0.261	0.410	0.786	0.216	0.420	0.336	0.369	0.618	0.241
2005	HR	--	--	--	--	--	6079 a	38669a	6.4a	12.5	10
	RR	--	--	--	--	--	3786 b	21632b	5.8b	12.4	7
	RR-SD	--	--	--	--	--	4060 b	23986b	5.9b	12.4	10
Significance											
	P	--	--	--	--	--	0.037	0.031	0.043	0.964	0.361

Values for yield represent the average of three subsample plots in each of two blocks. Values for Avg. wt., SSC, and HH represent the average of five fruit per subsample, three subsamples, and two replications. [y]Values followed by the same letter are not significantly different at a level of significance, $P \leq 0.05$. Means separation by Tukey's test.

Table 2-2. Biomass, nitrogen (N), phosphorus (P), and potassium (K) content, and total uptake of N, P, and K of watermelon plant material harvested (i.e., roots, foliage and fruit) from a 24 ft^2 area within each plot during 2005 after second harvest

Treatment	Biomass (g m^{-2})^x	Above ground (%)^y			Below ground (%)^y			Fruit uptake (kg/ha)^{z,y,x}			Total uptake (kg/ha)^{y,x}		
		N	P	K	N	P	K	N	P	K	N	P	K
HR	457	1.71	0.17	1.94	1.52	0.15	1.47	55.8	9.5	50.7	93.1	13.1	93.1
RR	223	1.36	0.24	0.67	1.30	0.22	0.79	31.5	5.4	28.7	59.5	10.1	42.4
RR-SD	203	1.56	0.18	0.78	1.32	0.18	0.86	34.6	5.9	31.5	59.5	8.7	44.8

^{x}1 g·m^{-2}=2.2297 g/24 ft^2; 1kg·ha^{-1}=0.8921lb/acre; 1 m^2=10.7643 ft^2. ^{y}Average of two replications. ^{z}N, P, and K analysis for fruit was performed for only one treatment; results assumed the same for all treatments (i.e., 2.41N–0.41P–2.19K). Fruit uptake of N, P, and K was determined from the weight of fruit harvested from the 2.23 m^2 areas; these weights were based on the estimated average number and weight of fruit from subsample plots in each plot. Associated weights (dry) were multiplied by the percent N, P and K assumed present in each watermelon. Total uptake is the sum of the N-P-K in above and below ground biomass and the fruit uptake.

Table 2-3. Partial budgeting analysis for watermelon over a range of yield and price expectations considering three different water and fertilizer (nitrogen, N; phosphorus, P; potassium, K) management strategies during 2004 and 2005

			Dollars/ha[z]	
		Cost/kg[z]	Low yield gain (14571 kg/ha)	High yield gain (16813 kg/ha)
Added cost of HR treatment	Harvest and marketing	$0.06	$ 946.4	$1,092.2
	Higher fertilizer cost[y]		$ 294.1	$ 294.1
Total added cost			$1,240.5	$1,386.3
Break-even price[x]			$ 0.09/kg[z]	$ 0.08/kg[z]
Added benefit of HR treatment	Low watermelon price [w]	$0.18	$2,698.4	$3,113.6
	High watermelon price [w]	$0.34	$4,979.3	$5,745.3
	Low watermelon price [w]	$0.18	$1,457.9	$1,727.3
Benefit-cost	High watermelon price [w]	$0.34	$3,738.8	$4,359.0

[z]$1.00/cwt = $0.0220/kg; $1.00/acre = $2.4711/ha; [y]HR: 297, 83, and 427 kg ha^{-1} of N, P, and K at $0.99/kg, $1.5/kg, and $0.4/kg, respectively; $1.00/lb = $2.2026/kg. RR: 168, 49, and 140 kg ha^{-1} of N, P, and K at $0.99/kg, $1.5/kg, and $0.4/kg, respectively. [x]Break even price calculated by dividing total added cost by expected yield gain. [w]Source: Vegetable acreage, production, and value report (Florida Agricultural Statistics Service, 2006).

Table 2-4. Soil moisture content (% by volume, biweekly average) and rainfall (depth, biweekly total) for watermelon plants with high fertilizer rate (HR), recommended fertilizer rate (RR), and same as RR but with subsurface irrigation (RR-SD) treatments during spring 2004 and spring 2005

2004					2005				
	Moisture content (%)[y]					Moisture content (%)[y]			
Weeks	HR	RR	RR-SD	Rainfall (cm)	Weeks	HR	RR	RR-SD	Rainfall (cm)
0-2	16.0	13.5	14.8	0.2	0- 2	14.9	8.4	15.8	6.9
2-4	--	--	--	0.1	2- 4	22.8	14.3	20.0	4.1
4-6	15.1	8.1	9.5	3.5	4- 6	20.4	14.1	17.8	0.4
6-8	22.0	9.9	12.0	2.2	6- 8	17.0	14.8	14.4	4.7
8-10	16.1	8.7	13.0	1.5	8-10	15.4	13.0	15.1	0.3
10-12	12.2	5.2	11.6	0.0	10-12	10.3	12.1	18.6	14.4
12-14	7.5	6.1	7.6	6.3	12-14	16.9	14.4	20.7	15.4
Season total				13.8					46.2
Season average	14.8	8.6	11.4			16.8	13.0	17.5	

[y]Measurements taken for the entire depth of bed (0-20cm)..

CHAPTER 3
FLORIDA TOMATO PRODUCTION AFFECTED BY WATER AND NUTRIENT MANAGEMENT[2].

Introduction

The flatwoods regions of Florida are unique to the USA and are known for their low lying poorly drained sandy soils. Their relatively high water tables fluctuate greatly during the wet season. Large portions of the flatwoods regions are used in a vibrant agricultural industry that supports more than 40,000 farms and utilizes 4.05 million hectares of land (NASS, 2004). Many crops are considered high-valued. For instance, commercial vegetables were grown on 56,253 ha during 2005-2006 and generated farm sales of more than $1.1 billion. This sales potential creates a strong incentive for this type of land use, but at the same time intensive agricultural operations are considered non-point sources of pollution for surface and ground waters (Florida Department of Agriculture and Consumer Service; FDACS, 2007).

A variety of vegetable farms are located throughout the state of Florida. Tomato production accounts for 27% of planted hectarage (FDACS, 2007). The vast majority (80%) of tomato production hectarage is located in central and south Florida (Glades Crop Care, 1999). The ability for flatwoods soils to support a high water table makes them suitable for extensive production of high valued crops such as tomatoes. Over a 10 year period, 1996 – 2006, the total value of tomatoes for fresh market production was consistently more than $400 million each year. Furthermore, Florida frequently ranks first or second in the U.S. for value of fresh market tomato production. For instance, during 2006, Florida was ranked first in value of fresh market tomato production and accounted for 35% of the total U.S. value for fresh market tomatoes

[2]This chapter is a manuscript currently under preparation for a peer-reviewed journal. Authors include: Gregory S Hendricks, Sanjay Shukla, Fritz M. Roka, Kent E. Cushman, Kenneth M. Portier, Thomas A. Obreza, Eugene J. McAvoy.

(FDACS, 2007). In addition, tomatoes (along with peppers, sweet corn, cucumbers and snap beans) accounted for the largest amount of sales among vegetable crops during the period 2005-2006 (FDACS, 2006b). The industry anticipates that the value of fresh market tomato receipts may exceed $4 billion (Lucier and Plummer, 2004). There is no question about the monetary significance of tomato production in the state's economy. However, the inherent nature of tomato production makes it a non-point source of pollution, which can adversely result in significant environmental costs.

Most of the tomatoes grown in south Florida are produced on parallel rows of plastic mulched raised beds (crop beds) with a single application of nutrients (N, P and K) applied during bed formation. Water is commonly applied using seepage irrigation (68% planted hectarage) in preference to drip irrigation (31% planted hactarage) (Glades Crop Care, 1999). Due to the low water retention capacity of sandy soils and the inefficiency of seepage irrigation in south Florida, the traditional nutrient management strategy for tomato production in south Florida experiences the following: 1) fertilizer applications in excess of the plant's immediate need, and 2) the application of copious amounts of water with seepage irrigation systems. These factors, along with the high water table conditions of flatwoods soils and high rainfall combine to make the surface and ground waters in south Florida vulnerable to nutrient contamination. This vulnerability to nutrient contamination is supported by the findings of Berndt et al. (1998), who found that more than 20% of samples taken from agricultural areas throughout the Georgia-Florida Coastal Plain had NO_3^- concentration above the 10 mg/L limit for nitrate-nitrogen set for drinking water by the USEPA. Surface and groundwater contamination from agricultural systems are major issues in Florida. To address these issues, Best Management Practices (BMPs) have been developed to reduce nutrient contamination of surface and ground waters by agricultural production systems.

In Florida, the responsibility for developing and implementing BMPs rests with FDACS as required by the Florida Watershed Restoration Act (1999). FDACS defines a BMP as "a practice or combination of practices determined by the coordinating agencies, based on research, field-testing, and expert review, to be the most effective and practicable on-location means, including economic and technological considerations, for improving water quality in agricultural and urban discharges" (FDACS, 2005). The Florida Department of Environmental Protection (FDEP) has designated specific managerial and structural BMPs to achieve water quality targets for impaired water bodies. One of the more common managerial BMP recommended by FDACS is a water and nutrient management strategy that aims to reduce agricultural pollutants [e.g., fertilizer nitrogen (N) and phosphorus (P)] and the means to transport (water) the pollutant. Typically, BMPs recommended by FDACS are less than the fertilizer and water rates used by commercial vegetable growers.

The effect of fertilizer BMPs on crop yields have been evaluated by several studies that have found no evidence to indicate any significant differences in fruit yield under reduced fertilizer loads. Everett (1978) conducted a study, during four crop seasons, to evaluate the effect of a range of nitrogen and potassium rates on yield on fruit size of mulch-grown staked tomatoes. The author determined that an optimum yield for tomatoes grown in this study was achieved with N and K rates of within the range 182-303 kg ha^{-1} and 210-349 kg ha^{-1}, respectively. Hochmuth and Cordasco (2000) summarized numerous nutrient rate studies for tomato; synthesis of these studies led to the current University of Florida recommended fertilizer rates for commercial tomato production in Florida. In general, field studies have been completed that establish fertilizer rates for optimum tomato production, but none have incorporated an evaluation of farm income (profits) that is associated with fruit yield derived from the established fertilizer rates.

Vegetable growers have been reluctant to accept and apply recommended fertilizer and irrigation water rates to their fields. Even though studies have shown that recommended fertilizer rates do not significantly affect crop yield, many farmers are still uncertain about the effect of recommended fertilizer rates on crop yield and farm income. For this reason, many farmers are still applying fertilizer loads in excess of plant needs during each crop season. Therefore, it is important that BMP studies be designed to develop a greater understanding of the impact that an adopted BMP would have on crop yield and farm revenues. Furthermore, BMP studies that include economic considerations often rely on theoretical or empirical crop models to evaluate the effect of BMPs on farm income. These studies, while useful, have to rely on many assumptions that may over-simplify the complex nature of a vegetable production system. However, large-scale BMP field studies that adapt management strategies similar to those of vegetable growers are likely to provide results that are more representative of a vegetable production system.

Objective

This study evaluated three water and nutrient management systems for tomato production in southern Florida with regard to tomato yield and farm income. The first system involved typical water and nutrient management practices encountered in southern Florida. The second and third systems involved soil moisture-based water table management systems with recommended fertilizer rates (Maynard et al., 2001). The objectives were to design a large scale experiment that would be operated the same as a typical vegetable production system in south

Florida, evaluate the effect of nutrient and water BMPs on the yield of a tomato crop, and assess the potential impact of reduced nutrient application on farm profitability.

Materials and Methods

A study was conducted during the summer-to-winter growing seasons of 2004, 2005, 2006 and the winter-to-spring growing season of 2006; and was located at the Southwest Florida Research and Education Center (SWFREC) in Immokalee, FL. The center is located in Collier county at an elevation of 10.7 m above mean sea level. The soil at the site is Immokalee fine sand (sandy, siliceous, hyperthermic, Spodic Psammaquent) with CEC of 12 Cmol/kg and pH of 5.6 (Carlisle et al., 1989), and 49 mg/L and 60 mg/L of Mehlich-1 extractable P and K, respectively. This soil is common in the flatwoods regions of southern Florida. Immokalee fine sands are characterized by poor drainage, nearly level surfaces (slopes less than 2%), and a poorly drained spodic layer situated approximately 0.9 to 1.2 m below the soil surface. This soil also has a moderately rapid permeability (5.1 to 15.2 cm/h) and low available water capacity (5 to 7%). The average annual rainfall for the region is approximately 137 cm (Fernald and Purdum, 1998). A field of approximately 1.5 ha was divided into six main plots of 0.24 ha each. Each plot was 0.1 ha of bedded area. Crop beds were 20 to 25 cm high and spaced 1.8 m apart

This study considered three nutrient and water management systems: high fertilizer rate with seepage irrigation (HR), university recommended fertilizer rate with seepage irrigation (RR), and recommended fertilization rate with sub-surface drip irrigation (RR-SD). The HR fertilizer rate was 418, 182, and 754 kg ha^{-1} N, P, and K, respectively, and the moisture level was held in the range of 16 to 20%. Both fertilizer rate and moisture level for the HR treatment were based on results from a survey of tomato producers in southwestern Florida (Shukla et al., 2004). The N rates for RR and RR-SD treatments followed University of Florida recommendations (i.e., 224 kg/ha). Rates for P and K were applied based on a soil fertility test. During spring 2004, 135 and 252 kg ha^{-1} of P and K were applied to RR and RR-SD treatments, respectively. For the remaining seasons, P was not applied and K was applied at 252 kg ha^{-1}. The moisture levels for the RR and RR-SD treatments were held in the range of 8 to 12%. This moisture content range was considered suitable based on the reported field capacity of this soil, which ranges from 8.5 to 12% and the wilting point, which is about 4% (Carlisle et al., 1989). Water tables in HR and RR were managed by water supplied to shallow irrigation ditches placed parallel to each set of three rows of plant beds. The water table in RR-SD was managed by water supplied to subsurface drip tubing (UniRam RC; Netafim Irrigation, Inc., Fresno, Calif.) that was installed approximately 46 cm beneath the soil surface and perpendicular to the plant beds. Drip tubing was operated at 137.9 kPa and emitter spacing was 0.9 m. Each emitter had a maximum flow rate of 3.48 L/h.

The three treatments in this study involved two levels of water table management. The water table for HR was higher than that of RR or RR-SD. However, maintaining two different water table regimes in neighboring fields would have been difficult due to exchanges of groundwater between HR, RR, and RR-SD. To maintain different water table depths for different treatments, main plots were separated from each other by a vertical polyethylene plastic barrier (PPB) to prevent lateral flow of water and nutrients between plots. The PPB also minimizes the amount of groundwater (external the experimental area) that would flow laterally into the experimental area. The PPB extended from the soil surface down into the spodic layer (approx. 0.9 m). An external drainage canal bordered most of the field's perimeter to convey runoff or drainage from the field. Soil samples were taken at regular intervals throughout the field to characterize the soil, especially the depth to the spodic layer. Soil characterization data obtained from the samples indicated that the depth of the spodic layer, on average, was lower on the east section relative to the west section of the field. To account for possible hydrologic differences introduced by a variable spodic layer, the field was divided into two statistical blocks to account for this variation. It was assumed that hydrological characteristics within each block were uniform.

Fertilizer was applied as 10N–0P–8.3K (4.1% nitrate nitrogen, 3.2% ammoniacal nitrogen, 2.7% other water soluble N and 10% soluble potassium as K_2O derived from potassium nitrate), 0N–20.2P–0K (triple superphosphate), and 0N–0P–49.8K (potassium chloride). Twenty percent of the N and K and 100% of the P fertilizer was incorporated into the bed. The remainder of the N and K was applied in two shallow grooves (5.1 to 6.1 cm deep) at the top left and right sides of the bed.

Soil moisture levels within each treatment plot were monitored on a daily basis by capacitance probes (EasyAg, Sentek Sensor Technologies, Stepney, South Australia.), each having sensors at depths 10, 20, 30, and 50 cm. Moisture content measurements were recorded as percent (volumetric, v/v). The grower survey indicated that growers in southwestern Florida often maintain soil moisture levels higher than the field capacity in the top 12 cm of a raised bed. To emulate this style of water management, soil moisture in the bed was maintained at a level that was higher than field capacity.

Seedlings of cv. BHN 586 were obtained from a commercial transplant production facility and transplanted on the dates shown in table 3-1. Seedlings of cv. Florida 47 were transplanted in place of cv. BHN 586 when the nursery was unable to supply sufficient numbers of cv. BHN 586. Seedlings were transplanted during the month of September 2004, 2005 and 2006, and during the month of February 2006. Tomato plants were staked and tied twice during each crop season so that plants were held upright keeping fruit off the ground to reduce the incidence of disease, and for the easy access to fruit during harvest. During a typical crop season, plants were regularly monitored for disease by a professional scout and sprayed weekly to deter the emergence of disease and fungi.

Fall 2005 was not considered a typical year for the tomato crop since it was affected by Hurricane Wilma which passed over the study site on October 24, and released 21 cm (8.2 in) of rain over 11hr that day. As a result the entire study site was inundated by water for most of the day; electricity was cut off which disabled the throw-out pump. Consequently, fertilizer rates for all treatments were supplemented with 67 $kg \cdot ha^{-1}$ (60 lb/ac) of N and K_2O. This was done to compensate for fertilizer loss by large amounts of leaching that likely occurred while the field was inundated during and after the storm. Tomato plants were able to develop to the point of harvest; this typically occurs during the month of December for the fall season and May during the spring season. The study was extended into fall 2006 in order to produce a third fall crop of tomatoes and collect data unaffected by a severe storm (i.e., Hurricane Wilma during fall 2005). This crop was implemented and maintained the same as previous tomato crops. Harvest dates (Table 3-1) for all tomatoes crops were determined by a professional grower who had many year of experience with tomato production.

Crop yield and biomass were monitored by regular harvesting of plant samples during the crop season and fruit harvesting at the end of the crop season. Crop yield and plant biomass monitoring was performed to quantify crop production, and to analyze plant nutrient (N-P-K) status. The analytes of interest were TKN, TP and K. The concentrations of these analytes in plant tissue were a function of the amount of fertilizer and the level of soil moisture present in each treatment (i.e., HR vs. RR). Total crop yield from each plot was recorded at the end of each crop season while leaf tissue and petiole sap was collected regularly from each plot throughout the crop season; samples were collected at least once every two weeks.

Crop yield was monitored on two levels: 1) fruit weight was taken from harvested sub sample plots within each plot and 2) the overall crop weight taken from each plot. Subplots for tomato crops were created by identifying six sets of ten adjacent plants located in the center row of a land (Fig. 3-1); rows with cv. Florida 47 were not included.

Each set of ten tomato plants were considered to be the healthiest looking plants within the bed. These subplots were located to the north and south of groundwater wells within each treatment plot. Sub plots were harvested at least three times per crop season. When sub plots were harvested, the fruits were sorted, graded and then weighed. Tomatoes were graded according to their maturity (red, breakers and mature green) and size (medium large and extra large).

Plant biomass was quantified using whole plants that were extracted on a weekly to biweekly basis during the spring and fall of 2006; whole plants were used to determine above and below ground biomass. Samples for leaf tissue and petiole sap analyses were collected biweekly for all crop seasons. The most recently matured leaf (MRML) was removed for leaf tissue analysis. Two sets of six to eight MRMLs were collected from each plot. Composite samples were dried, ground and then sent to a commercial lab for analysis of N and K. Petioles from two sets of six to eight MRMLs were also selected from each plot during spring 2005 through fall 2006. Each composite sample was chopped and mixed; a sub sample was taken for petiole sap analysis using a specific ion meter. Each meter was calibrated biweekly according to the user manual specifications for nutrients N and K (Spectrum Technologies, 2006a, 2006b).

The experimental design was a randomized complete block design with two replications and three subsample areas within each experimental unit. Initially, the study was evaluated as a nested design, accounting for block, experimental treatment, and crop season (or year) as fixed effects and estimation of replication (block by treatment interaction) and subsampling variability. Test for treatments, however, had low power due to low replication. Wald's test was then used to compare replication and subsampling variance component estimates and in all cases the two estimates were not statistically different. A second analysis model was used that pooled replication and subsampling variability for the test of treatment effects. Results are reported using this second analysis model, which typically had a pooled variance estimate that was larger than the replication residual variance but also more denominator degrees of freedom for the statistical tests (and hence more powerful tests). Pooling variance estimates for testing of main plot effects is typically not a valid substitute for increased main plot replication, but in this case increasing main plot replication was infeasible. Estimation and test computations were performed using SAS (SAS Institute Inc., 2004), general linear model (GLM), and linear mixed model (MIXED) procedures for yield and biomass responses. Significance of statistical tests is indicated at P-values less than 0.05 and means separation was performed using Tukey's test.

Economic data were collected on south Florida shipping point prices for mature green tomatoes during 2004 through 2006 (USDA, 2007). Average yield differences were calculated from the experimental data and compiled by harvest season and grade quality. Yield differences were cumulated over the four harvest periods and per acre revenues were calculated from three pricing sceneries – prevailing market prices, a consistent low market price, and a consistent high market price. The low and high market prices were chosen from the range of prevailing market prices over the experimental period (December 2004 through December 2006).

Results and Discussion

Yield Analysis

Overall, the average seasonal yield from all treatments was significantly higher during the spring crop season compared with the fall crop seasons. The average crop yield for the treatments during spring 2006 was 6,964 box/ha, which is 27% greater than the largest average yield for the treatments from the fall crop seasons (5,461 box/ha during fall 2006). This may be due to the timing of transplantation of tomato seedlings and the period of watering in the seedlings (crop establishment) during each season. The transplantation of tomato seedlings for the fall crop season typically occurs within the rainy season that starts during June and ends in September. Climatic data revealed that there were four rainfall events during the establishment period for fall 2004 (Aug 21-1.7 cm, Aug 26-1.6 cm, Aug 29-2.7 cm and Aug 30-1.9 cm) that may have resulted in the following: 1) nutrient leaching, 2) root damage resulting from salt accumulation in the root zone, or 3) both nutrient leaching and root damage-fall 2004 had the second lowest average yield for treatments (i.e., 4,653 box/ha). This is in contrast with two such rainfall events during fall 2006 (Aug 11-4.3 cm and Aug 18-1.5 cm) and no such rainfall event that occurred during spring 2006. Fall 2005 record the lowest average yield for treatments (1,943 box/ha) out of all the crop seasons. This was most likely due to the flooding effect of Hurricane Wilma that generated rainfall (20 cm in 1 day) that was much greater than that considered for a leaching rainfall event (8 cm in 3 days or 10 cm in 7 days). Excessive nutrient leaching and root damage are most likely the cause for the lowest yield produced during fall 2005.

The treatment effect within each season was not found to be significant at the $P = 0.05$ level. However, table 3-2 revealed that the P-value determined for treatments within each season generally decreased as the study progressed. Furthermore, it is very interesting that the decreasing trend of P-values for each season may be the result of a gradual removal of external nutrient sources (and sources antecedent to the study) that can mask any treatment effect in the experiment. This point is highlighted by the fact that the P-value for spring 2006 decreased by 64 points compared with the previous season’s P-value. This dramatic fall may be explained by the

20 cm of rain that fell on the study site, which would have acted as a large flushing agent for nutrients within each plot. This finding is significant because it indicates that as the study progresses the chance of committing a type I error diminishes (a type I error is the likelihood that the null hypothesis is reject when in fact it is true). Therefore, treatment effects may have been identified if the study had been able to continue for several more seasons.

For each season except fall 2005, yields from each treatment were comparable with the average yield (5,622 box/ha or 2275 box/ac) for Florida reported by (Maynard, 2003). Table 3-2 shows that during fall 2004, the RR-SD treatment had the highest numerical yield (4,811 box/ha) while the RR treatment had the lowest numerical yield (4,488 box/ha). In contrast to 2004, the RR treatment had the highest numerical yield (2,108 box/ha) during fall 2005 while the HR treatment had the lowest numerical yield (1,628 box/ha). Relatively low yields recorded for fall 2005 was due to the occurrence of Hurricane Wilma; as a result, the experiment for this season was compromised. During both spring and fall 2006 seasons, the HR treatment had the highest numerical yield (spring, 7,969 box/ha; fall, 6054 box/ha) while the RR-SD treatment had the lowest numerical yield (spring, 6,408 box/ha; fall, 5,162 box/ha). Despite numerical differences for all seasons, there were no significant differences among treatment averages at the 0.05 level of significance (Table 3-2).

Tomato yield (by grade) in the HR treatment was numerically larger than those in the RR treatments in most cases (Table 3-2). However, the reverse was found to be the case for fall 2004 (extra-large) and 2005 (large and extra-large). Table 3-2 also shows that extra-large fruit consistently accounts for 50-70% of the total yield for all treatments in all seasons. The HR treatment during fall 2005 was the only exception where extra-large fruit only accounts for a third of the total fruit yield. Again, Hurricane Wilma was likely the reason for diminished yields within these grade categories for this season. Medium and large fruit yields were consistently comparable for each treatment in all seasons. Even though trends in numerical differences were indentified, statistical analysis of the data did not detect any treatment effects for tomato yield for different grades in each season (Table 3-2).

Figure 3-2 displays the leaf tissue analyses for N, P and K. All nutrients (N-P-K) found within tomato leaf tissue from each treatment for all the growing seasons started within or above the sufficiency range and steadily declined to a seasonal low by the second crop harvest. The nutrient concentrations (N-P-K) for HR were found to be always numerically higher than the RR and RR-SD treatments. The HR tissue N-P-K concentrations never fell below their sufficiency ranges during any of the crop seasons. Phosphorus concentrations for RR and RR-SD during spring 2006 fell to the lower limits of the sufficiency range during weeks 10 thru 14 of the crop season (Fig. 3-2). K concentrations for the RR and RR-SD remained above or within their sufficiency range during all crop seasons, except for the weeks nearing the end of crop seasons fall 2004 and spring 2006. Concentrations of K in plant tissue during fall 2004 and spring 2006 for RR and RR-SD fell below the sufficiency range after week 10 and remained below the sufficiency range until the end of the crop season (Fig. 3-2A and 3-2C). Similar results are shown in Figure 3-3A and 3-3C; K concentrations in petiole sap have notably fell beneath the sufficiency range after week 10 for RR and RR-SD during fall 2004 and spring 2006. Deficiencies in K detected for RR and RR-SD treatments were likely the result of nutrients translocated from root, stem and leaves to fruit. Scholberg et al. (2000) showed that total dry matter accumulation shifted from stems (25-30%) and leaves (40-65%) at the initial stages of plant growth to fruit (55-65%) and stem (20-25%) near the end of the growing season.

Table 3-3 shows the average plant biomass for each treatment during spring and fall 2006. Although HR treatment (174.9 g) had a numerically higher annual average than that of the RR (154.4 g) and RR-SD (153.5 g) treatments, statistical analysis of this data revealed no treatment effect ($p = 0.6916$). Overall, result suggests that the plants in the HR treatment did not gain any significant benefits from the higher fertilizer and water input compared with the RR and RR-SD treatments.

Economic Analysis

A null hypothesis[3] was that tomato yields from blocks receiving a university recommended nitrogen fertilizer rate of 224 kg/ha are equal to blocks receiving a grower preferred rate of 418 kg/ha. That is,

H_o: $Y_{HR(418)} = Y_{RR(224)}$

The alternative hypothesis, one held by commercial tomato growers is that,

H_a: $Y_{HR(418)} > Y_{RR(224)}$

At the 95% confidence interval, yield differences among treatments were not statistically significant both in terms of total yield and yields by market grade (Table3-2). Therefore, we "fail to reject" the null hypothesis. The semantics of this statistical conclusion are important. Given our experimental design, the length of time over which the experiment was run, the limited number of replications, and the inherent variability in the field experiment, we could not measure a fertilizer-water treatment effect. Our results, on the other hand, can not conclusively affirm the null hypothesis. Thus, the alternative hypothesis of a positive yield response to higher nitrogen fertilizer rates cannot be completely refuted.

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[3]Analysis and discussion in this section was completed by Fritz M. Roka; Food and Resource Economics, Southwest Florida Research and Education Center. University of Florida institute of Food and Agricultural Sciences (UF/IFAS), 2686 State Road 29 N, Immokalee, Fl. 34142.

Over the 4-harvest periods, the HR treatment produced at least 1835 more 11 kg boxes than from either RR treatments (Table 3-4). Interestingly, year to year differences varied. In both the spring and fall 2006 trials, HR plots produced more boxes in all size categories than did RR plots. In fall 2004, RR treatments produced more "extra large" boxes, and in fall 2005 both RR treatments numerically out produced the HR treatment. As mentioned previously, however, the fall 2005 trial was compromised by Hurricane Wilma and the flooding conditions she caused.

Prevailing price for nitrogen fertilizer during the trial period was 88 per kilogram of elemental N. The amount of extra yield required to pay for a 194 kg/ha increase in nitrogen fertilizer (i.e., from 224 kg/ha to 418 kg/ha) varies with market prices (Fig. 3-4). Assuming a market price of $4.50 per box, an additional 171 box/ha would have to be produced to cover the added fertilizer cost[4]. As market prices increase, required yield increases fall dramatically. Between August of 2007 and June of 2008, nitrogen prices have doubled. Consequently, the yield threshold curve increases accordingly (Fig. 3-4).

Fresh market tomato is a high valued crop, and market prices on any given day can vary significantly according to the current supply and demand conditions. For the harvest dates of this trial, prevailing shipping point prices are reported in table 3-5. Over the four harvest periods, prices varied from a low of $4.45 to a high of $28.95 per box. Overall, prices averaged $11.50, $10.50, and $9.50 per box of extra large, large, and medium, respectively. At nitrogen prices of 88 cents per kilogram and market prices of $10.50 per box, only 24 extra boxes per hectare would have to have been produced, or a production increase of one-half of one percent from a

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[4]More precisely, the added yield (Y) is determined by the following equation:

$$\Delta Y = \frac{P_N \times \Delta N}{P_T - C_H}$$

where the added cost of nitrogen ($P_N \times \Delta N$) is divided by the difference between the market price and the unit costs to harvest, haul, and pack ($P_T - C_H$).

base production goal of 4,942 boxes per hectare (Fig. 3-4). From this perspective, it is easy to sympathize with a grower's argument that while a numerical production advantage of 2045 boxes over a 4-harvest period from a HR treatment may not be statistically significant, the inherent variability of such field trials may mask a true treatment effect and one that would not have to be very large for the difference to more than pay for the added fertilizer costs.

Growers are quick to dismiss the "statistically insignificant" yield response reported by this and other research trials. Instead, they focus on numerical differences that frequently show greater production from higher rates of nitrogen fertilizer (HR) versus a recommended lower rate (RR). Results of this paper, however, do not entirely support a grower's argument that simply valuing numerical differences will necessarily add to grower returns. Prevailing market prices determine whether a grower gains or loses. If all numerical yield differences were valued at the prevailing market prices, the RR treatments would have produced nearly identical revenues to the HR treatment as measured by the cumulative revenues over the 4-harvest period (Table 3-6). Numerical yield differences collected during fall 2005 favored RR over HR treatment, and when coupled with exceptionally high market prices, produced over $12,000 additional revenue per hectare, offsetting lower revenues from the other three harvest periods. Conversely, when all harvest periods were valued at a consistent set of market prices, HR treatment generated more cumulative revenue than either RR treatment (Table 3-7).

Summary and Conclusion

The effect of vegetable BMPs on crop yield and farm income for tomato production in southern Florida was evaluated. A three-year study (2004 – 2006), four crop seasons, was conducted at the Southwest Florida Research and Education Center (SWFREC),UF/IFAS, to compare the typical grower practices (HR) and recommended practices (RR) for seepage irrigated tomato production on plastic mulch with regards crop yield and farm income. Results revealed that there were significant differences among the average yield for each crop season. These differences may have been a result of rainfall events that caused sufficient nutrient leaching and/or root damage (from salt accumulation) during the period of crop establishment. Crop yield for fall 2005 was exceptionally low due to the effects of Hurricane Wilma. The P-values for each crop season had a decreasing trend. This was attributed to the diminished effect of external factors (nutrient sources) that are able to mask any treatment effect within the study site. Background levels of nutrients at the site prior to the study were constantly flushed away each season with every rise and fall of the water table.

No statistical differences were detected among yields from the HR treatment and the RR treatments each year. Treatment yields for each crop season were comparable with the average for the state of Florida. There were only numerical differences among treatment for each crop season. Crop yields from HR were numerically greater in RR for some crop season and RR was numerically greater than HR for other crop seasons. In most instances, leaf tissue, petiole sap and plant biomass data supported the yield data.

Economic analyses of the yield data for this study revealed that HR frequently generated more revenue than RR on a seasonal basis. Added cost for increased fertilizer N use in HR compared with RR would easily be compensated for by a one percent increase in yield. Overall, RR was able to generate nearly identical revenues compared with HR. Differences in crop revenue for HR and HR were highly dependent on a combination of yield and current market prices reported at the time of harvest. Since market prices, can fluctuate widely, it is difficult for this study to determine if one treatment has a revenue advantage over the other.

With this in mind, studies are need that can determine if it is worth the cost of added fertilizer-N to maximize yield. The added yield required to compensate for the added cost of fertilizer-N can be as little as one half of one percent (24 box/ha). For a study to statistically detect differences in crop yield (as little as 24 box/ha), variations in crop yield measurements must be reduced. Such a study would require more treatment replications (≥3) in the field and a longer study period (≥5 years) to minimize variations associated with crop yield.

Certainly, farm cost and revenue are important economic considerations for implementing a BMP. However, these considerations should include the environmental cost of nutrient enrichment of surface and ground waters in Florida. The cost of nutrient enrichment of surface and ground water by agricultural nutrient transport can be measure by the monetary loss of use of these resources (e.g., fish kills in rivers and lakes), or by the effort taken to remove excess nutrients from these resources (e.g., reverse osmosis filters for drinking water). At any rate, environmental costs are real and would be useful if considered with farm costs when evaluating BMP.

In conclusion, there was no statistical difference in yield between the high rate (HR) and reduced rate (RR) the recommended fertilizer and water inputs (RR) for tomato production on plastic mulch with seepage irrigation in southern Florida. However, the effect of treatment on farm income/economy is uncertain due to the inability to show a treatment effect for very small yield differences. On a whole, the RR treatment may be considered a BMP with respect to crop yield. However, the treatment effect on farm income/economic is not fully understood for tomato production and further research is required.

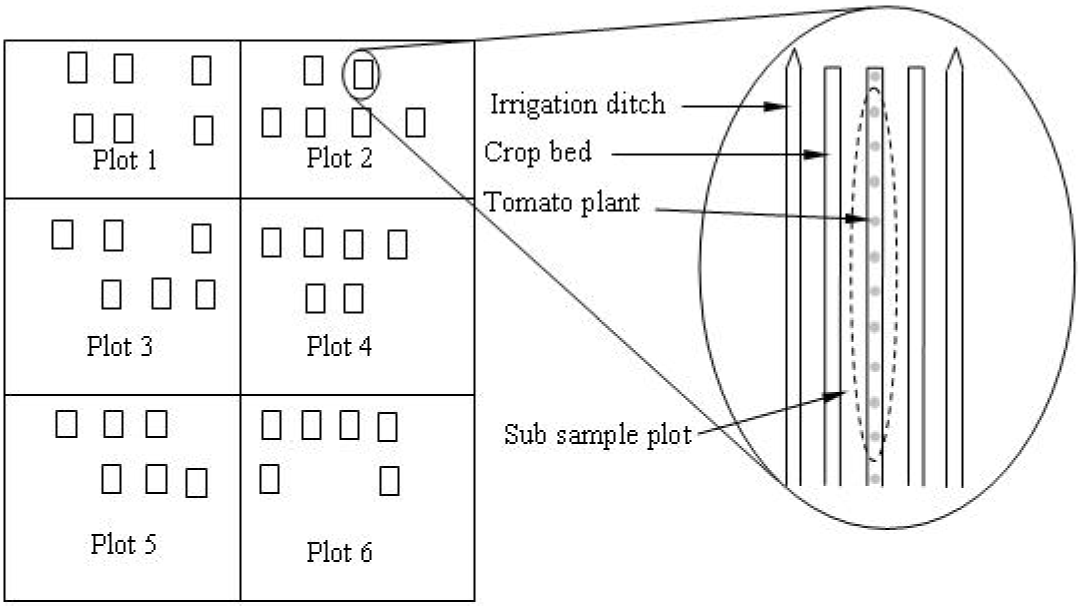


Figure 3-1. Example of the sub plot design used for sampling fruit yield from tomato production during crop seasons fall 2004, 2005, 2006 and spring 2006.

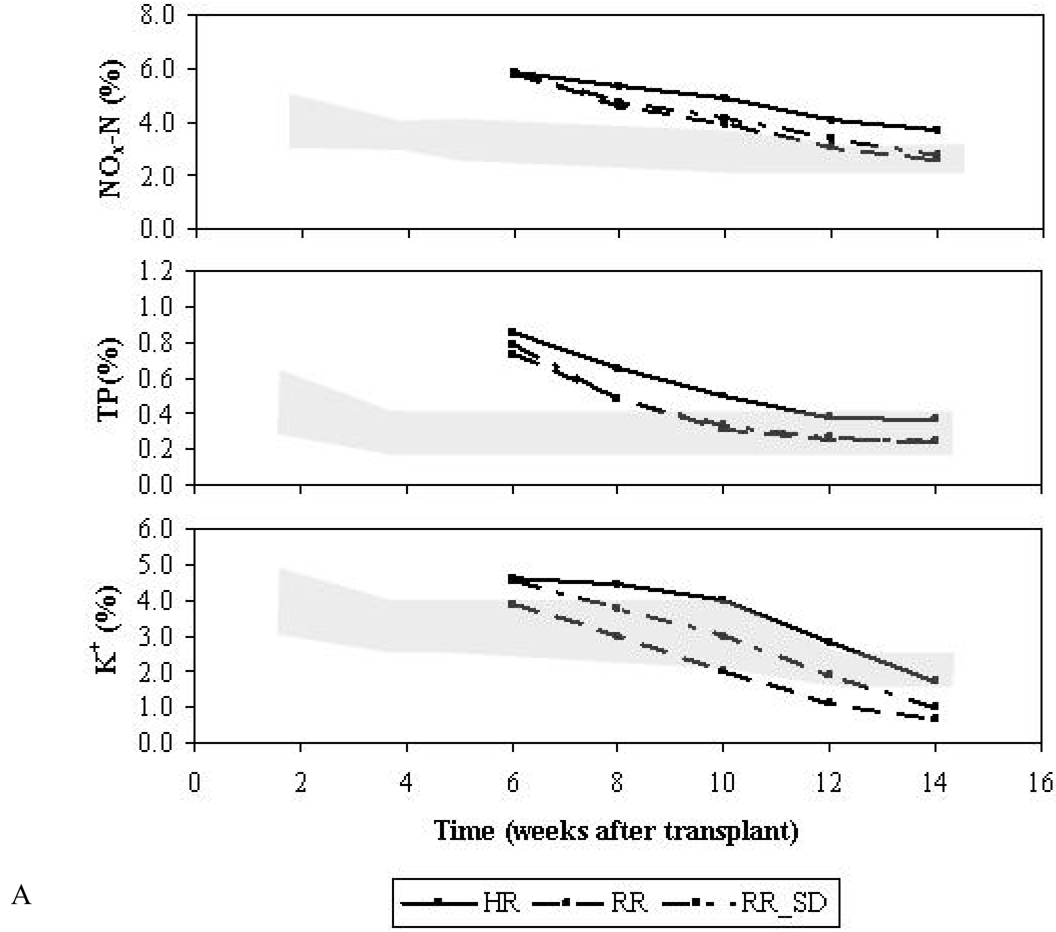
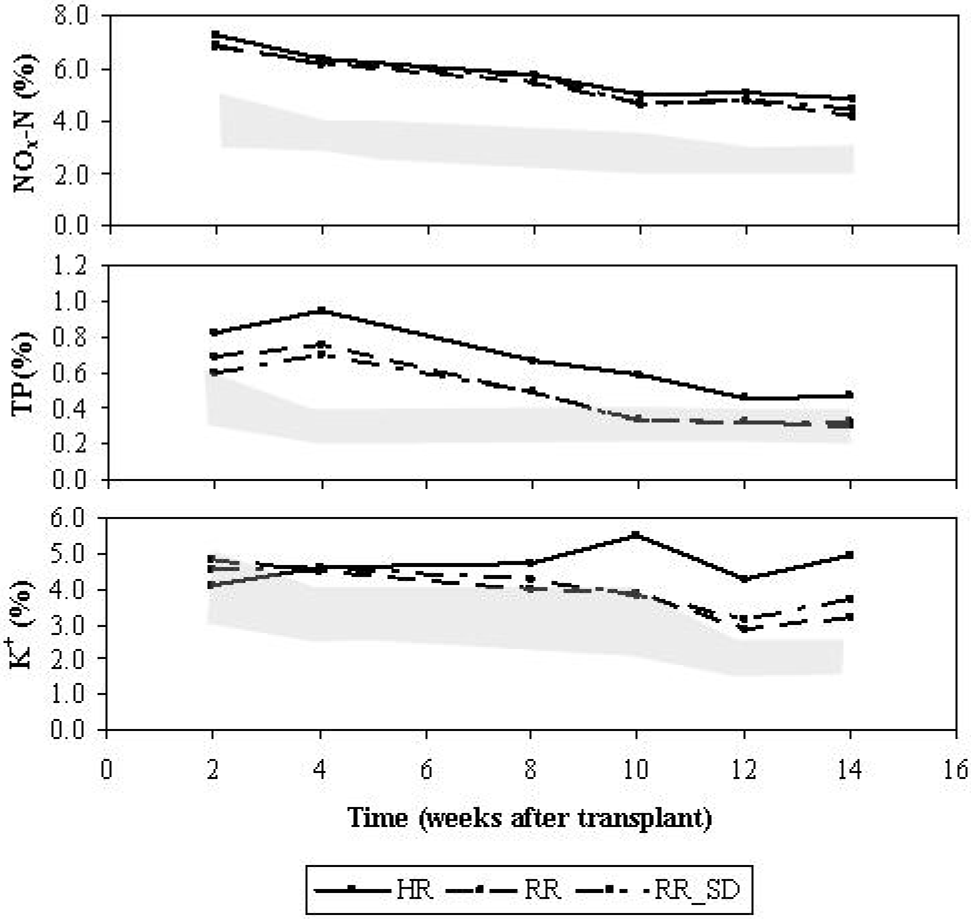


Figure 3-2. Average leaf tissue nitrogen (NOx-N), total phosphorus (TP) and potassium (K+) for tomato. A) fall 2004, B) fall 2005, C) spring 2006, and D) fall 2006. Shaded region shows nutrient sufficiency range. First harvest occurred during week 12 and second harvest occurred during week 14.



B

Figure 3-2. Continued

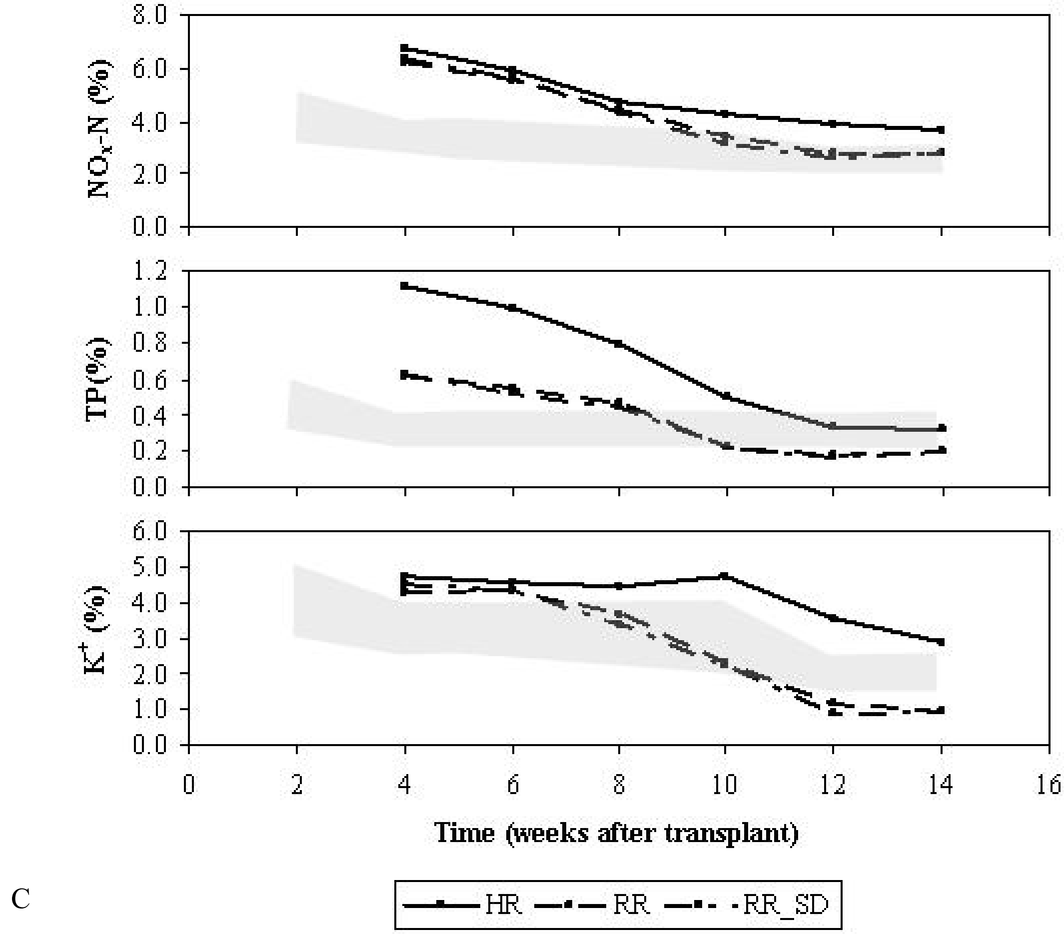
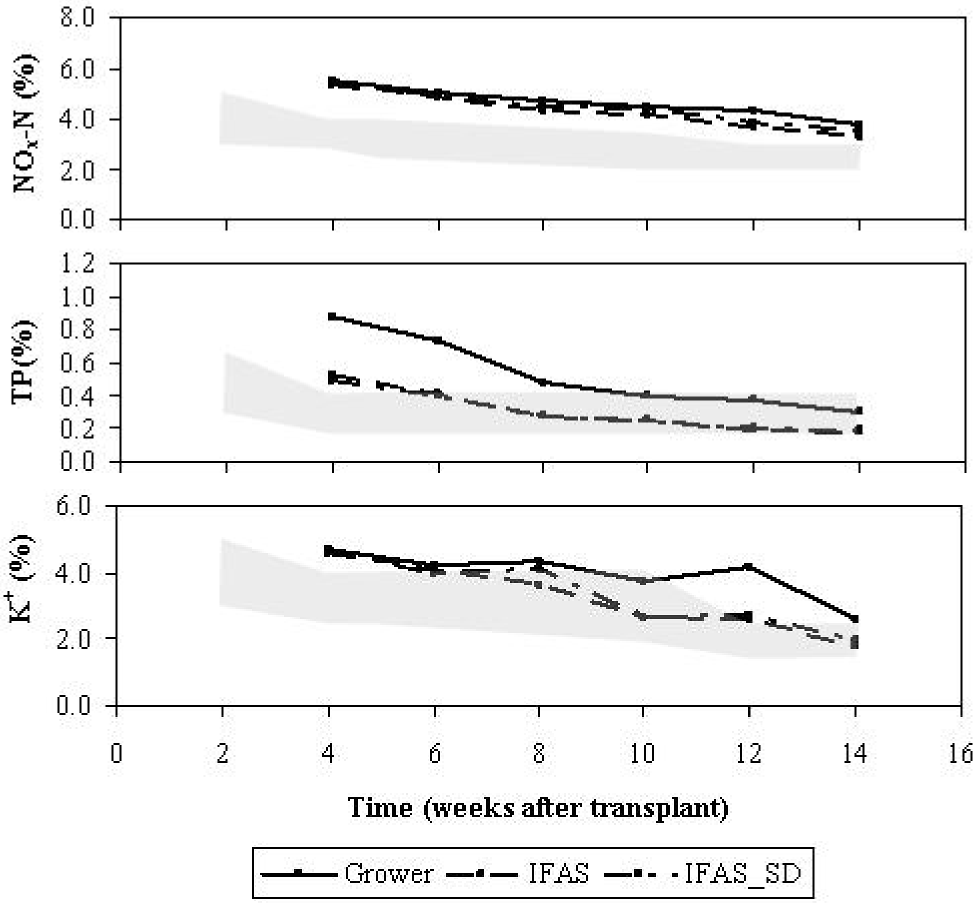
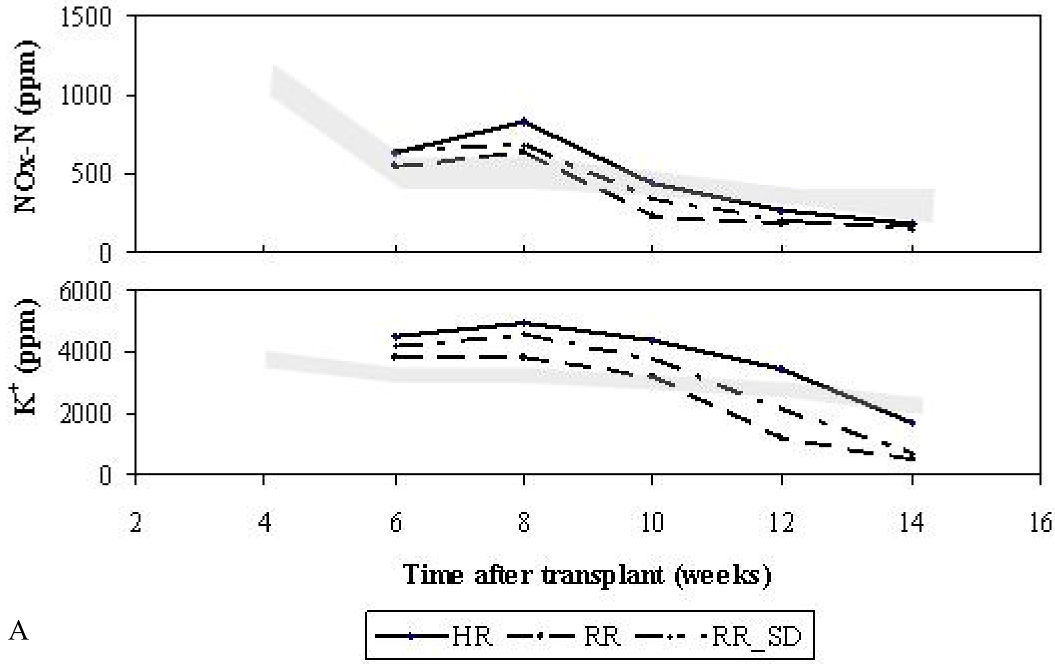


Figure 3-2. Continued



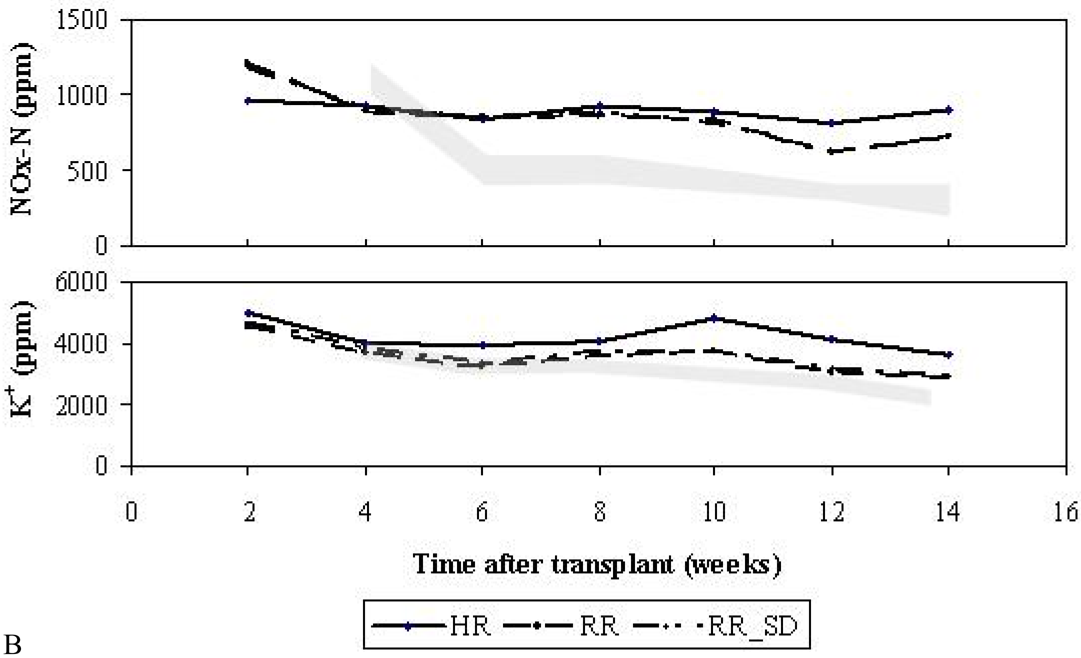
D

Figure 3-2. Continued



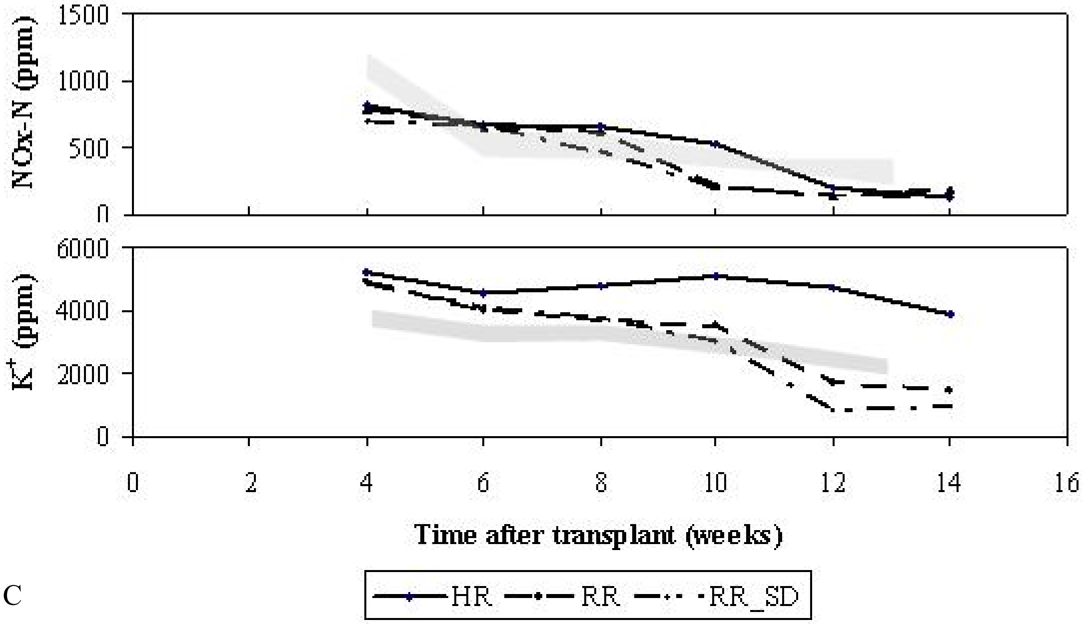
A

Figure 3-3. Average petiole sap N and K for tomato. A) fall 2004, B) fall 2005, C) fall 2006, and D) spring 2006. Shaded region shows nutrient sufficiency range. First harvest occurred during week 12 and second harvest occurred during week 14.



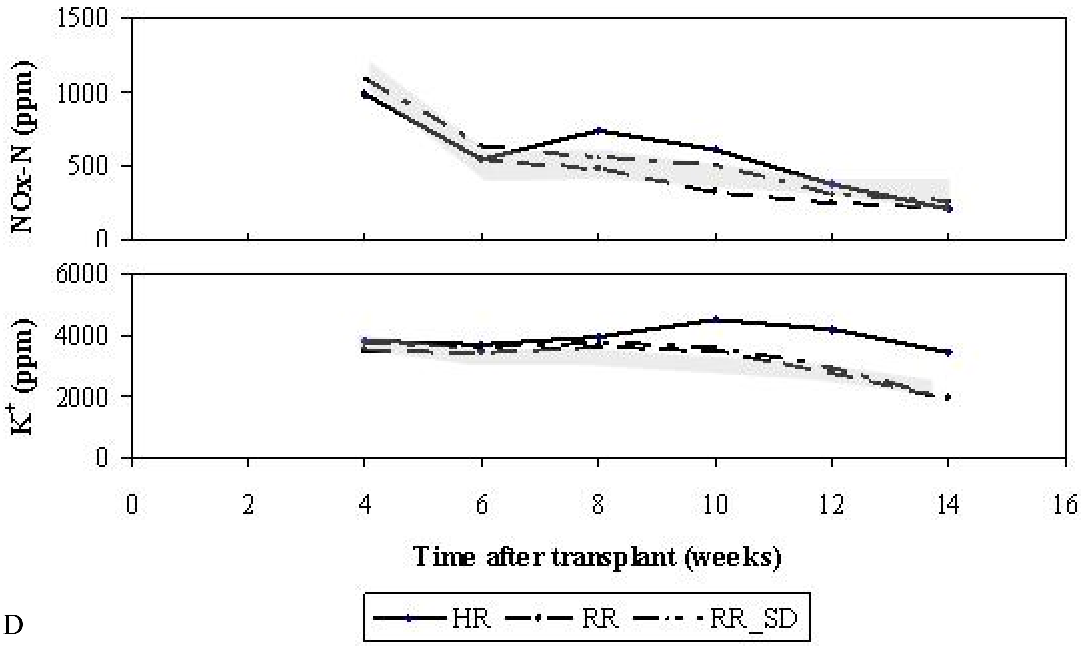
B

Figure 3-3. Continued



C

Figure 3-3. Continued



D

Figure 3-3. Continued

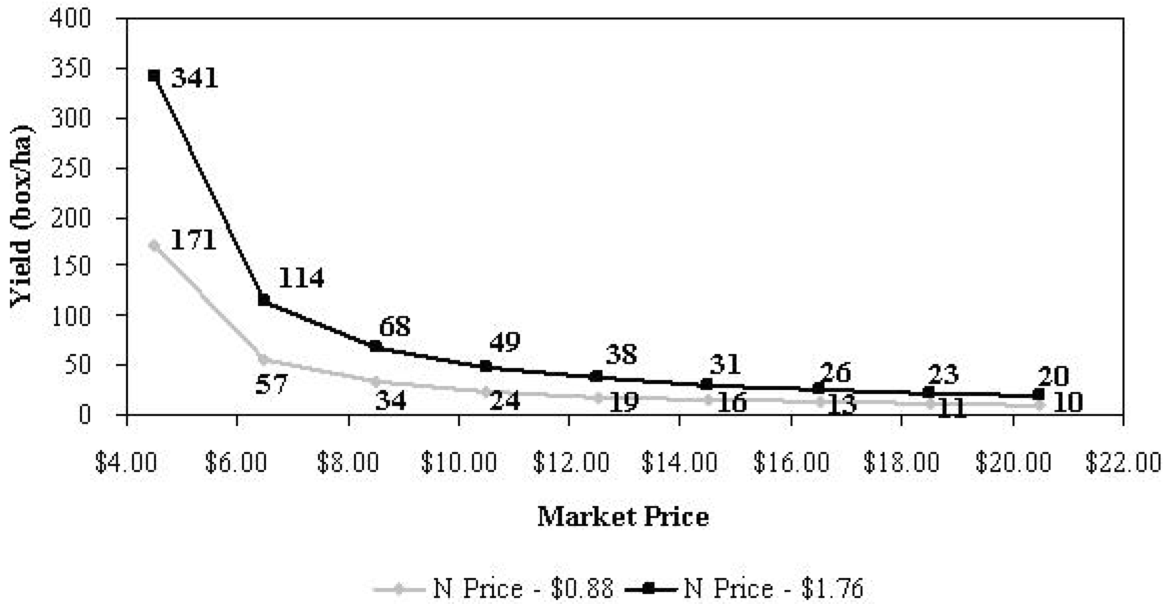


Figure 3-4. Market threshold by market price for fresh market tomatoes in Florida. Two curves: nitrogen at $0.88 and N at $1.76. Threshold yields by market prices above which the cost of an additional 45 kg of nitrogen is paid. Cost of elemental nitrogen assumed to be 88-cent per kg.

Table 3-1. Transplant dates and harvest dates for each cut for tomatoes produced during the crop seasons fall 2004, 2005, 2006 and spring 2006

Season	Transplant date	Harvest date		
		1st pick	2nd pick	3rd pick
Fall 2004	September 15	December 6	December 20	--
Fall 2005	September 13	December 5	December 19	--
Spring 2006	February 21	May 11	May 24	June 07
Fall 2006	September 05	November 29	December 13	December 21

Table 3-2. Average tomato yield (box/ha.) for each treatment during fall 2004, 2005, 2006 and spring 2006

Season	Treatment	Grade quality				Seasonal average
		Medium	Large	Extra large	All grades	
Fall 2004						4651
	HR	1195	1040	2426	4658	
	RR	603	652	3228	4486	
	RR-SD	818	687	3305	4809	
Significance						
	P-Values	0.1904	0.1921	0.1711	0.8067	--
Fall 2005						1944
	HR	571	440	618	1628	
	RR	571	521	1015	2107	
	RR-SD	561	526	1013	2097	
Significance						
	P-Values	0.9917	0.803	0.6339	0.7406	--
Spring 2006						6960
	HR	1141	1233	5595	7966	
	RR	963	976	4572	6511	
	RR-SD	835	956	4614	6405	
Significance						
	P-Values	0.4524	0.1769	0.2414	0.1042	--
Fall 2006						5459
	HR	1403	1146	3502	6052	
	RR	983	766	3414	5162	
	RR-SD	1067	966	3127	5160	
Significance						
	P-Values	0.1223	0.1811	0.7569	0.2925	< 0.0001

[a] 1 box = 11 kilograms.

Table 3-3. Average whole plant biomass (dry weight in grams) for each treatment during spring and fall of 2006

Treatment	Average plant biomass for each treatment		
	Spring	Fall	Annual
HR	194.08	146.19	174.92
RR	174.27	124.70	154.44
RR-SD	165.89	134.98	153.53
Significance			
P-value	--	--	0.6916

Table 3-4. Average yield differences[a] (box/ha) by grade quality and season

Season	Treatment	Grade quality			Total yield difference
		Medium	Large	Extra large	
Fall 2004	RR	-593	-388	803	-178
	RR-SD	-378	-353	879	148
Fall 2005	RR	0	82	398	479
	RR-SD	-10	86	395	472
Spring 2006	RR	-178	-257	-1023	-1457
	RR-SD	-306	-277	-981	-1564
Fall 2006	RR	-420	-380	-89	-889
	RR-SD	-336	-180	-375	-892
4-harvest cumulative difference:					
	RR	-1191	-944	89	-2045
	RR-SD	-1030	-724	-82	-1835

[a]Yield differences are calculated by subtracting HR yields from RR yields.

Table 3-5. Prevailing market prices of U.S. mature green tomatoes (#2) in 11 kg box loose

Date	$/box Extra Large (5x6)	Large(6x6)	Medium (6x7)
04-Dec-06	11.70	11.70	11.70
04-Dec-20	10.20	8.70	6.70
05-Dec-05	25.95	22.95	20.95
05-Dec-19	28.95	26.95	22.95
06-May-11	5.45	5.45	5.45
06-May-24	6.95	6.95	6.95
06-June-07	6.45	6.45	6.45
06-Nov-29	5.30	4.95	4.95
06-Dec-13	6.45	5.45	4.45
06-Dec-21	7.45	5.45	4.45
Average	11.50	10.50	9.50

Table 3-6. Value ($/ha) of yield differences between RR and HR for prevailing market prices on harvest date. Values in the parenthesis represent difference when RR is less then HR

Season	Treatment	Grade Quality Medium	Large	Extra large	Total value of yield difference
Fall 2004	Prevailing prices	$ 6.75/ctn	$ 8.75/ctn	$10.50/ctn	
	RR	$(4,001)	$(3,393)	$ 8,429	$ 1,034
	RR-SD	$(2,551)	$(3,091)	$ 9,233	$ 3,591
Fall 2005	Prevailing prices	$21.00/ctn	$23.00/ctn	$26.00/ctn	
	RR	--	$ 1,875	$ 10,339	$ 12,214
	RR-SD	$(207)	$ 1,988	$ 10,275	$ 12,056
Spring 2006	Prevailing prices	$ 6.50/ctn	$ 6.50/ctn	$ 6.50/ctn	
	RR	$(1,156)	$(1,670)	$(6,647)	$(9,472)
	RR-SD	$(1,991)	$(1,798)	$(6,374)	$(10,163)
Fall 2006	Prevailing prices	$ 4.50/ctn	$ 5.50/ctn	$ 6.50/ctn	
	RR	$(1,890)	$(2,092)	$(578)	$(4,560)
	RR-SD	$(1,512)	$(992)	$(2,440)	$(4,944)
4-Harvest cumulative difference:					
	RR				$ (784)
	RR-SD				$ 541

Table 3-7. Value ($/ha) of yield differences between RR and HR for low market prices: $6.50, $5.50, and $4.50 per box for extra large, large, and medium, respectively. Values in the parenthesis represent difference when RR less then HR

Season	Treatment	Grade quality ($/ac) Medium	Large	Extra large	Total value of yield difference ($/ha)
Fall 2004	RR	$(2,668)	$(2,133)	$ 5,218	$ 417
	RR-SD	$(1,701)	$(1,943)	$ 5,716	$ 2,072
Fall 2005	RR	--	$ 448	$ 2,585	$ 3,033
	RR-SD	$(44)	$ 475	$ 2,569	$ 3,000
Spring 2006	RR	$(800)	$(1,413)	$(6,647)	$(8,860)
	RR-SD	$(1,378)	$(1,522)	$(6,374)	$(9,274)
Fall 2006	RR	$(1,890)	$(2,092)	$(578)	$(4,560)
	RR-SD	$(1,512)	$(992)	$(2,440)	$(4,944)
4-harvest Cumulative Difference:					
	RR				$(9,969)
	RR-SD				$(9,145)

CHAPTER 4
EFFECT OF NUTRIENT AND WATER BMPs ON SOIL AND GROUNDWATER QUALITY UNDER VEGETABLE PRODUCTION IN SANDY SOILS WITH A HIGH WATER TABLE

Introduction

Nitrogen (N) pollution continues to threaten the quality of surface and groundwaters of the continental United States of America (USA). A review (Lombardo et al., 2000) of data collected by the nonpoint source national monitoring program revealed that agriculture ranked as the number one source of water pollution in the USA for rivers, streams, lakes, ponds and reservoirs. A report by the United States Geological Survey, USGS, (1999) found that two-thirds of the agricultural areas studied across the nation had elevated nitrate concentrations in groundwater. Berndt et al. (1998) reported that nitrate concentrations exceeded the USEPA's maximum contamination level (10 mg/L) in more than 20% of groundwater samples from surficial aquifers in agricultural areas within the Georgia- Florida coastal plain. This is in contrast to total phosphorus (TP) concentrations that were less than 0.05 mg/L in 50% of groundwater samples taken, and TP concentrations did not differ by land use. The authors also reported that inorganic fertilizer was one of the predominant sources of nitrate in groundwater beneath the row-crop agricultural study area; elevated P concentrations were associated with streams draining urban as well as agricultural basins (Berndt et al., 1998). McPherson et al (2000) reported that groundwater nitrate concentrations in southern Florida were low for most of the wells sampled; however, some samples occasionally had elevated nitrate concentrations in areas with agricultural land use. However, P in groundwater samples taken from shallow wells in southern Florida varied widely (0.001-0.79 mg/L), and elevated concentrations were associated with fertilizer use and naturally occurring sources that include silt and clays (McPherson et al., 2000). This illustrates that agricultural management practices such as N and P fertilizer rates typically used for crop production (e.g. citrus and vegetable) in south Florida are a likely source of groundwater contamination.

Sugarcane, citrus, and vegetable production are common agricultural operations in south Florida that use large amounts of fertilizer, which mainly consist of nitrogen (N), phosphorus (P) and potassium (K). The inherent nature of vegetable production systems creates a greater potential to contribute N and P loadings to surface and groundwater compared with other crops in Florida. Unlike citrus or sugarcane production, vegetable production requires seasonal tilling and fertilizer application for each crop cycle (usually twice a year) that results in considerable soil disturbance, which in turn promotes mineralization of nutrients such as N and P and increases the potential for sediment losses and nutrient leaching. Furthermore, vegetable producers rely heavily on inorganic N-P-K fertilizers as a nutrient supplement in the production of high-value crops grown on extensive hectarages of land (55,000 ha; NASS, 2004) throughout southern Florida.

Generally, vegetable producers apply inorganic N-P-K fertilizers as a one-time application into raised beds covered with plastic mulch. The plastic mulch confines fumigants, suppresses weeds, helps to maintain an optimum temperature for plant growth, and reduces the leaching of fertilizer inorganic N (or P or K) induced by rainfall. Water is typically applied to the field using seepage irrigation. Seepage irrigation is a traditional form of irrigation in southern Florida and is the system most likely used by vegetable producers (60% in acreage) for crop production (Marella, 2004). Seepage irrigation controls the water table with water supplied to lateral open ditches that are spaced between several crop beds. Water "seeps" from the ditches and travels to the water table that ascends toward to the base of the crop beds. The water table's capillary fringe at some point enters into the root zone for crop uptake. The moisture content within the root zone is controlled by managing the level of the underlying water table.

Traditionally, vegetable producers apply inorganic fertilizer in excess of crop's need in a single application and soil moisture within the root zone is kept above field capacity for most of the crop season (Chapters 2 and 3). Both of these factors can increase the N and P leaching potential. First, soil moisture provides a medium in which fertilizer is dissolved and creates a continuous pathway that permits the movement of dissolved nutrients though the soil for plant uptake or down to the water table (leaching). As the water table approaches the surface of a seepage-irrigated soil, greater numbers of pore spaces are connected to create a series of capillary conduits. These conduits permit the movement of nutrients between the water table and the nutrient source (fertilizer granules in the bed). Therefore, water table levels that are brought closer to crop beds will facilitate dissolution of greater quantities of nutrients that can move through the soil since larger-sized pore spaces are filled with water that increases dissolution rate and leaching potential. Second, increased quantities of fertilizer added to the crop bed act as a constant source for nutrients present in soil solution. Typically, a portion of granular fertilizers used for vegetable production may be coated to some extent (e.g. sulfur coated urea or polymer coated urea) with a material that attenuates the rate of dissolution, which depends on soil moisture or temperature conditions. Fertilizer coatings were designed to gradually release nutrients during the period of plant growth and production. However, some uncertainty still exists regarding the period of release and concentration levels of nutrients dissolved from granular fertilizer. Cabrera (1997) noted that a high release of nutrient may occur during the beginning of the crop season when the nutrient demand of transplants is low. In fact, N concentrations can become so high that slugs of N (in the form of nitrate, NO_3^-) can move vertically down and out of the unsaturated root zone due to specific gravity differences of the soil solution. This phenomenon was observed and termed as “fertilizer dropout” by Bonczek and McNeal (1996) based on laboratory experiments; the authors determined that rapid fertilizer loss to the water table occurs when the water table is static and sufficiently close to the base of crop beds. However, the dynamic nature of field conditions is different from the control settings of laboratory. For instance, intense rainfall events can result in the sudden raise (into the crop bed) and fall of inherently high water tables associated with seepage irrigation systems (SIS). As a result, large amounts of fertilizer granules may dissolve, resulting in a concentrated solution of N, P and K; a large portion of some of these nutrients can be carried away from the root zone by a descending water table. Consequently, N leached from fields under vegetable production depends on a combination of several factors including rainfall, irrigation rate, antecedent water table depth and soil moisture content field capacity and saturated hydraulic conductivity of the soil, and the type, rate, and timing of fertilizer applied.

Nitrogen is relatively mobile in solution while P is relatively immobile. Excess N in the environment is a known contaminant that can have adverse effects on ecosystems and humans, while P is not known to be toxic to fish, livestock or humans, but can have some negative impacts on the environment (McCullum, 1996). Many studies have been carried out across the U.S. including Florida to determine the effect of fertilizer and irrigation practices on N leaching and to a lesser extent, P leaching. Ghel et al. (2005) quantified the effects of a fertilizer-N/irrigation management strategy on NO_3^- leaching under sprinkler irrigated corn on the loamy fine sands of Kansas over a two-year study. Nitrogen rates applied were 0, 185 split, 250 split, 250 and 300 kg N/ha; irrigation strategies applied were: 1) optimal water rate (OWR) and 2) 1.25 OWR. Estimates of average N leaching were as low as 11 kg N/ ha for OWR up to a high of 109 kg N/ha for 1.25 OWR. In addition, N leaching was significantly greater for 1.25 OWR than OWR for all N application rates for both years. Finally, N leaching rates for 1.25 OWR was significantly greater when single N application rates (200 and 300 kg N/ha) were applied as compared with split N application rates (185 split and 250 split kg N/ha) for both years.

Paramasivam et al. (2001) evaluated the effectiveness of irrigation and N fertilizer practices for N leaching losses under microsprinkler irrigated citrus on for a fine sandy Entisol of Florida. Several N input rates, ranging from 56 kg N/ha to 280 kg N/ha, were applied under optimum irrigation rates using three sources (fertigation, FRT; dry granular fertilizer, DGF; controlled release fertilizer, CRF). Nitrogen leaching estimates ranged from 2.2 kg N/ ha (CRF at 56 kg N/ha/yr) to 32.2 kg N/ha (FRT at 280 kg N/ha/yr).

Zotarelli et al. (2007) evaluated three different methods for monitoring and quantifying N leaching below mulched vegetable production beds in Florida on Tavares sand. Three crops (pepper, tomato, and zucchini) were grown under drip irrigation with two to three application rates. Two N fertilizer rates were applied, the recommended IFAS rate and 1.5 times greater than IFAS (1.5IFAS). N-leaching estimated for tomato in this study was 12 kg N/ha for the IFAS rate and 19 kg N/ha for the 1.5IFAS rate. Although several studies have been conducted to evaluate N leaching below the root zone, limited research-based data exist to evaluate the effects of practices on surface and ground water concentrations and loadings.

Jaber et al. (2006) compared the effects of three organic fertilizers and an inorganic fertilizer on groundwater P in selected sandy soil (Ft Pierce) and calcareous soil (Homestead) of south Florida. Three crops (tomato, squash and calabaza) were grown under seepage irrigation (38 cm water table depth) using fertilizer rates that were recommended the University of Florida. Treatments applied were: yard and food waste compost (YFC); locally produced biosolids (BS);

municipal solid waste-biosolids Bedminster compost (MSW-BS); and water soluble fertilizer (FERT). Groundwater samples were tested for soluble reactive P (SRP) and total Kjeldahl P (TKP). Results from this study revealed that soluble reactive phosphorus (SRP) contributions from the study areas were less than or equal to 0.2 mg P/L (Homestead) and less than 0.6 mg P/L (Ft. Pierce) throughout the study period. No treatment effects were detected for groundwater P from shallow wells.

Studies that evaluate nutrient transport into groundwater, associated with crop production, typically fall short of addressing the criteria needed to develop agricultural best management practices (BMPs). The Florida Department of Agriculture and Consumer Services (FDACS) defines a BMP as "a practice or combination of practices based on research, field-testing, and expert review deemed to be effective and practicable for producers and for improving water quality in agricultural discharges (FDACS, 2005)." Several BMPs (e.g. Indian River Citrus, Florida Sod and Vegetable and Agronomic Crops) have been proposed and encouraged by FDACS to reduce non-point-source (NPS) loading of nutrients from agricultural areas. However, few of these BMPs have been actually evaluated for water quality and economic effects on crop production. Also, some of the important BMPs (e.g. recommended fertilizer and irrigation rate … etc.) have not been quantified for several land uses (e.g. vegetable production on plastic mulched raised beds with seepage irrigation). The quantification of a BMP's effect on nutrient transport to surface and ground waters are required to determine if allocated Total Maximum Daily Loads (TMDLs) are achieved for vulnerable water bodies (e.g. Lake Okeechobee) in southern Florida. Furthermore, quantification of nutrient transport would provide reference data for predicting a BMP's effect on nutrient transport using hydrologic and water quality models to develop water quality management plans for environmentally sensitive watersheds such as the Kissimmee-Okeechobee-Everglades watershed.

The above mentioned studies have reported leaching estimates of N (kg/ha) for some form of micro-irrigation (micro-sprinkler or drip). No estimates for leaching exist for seepage irrigation, the most common irrigation system in south Florida for vegetable production. Seepage irrigation is also used for other crops; all sugarcane production in south Florida uses seepage irrigation. Seepage irrigated systems are quite different from drip or sprinkler irrigation systems (DSIS) for vegetable production for the following reasons: 1) SIS involves raising the water table in the entire field close to the crop root zone; 2) SIS introduces water into the root zone from beneath the crop bed by upflux, which is the opposite of DSIS; and 3) all the fertilizer is applied pre-transplant as opposed to DSIS where fertilizer can be applied with irrigation. Given the large vegetable production acreage in south Florida under SIS and the basic differences between the rate and mode of water and fertilizer input delivery compared with DSIS, studies are needed to evaluate the BMP effectiveness for SIS. The comparison of different BMPs using SIS should be conducted with different fertilizer-water treatments applied to different experimental sites that are remotely separated. However, the use of experimental sites that are located on separate farms would introduce errors possibly generated by differences in rainfall, soil, topography, hydrology and/or cultural practices. The use of a single field with a range of fertilizer-water treatments placed adjacent to each other would minimize errors compared with a study that used fields on different farms. The problem with using of a single field is the flow of water and nutrients from one treatment to another. Such flows will limit the ability to detect the effect of different fertilizer-water treatments. Mixing of groundwater as well as dissolved nutrients from one treatment to another would mask any treatment effect on soil and groundwater quality.

Therefore, hydrological separation of treatment areas is essential to increase the chance of detecting treatment-driven water quality differences. To address the problem of groundwater mixing between treatments for vegetable production system BMPs with seepage irrigation, a large scale field study (> 0.2 ha) was conducted with treatments that were hydrologically separated.

To determine the effect that seepage-irrigated vegetable production systems have on surface or groundwater quality, variable water and nutrient application rates (treatments) must be considered. Any treatments must show that it can improve surface or groundwater quality (while maintaining crop yield) before it can be termed a BMP. The Institute of Food and Agricultural Sciences at the University of Florida (UF/IFAS) proposed fertilizer rates for BMP use on vegetable crops (Olson and Simonne, 2005) that are lower than industry rates in south Florida. Currently, the University also proposes that irrigation scheduling be based on a combination of soil water tension measurements, soil moisture content measurements and stage of plant growth (Simonne et al., 2005). Although BMPs have been recommended, they have not been backed up by science-based information. In this experiment, seepage irrigation was used to apply water to experimental plots as it is commonly used by vegetable growers in south Florida. The experimental plots were located next to each other and were hydrologically isolated from each other above the spodic horizon with a geotextile material. Since seepage irrigation has a low application efficiency, an alternative method of irrigation (subsurface drip) was applied with recommended fertilizer rates to determine if there was any improvement in groundwater quality while improving the irrigation application efficiency.

Objective

The goal of this study was to determine the efficacy of fertilizer-water BMPs on minimizing nutrient losses in the vadose zone and to the groundwater from plastic-mulched vegetable crop systems. Specific objectives of the study were to: 1) quantify and compare the amount of fertilizer N and P leaching from BMP and industry water-nutrient inputs; 2) evaluate the effectiveness of the nutrient and water BMPs with respect to groundwater quality (N and P) beneath crop beds. To attain objective 1, an experiment was conducted during spring 2006 that was part of a wider study (fall 2004 to fall 2006). The second object was attained by collecting and analyzing the data collected during fall 2004 to fall 2006 for a tomato-watermelon rotation.

Methods and Materials

Study Location

The study was conducted at the Southwest Florida Research and Education Center (SWFREC), UF-IFAS, Immokalee, FL. The center is located in Collier County at an elevation of 10.7 m (35 ft) above mean sea level and is underlain by the undefined surficial aquifers of Florida, which consist mostly of unconsolidated sands. The geology of the area is dominated by shelly sand and clay, and is covered by the soils of the flatwoods. The soil at the site is Immokalee fine sand (sandy, siliceous, hyperthermic, Spodic Psammaquents) with CEC of 12 Cmol/kg and pH of 5.6 (Carlisle et al., 1989), and 49 mg/L and 60 mg/L of Mehlich-1 extractable P and K, respectively. These values (e.g.,CEC) are representative of a native Immokalee find sand, which is a common soil type in the flatwoods physiographic region of southern Florida. Areas with Immokalee fine sand soil that have been under crop production tend to have lower CEC values (i.e., < 10 Cmol/kg). Immokalee find sands are characterized by poor drainage, nearly level surfaces (slopes less than 2%), and a poorly drained spodic layer situated approximately 0.9 to 1.2 m below the soil surface. This soil also has a moderately rapid permeability (5.1 to 15.2 cm/h) and low water holding capacity (5 to 7%).

Water and Nutrient Treatments and Hydrologic Isolation

Two nutrient and water management systems (experimental treatments) for tomato production were considered for this study (i.e., HR and RR treatments). Implementation of the HR treatment (Table 4-1) was based on results of a grower survey conducted on tomato and watermelon growers in southern Florida (Chapters 2 and 3). The frequency and amount of fertilizer (N, K and/or P) applications were based on the survey results; 20-25% of fertilizer was placed near the base of the crop bed (bottom mix) and the remaining 75-80% of fertilizer was placed in two narrow bands at the surface of the beds (Fig. 4-1A). The RR treatment was based on recommendations made in the vegetable production handbook for Florida (Maynard et. al. 2001); recommended P and K fertilizer rates were added to RR treatments when soil tests for these elements showed a nutrient deficiency (Table 4-1).

A field was divided into six experimental units (plots) of 0.24 ha each. Experimental treatments (HR, RR and RR-SD) were randomly assigned to the six plots; these treatments held their position for the entire study period (Fig. 4-1B). To address the issue of hydrologic isolation, each 0.24-hactare plot was hydrologically separated by a barrier made from four sections of a geotextile material (Fig. 4-1C). The geotextile barrier was used to prevent the lateral flow of water and dissolved nutrients among plots and the movement of water from plots to areas external to the plots above the spodic layer.

During each crop season, a series of plastic covered raised beds and irrigation ditches (one ditch between every three consecutive raised beds) were constructed in each plot. Plastic mulch, fertilizer (for each treatment) and fumigant (Telone®) were applied simultaneously as raised beds were formed. Field operations were initiated 3 weeks after fumigation; this delay permitted the fumigant to work effectively within each bed. During this period, the moisture contents in all plots were kept at the same level (approx. 16-20%) to maintain the integrity of the bed structure and to maintain soil moisture levels that would avoid moisture stress in transplants. After the transplantation of seedlings (watermelon or tomato), the moisture content in each plot was maintained within the range 16-20% for up to two weeks to allow transplants to establish themselves properly. Proper seedling establishment and development was assisted by watering plants with hand held sprinklers up to a week after transplantation; the water source contained a 20N-20P-20K starter solution. After a two week period, irrigation inputs for different treatments were controlled to achieve the desired moisture level within each plot. The fertilizer-water treatment for each plot was implemented and maintained by observing the soil moisture within crop beds of each plot along with the associated water table depths.

Water was applied via irrigation ditches until the soil moisture content increased to the desired target range. The target soil moisture for each plot was achieved by maintaining a relatively stable water table depth around the depth noted earlier. Water table depths were managed by adjusting the irrigation flow rates at the risers' ball valve that discharged water into the irrigation ditches. Ball valves were regularly adjusted to increase or decrease soil moisture content within crop beds, which was done in anticipation of or in reaction to rainfall events. This active water management was maintained until a week before the first harvest. One week before the first harvest, soil moisture levels were lowered to prevent the fruits from cracking.

Tomato was grown during four crop seasons, fall 2004 , fall 2005, spring 2006 and fall 2006 (Chapter 3) while watermelon was grown during spring 2004 and spring 2005 (Chapter 2). A drainage canal bordered the majority of the field. The canal received surface and subsurface discharges from any of the six plots (Fig. 4-1B). The canal was approximately 1.0 m deep and 3 m wide and was located approximately 9.1 m from the outer boundary of each plot.

Data Collection

A number of soil and hydrologic parameters were monitored and recorded to evaluate the three treatments. Soil parameters (Table 4-2) and hydrologic parameters (Table 4-3) were monitored to evaluate the transport of soil N from beneath crop beds in each treatment. Soil moisture content and water table depth were monitored by soil moisture capacitance probes (Model: EasyAg®; Campbell Scientific, Inc., 2002a) and pressure transducers (Model: KPSI™; Pressure Systems, Inc., 2006), respectively. To evaluate the effects on nutrient leaching and transport to ground water, soil core samples (only during spring 2006), soil solution samples, and ground water samples were taken and analyzed for N and P concentrations.

Irrigation, drainage and runoff

Water fluxes into/out of each plot were monitored by a set of instruments that included flow meters, V-notched weirs (drainage and runoff) and a rain gauge. A flow meter was installed in each sub main line that entered into each plot (Fig. 4-2A). These flow meters monitored the flow of surface and sub-surface irrigation volumes (gal.) on a 15-minute basis. Data from each flow meter were transmitted and stored in the CR205 (Campbell Scientific, Inc., 2002b) data logger within each plot. Surface runoff from each plot was routed through a swale and was measured before being discharged to perimeter canal (Fig. 4-1B). Surface runoff was measured by a weir box that was placed down gradient of each swale. Each weir box had a V-notched crest board designed for peak flows of 136 L per minute. The hydraulic head before the V-notch board was measured by pressure transducers that were placed 30 cm upstream from the crest of the V-notch. Sub surface drainage from each plot was facilitated by a drain tile (20 cm inside diameter.) installed at 0.9 m below the soil surface. Drain tiles were connected to a PVC control structure (Fig 4-2B) fitted with several adjustable flash boards (Fig. 4-3A). AV-notch was cut into the top board to facilitate the measurement of drainage (Fig. 4-3B). Pressure transducers continuously monitored discharge heads above the crest of the v-notch at 15-minute intervals. Data collected from the pressure transducers were also transmitted and stored in the CR205 within each plot. Each CR205 (Fig. 4-4) was programmed to remotely download its data regularly on a server located in the Water Resources Program building at SWFREC, Immokalee, FL.

Soil and groundwater dynamics

Capacitance moisture probes were used to measure soil moisture content at different depths within two plastic mulched beds of each plot (Fig. 4-5). EasyAg® probes were placed within 15 cm of a plant to monitor the soil moisture within the root zone. An EasyAg® probes consisted of an electronic board that supports an array of four ring shaped sensors. This array of sensors measured the average moisture contents (volume %) at four depths beneath the bed surface (10 cm, 20 cm, 30 cm, and 50 cm).

Pressure transducers were used to determine the water table depth from top of the bed. Transducers were installed at the bottom of two shallow wells and one deep well (Fig. 4-5). Data from EasyAgs® and KPSI™ instruments were transmitted and stored in a CR205 data logger housed in a weather resistant instrument enclosure (Fig. 4-4). One CR205 was assigned to each plot. All CR 205's were powered by a 12-volt battery that was recharged by a solar panel. Data from EasyAg® and KPSI™ probes were collected continuously at 15-minute intervals. Data were transmitted wirelessly from the CR205 to a computer server located in SWFREC and facilitated real time observation of field parameters from locations in SWFREC as well as in Gainesville. This helped to quickly detect major data collection problems or accidents (e.g., break in pipes). Weather conditions during each crop season were monitored by a weather station at SWFREC (located approximately 300 m from the site) that was part of the Florida Automated Weather Network (FAWN), University of Florida. The weather station measured climatic parameters such as rainfall, temperature, and relative humidity (Table 4-3). Weather parameters for the study period were downloaded from the FAWN database (UF, 2008).

Plant characteristics

Whole plants were extracted (one from each plot) on a weekly to biweekly basis to measure plant biomass; whole plants were used to determine above and below ground biomass. Whole plants were separated into shoot and root samples, and then dried at 41 ^{o}C. Fruits found on each whole plant were sampled and then sliced and dried at 41 ^{o}C. Dried plant parts (fruit, shoot and root) were ground into small pieces, separately packaged and sent to a laboratory (Analytical Research Laboratory, ARL) operated by the University of Florida for analyses of N, P and K in soil and plant samples.

Soil nutrient

Soil core samples were collected to measure the concentration of soil N within the crop bed (0-10 cm and 10-20 cm depth) and below the crop bed (20-30 cm and 30-40 cm depth) during the spring 2006 tomato growing season. These N concentrations were used to estimate the amount of soil N leached out of the crop bed during the growing season. Soil sampling began February 23 and ended June 27 during the spring 2006 growing season. A core sampler (AMS, 2008) was used to extract 40 cm soil cores (5 cm in diameter) from a single bed within HR and RR treatments. A butterfly valve was located at the bottom of the sampler that retained the sample while the sampler was pulled out of the soil profile. Two sets of cores were taken from the selected beds within each plot. Each set was randomly taken from the north and south side of the bed selected (Fig. 4-1A). Collecting samples north and south of the bed center ensured that sampling was representative of the entire bed. For the first four weeks, samples were taken once each week; for the remainder of the crop season they were taken every 10 to 14 days. At each sample location, four 40 cm soil cores were taken from points evenly distributed across the width of the bed; sample points were separated by 18 cm (Fig. 4-1A). After the 40 cm cores were taken, each core was divided in four 10 cm sections: 0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm. Each sample section was individually bagged and air dried before it was sent to ARL for analyses. Samples were analyzed for NO_x-N, NH_4-N and TKN.

Suction lysimeters (Soilmoisture Equipment Corp., 1999) were used to determine the NH_4 and NO_3 concentration in soil solution 20 cm beneath the bed surface (within the root zone) during each week of the growing season. Two suction lysimeters, one each in two crop beds within each treatment were used to collect soil solution samples. Each lysimeter was placed within 20 cm of the plant and was located between the plant and the adjacent fertilizer band. This placement exposed the suction lysimeters to N that had the potential of being leached from the root zone. A pressure of 50-70 kPa was created within the plastic tube of the suction lysimeters using a hand held pump. This pressure range was high enough to draw sufficient soil solution samples through the lysimeter's ceramic cup within a sampling period. Solution samples were taken from the plastic tube with a syringe on a weekly basis. The solution samples were sent to ARL lab for NH_4 and NO_3 analyses.

Groundwater monitoring

Groundwater quality samples were taken from two types of wells installed in each of the four plots, shallow and deep. Each plot had four shallow wells and two deep wells (Fig. 4-5) made of PV pipes. Shallow wells were 64 cm in total length with a 5 cm inside diameter, the last 15 cm length of these wells was screened. Deep wells were 244 cm in total length with a 5 cm inside diameter, the last 30 cm length of these wells was screened. Clean coarse sand was poured around the screen of all wells to prevent or reduce the amount of silt that entered the well. A layer of cement was poured above the clean sand to help stabilize the well casing and prevent preferential flow. All wells were designed so that the top section (approx. 61 cm) was removable; the bottom section was capped and buried between crop seasons. Such a design allowed for the tilling and rotorvating of plots at the end of a crop season without the need for reinstalling the wells or plowing around wells during the fallow period. All wells had removable caps to prevent the entry of foreign material such as soil or insects. One of the four shallow wells was used for water quality sampling and water table depth monitoring.

Groundwater quality samples were taken using a reversible flow peristaltic pump (Solinst, 2007). The wells were flushed by pumping out the well volume three times prior to sampling. A portion of the sample was collected in a 50 mL measuring cylinder and immediately tested for pH, temperature and electrical conductivity (EC). A second portion of the sample was collected in a clean 100 mL bottle (filled to capacity) and stored in an ice box immediately after collection. Samples were acidified within the day of sampling to prevent transformation of the analytes in solution for analyses within 28 days of its collection. Groundwater quality samples were collected according to a protocol outlined by the Florida Department of Environmental Protection (FDEP) standard operating procedures for groundwater sampling (FDEP, 2002). Groundwater samples were sent to the ARL for analyses of N and P species (Table 4-2).

Data Analysis

Soil and groundwater dynamics

Soil and groundwater dynamics were analyzed with the aid of time series graphs of daily rainfall, moisture content (MC) and water table depth (WTD). General and specific trends in MC and WTD were identified and used to help determine the effect of each treatment on N leaching and groundwater quality; trends in graphical data were also used to compare the effect of HR and RR treatments on groundwater quality.

Core samples, suction lysimeters and groundwater quality

Core sample data were analyzed using a completely randomized block design with two replications (for HR and RR only). Analyses for a treatment effect were considered only to samples taken from the same depth in each treatment. A test for equal variance among blocks, for soil N species (NO_3^-, NH_4^+ and TKN) data, revealed that variances were not similar. Similar variances among the blocks are required before the samples can be pooled for use in the applied statistical model (PROC GLM procedure of SAS). Therefore, the common logs of N concentrations were used for analysis of treatment effects on soil N levels within and below the root zone. The log transformation resulted in similar variances for treatments across blocks. Hence, samples were pooled within each treatment from each block. The ANOVA was applied over the soil N data for the spring 2006 growing season.

Leaching of N from the crop bed (0- 20 cm) of each treatment was estimated using a mass balance approach where N sources and sinks were measured or estimated using literature values. The mass balance for TN is described by the equation:

$$N_{soil\_n} + N_{fertilizer} + N_{rain+\ irri} - N_{uptake} - N_{leach} - N_{gas} - N_{soil\_n+1} = 0 \qquad (4\text{-}1)$$

where n and n+1 represent two successive sampling periods, N_{soil_n} is the total N stored in the soil at the beginning of the sampling period, and N_{soil_n+1} is the total N stored in the soil at the end of a sampling period. The component $N_{fertilizer}$ is the fertilizer N added to the crop bed during the sampling period; no fertilizer was added during sampling period n through n+1, so this component was set to zero. For simplicity, we will let $\Delta S_N = N_{soil\ 12\ DAT} - N_{soil\ 126\ DAT}$. ΔS_N was determined from core sampling data (Table 4-2). Nitrogen uptake by plants (N_{plant}) was based on the bi-weekly whole plant sample data (root, shoot and fruit). $N_{rain+\ irri}$ is the total amount of N added to each experimental plot by rainfall and irrigation; average total N in well water used for irrigation was 0.8 mg/L. However, water introduced to the field by irrigation and rainfall was not applied directly to crop beds. Irrigation was applied to irrigation ditches placed between every third crop bed. Rainfall, however, is mostly blocked from entering crop beds by a plastic mulch cover and enters the soil via irrigation ditches and furrows. Water from irrigation and rainfall percolates to the water table, which moves through upflux to the root zone. The water table was managed so that moisture entered the root zone via upward flux and was the predominant pathway for N in irrigation and rainfall water to enter the root zone. However, due to groundwater mixing, only a portion of $N_{rain+\ irri}$ would travel with upward flux into the root zone within the crop bed. Therefore, $N_{rain+\ irri}$ was assumed negligible for this study. The N gaseous loss (N_{gas}) by volatilization and denitrification for crop beds in both treatments was assumed negligible since the soil moisture level was never more than 60% of the total soil pore volume (Fig. 4-7). This assumption has been supported by several studies (Linn and Doran, 1984; Weier et al., 1993; Shelton et al., 2000; Machefert and Dise, 2004; del Prado et al., 2006), which concluded that denitrification is negligible when water-filled pore space is less than 60%. Since the fertilizer granules were buried within the crop bed and covered by an impermeable sheet of plastic mulch, the expected ammonia volatilization losses were minimal and therefore neglected. Hence, the mass balance equation (eq. 4-1) for N becomes:

$$\Delta S_N - N_{leach} - N_{uptake} = 0 \quad (4\text{-}2)$$

Since ΔS_N and N_{uptake} were obtained by field measurements, Equation 4-2 was used to estimate the amount of N leaching that occurred beneath crop beds (below 20 cm) between sampling periods (Table 4-4). Cumulative N leaching for the spring 2006 growing period (Feb 2, 2006 to Jun 10, 2006) was calculated from the sum of all the leaching estimated between the successive sampling events.

Leaching of P from the crop bed (0-20cm) of each treatment was estimated using the mass balance approach where P sources and sinks were measured values. Soil samples were tested for Mehlich-1 extractable P (M1P) which only accounts for a portion of the total P in the soil and is correlated with the amount of soil P available for plant uptake. A correlation equation for total P (TP) and M1P, developed with data taken from several Spodosols[5], was use to estimated TP concentration for the soil in each treatment (Obreza, Thomas A., Interim Associate Dean for Extension and Extension Specialist, University of Florida. Gainesville, FL. Personal Correspondence. February 19, 2009). The correlation equation is as follows:

$$TP = 5.54M1P + 4.69 \qquad r^2 = 0.86 \tag{4-3}$$

Data used to develop equation 4-3 were obtained from four sample sets taken from Spodsols that had only fertilizer P added to them; one of the sample sets was taken from a citrus field within a kilometer from the study area.

The mass balance for estimated TP is described by the equation:

$$P_{pre\text{-}plant} + P_{fertilizer} + P_{rain+\ irri} - P_{plant} - P_{leach} - P_{post\text{-}harvest} = 0 \tag{4-4}$$

where $P_{pre\text{-}plant}$ is the estimated TP stored in the soil at the beginning of the growing season, and $P_{post\text{-}harvest}$ is the estimated TP stored in the soil after the growing season. The component $P_{fertilizer}$ is fertilizer inorganic P added to the crop bed at the beginning of the growing season. A portion of $P_{fertilizer}$ added to the soil is fixed by soil particles (fixed-P) and moves in and out of solution (dissolved-P) depending on microbial and plant activity, and soil pH. Total P stored in the soil was estimated (using eq. 4-3) to be as much as 34 times the elemental P applied in inorganic fertilizer for HR (80 kg/ha) and RR (60 kg/ha) treatments, and shows the vast difference between fixed-P and dissolved-P present in the soil. Therefore, it is likely that any $P_{fertilizer}$ added to the

[5] Spodosols only had fertilizer P added to them.

soil will not significantly affect the soil P. As a result, an assumption of steady state conditions for soil P was made, which leads to $P_{pre\text{-}plant} = P_{post\text{-}harvest}$. In addition, all $P_{fertilizer}$ is assumed to be dissolved into soil solution. Phosphorus uptake by plant and stored in fruit, shoot and root (P_{plant}) was based on P concentration measured in fruit, shoot and root samples during harvest, multiplied by the dry weight of the corresponding plant matter to give total organic P. $P_{rain+\ irri}$ is the amount of dissolve organic and inorganic P introduced to the field with rainfall and irrigation; average total P in well water used for irrigation was 1.8 mg/L.. However, $P_{rain+\ irri}$ added to the crop bed was assumed negligible for reasons described above for $N_{rain+\ irri}$. Hence, equation 4-4 becomes:

$$P_{fertilizer} - P_{fruit} = \Delta S_P \tag{4-5}$$

where ΔS_P is the change in the amount of dissolved fertilizer inorganic P present (considering any P leaching that may occur) in the soil (0-20 cm with no crop beds) after plant uptake.

All statistical analyses were performed using the statistical software program SAS for Windows Version 9.0 (SAS Institute Inc., 2004). Soil and groundwater quality data were analyzed using the ANOVA method; the linear mixed model procedure was applied to all response variables. Significance of statistical tests was indicated at P-values less than 0.05 and means separation was performed using Tukey's test within SAS for Windows Version 9.0 (SAS Institute Inc., 2004).

Results and Discussion

Water use

Water use was calculated from the difference between total depth of water applied to each treatment and the total drainage from each treatment during each crop season. Table 4-6A shows the depth of water applied to each plot to maintain the treatments. Table 4-6B shows the depth of water discharged from the field as sub-surface drainage via drain tiles. Sub-surface drainage water volume was typically highest in the RR-SD treatment and lowest in the RR treatment for all seasons, except for spring 2005 and fall 2005. During spring 2005, water table levels were managed to prevent sub-surface drainage in all plots.

Water used by crops with traditional seepage irrigation (HR and RR) was greater compared with crops irrigated by subsurface drip irrigation (RR-SD) for all seasons, as shown in Figure 4-6A. The lower water use for the RR-SD was due lower evaporation losses from the open ditch-based irrigation system used for HR and RR. Furthermore, since the drip lines in the RR-SD treatment were located 45 cm below the soil surface, they facilitated direct delivery of water to the water table resulting in less water applied per unit increase in the water table level. Figure 4-6A also reveals that irrigation depths (average of treatments) during the spring crop seasons were larger compared with the fall crop seasons. Larger irrigation depths during the spring were mainly due to higher general water table and higher rainfall during fall season compared with the spring (Figure 4-6D). It was anticipated that water use for the RR treatment would have been lower compared with the HR treatment. However, seepage irrigated treatments (HR and RR) recorded similar water use across the seasons where values for the HR treatment were greater than those for the RR treatment, and vice-versa. One explanation for this observation is that, the southern half of the study site most likely had a "leaky" spodic layer compared with the northern half of the field. As a result, water use in the southern half of the field required greater quantities of water just to maintain a water level similar to that in the northern half of the field. Hence, there were times when more water was used in the RR treatment (compared with the HR) since the permeability of the spodic layer was not uniform.

Overall, the HR treatment used the greatest amount of water (194 cm/season) to irrigate crops during the study period compared with the RR treatment (185 cm/season). The water used by the RR-SD treatment (113 cm/season) was about 60% of that used in the HR and RR treatments. Differences in water use across treatments (seepage vs. subsurface drip) can be explained by the effect of ET on the type of irrigation. Seepage irrigation had higher evaporation losses compared with drip since the water was applied to surface ditches for the former.

Soil and groundwater dynamics

Figure 4-7 displays the treatment average of soil moisture within the crop bed during each crop season. In most cases, the average soil moisture in the HR treatment was greater than that of RR and RR-SD treatments. In several instances soil moisture values fell outside the target range for each treatment. This is not surprising with seepage irrigation considering the difficulty with maintaining a water table depth, especially after rainfall. Instances where soil moisture contents fell outside of their target range were mainly due to adjustments made to irrigation depth in response to potential or actual rainfall events. For instance, after a large rainfall the water table within each treatment descended in response to a drop in the regional water table. A drop in the water table leads to a decrease in the moisture content of the crop beds. This external factor requires an increase in irrigation volume for all plots to prevent moisture levels from dropping below their target range. An increase in irrigation volume increases the chance of exceeding the target moisture contents for each plot. The exceedance of target moisture contents was more apparent in RR treatments since they were maintained at lower moisture levels. This appeared to be the case for the RR-SD treatment during spring 2005 and the RR and RR-SD treatment during fall 2005 (Figure 4-7). Figure 4-8 shows the average depth of the water table below the crop bed in each plot; on average, the water table depth for HR was 5 cm higher than RR. The HR treatment had a consistently higher average water table depth compared with the RR treatments during the study period. Differences between the average daily water table depths for the HR and RR treatments for the period of record ranged from 3 to10 cm. Although the irrigation depths applied were able to maintain differences in water table depths among the treatments in some cases, this difference was not reflected in the average soil moisture levels. At times, while the water table was lower in the RR treatment (approx. 50 to 60 cm) compared with the HR treatment (approx. 30 to 40 cm), the water table in RR was not low enough to maintain soil moisture contents that fell within their target range. For example, 2 cm of rain fell on November 29, 2005, which raised the water table depth in the RR treatment from 60 cm to 30 cm. During this time, the moisture content of the RR treatment increased above its target range to a value of 23% (point A in Figure 4-9) and did not return to its target range for another 2 days even though the water table depth returned to its target range (50 cm to 60 cm). Apparently, the geotextile barrier installed to minimize lateral flows restricted subsurface drainage to deep seepage; as a result, it took more time for soil to drain from 23% to 5-10%. This helps to explain why the moisture content for the RR treatment was similar to that of the HR treatment during 2005, which experienced unusually wet conditions during spring as well as fall 2005 growing seasons.

The available soil water storage volume after a rainfall/irrigation event depends on the antecedent soil moisture. Typically the HR treatments, on average, had a higher soil moisture content compared with the RR treatment. For instance, the average soil moisture content within the crop bed of the HR treatment (18%) during spring 2006 was higher than that for the RR treatment (13%). The porosity (47%) of the crop beds was calculated based on bulk density measurements taken from soil sampled at SWFREC. Therefore, on average, the HR treatment had 28% less storage than the RR treatment, which shows that the RR treatment had a greater amount of storage for rainfall.

In general, the HR had a higher average water table and soil moisture content within crop beds compared with the RR. A higher water table led to less available storage for rainfall in the

HR treatment compared with RR. Therefore, the water table in the HR treatment (compared with the RR treatment) was more likely to enter into the crop beds during intense rainfall events and result in near saturation of part or all of the bed. As a result, fertilizer N and P was more likely to dissolve and leach out of crop beds in HR compared with RR treatments.

Soil N and P

Data from deep core sampling during spring 2006 were analyzed to determine the state and fate of N in crop beds under HR and RR fertilizer-water treatments. Concentrations of NO_x-N in the crop bed (0-10 cm and 10-20 cm) of the HR treatment were significantly higher than the RR treatment (Table 4-5). Processes affecting NO_x-N concentration (i.e., denitrification mineralization, plant uptake and leaching) were not enough to mask a treatment effect on NO_x-N concentrations within the crop beds.

There is some evidence of a treatment effect for the NO_x-N concentration between the HR and the RR treatment below the beds (20-30cm at $P = 0.051$ and 30-40 cm at $P = 0.072$; Table 4-5). It is not uncommon to find the water table at the 20-40 cm depth, which results in near saturated moisture levels at this depth, increasing the likelihood of N leaching. In addition, elevated moisture increases the availability of N for plant uptake within the 20-30 cm and 30-40 cm layers. Therefore, leaching and plant uptake of NO_x-N were likely factors that would have induced variations in NO_x-N concentrations at the 20-30 cm and 30-40 cm depths below the crop beds.

Table 4-5 shows that there was no significant difference ($P<0.05$) in soil NH_4-N concentrations between the HR and RR treatments within the bed at the 0-10 cm depth. Soil sampled at the 0-10 cm depths for each crop bed had a high spatial variability in moisture level; this could be attributed to evaporation through plant holes and the uneven wetting of the crop bed by upflux. Spatial variability in soil moisture content at the 0-10 cm depth would result in variability in nitrification rates for both treatments. Consequently, nitrification at the 0-10 cm depth (neglecting N volatilization) may result in the variability of NH_4-N concentrations for both treatments. In addition, variability in the dissolution of fertilizer NH_4-N may have contributed to variability of the NH_4-N concentrations. Such variability was large enough to mask a treatment effect at the $P = 0.05$ significance level.

A treatment effect was seen for NH_4-N concentrations at the 10-20 cm depth. At the 10-20 cm depth, variability of nitrification would have decreased compared with that at the 0-10 cm depth as a result of higher uniformity in moisture content. Hence, nitrification may have decreased enough to limit the range of fluctuations of NH_4-N in the 10-20 cm layer for each treatment, and explains the reason for the treatment effect ($P < 0.05$) seen at this depth (Table 4-5).

There was no treatment effect for depth 20-30 cm and 30-40 cm below the beds. The limited mobility of NH_4-N may have resulted in nitrification of most NH_4-N while in the crop bed before moving into lower layers (20-30 cm and 30-40 cm). Therefore, it is likely that the absence of a treatment effect below the crop beds was due to variations in relatively lower NH_4-N concentrations caused by plant uptake and leaching.

Nitrogen leaching is the transportation of N from the root zone, and may be driven by NO_x-N concentration gradients developed by processes of diffusion, advection or dispersion. Table 4-5 shows the presence of a vertical concentration gradient from the 0-10 cm to the 30-40 cm depth for all species of N measured. Soil layers within the crop bed (0-20 cm) for HR and RR had numerically higher N concentrations than layers beneath the crop bed (20-40 cm) (Table 4-5). In some cases, concentrations of NO_x-N and NH_4-N (for HR and RR) at a depth were an order of magnitude higher than the underlying depth. The distinct vertical distribution of soil N observed was a result of how fertilizer granules were distributed within the beds at the beginning of the season; 75-80% of total fertilizer was placed at the 0-10 cm depth while the remainder (20-25%) was placed at the 10-20 cm depth. High rates of fertilizer placed at the top of the bed (0-10 cm) induced the highest NO_x-N and NH_4-N concentrations (Table 4-5), and acted as a constant source of N for underlying layers throughout the season (Figs. 4-10 and 4-11). For instance, Figure 4-10 shows that NO_x-N and NH_4-N concentrations in the HR treatment remained in the 80 kg/ha to 350 kg/ha range at the 0-10 cm depth during the sampling period. Similarly, the NO_x-N and NH_4-N concentrations in the RR treatment remained within an approximate range of 40 kg/ha to 200 kg/ha for the 0-10 cm depth during the growing period (Fig. 4-11). Since NO_x-N and NH_4-N concentrations were consistently higher in the HR treatment, a higher leaching potential likely existed in the HR treatment.

Processes affecting N can lead to its transformation (within a sampled layer) from one species to another and/or the transport of N from one depth to another. Evidence of several instances of N transportation/transformation are identified and labeled in Figure 4-10 (HR treatment) and Figure 4-11 (RR treatment). Possible instances of NO_x-N leaching from the 0-10 cm depth in HR and RR can be seen by examining NO_x-N values between consecutive sample dates; an example of such an instance is displayed in Figures 4-10 and 4-11 by point A. Denitrification of NO_x-N and volatilization of NH_4-N are processes that would remove N from the soil, but these processes are assumed negligible as discussed. Evidence of N transported from overlying layers through leaching may be evident by the increase of NO_x-N and NH_4-N values in lower layers that corresponded simultaneously with an event displayed by point A; an example of such instances is displayed in Figures 4-10 and 4-11 by point A1.

Evidence of mineralization maybe seen in Figures 4-10 and 4-11 where values of organic nitrogen (ON) decrease between consecutive core sampling dates, and are accompanied by an increase in NO_x-N within the same sampling period. Point B, in Figures 4-10 and 4-11, indicates a period where ON values decreased; point B1 indicates a corresponding increase in NO_x-N and/or NH_4-N values for the same layer.

Overall, Figures 4-10 and 4-11 show evidence of N leaching from layers within the crop beds (0-10 cm and 10-20 cm) into underlying layers (20-30 cm and 30-40 cm) during the spring 2006 growing season. However, demands of plant uptake need to be combined with values in Figure 4-10 and 4-11 to further characterize N leaching from the two treatments.

Nitrogen leaching (N_{leach}) was calculated using components (ΔS_N and N_{uptake}) of equation 4-2 (Table 4-4). N-leaching beneath crop beds of HR and RR treatments was calculated for periods between consecutive sampling dates. Table 4-4 shows that total N leaching in the HR treatment (283 kg/ha) was 60% higher compared with the RR treatment (177 kg/ha) during spring 2006. Higher N leaching from the HR treatment can be explained by the frequency and magnitude of N leaching events observed during the season. There were a total of five N leaching events for HR compared with two for RR during the season (Table 4-4). Further, considering instances where N leaching was observed for both treatments, it was greater in HR by up to 26% compared with RR (Table 4-4). N-leaching in both treatments appeared to be affected by fluctuations in the water table during the growing season (Figs. 4-12 and 4-13).

All N leaching events detected in the HR treatment can be attributed to a fall of the water table, shown for periods (a), (b), (c), (d) and (e) of Figure 4-12 during the soil core sampling period. Water table depth and soil moisture levels changed in response to changes in irrigation volume or rainfall. Moisture levels within the crop bed decreased and increased in response to the changing water table. Evidently, the descending water table carried NO_x-N (and to some extent NH_4-N) with it. Similarly, period (b) of Figure 4-13 shows an N leaching event observed in the RR treatment that was induced by a descending water table. For comparative purposes, N leaching events observed in HR (Figure 4-12) were also indicated in Figure 4-13.

Nitrogen leaching occurred for both HR and RR treatments during periods (b) and (d) of Figures 4-12 and 4-13. During period (b), irrigation in the HR treatment was reduced in anticipation of a rainfall event (0.44 cm) that occurred on March 13, 2006 (Fig. 4-12). Reduced irrigation caused a drop in the water table level that led to N leaching during the sampling period. Some evidence of N transport from the vadose zone to groundwater is seen in Figure 4-14 where a decreasing trend in NOx-N concentration was interrupted during period (b) for the HR treatment. The fact that a similar trend was also detected for total P (Fig. 4-14) indicated that this period experienced extensive leaching of N and P to the groundwater. Irrigation in RR was reduced during period (b) of Figure 4-13 to begin applying the treatment's moisture content (8-12%) after a period of watering-in tomato transplants. The lowering of the water table resulted in N leaching for the RR treatment. However, no evidence of N transport to groundwater was observed for RR during this period.

During period (c) of Figure 4-12, the water table in the HR treatment was lowered to offset the effect of the rainfall event (0.61 cm) that occurred on April 26, 2006. As a result, the water table level experienced some obvious fluctuations that led to N leaching during this period. In contrast, the RR treatment (during period (c) of Figure 4-13) had a moisture content (9%) that did not warrant any water table manipulation due to rainfall. The water table only rose 3 cm in response to the rainfall event; no leaching was detected during this sampling period for the RR treatment.

During the period (d) of Figure 4-12, the water table in the HR treatment was allowed to drop in an attempt to maintain the required moisture content for the treatment. It is possible that a gradual decline in the water table level would cause N to be transported out of the crop bed. A leaching event was indicated by the groundwater N concentration data for the same period (period (d), Fig. 4-14) and showed that N may be leached from crop beds without a sudden change in the water table level. In contrast to the HR treatment, the water table level in the RR treatment (period (d), Fig. 4-13) was raised to prevent the moisture content in the crop bed (0-20 cm) from falling outside the desired range (8-12%). In this case, transport of N from crop beds would not have resulted from a descending water table. Fertilizer dropout may have caused leaching of N during this period for HR, RR, or both. Period (d) of Figure 4-15 shows a spike in groundwater NO_x-N and TP during this period, which provides evidence of N leaching from the vadose zone during period (d) for the RR treatment.

While the NO_x-N and NH_4-N concentrations represent the N that is available for plant uptake, TKN measurements provides an estimates of organic N that may be available for future plants use. Total Kjeldahl N was found to be significantly higher in the HR treatment compared with the RR treatment for all layers except for the 30-40 cm depth (Table 4-5). TKN concentrations for all depths of both treatments had values within the same order of magnitude. The majority of TKN was composed of ON (Table 4-5). It can be calculated from Table 4-5 that, NH_4-N constituted less than 25% of TKN found in the 0-10 cm layer for the HR (22%) and RR (15%) treatments. This observation provides evidence of considerable a amount of ON in all soil layers sampled beneath the bed surface. Concentrations of TKN in the 0-10 cm layer of both treatments ranged from 400 to 600 mg/kg, and were notably higher than TKN concentrations for underlying layers (200 to 325 mg/kg). Soil TKN is a function of organic matter embedded by postharvest tilling of plant material into the upper 25 cm of soil at the end of each season. The presence of organic N beyond the crop season indicates the potential for its mineralization and availability for future plant use and/or leaching. Hence, the consistently higher levels of TKN in the HR treatment (Fig. 4-10) as compared with the RR treatment (Fig. 4-11) indicated that there was a higher potential for N leaching in HR between growing seasons.

Dissolved inorganic fertilizer P (DIFP) remaining in the soil after plant uptake (P_{plant}) was calculated using equation 4-5 and is presented in Table 4-6. The DIFP levels for the HR treatment were higher compared with the RR treatment. When fertilizer P was added to both treatments during spring 2004, the DIFP in the HR treatment was approximately 7% higher than in the RR and RR-SD treatments. During fall 2005, spring 2006 and fall 2006, DIFP was consistently added to the soil in HR while P was removed (seen as negative values in Table 4-6) from the fixed-P pool in RR and RR-SD. A portion of DIFP added in HR was likely fixed to soil particles or nutrient elements such as calcium, iron and aluminum. The remaining P not fixed to the soil would be available for leaching. Furthermore, if the soil's P adsorption capacity is exceeded, P leaching would occur. Evidence of P leaching is seen in the groundwater P concentrations for the HR treatment at the beginning of crop season spring 2006. This observation was the result of the accumulation of total P, based on cultural practices, applied in the HR treatment when compared with the RR treatment. Phosphorus was added to the HR treatment prior to all crop seasons (spring 2004-fall 2006) regardless of the residual P present in soil. Phosphorus application to the RR treatment was based on soil test P measured before the beginning of each growing season. Therefore, P likely accumulated until the P adsorption capacity of the soil in beds was exceeded in the HR treatment compared with the RR treatment. This was evident in Table 4-6, which shows a progressive build up of residual fertilizer P in the

HR treatment from fall 2004 (49.2 kg P/ha) to fall 2006 (192.7 kg P/ha). This is in contrast to the progressive decline of residual fertilizer P in the RR treatments from fall 2004 (RR=46.1 kg P/ha, RR-SD=45.2 kg P/ha) to fall 2006 (RR=5.6 kg P/ha, RR-SD=3.8 kg P/ha). As a result, under conditions of P saturation, P moved readily with the water table in the HR treatment (compared with RR treatment) and was reflected in the measured TP in groundwater samples (Figs. 4-14, 4-15 and 4-16). This observation is supported by the findings of a study conducted by Rhue and Everett (1987) at SWFREC that evaluated the response of tomatoes to lime and fertilizer P when grown on an acid, sandy Spodosol (i.e., Immokalee fine sand). The authors concluded that low concentrations of Mehlich-1 extractable P in Immokalee find sand were due to P leaching and not to immobilization of P. However, Mehlich-1 extractable P measurements for this study (Appendix A) were found to be relatively higher in HR (compared with RR and RR-SD). Higher Mehlich-1 P values indicate that there may have been some accretion of soil P in HR (compared with RR) during the spring and fall 2006 crop season.

To summarize, higher levels of fertilizer N and P and moisture content within crop beds for the HR treatment led to consistently higher N and P leaching potential in the crop beds throughout the spring 2006 crop season. As a result, N and P leaching from crop beds was larger in the HR treatment compared with the RR treatment. Higher water tables in the HR treatment (compared with RR) likely resulted in more frequent N and P leaching events during the spring 2006 growing period.

Soil solution N

Analysis of soil solution N data included all samples collected by suction lysimeters during six growing seasons within the period spring 2004-fall 2006. Inorganic N data from suction lysimeters seem to confirm the conclusions from the core sampling data for the HR and RR treatments. Soil solution NO_x-N and NH_4-N leached from the crop beds were numerically higher (up to 45%) in the HR compared with the RR. There was some evidence of a treatment effect for leached NO_x-N (P = 0.0526) and dissolved inorganic nitrogen (DIN) (P = 0.0695) beneath crop beds (Table 4-7) where measured DIN values for the HR treatment were larger than those in the RR treatment. The fact that there was only some evidence of higher NOx-N concentrations indicates that the temporal variability in the extent of NO_x-N losses through processes such as denitrification, plant uptake and leaching from crop beds in each treatment was large enough to mask the treatment effect. Such masking was also observed for the core sampling data at the 20-30 cm layer (Table 4-5). Even though denitrification is a factor that affects NO_x-N, the absence of an anaerobic environment (moisture contents > 28%) (Fig. 4-7A), minimizes the extent of denitrification in the beds. Plant biomass and nutrient analysis revealed that there was no significant difference in plant uptake (Chapter 3, Table 3-3). However, fluctuations in moisture content in each treatment (Fig. 4-7) were high enough to promote leaching of NO_x-N from crop beds of both treatments. The absence of a treatment effect for NH_4-N is reflected in the relatively high variability in NH_4-N concentration for the HR (15 ± 3 mg/L) and RR (11 ± 2 mg/L) treatments.

To summarize, suction lysimeter data show evidence of high leaching potential of NO_x-N for the HR treatment compared with the RR and RR-SD treatments. Higher leaching was a result of high water and fertilizer input for the HR treatment compared with the RR treatment. The suction lysimeter data supports the conclusions from the core sampling data for spring 2006. Higher N transport from the vadose zone for the HR treatment (compared with the RR treatment) indicates higher potential for leaching to groundwater for HR.

Ground Water N and P

Shallow wells

Concentrations for DIN, NH_4-N, TKN, TN and TP were significantly higher for the HR treatment compared with the RR and RR-SD treatments ($P \leq 0.05$; Table 4-7). Additionally, there was moderate evidence of a treatment effect in the measured NO_x-N concentration for the HR treatment (28 mg/L) which was larger than that in the RR (12 mg/L) and RR-SD (15mg/L) treatment ($p \leq 0.055$; Table 4-7). The high mobility of NO_x-N and fluctuations in soil moisture and water table may have caused large spatial and temporal variability in groundwater NO_x-N concentrations beneath the three treatments. These variations within each treatment would have the tendency to mask the treatment effect on groundwater NO_x-N. On the other hand, NH_4-N concentrations for the HR treatment (10 mg/L) were significantly higher ($p = 0.05$) than the RR (3 mg/L) and RR-SD (4 mg/L) treatments. The adsorptive nature of NH_4-N in soils would have reduced its variability compared with NO_x-N. When the NH4-N and NOx-N were combined to obtain DIN, the treatment effect became clear. The average DIN concentration for the HR treatment (37 mg/L) was significantly higher ($P = 0.05$) than the RR (15 mg/L) and RR-SD (19 mg/L) treatments. Higher levels of groundwater NOx-N and NH_4-N for the HR treatment compared with the RR and RR-SD treatments is indicative of the higher levels of N transported from the crop beds in HR compared with RR and RR-SD. Furthermore, higher concentrations of TKN measured at depths 20-30 cm beneath the bed surface of HR provided a greater source of N (compared with RR and RR-SD) that may have entered into solution when the water table reached the 20-30 cm depth.

The amount of N transported to the shallow groundwater beneath the HR treatment was large enough to overcome the masking effect of dilution. This is evident in the sampling variability of all the nutrient concentrations measured for shallow groundwater (Table 4-7), which was not large enough to mask the treatment effect. For example, the standard errors in TKN for the HR (± 2 mg/L), RR (± 1 mg/L) and RR-SD (±1 mg/L) treatments are smaller than the differences between the means (Table 4-7). Additionally, the dilution effect would be more apparent if the HR and RR treatments had the same fertilizer rates but maintained different water table levels beneath. However, since data from core samples and suction lysimeters indicated that N leaching from the HR treatment was much higher than the RR treatment, the effect of dilution on shallow groundwater N concentrations was considered negligible.

Total P concentration (3,090 µg/L) in the HR treatment was highest among the three treatments and was approximately 33% higher than the two RR treatments (RR = 2098 µg/L and RR-SD = 2048 µg/L). The relatively high groundwater P concentrations measured for the HR treatment was expected in light of a progressive increase in residual P concentrations for HR (compared with RR) as shown in (Table 4-6). This result reflects the higher potential for P leaching from crop beds for the HR treatment compared with the RR treatment.

Overall, groundwater above the spodic layer for the HR treatment likely received greater amounts of nutrient N and P compared with that of the RR and RR-SD treatments during each crop season. On average, concentrations of N and P in groundwater for HR (3.1 mg/L for TP and 28 mg/L for NO_x-N) and RR (2.1 mg/L for TP and 12 mg/L for NO_x-N) were at least three orders of magnitude greater than the background levels measured for the Everglades (< 0.004 mg/L for TP and 0.005 mg/L for NO_x-N). While both treatments have groundwater N and P concentrations that are much higher than the background levels of the Everglades, the RR treatments are likely to improve the water quality of surface water discharges from fields under vegetable production. This observation is especially important when the affected groundwater is likely to discharge into adjacent ditches, canals, and streams as drainage. Such drainage losses are especially likely during dry conditions for waterways adjacent to crop fields found within the flatwoods of south Florida. Flatwoods soils typically have a low conductivity layer (e.g. spodic layer) that is restrictive to vertical flows. Hence, groundwater is able to move laterally over the spodic layer in the direction of a hydraulic gradient. Such conditions result in movement of most water, which infiltrates the soil, into a ditch/canal.

Deep wells

Statistical analyses indicated that there were no significant differences ($P \leq 0.05$) in NO_x-N, NH_4-N, DIN, TKN and TP concentrations (Table 4-7) between HR, RR and RR-SD. Table 4-7 reveals that the RR treatment had an average DIN concentration of 12 mg/L, which was numerically greater than the HR treatment concentration of 8 mg/L. The HR treatment had the highest TP concentration (1302 μg/L), while the RR treatment had the lowest TP concentrations (1115μg/L) (Table 4-7). Also, the numerical differences in concentrations between treatments were small and in most cases the concentrations in the HR treatment were less than those for the RR and RR-SD treatments. Overall it appears that the effect of treatment on deep groundwater N and P concentrations could not be detected for deep groundwater.

The lack of a treatment effect shows that, below the spodic layer, extensive mixing of groundwater from individual treatments with other treatments, as well as outside the study area, may have occurred. Such mixing likely resulted in the masking of a treatment effect. On the other hand, it is possible that the spodic layer may have restricted the transport of groundwater N and especially P from above the spodic layer to the extent that a treatment effect could not be detected.

Summary and Conclusions

A 3-year study (spring 2004 – fall 2006) was conducted to compare the effect of two fertilizer-water treatments on crop yield (tomato and water melon), groundwater quality and the impact on farm income. The fertilizer-water treatments evaluated were based on current surveyed grower fertilizer rates in south Florida (HR) and IFAS recommended fertilizer rates (RR). Seepage irrigation was applied in the HR treatment while the RR treatment utilized soil moisture-based seepage irrigation (RR) and sub-surface drip irrigation (RR-SD) during the study period. The data presented in this chapter examined the effect of RR, RR-SD and HR on nutrient (N and P) transport from crop beds to the groundwater.

The HR treatment received fertilizer-water inputs that were greater than the RR treatments during the growing season. Hydrological parameters (water use and water quality) were measured for each treatment. The data indicated that the HR treatment required more water input than the RR and RR-SD treatments on average. The higher water table maintained for the HR treatment (compared with the RR treatment) reduced the capacity of the soil to store rainfall. Hence, compared with the RR treatment, the water table in the HR treatment was found to more likely approach or enter crop beds during and after a rainfall event. In general, higher water table levels created conditions that were more likely to increase the transport of nutrients (N and P) from crop beds to the groundwater.

To evaluate the effect of water table level on the transport of N and P into the groundwater, measurements of soil nutrients (N and P) in the vadose zone were collected. Soil samples were collected to quantify the amount of N and P transported during a single crop season (spring 2006). A nitrogen mass balance equation was used to determine the amount of N leached from the crop beds. To evaluate the effect of water table levels on the transport of P into the groundwater, measurements of Mehlich-1 extractable P were taken pre- and post-growing season. This data was used in a P mass balance equation to estimate potential P leaching to the groundwater.

Soil core data showed that, on average, the HR treatment had significantly higher N concentrations within the crop bed compared with the RR treatment. Higher concentrations of nutrients in the crop beds created a larger N concentration gradient that enhanced N leaching in HR compared with RR. Conclusions drawn from soil core data were supported by data collected from suction lysimeters. The consistently higher N concentrations and moisture content in crop beds of the HR treatment led to more frequent N leaching events compared with the RR treatment. Leaching events were associated with a rise and/or fall in the water table level. The HR treatment had more leaching events than the RR treatment. Estimates revealed that the RR treatment reduced N leaching by 38% when compared with the HR treatment.

Phosphorus mass balance results showed that the potential for P leaching beneath the HR treatment seemed higher than that beneath the RR treatment. Continued application of P in the HR treatment during each season resulted in higher P content in the soil compared with RR. Fertilizer P was applied to RR only when soil test P showed a lack of P for optimum crop production. Evidence of higher nutrient leaching from the HR treatment (compared with the RR treatment) was supported by the groundwater N and P concentration data.

Data from groundwater N and P above the spodic layer showed that NO_x-N, NH_4-N, TKN and TP concentrations in the HR treatment were significantly higher than in the RR and RR-SD treatments. Average concentration of TN in the HR treatment was higher than the RR (137%) and RR-SD (81%) treatments, while the concentration of TP in the HR treatment was higher than RR (47%) and RR-SD (51%) treatments. It is evident that higher concentrations of soil N and P or soil solution N and P in the vadose zone led to higher groundwater N and P concentrations.

In contrast to shallow groundwater data, no evidence of a treatment effect on deeper (below the spodic layer) groundwater NO_x-N, NH_4-N, DIN, TKN, TN and TP concentrations was observed. It is likely that mixing of groundwater beneath a single treatment with groundwater beneath other treatments (and/or from outside areas) is large enough to mask the effect of the treatments on deep groundwater.

Overall, the following conclusions are made based on this study:

- Higher fertilizer rates and soil moisture levels in crop beds resulted in high nutrient transport into the shallow groundwater.
- The RR treatments reduced the amount of water pumping required for tomato production.
- The RR treatments (compared with the HR treatment) reduced the potential of N and P leaching from crop beds and significantly improved groundwater quality.
- The RR treatment, identified in the FDACS BMP manual, is likely to improve surface and groundwater quality in the vegetable producing areas of south Florida.

Results from this study can be beneficial for BMP adoption for tomato farms in south Florida. Future studies should measure N and P losses via runoff and drainage for the HR and RR treatments.

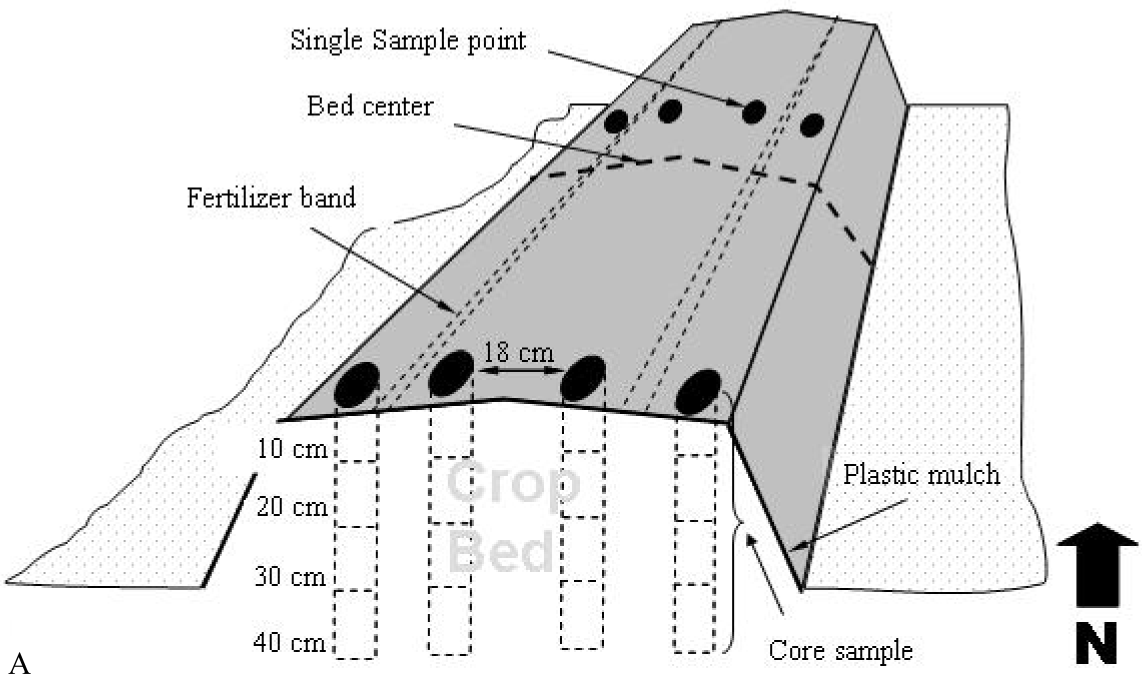


Figure 4-1. Schematics of layout for soil core sampling, plot arrangement and location of geotextile barrier. A) Core sampling. Core samples were collected at weekly and biweekly intervals in selected beds of HR and RR treatment for a tomato crop grown during spring 2006. B) Plot arrangement in field of the study site – drawing not to scale. C) Geotextile barrier used to hydrologically isolate six experimental plots; the geotextile barrier extends from the soil surface down into the spodic layer.

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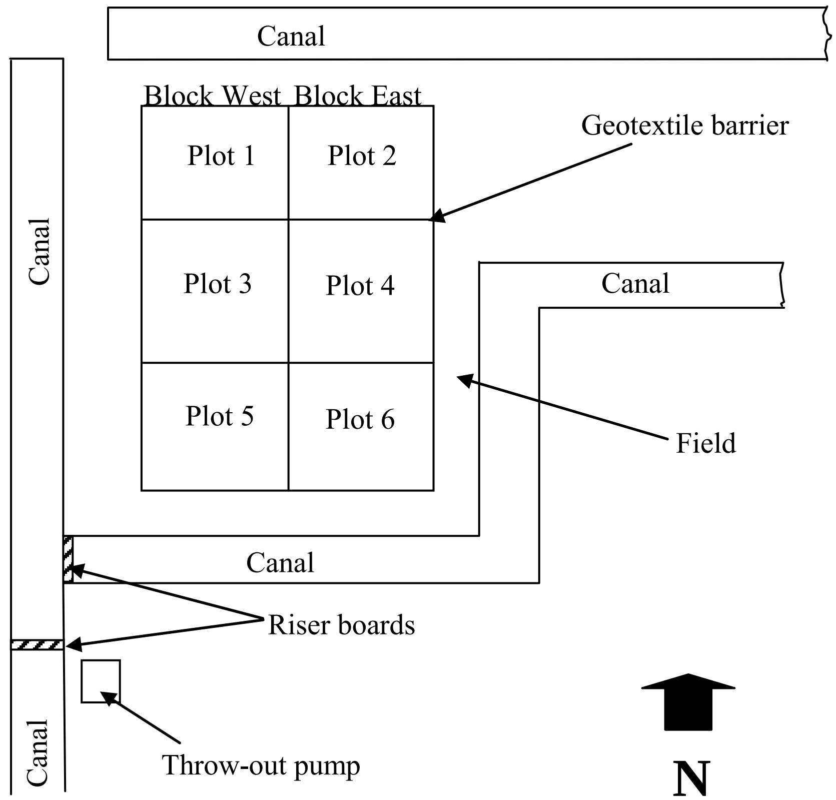

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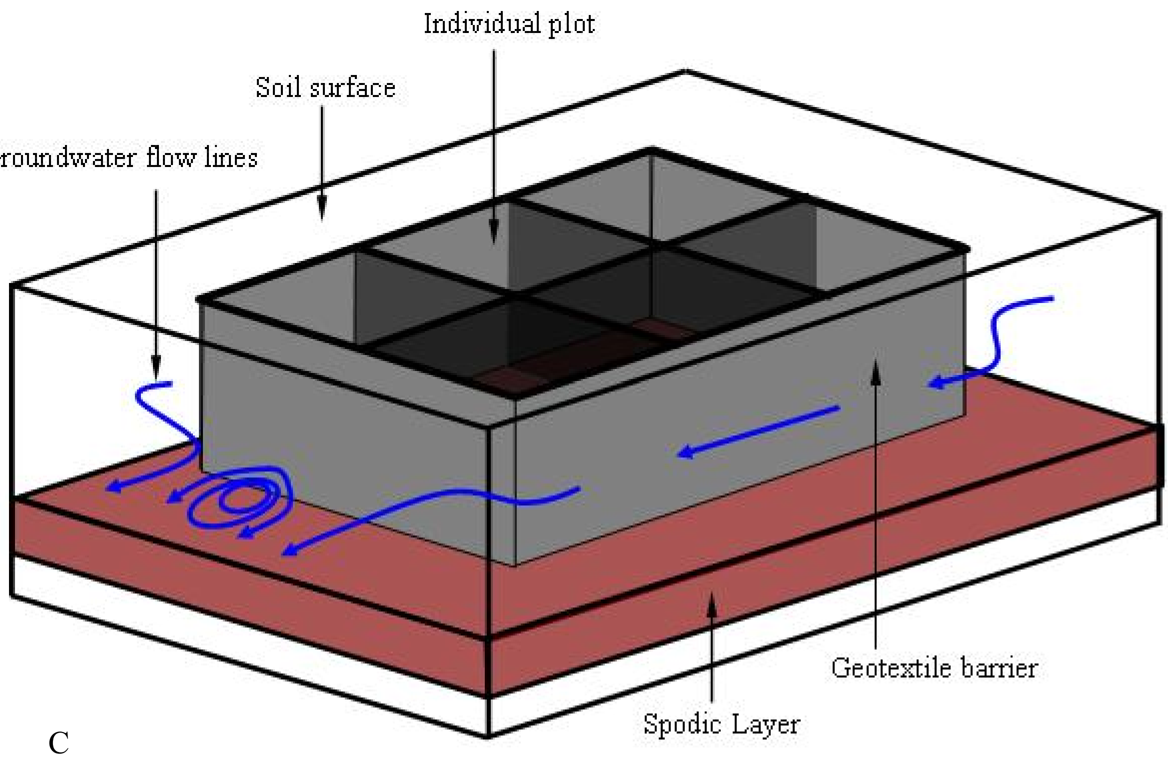
Figure 4-1. Continued



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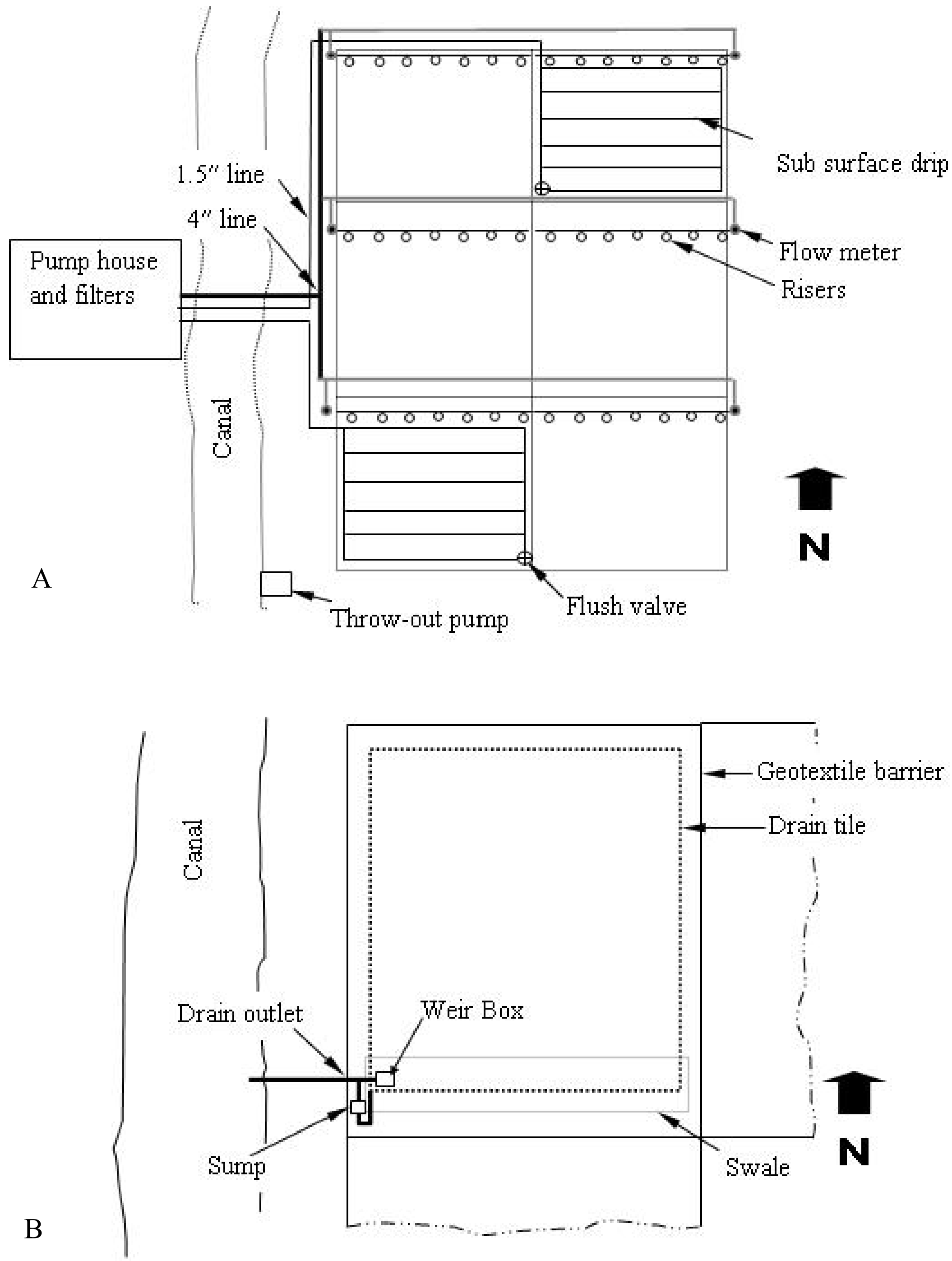


Figure 4-2. Layout for irrigation and drainage within each experimental plot. A) Irrigation lines for seepage and sub surface irrigation system.-drawing not to scale. B) Surface and subsurface drainage for each plot. Drawings are not to scale.

A

B

Figure 4-3. Water control structure and it's components. A) Drain box installed in each experimental plot to help manage the water table level beneath crop beds (AgriDrain Corporation, 2008). B) Ninety degree V-notch modification made to top board of drain box.

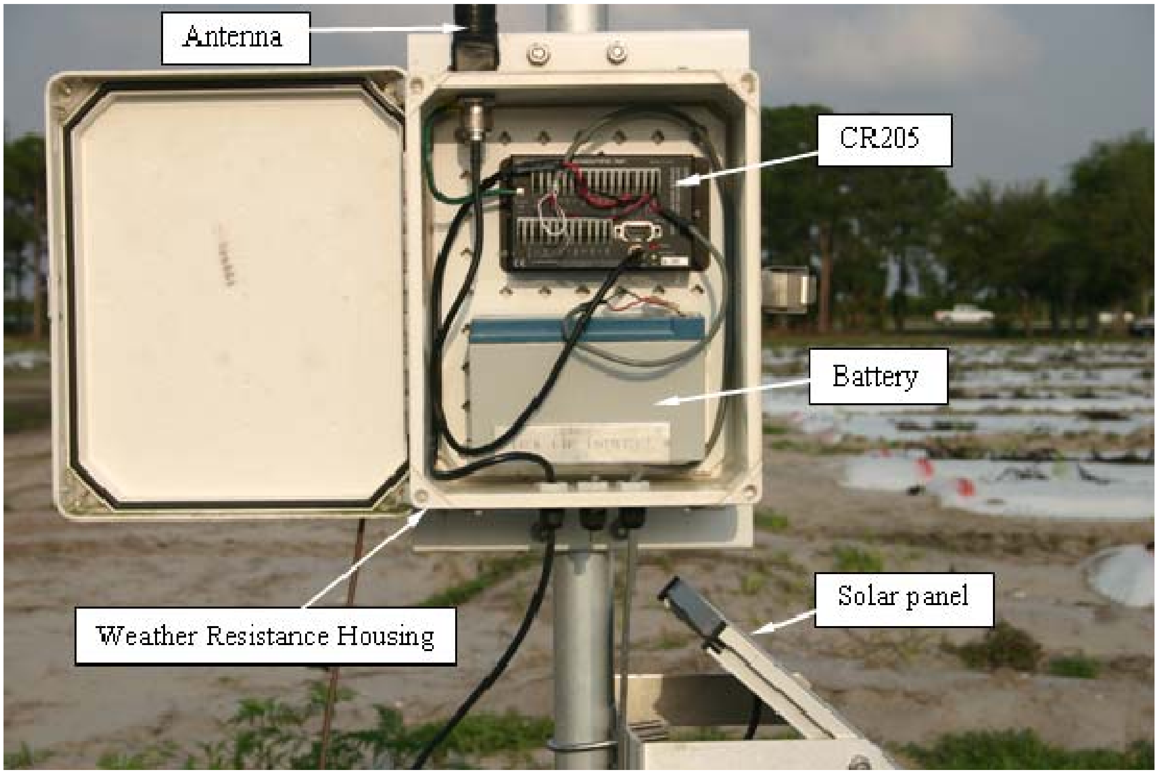


Figure 4-4. Weather resistant housing used to shelter a CR205 and a 12 V battery. The CR205 was used to store data collected from instruments in the field. A solar panel used to power the system can be seen directly below the housing. An antenna transmitted data to a server for permanent storage.

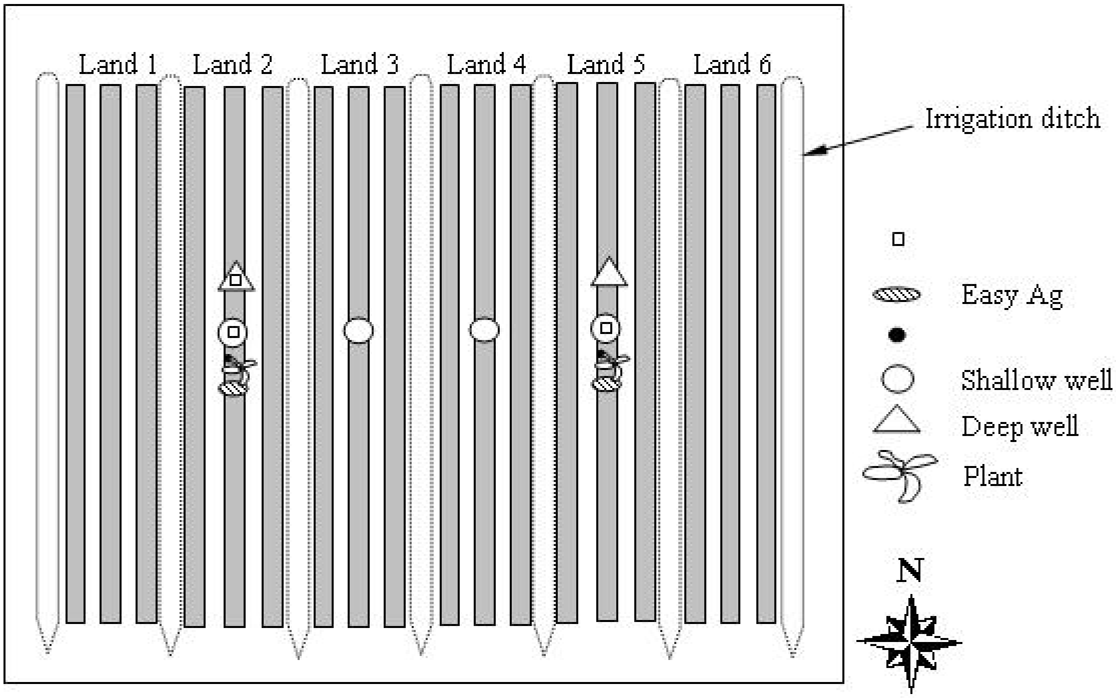
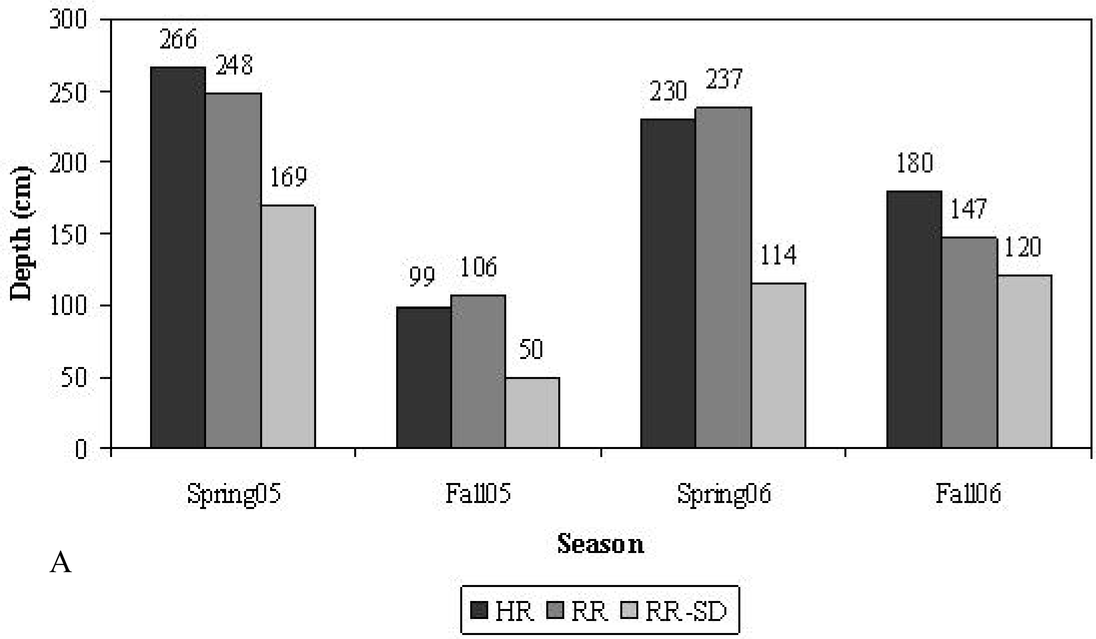


Figure 4-5. Schematic of instrument layout in each plot (Drawing not to scale).



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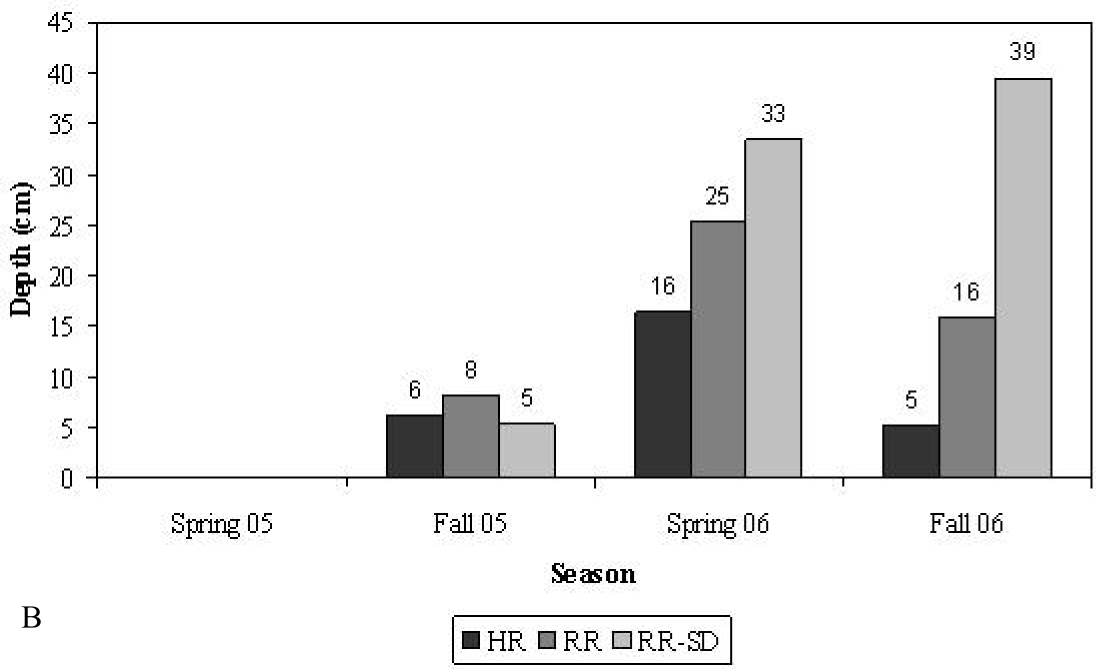
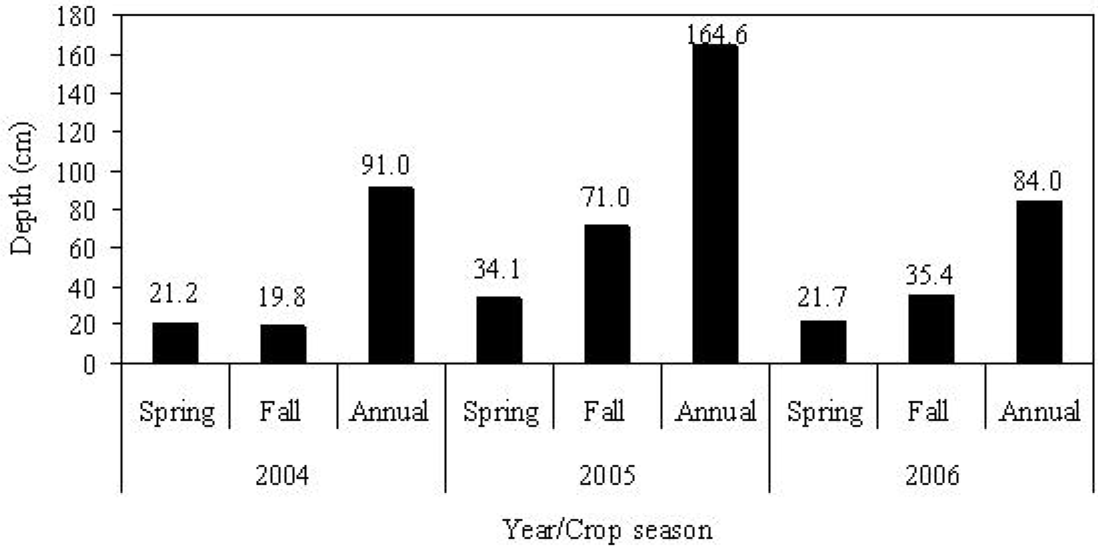


B

Figure 4-6. Bar graphs for water use, subsurface drainage and rainfall for each treatment during crop seasons spring 2004 thru fall 2006. A) Average water used per treatment during each crop season, spring 2005 thru fall 2006. Water used is the total depth of water applied to the field minus the total depth of water drained from the field. B) Seasonal sub surface drainage calculated for each treatment during spring 2005-fall 2006. C) Seasonal and annual rainfall for the study period. D) Overall average of water used per treatment.



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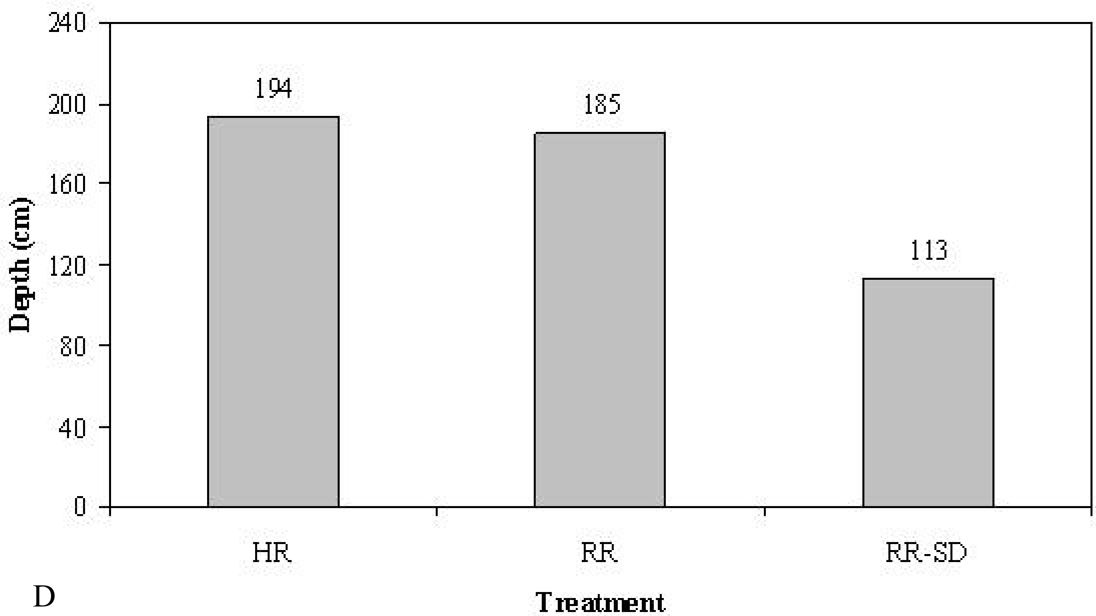

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Figure 4-6. Continued

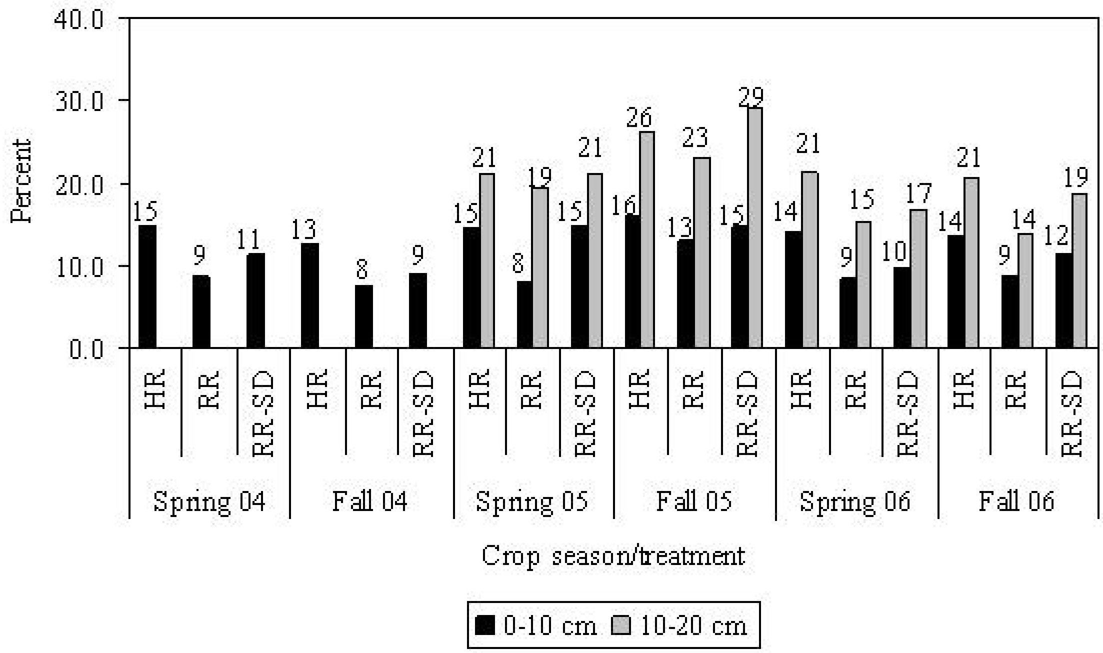


Figure 4-7. Seasonal average soil moisture contents (% by volume) for each treatment during crop seasons spring 2004 through fall 2006.

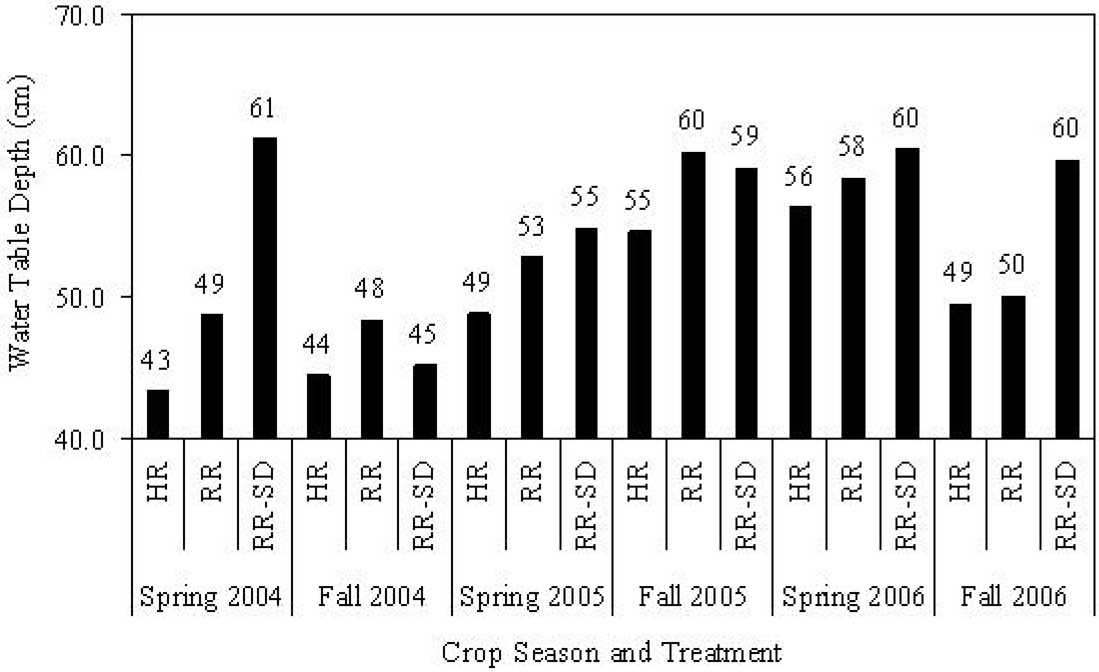


Figure 4-8. Seasonal average depth to water table (cm) for each treatment during spring 2004 thru fall 2006 crop seasons.

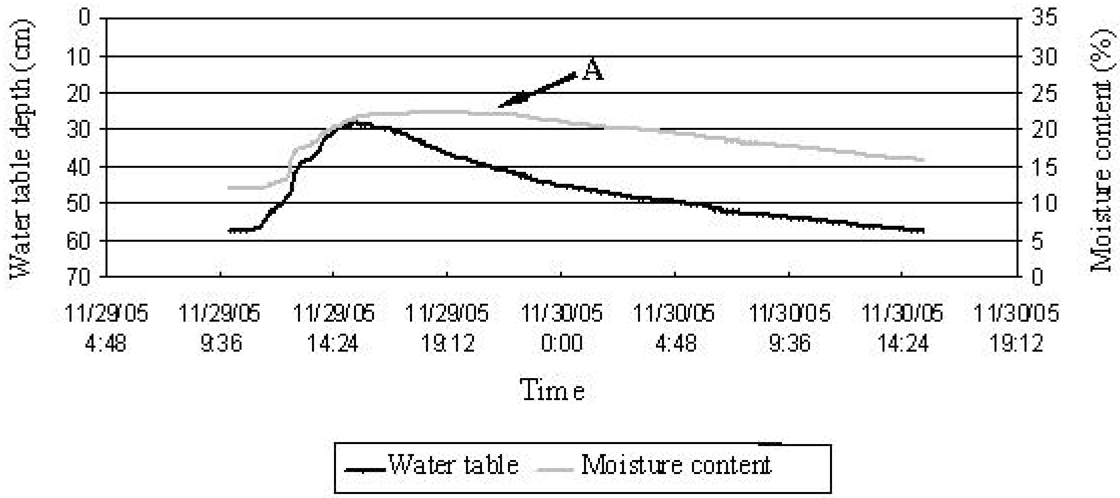


Figure 4-9. Example of relationship between water table and moisture content for RR treatment.

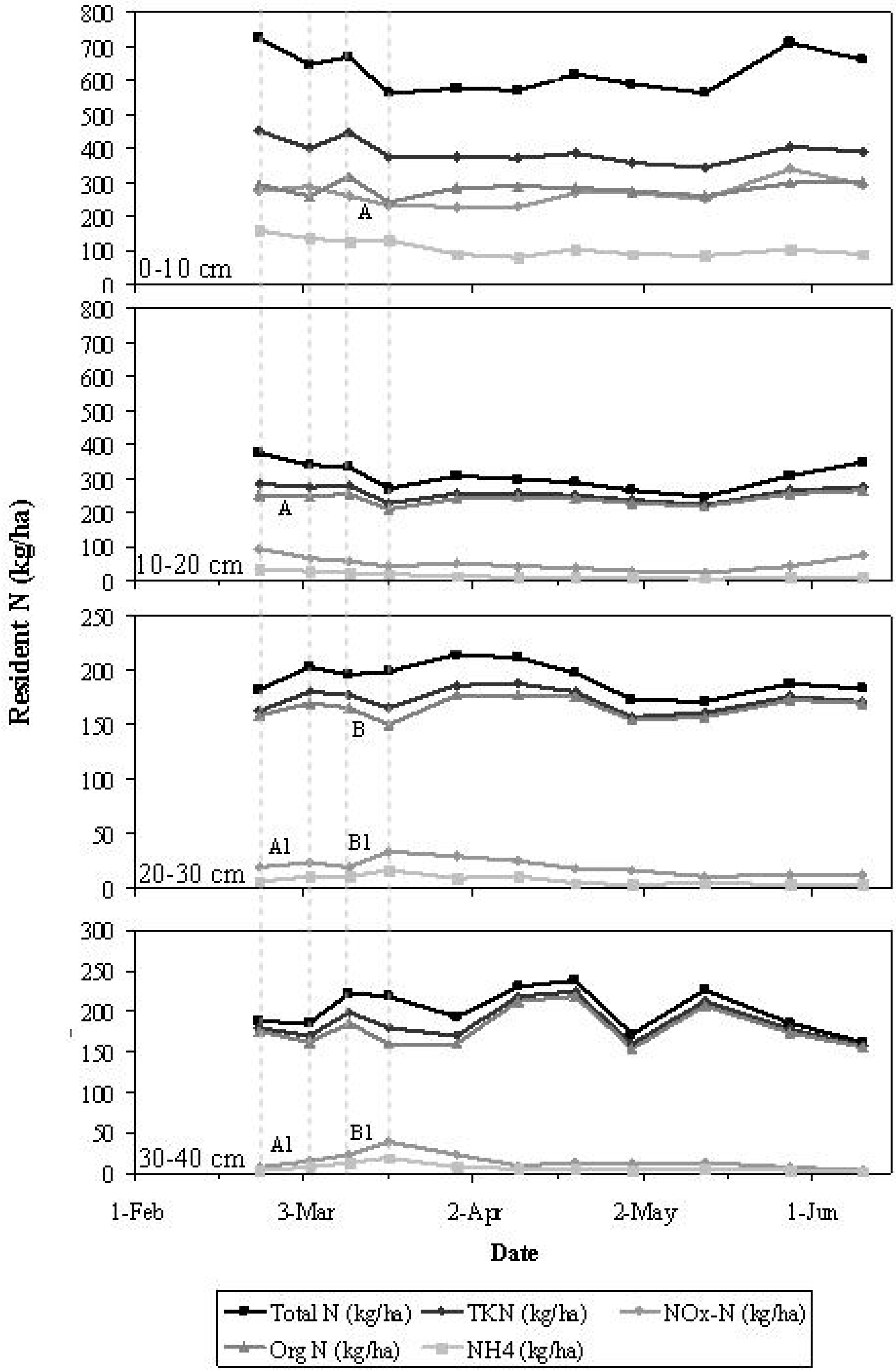


Figure 4-10. Resident soil TN, TKN, NOx-N, NH4-N and organic N for the four depths beneath crop beds for the HR treatment during spring 2006.

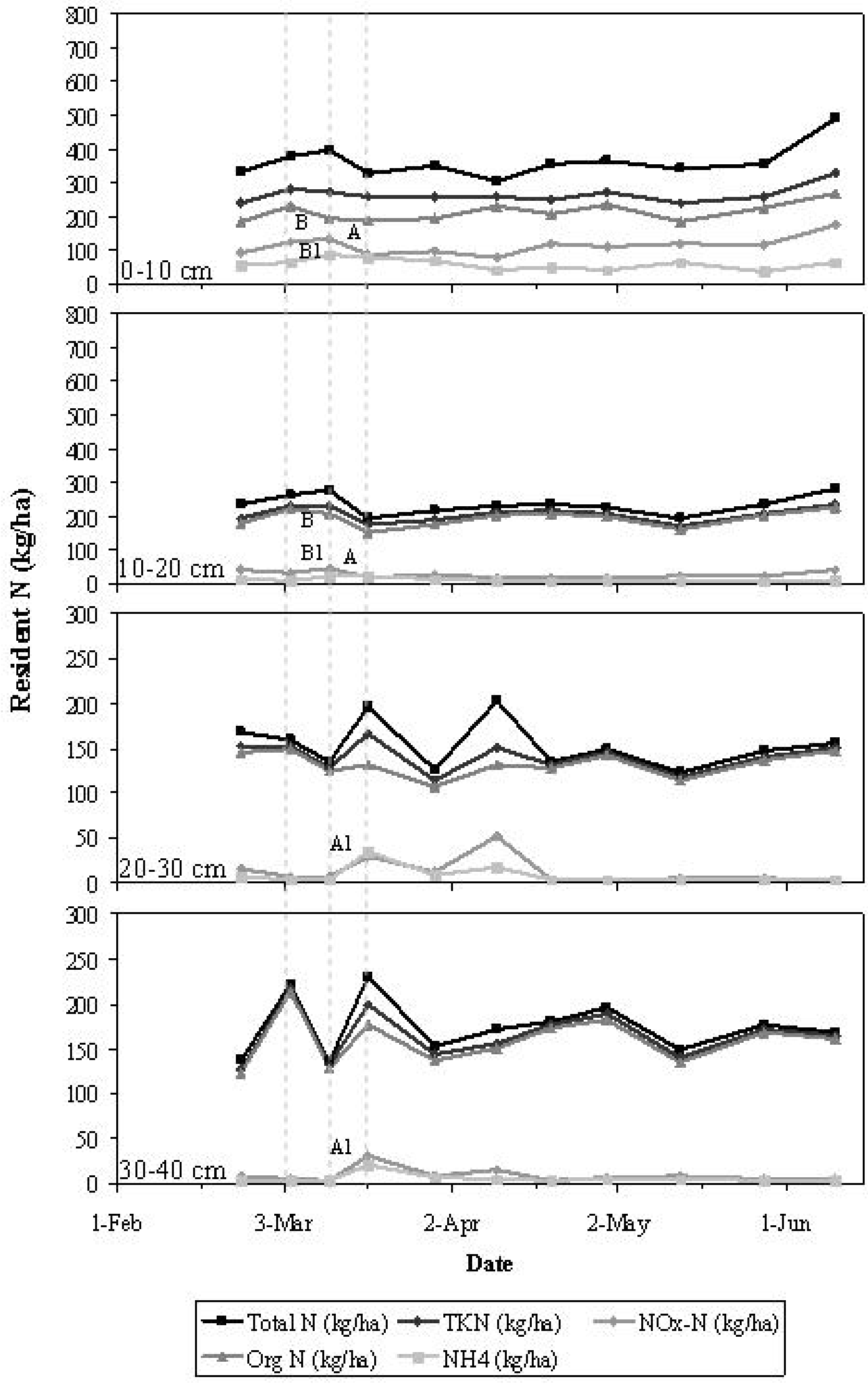


Figure 4-11. Resident soil TN, TKN, NO_x-N, NH_4-N and organic N for the four depths beneath crop beds for the RR treatment during spring 2006.

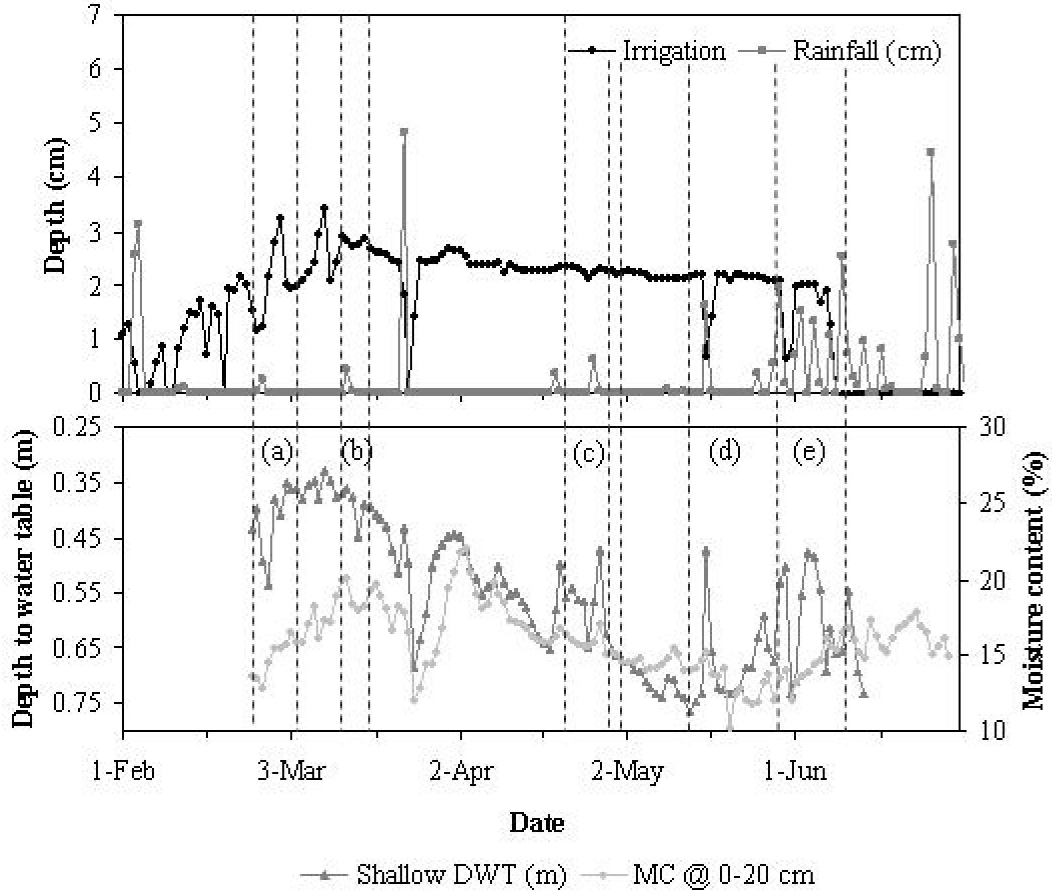


Figure 4-12. Average irrigation depth, rainfall depth, depth to shallow water table and moisture content within crop bed (0-20 cm) for HR treatment during spring 2006. Letters in parentheses indicate periods (delineated by dotted lines) of leaching observed in the HR treatment (Table 4-4) and are defined as follows: (a) = Feb 24-Mar 4, (b) = Mar 12-18, (c) Apr 21-30, (d) May 1-13 and (e) May 29-Jun 10.

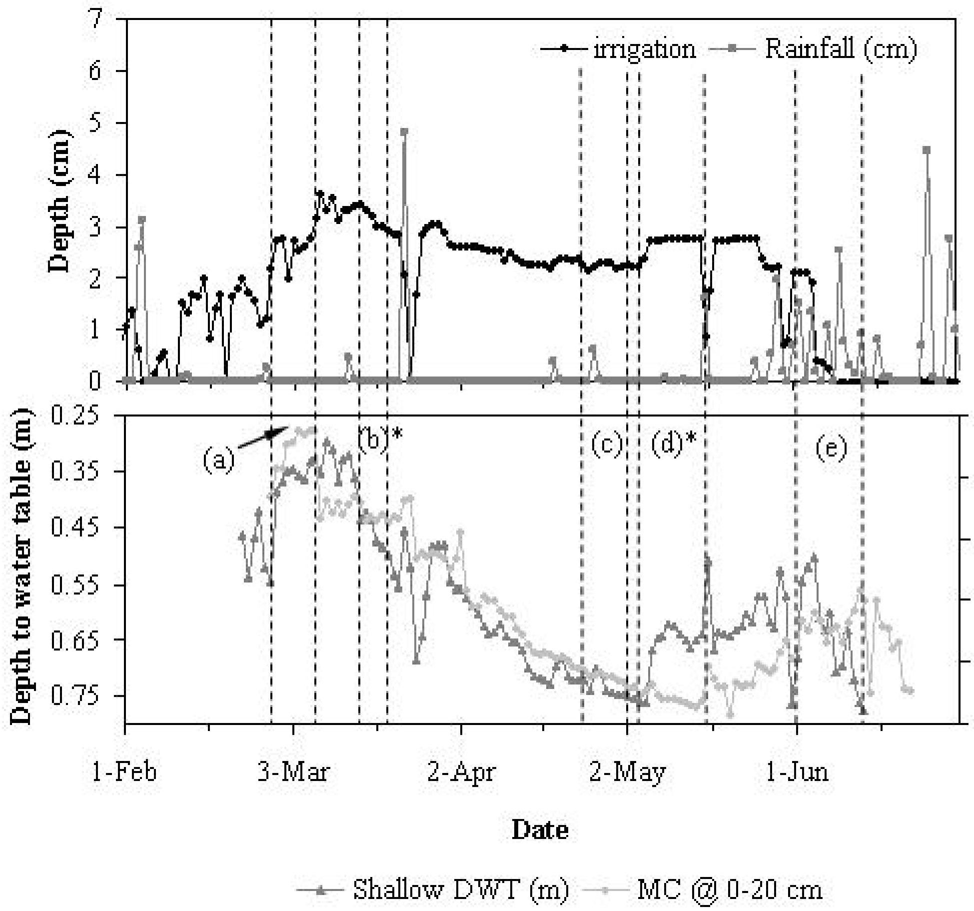


Figure 4-13. Average irrigation depth, rainfall depth, depth to shallow water table and moisture content within crop bed (0-20 cm) for RR treatment during spring 2006. Letters in parentheses indicate periods (delineated by dotted lines) of leaching observed in the HR treatment (Table 4-4) and are defined as follows: (a) = Feb 24-Mar 4, (b) = Mar 12-18, (c) Apr 21-30, (d) May 1-13 and (e) May 29-Jun 10. Symbol (*) indicates period when N leaching was detected in RR.

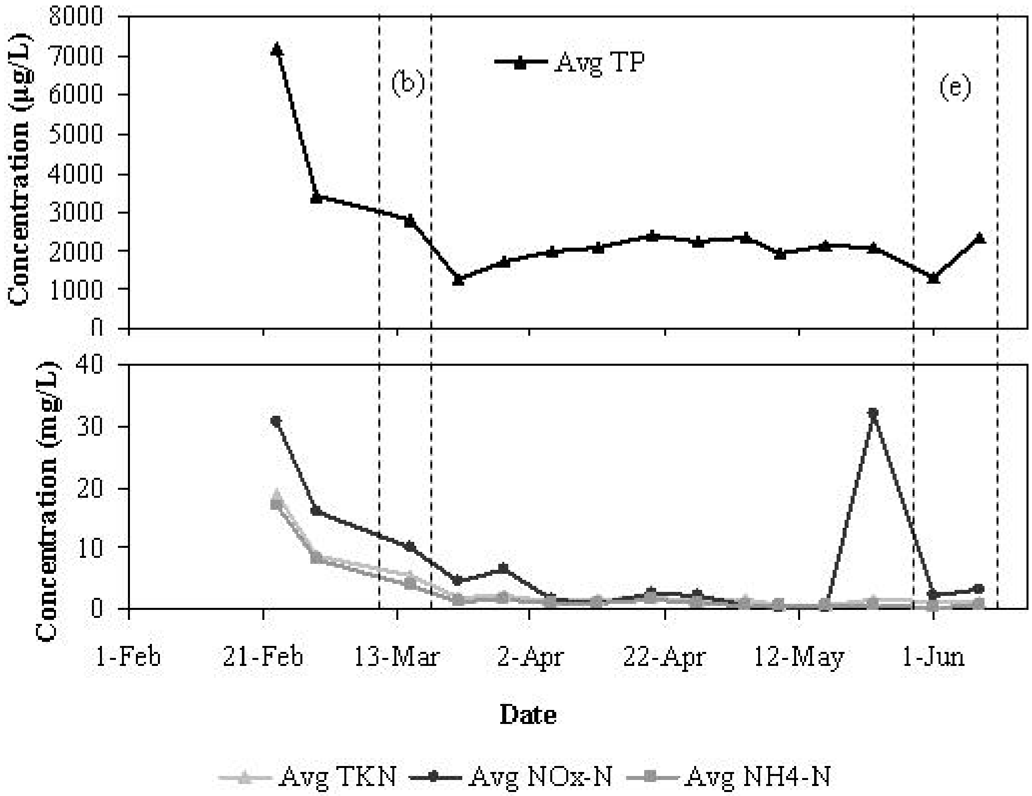


Figure 4-14. Average TP, TKN, NOx-N and NH4-N in shallow groundwater for HR treatment during spring 2006. Letters in parentheses show two periods (delineated by dotted lines) of leaching observed in the HR treatment (Table 4-4) and are defined as follows: (b) = Mar 12-18, and (e) May 29-June 10.

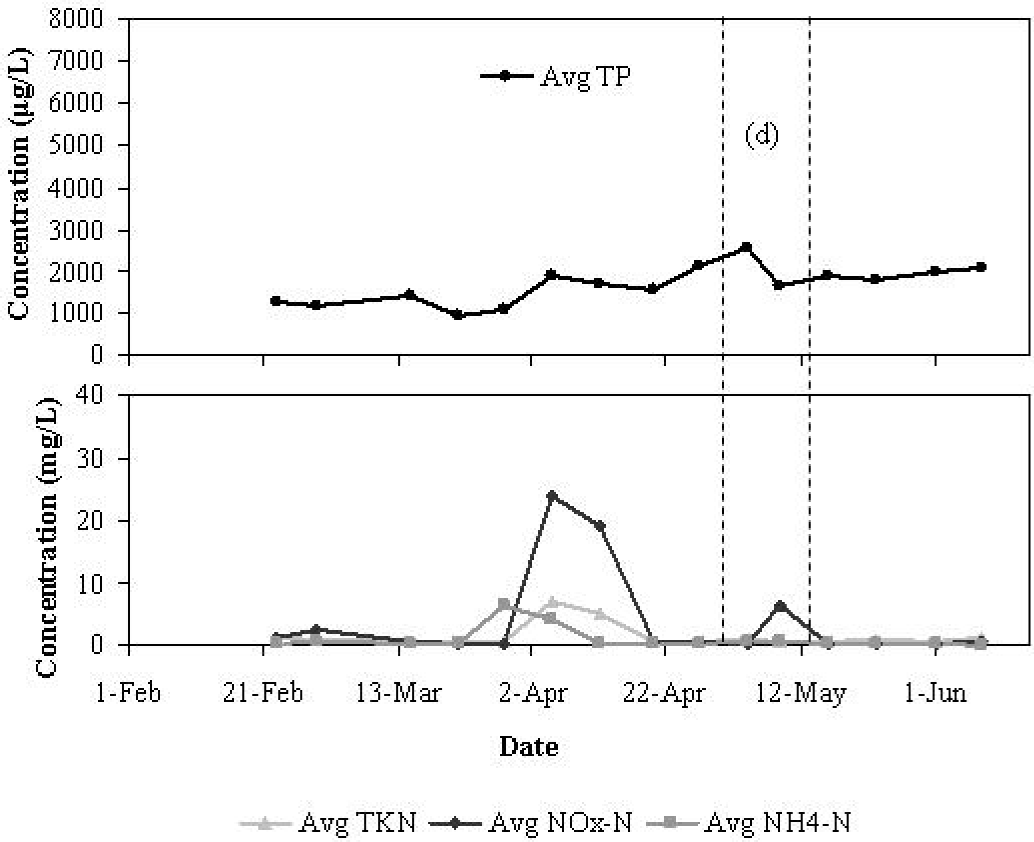


Figure 4-15. Average TP, TKN, NOx-N and NH4-N in shallow groundwater for RR treatment during crop season spring 2006. Letter in parenthesis shows a period (delineated by dotted lines) of leaching observed in the RR treatment (Table 4-4) (i.e., (d) = May 1-13).

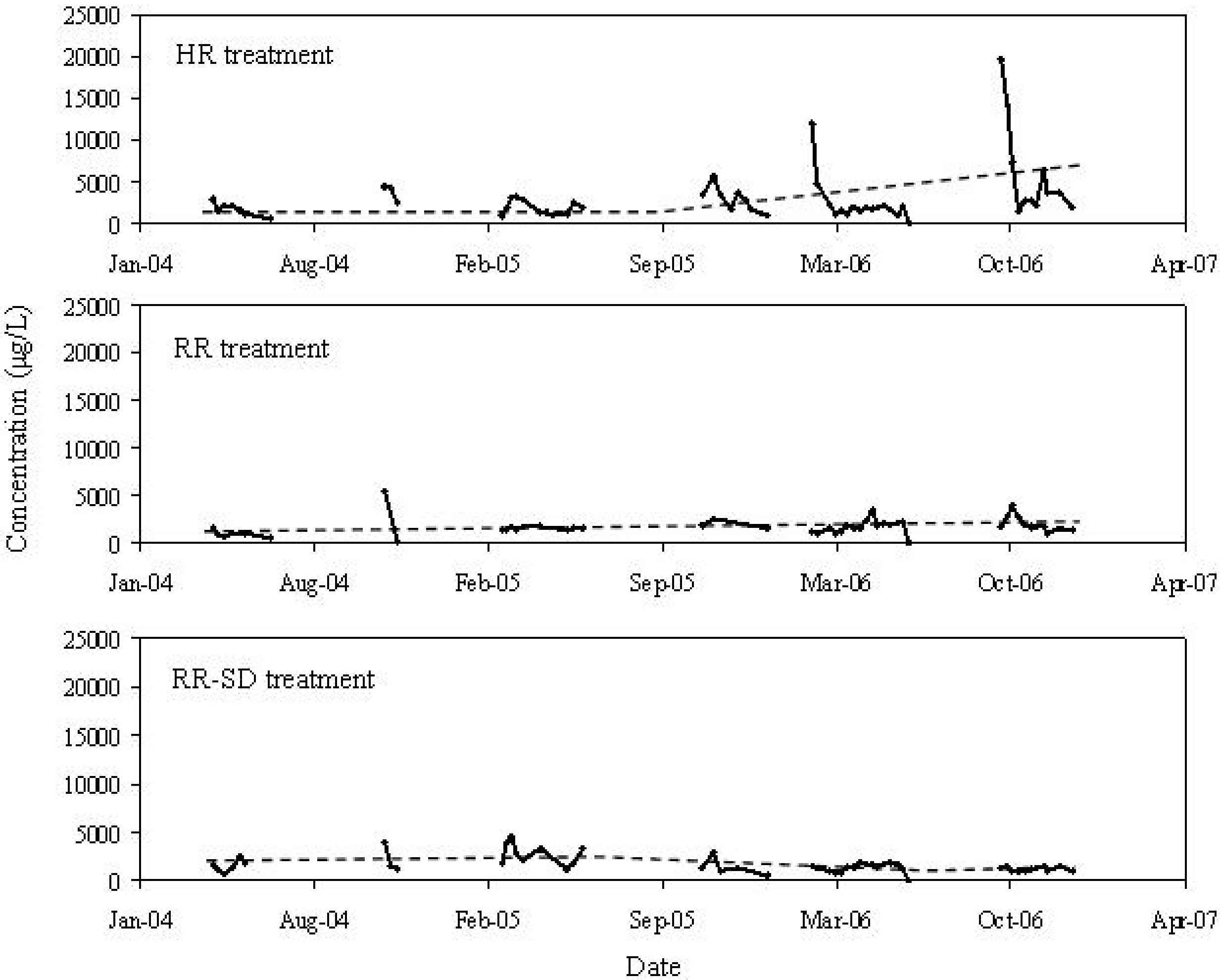


Figure 4-16. Average total P concentration detected in groundwater for shallow wells in each treatment during spring 2004, fall 2004, spring 2005, fall 2005, spring 2006, and fall 2006. Values presented are representative of each treatment. Solid line depicts total P concentration. Dotted line depicts the trend of the seasonal average of total P.

Table 4-1. Average fertilizer rates and moisture levels applied to each HR, RR and RR-SD treatment for watermelon and tomato crops during the study period. The HR treatment was based on a survey of 22 growers in southwest Florida. The RR treatments were based on rates recommended by UF/ IFAS

Treatment	Season	Watermelon			Tomato			Moisture content
		N kg/ha	P_2O5 kg/ha	K_2O kg/ha	N kg/ha	P_2O5 kg/ha	K_2O kg/ha	
Grower	All seasons	297	191	514	418	182	754	16-20%
IFAS & IFAS_SD	Spring 04	168	112	168	--	--	--	8-12%
	Fall 04	--	--	--	224	135	252	8-12%
	Spring 05	168	112	321	--	--	--	8-12%
	Fall 05	--	--	--	224	0	252	8-12%
	Spring 06	--	--	--	224	0	252	8-12%
	Fall 06	--	--	--	224	0	252	8-12%

Table 4-2. Soil and water quality sampling method and analytes for each experimental plot during crop seasons spring 2004, fall 2004, spring 2005, fall 2005, spring 2006, and fall 2006

Period	Parameter	Medium	Instrument	Depth	Frequency/Duration
All crop seasons	N, Mehlich 1-P and K	Soil	Auger	0 – 15 cm	Two samples per season
Spring 2006	NOx-N, NH4-N and TKN	Soil	Core sampler	0 – 10 cm, 10 – 20 cm, 20 – 30 cm, 30 – 40 cm	Weekly to bi-weekly (Spring 2006)
All crop seasons	NO_x-N	Soil solution	Suction lysimeter	18 – 23 cm	Weekly
All crop seasons	NO_x-N, NH4-N, TKN, TP	Ground water	Peristaltic pump	Shallow (64 cm), deep (244 cm)	Weekly

Table 4-3. Hydrologic parameters measured in each experimental plot and climatic parameters monitored at the weather station

Parameter	Instrument	Sensor depth	Measurement frequency
Moisture content	Capacitance probes	10 cm, 20 cm, 30 cm, 50 cm	15 min and daily
Water table depth	Pressure transducer	64 cm, 244 cm	15 min and daily
Water use	Flow meter		15 min and daily
Drainage	V-notch weir and pressure transducers		15 min and daily
Rainfall	Tipping bucket rain gauge		15 min
Wind speed	Ultrasonic wind sensor		15 min
Radiation	Pyranometer		15 min
Relative humidity	Hygrometer		15 min
Temperature	Temperature Probe (thermistor)		15 min

Table 4-4. Estimated N leached from crop bed (0-20cm) for ten sampling periods during spring 2006 crop season.

Sampling period		Net loss, ΔS_N (kg/ha)		Plant uptake, (N_{uptake}) (kg/ha)		N leaching (N_{leach}) (kg/ha)	
		HR	RR	HR	RR	HR	RR
2/23/2006	3/5/2006	51.03	--	3.84	2.88	47.20	--
3/5/2006	3/12/2006	--	--	2.69	2.01	--	--
3/12/2006	3/19/2006	163.61	143.13	2.69	2.01	160.92	141.12
3/19/2006	3/31/2006	--	--	18.67	16.46	--	--
3/31/2006	4/11/2006	15.60	--	23.40	19.05	--	--
4/11/2006	4/21/2006	--	--	44.62	40.79	--	--
4/21/2006	5/1/2006	52.93	0.63	23.01	33.52	29.91	--
5/1/2006[a]	5/14/2006	52.64	51.48	7.63	15.68	45.01	35.80
5/14/2006[b]	5/29/2006	--	--	96.68	12.00	--	--
5/29/2006[c]	6/10/2006	19.26	--	18.94	1.19	0.32	--
Total		355.07	195.25	242.16	145.60	283.36	176.92

[a]1st crop harvest occurred on May 05. [b]2nd crop harvest occurred on May 24. [c]3rd crop harvest occurred on June 07. "–" = represents negative values obtained when calculation N leaching with equation 4-2. Negative values is the apparent gain of NOx-N that can be the result of core samples tested with residual granular fertilizer, or NOx-N that moves in the crop beds with upflux.

Table 4-5. Overall treatment averages (spring 2006) with standard errors for NOx-N, NH_4-N, TKN and TN concentration detected in core samples (dry weight) extracted from several depths within each treatment

Nutrient	Treatment & significance	Soil depth beneath surface of crop bed			
		0-10 cm	10-20 cm	20-30 cm	30-40 cm
NOx-N (mg/kg)	HR	276 ± 18	56 ± 4	30 ± 4	23 ± 3
	RR	136 ± 9	30 ± 3	22 ± 5	14 ± 2
	P-value	0.0030	0.0001	0.0512	0.0724
NH_4-N (mg/kg)	HR	126 ± 10	17 ± 1	10 ± 1	8 ± 1
	RR	62 ± 6	11 ± 1	10 ± 2	6 ± 0.4
	P-value	0.0523	0.0277	0.5151	0.5182
TKN (mg/kg)	HR	586 ± 21	323 ± 6	285 ± 7	246 ± 9
	RR	403 ± 13	266 ± 6	230 ± 5	216 ± 9
	P-value	0.0211	<0.0001	0.0004	0.2246

Table 4-6. Residual fertilizer P in crop beds after each crop season during crop seasons fall 2004, fall 2005, spring 2006 and fall 2006

Seasons	Treatments	P in fertilizer, $P_{fertilizer,}$ (kg/ha)	P removed with plant, $P_{plant,}$ (kg/ha)	Change in dissolve P present in soil, ΔS_P (kg/ha)*	Cumulative soil P balance (kg/ha)
Fall 2004	HR	80.08	30.92	49.16	49.2
	RR	59.40	13.30	46.10	46.1
	RR-SD	59.40	14.25	45.15	45.2
Fall 2005	HR	80.08	23.80	56.28	105.4
	RR	0.00	8.93	-8.93	37.2
	RR-SD	0.00	9.27	-9.27	35.9
Spring 2006	HR	80.08	38.69	41.39	146.8
	RR	0.00	17.02	-17.02	20.2
	RR-SD	0.00	17.18	-17.18	18.7
Fall 2006	HR	80.08	34.19	45.89	192.7
	RR	0.00	14.54	-14.54	5.6
	RR-SD	0.00	14.90	-14.90	3.8

*ΔS_P takes into consideration the possibility that P leaching occurred. "–ve" values indicate the amount of P that was likely taken from the fixed-P in the soil.

Table 4-7. Treatment averages with standard errors for DIN, NOx-N, NH4N TKN, TN and TP during the period spring 2004 to fall 2006 for soil solution and groundwater. Statistical analysis was performed on the common log of the nutrient means

Source	Treatment & significance	DIN[x] (mg/L)	NOx-N[x] (mg/L)	NH4N[x] (mg/L)	TKN[x] (mg/L)	TN[x] (mg/L)	TP[x] (µg/L)
Soil solution	HR	119 ± 13a	112 ± 12a	15 ± 3a			
	RR	82 ± 11a	76 ± 10a	11 ± 2a			
	RR-SD	94 ± 12a	88 ± 10a	10 ± 2a			
	P-Value	0.0695	0.0526	0.4451			
Shallow groundwater	HR	37 ± 5a	28 ± 3	10 ± 2a	10.0 ± 2a	38 ± 5a	3090 ± 175a
	RR	15 ± 2b	12 ± 2	3 ± 1b	4.0± 1b	16 ± 2b	2098 ± 107b
	RR-SD	19 ± 3b	15 ± 2	4 ± 1b	6.0 ± 1b	21 ± 3b	2048 ± 92b
	P-Value	0.0195	0.0545	0.0003	0.0012	0.0093	0.0019
Deep groundwater	HR	8 ± 1a	6 ± 0.9a	2.1 ± 0.3a	3.1 ± 0.3a	9 ± 1a	1302 ± 141a
	RR	12 ± 2a	10 ± 1.4a	2.2 ± 0.4a	2.9 ± 0.3a	13 ± 2a	1115 ± 79a
	RR-SD	12 ± 2a	9 ± 1.2a	3.1 ± 0.4a	4.4 ± 0.5a	14 ± 2a	1181 ± 97a
	P-Value	0.8101	0.7473	0.4451	0.7544	0.8091	0.9409

[x]Data with the same letter are not significantly different at the P = 0.05 level of significance.

CHAPTER 5
MODIFICATION AND EVALUATION OF A LUMPED HYDROLOGICAL MODEL FOR BEDDED VEGETABLE FIELDS IN SOUTHERN FLORIDA

Introduction

Hydrological models are frequently used by water-resource managers to develop management strategies for addressing water quality and quantity issues associated with different land uses, such as vegetable production. It is important that these models have a reasonable representation of the land use being evaluated to minimize simulation errors; this helps identify solutions to water resource problems for making land use management decisions. Vegetable production fields are commonly found in the extensive Flatwoods regions (48,109 km^2) of Florida. Flatwoods regions are generally characterized by a nearly level terrain with poor drainage and shallow water table conditions; the water table that enters within 13-51 cm of the soil surface for 1-4 days at least once during the growing season (UF/IFAS, 2006). Shallow water table conditions are magnified by rainfall events that are short and intense, but isolated or by rainfall events that are of low intensity and lengthy, but extensive. These rainfall events can lead to flooding that can cause irreversible damage to plant roots in vegetable fields and ultimately reduce crop yield. Raised crop beds (with or without mulch) are used, in part, to improve drainage of a cropped field in the event that the water table enters the root zone of a crop. Inorganic fertilizers (nitrogen (N) and phosphorus (P)) used for vegetable production can interact with a fluctuating water table and leach below the root zone, polluting groundwater and surface waters. The water table level within some Floridian soils can fluctuate sharply in response to rainfall events.

Government agencies and research institutes often rely on the results of hydrological models to determine the efficacy of different agricultural management practices for conserving water and reducing the nutrient loadings to surface and ground waters. It is not uncommon to find that lumped hydrological models have been applied on the field scale to evaluate water and nutrient management strategies. However, a problem may arise for lumped models for crops where a large numbers of crop beds are present. The introduction of raised crop beds changes the hydrology of the field when compared with an open field. The representation of these bedded areas in the model (e.g., FHANTM 2.0 (Fraisse and Campbell, 1997)) would be seen as a surface soil layer composed of alternating soil cells and open air spaces; this is notably different from other agricultural land uses such as pasture where the surface layer is relatively smooth (Fig. 5-1A and 5-1B). Therefore, the use of lumped models to simulate the hydrological processes for bedded fields would likely lead to unacceptable simulation errors in water storage and movement in the unsaturated and saturated zone, especially for high water table conditions. This is due to differences in upward flux, infiltration of rainfall into the soil, and the resulting groundwater table response between the raised beds and the level crop rows. If the raised beds are covered with plastic mulch, these differences become more complex to represent. Therefore, suitable modifications must be performed for lumped models to achieve simulation results that are hydrologically representative of raised plastic mulch bed production systems.

Currently, there are field-scale hydrologic/water quality models that can simulate hydrologic and nutrient processes in exposed soils under high water table conditions in south Florida, e.g., FHANTM 2.0 and EAAMOD-FIELD (Bottcher et al., 1998). FHANTM's development was based on the design concept of DRAINMOD (Skaggs, 1982) and was developed to investigate the effect of nutrients on surface and groundwater sources within regions that are affected by high water tables. EAAMOD-FIELD was developed to simulate the hydrology of the Everglades Agricultural Area (EAA) along with associated P transformations and transport. These models have been tested for field scale hydrologic conditions in south

Florida. Hendricks (2003) determined that both models performed similarly when simulating a pasture's hydrology in south Florida, but had a tendency to overestimate observed runoff. This overestimation was partly due to lack of the model's representation of existing wetlands which were considered large areas of surface storage (10%). Nevertheless, both models were considered accurate enough to perform screening applications. A new model ACRU2000 (Clark et al. 2001) has recently become available and offers several advantages compared to other models with regards to its structure. There are certain features of this model that make it more attractive for modifying it for the raised bed production system compared with the above-mentioned models.

ACRU is a physical-conceptual model that was originally developed for hydrological conditions in southern Africa, but has since been applied to a variety of hydrological conditions internationally. The original FORTRAN version of ACRU (Smithers and Shulze, 1995) was designed for daily time step simulations of both watershed scale and field scale conditions by applying lumped parameters or by disaggregating a watershed into sub-basin areas. A watershed's hydrology is represented in ACRU by a water balance of hydrological processes present in the biosphere. The hydrological component (e.g. potential evaporation) is defined by equations that have been tested and widely accepted (e.g. FAO Penman-Monteith equation for evapotranspiration). Water is transferred into, through and out of the model's multi-soil-layer system by using a tipping bucket method. The original model of Smithers and Shulze (1995) was later converted to a JAVA-based platform and used an object oriented design (OOD) method to create a system which provides increased flexibility in design and development (Kiker et al., 2006). This version was named ACRU2000. The OOD method views a domain as a composition of "objects," i.e., Component object, Process objects, and Data objects. Component objects represent the physical components of the hydrological system in the domain, Process objects model the behavior of hydrologic processes in the domain, and Data objects are used to define attributes of Component objects. Each Component object has a unique set of attributes and behaviors (functions) that describe the object. Attributes and behaviors consist of a list of data constants and equations that determine the object's state and manner in which it will interact with other objects within a domain. A more comprehensive description of the OOD method used on ACRU can be found in Kiker et al. (2006). Many hydrological processes from the original model were maintained to create ACRU2000. However, Martinez (2006, 2008) showed that ACRU2000 was poorly suited for the flatwoods of southern Florida and as a result modified several processes affecting water table depth and runoff to increase the model's ability to represent shallow water table environments. In addition, Martinez (2006) evaluated the N and P components of the model for flatwood soils of south Florida. From here onwards, the updated version of ACRU2000 developed by Martinez (2006) will be referred to as ACRU2K.1.

Martinez (2006, 2008) recognized that several model extensions were needed to improve ACRU2000, one of which was an explicit representation of the water table depth and its effects on evapotranspiration. These model extensions involved the modification of several processes including evapotranspiration (ET), interception, infiltration and soil-moisture distribution. Extensions ranged from the addition of new methods within a Process object, to the introduction of new Process objects that were used to enhance ACRU2000's representation of Florida's flatwood soils. For instance, the Food and Agricultural Organization Penman-Monteith method (FAO56-PM) (Allen, 1998) was added to the list of methods ACRU2000 used to calculate potential ET. Another notable example was the method used to determine water table depth and associated water stored in saturated and unsaturated zones of the soil. Here, ACRU2K.1 uses one of the three soil-moisture characteristic curve equations (Van Genuchten (1980), Brooks and Corey (1964) and, Hutson and Cass (1987)) to define soil water distribution in the unsaturated zone. Each equation when integrated (given the total profile storage), determines the average moisture content of individual soil layers (Martinez, 2006 and 2008). Furthermore, upward redistribution of water (upward flux) in response to upward gradients created by evapotranspiration demand and its effects on the water table was added to ACRU2000 by Martinez (2006 and 2008), creating a version that will be termed ACRU2K.1 for this study. ACRU2K.1 relies heavily on the assumption that the soil moisture distribution in the soil profile achieves a state of hydrostatic equilibrium. Martinez (2006 and 2008) applied this assumption since it was determined from the literature to be most accurate for higher conductivity soils and shallower water tables.

ACRU2K.1 was calibrated and evaluated for fields with improved or semi-improved pasture land uses in south Florida where water table levels were not maintained artificially high. However, vegetable production in south Florida relies on a restrictive spodic layer to maintain a high water table. The hydrological component of ACRU2K.1 was designed to infiltrate rainfall (after initial abstraction and evaporation) directly into the soils top layer and any excess was assigned to runoff. Consequently, if ACRU2K.1 was applied to fields with crop beds covered by plastic mulch, portions of rainfall would be incorrectly transferred into these crop beds. However, rainfall does not enter into beds covered with plastic mulch, except through plant holes in the plastic. Similarly, soil evaporation calculated for the top soil layer would be taken from crop beds even though they would be covered by an impermeable plastic mulch layer. Finally, surface ponding is set to occur when the water table reaches the top of the bed layer, when in fact, surface ponding occurs within furrows when the water table reaches the bottom of the bed layer. Therefore, several processes in ACRU2K.1 needed to be modified to enhance its representation of plastic mulched bed (PMB) field conditions.

Frequently, lumped hydrological models are used to simulate field conditions that vary widely. Rather than modifying these models, adjustments would be made to model parameters to compensate for the effect of spatial variations. It is possible to apply simple modifications to lumped hydrological models to account for some of the spatial variability in surface features. Currently, no lumped hydrological model is available for application to PMB vegetable production system with high water table environment of south Florida.

Objectives

The goal of this study was to modify ACRU2K.1 to represent hydrological processes for a plastic mulch raised bed system for vegetable production in shallow water table environment. The resulting model will be termed ACRU2K.2. Specific objectives include:

1. Develop ACRU2K.2 by introducing new code and modifying existing code of ACRU2K.1 to simulate the water dynamics for the plastic mulch raised beds for vegetable production system.
2. Calibrate and evaluate ACRU2K.2 by using three crop seasons of soil, plant, weather, and hydrologic data collected for a vegetable BMP study in south Florida.

Only the hydrological processes of ACRU2K.1 were considered for this study for modifications. The nutrient components of ACR 2K.1 are beyond the scope of this study and will not be considered any further.

Methodology

Study Area

The soil, crop, weather, and hydrologic data were collected during the winter-to-spring growing seasons of 2005 through 2006 from a field within the research farm of the Southwest Florida Research and Education Center (SWFREC) in Immokalee, Fla. The soil at the site is

Immokalee fine sand (sandy, siliceous, hyperthermic, Spodic Psammaquents) with CEC of 12 Cmol/kg and pH of 5.6 (Carlisle et al., 1989), and 49 mg/L and 60 mg/L of Mehlich-1 extractable P and K, respectively. This soil type is common in the flatwood regions of southern Florida and is one of the most common soils used for vegetable production in south Florida. Immokalee fine sands are characterized by poor drainage, nearly level surfaces (slopes less than 2%), and a poorly drained spodic layer situated approximately 0.9 to 1.2 m below the soil surface. Table 5-1 shows some of the physical characteristics report by Carlisle et al. (1989) for this soil. The spodic layer's low saturated hydrologic conductivity ($K_{sat,}$ 1.5-5 cm/h) is ideal for supporting the high water table levels desired for seepage irrigated vegetable fields. This soil has a moderately rapid permeability (5.1 to 15.2 cm/h) and low available water capacity (5% to 7%). Specifically, the site has a spodic layer located approximately 0.9-1.2 m beneath the soil surface and sloping from west to east.

Monitoring Data

A field within SWFREC was selected and divided into six experimental units (plots) of 0.6 acres each (Fig. 5-2A and 5-2B). Experimental treatments consisting of recommended and high input of water and nutrient were randomly assigned among the six plots; these treatments held their position for the entire study period (Fig. 5-1). Details of the experimental design and setup of treatments can be found in Chapter 4 (Water and Nutrient Treatments and Hydrologic Isolation). Treatments were maintained at different water table depths throughout the growing season. The geotextile barrier prevented water from flowing laterally among plots and areas external to the plots. Runoff and drainage were contained within each plot by the geotextile barrier, a perimeter berm, a swale and a system of drain tiles that were located approximately 0.9 m beneath the soil surface. For each crop season, an alternate series of plastic covered raised beds and irrigation ditches (one ditch for every three raised beds) were constructed in each plot.

A single swale was located down slope of the bedded area to provide storage for runoff from the bedded area. A drainage canal bordered the majority of the field and conveyed surface and subsurface discharges from the six plots (Chapter 4, Fig. 4-1B) to a downstream ditch. The drainage canal was approximately 5-9 m from the plot areas, and the canal's bottom was approximately 0.9 m beneath the soil surface of the plots.

Surface and groundwater monitoring was done as described in Chapter 4. Climatic data was monitored by a local weather station as described in Chapter 4. All data were collected at 15-minute time intervals and were later averaged to obtain daily input values required by ACRU2K.1.

Model Domain

The period of record considered for this modeling effort was October 2005 through December 2006. Two crops of seepage irrigated tomato were grown during this period. The crop season typically lasted for 14 weeks. The study area remained fallow between the two tomato crop seasons for 5 to 7 weeks during summer. Plot 1 (Fig. 5-2B) was selected for initial simulation runs since the data collected from this plot had the fewest number of missing data. The domain of the model included the area within each plot that was contained within the boundary of the geotextile barrier. The vertical extent of the domain ranged from the surface of the raised soil beds to 2.48 m below the spodic layer (Fig. 5-3A).

Model Concept

Several assumptions were made to simulate a PMB field used for vegetable production. The following assumptions were made to create ACRU2K.2:

1. The soil profile within the model domain can be represented by four distinct homogeneous soil layers,
2. Each soil layer has a uniform thickness and density,

3. The spodic layer is horizontal,
4. Irrigation and rainfall were the only sources of water inputs for the model domain,
5. Water only exited the domain via deep percolation, subsurface drainage (drain tiles) and evapotranspiration,
6. The water table depth was uniform throughout the model domain,
7. Single raised beds all have the same shape, size and volume.
8. Multiple raised soil beds within the domain can be integrated to form a composite raised bed (CRB), having a volume that is equal to the sum of the single beds within the domin,
9. The amount of rainfall that enters the CRB through plant holes is negligible,
10. Water from seepage irrigation was transferred directly to the soil layer directly above the restrictive spodic layer,

Base on the assumptions outlined above, the bedded area of the field was converted to a homogeneous system. Raised beds were represented in a model by a single soil layer covered by a plastic mulch barrier (Fig. 5-3B) and had the soil water storage capacity of CRB. With the presence of a plastic barrier, infiltration resulting from rainfall was transferred directly into the layer beneath the beds. Field measurements revealed that the total effective area of plant holes only occupied 0.732 m^2 per plot, or 0.03% of each plot. Therefore, rain that fell into plant holes was considered negligible. Evaporation of ponded water and soil evaporation was made proportional to the area of field without plastic mulch. Water removed from the field via tile drains was taken from soil layer above the spodic layer.

Model Structure and Design

ACRU2K.2 was designed using the extended method described by Martinez et al. (2008). This method includes the following four steps: 1) identify existing components and objects in ACRU2K.1 that will be required for ACRU2K.2, 2) find existing Process object which can be extended and are similar to new ones, 3) create new Component, Process and Data objects from steps one and two, and 4) write the code for the new objects. For this study, Component objects described in ACRU2K.1 were sufficient to represent the hydro-geologic structure of the field within a treatment plot. Most of the Process objects required for this study were determined to be similar to preexisting Process objects in ACRU2K.1. Hydrologic processes considered for this study included deep seepage, evapotranspiration, evaporation, infiltration, seepage irrigation, tile drainage, daily rise and fall of the water table depth, and soil water redistribution above the water table. Some of these Process objects (Table 5-2) were modified with the introduction of new Data objects along with changes in code logic that enabled ACRU2K.2 to better represent the hydrological system within the study site. New processes (described later) were introduced to ACRU2K.1 to enhance the water balance of a PMB field with seepage irrigation.

Figure 5-4A through 5-4B is an activity diagram that shows the sequential execution of activities required to run the simulation of ACRU2K.2. An activity, such as “calculate deep seepage” (Fig. 5-4B), typically represents an action or a set of actions that may cause a change in state (e.g., water table depth) of the modeled system (Papajorgji and Pardalos, 2006). An action is governed by the execution of an equation that performs a simple algebraic function or describes a physical process (e.g., evaporation) that exists in the model domain. Each activity was executed by a Process object (Table 5-2), which can be composed of one or several methods (Fig. 5-5) and has the ability to call methods located in other Process objects. Figure 5-5 displays an example of an interaction diagram that shows the relationship between a process and other processes required to execute an activity. New activities added to ACRU2K.1 are highlighted in Figure 5-4A through 5-4B by a dotted rectangular box and modified activities are highlighted by an asterisk. In addition, an asterisk also indicates the addition of Data objects to previous Process object (Fig. 5-5). In general, modifications were made by introducing a plastic mulch factor (PMF) to obtain the correct soil storage volumes and by redirecting water transferred from the soil surface into (and out off) underlying soil layers. Appendix B shows interaction diagrams for all the Process objects that were modified in ACRU2K.1 for use in ACRU2K.2.

The fundamental difference between ACRU2K.1 and ACRU2K.2 is how each version views the soil storage capacity (S_c) of the soil profile's top layer. ACRU2K.1's top soil layer has a given thickness that is assumed uniform throughout the model domain. This soil layer has a particular S_c governed by the layer's porosity. However, part of the top layer is bedded for the PMB system and has a storage volume that is a fraction of S_c since there are sections of the layer that are occupied by furrows and ditches (Fig. 5-3). To incorporate the PMB into ACRU2K.1, a coefficient was introduced that gives the correct Sc value for the top layer of a PMB system. This coefficient (PMF) is the ratio of the area covered by plastic mulch and the area of the plot. Hereafter, furrow will be defined as spaces between crop beds and ditches as those furrows used to apply irrigation water. Therefore, relevant Process objects (Table 5-2) were modified to obtain the correct S_c in the top layer for ACRU2K.2. Note that the top layer in ACRU2K.2 is the bedded layer in the model domain. This modification was carried out by introducing the PMF into calculations involving soil storage for ACRU2K.2's top soil layer. The following paragraphs describe Process objects that were new to the model and how previous Process object were modified to enhance ACRU2K.2. Detailed descriptions of all the hydrological processes and governing equation can be found in Martinez (2006)

Simulations for ACRU2K.2 start with the initialization of several soil parameters in the model domain. In ACRU2K.1 the *PInitialiseSoilUFOptionHWT* object is used to start simulation runs. In this study, the *PInitialiseUFBeddedLayerOptionHWT* object was introduced ahead of the *PinitialSoilUFOptionHWT* object to generate Data objects necessary to adjust soil storage values for ACRU2K.2. The *PInitialiseUFBeddedLayerOptionHWT* object retrieves data inputs of measurements for five distinct areal units. The areal units were total plot area, total bedded area, total furrow area, total irrigation ditch area and total area covered by plastic mulch. These values were used to calculate the portion of total plot area occupied by each areal unit. Values obtained for these portions were stored as Data objects (e.g., *DPlasticMulchFacto*r). *PInitialiseSoilUFOptionHWT* process object initialized several parameters in the model including the moisture content and total storage for each soil layer, and the relationship between the soil air volume and the water table depth. *PInitialiseSoilUFOptionHWT* process object also sets the lower boundary of soil layers relative to the soil surface.Water storage and air volumes were set by applying the value stored in the *DPlasticMulchFactor* to the original volumes. Both of these Process objects were used once at the start of the simulation.

The *PAcruHWTRitchieEvapoTranspiration* process determines the amount of evapotranspiration for the day and calls two methods, evaporateWater and transpireWater, to complete this process. The evaporateWater method uses the *PHWTRichiSoilWaterEvap* process to determine the daily soil water evaporation (SWE) and the transpireWater method uses the *PHWTCropCoefTran* process to determine the daily transpiration. Reference evapotranspiration (ET_o) is applied using a top-down approach described in Martinez (2006). A portion of ETo is first satisfied by removing any water stored as canopy interception and the remaining ET_o is applied to soil evaporation and transpiration. This portion of ET_o would be partitioned by ACRU2K.1 into potential transpiration (T_p) and potential SWE (E_p), where T_p was estimated using the following function (Ritchie, 1972):

$$T_p = \left(0.7LAI^{0.5} - 0.21\right)PET \quad \text{for} \quad \text{LAI} < 2.7 \qquad (5\text{-}1)$$

$$T_p = 0.95PET \quad \text{for} \quad \text{LAI} \geq 2.7 \qquad (5\text{-}2)$$

where LAI is the leaf area index of the crop. The remaining evaporative demand was assigned to E_p and taken from the soil layers that fall within the depth of the root zone in the model domain.

The *PHWTRichiSoilWaterEvap* object retrieves E_p and takes this volume from a depth down to as much as 15 cm below the soil-atmosphere interphase in ACRU2K.1's domain, this may include more than one soil layer outside of the top layer. In ACRU2K.2 the soil-atmosphere interphase is located at the bottom of the bedded layer. Therefore, E_p is taken from a soil depth 20-35 cm. Evaporation can be adjusted for a percent surface area covered by a mulch lining. However, SWE from a plastic mulched bed is limited by the plastic mulch covering and the percent of surface area exposed to the atmosphere is located at the top of the second layer (the layer beneath the top layer). Therefore, ACRU2K.1 was modified enabling ACRU2K.2 to remove E_p from the soil layer beneath the bedded layer.

The *PHWTCropCoefTran* object in ACRU2K.1 calculates transpiration using equations 5-1 and 5-2 and removes it from soil layers according to a linear root distribution function proposed by Hoogland et al. (1981) and used by Martinez (2006):

$$g(d) = \frac{c(2d - L) + L}{L^2} \qquad -1 \leq c \leq 0, \qquad d \leq L \qquad (5\text{-}3)$$

where c is the relative density of roots between the soil surface (d = 0) and the maximum rooting depth (d = L). Equation 5-3 provides an estimate of the plant root density within the soil profile. Plant roots were estimated to have a maximum depth of 1 m (Machado, 2005). PMF was used to determine the volume of water in the bed at wilting point to prevent transpiration below the wilting point.

The *PStorageInfiltration* object determines the amount of ponded water that infiltrates the top soil layer of the model domain. The calculated amount of infiltration is based on the assumption that the infiltration capacity of the soil is rarely limiting; a result of the high conductive nature of sandy soils in the flatwood region. Therefore, infiltration amounts were dependent on the available storage in the soil above the water table. When the amount of water is determined for infiltration, ACRU2K.1 transfers the infiltration amount from the soil surface into the top soil layer. The amount of water transferred from the surface is determined by the available soil storage of the entire soil profile. However, the plastic mulch in bedded fields prevents water from infiltrating into crop beds and water stored on the surface does so within furrows between beds (Fig. 5-3A). Therefore, ACRU2K.2 was modified to transfer water allocated for infiltration from the soil surface to the soil layer beneath the bed (Fig. 5-3B).

ACRU was originally designed to apply supplemental water in the form of sprinkler irrigation and does not consider the presence of high water table conditions above a spodic layer. *PSeepageIrrigation* was developed and added to ACRU2K.2 to represent seepage irrigation on sandy soils with an underlying spodic layer. Daily irrigation depths were read into the model and transferred directly to the soil layer above the spodic layer. Water transferred into the soil layer was based on the assumptions applied in the *PStorageInfiltration* object. Water in excess of the available storage between the bottom of the bedded layer and the top of the spodic layer was stored on the soil surface.

ACRU2K.1 does not take into account water discharged from a field via drain tiles. Therefore, *PTileDrainage* was developed and added to account for water discharged in this manner. Water discharged from the field daily via tile drains was calculated and read into ACRU2K.2. Since tile drains were located just above the spodic layer, drainage was taken from the soil layer(s) above the spodic layer. Water was first removed from any surface storage and then taken from higher soil layers down to lower soil layers above the spodic layer until the drainage demand was met. Water was removed from each soil layer until the equilibrium moisture content of the layer was reached.

Deep seepage was calculated in ACRU2K.1 using the *PDeepSeepage* object. Water that moved through the spodic layer was described by Darcy's law:

$$q = -C_r\left(H_{wt} - H_d\right) \tag{5-4}$$

where H_{wt} is the hydraulic head above the restrictive layer (m), H_d is the hydraulic head below the restrictive layer (m), and C_r is the conductance of the restrictive layer (day^{-1}) defined as:

$$C_r = K_r/L_r \tag{5-5}$$

where K_r is the hydraulic conductivity of the restrictive layer and L_r is the thickness of the restrictive layer. Water table depths measured below the spodic layer were used as inputs for H_d. The value of q calculated in ACRU2K.1 was only removed from the lowest soil layer. *PDeepSeepage* was modified for ACRU2K.2 to first remove water stored on the soil surface, and then remove water from higher soil layers down to lower soil layers of the model domain. This method of draining the soil profile helped prevent ACRU2K.2 from discharging water (via tile drainage) in excess of the depth of water stored in soil layers.

A list of standard processes (e.g., infiltration and deep seepage) was organized to determine the order in which these processes are executed to complete a simulation run for ACRU2K.1. With the addition of new processes (e.g., *PTileDrainage* and *PSeepageIrrigation*) for ACRU2K.2, the order of the standard process list was modified to avoid the occurrence of fatal errors to during simulation runs.

Model Parameterization

Considering the study site's relatively small area, uniform nature of sandy soils (> 97% sand) and flat topography (slope < 0.02), point measurements for different soil parameters were assumed sufficient to characterize entire soil layers throughout the model domain. Soil parameters for the model were obtained from the literature or measurements taken on site. Soil parameters including K_{sat}, field capacity and permanent wilting point were obtained from Carlisle et al. (1989). Some soil parameters (e.g. bubbling pressure head and bulk density) were based on both field measurements and literature values. The bubbling pressure head is the pressure head at which air begins to enter the largest soil pores of saturated soil layers. This value was used to help define the shape of the soil-moisture characteristic curve. Rooting depth and distribution for tomato plants were based on values obtained from Machado (2005).

The ET_o values were estimated with the use of Ref-ET (Ref-ET, 2000). Daily values of climatic data (i.e. solar radiation, wind speed, relative humidity and temperature) obtained from a weather station on site were used as inputs for Ref-ET. The FAO-56 Penman-Monteith method was selected for generating ET_O values and these values were used as input data for the model.

Water table depths measured (15-minute time step) below the spodic layer were averaged to provide daily values. These values were used as an input for the hydraulic head of the ground water beneath the spodic layer. This hydraulic head was use to determine the amount of water that moved through the spodic layer as deep seepage on a daily basis. Table 5-3 shows a list of some of the parameters used in ACRU2K.1 and ACRU2K.2

Calibration and Evaluation Statistics

Calibration, simply defined, is the adjustment of the model for a particular function. For this study, the model was calibrated in its ability to simulate the water table monitored at the study site. To determine how well the model predictions compared with observed values, some form of quantitative measure must be applied in a meaningful way. There are at least two general methods of evaluating a model’s performance, visual comparisons and statistical measures. Visual comparisons are done using graphical methods that can be very insightful. Wilmott

(1981) points out the data plots provide visual credibility to quantitative comparisons and may expose possible erroneous measurements and computations. However, interpretations of these graphs are subjective. Therefore, it is important that data plots are complemented with meaningful statistical measures. Common statistical measures used are: 1) coefficient of determination (R^2), 2) root mean square error (RMSE), 3) coefficient of efficiency (E), and 4) index of agreement (d) (Wilmot, 1981).

The coefficient of determination (R^2) is commonly used and is a statistical measure that shows the portion of total variation in the predicted values that can be explained by the model. However, large prediction errors may be masked by large standard deviations and small prediction errors can appear significant with the occurrence of relatively small standard deviations (Willmott, 1981). Willmott (1981) argued that RMSE and the mean absolute error (MAE) are among the "best" overall measures of model performance since they summarize the mean difference of simulated and observed data. Legates and McCabe (1999) pointed out the appropriateness of using RMSE and MAE to quantify error measures that have the same metric as the predicted and observed values. The coefficient of efficiency (E), also know as the Nash-Sutcliffe coefficient (NS-coefficient), is one of the more commonly applied statistic measures to evaluate the performance of hydrological models. The value of E has the range $-\infty < E \leq 1$ and is governed by the equation:

$$E = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \overline{O})^2} \qquad (5\text{-}6)$$

Values of E closer to 1 indicate better agreement between observed (O_i) and predicted (P_i) values. However, if $E \leq 0$, then the mean of the observed values ($\overline{O_i}$) is as good a predictor or better than the model's predicted values (Legates and McCabe, 1999). This indicates that the model error is so large that its predictive value is no better than the mean of the observed value.

Another well known statistical measure for the evaluation of hydrologic models is the index of agreement. It ranges from 0 to 1 and is given by the equation:

$$d = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}\left(|P_i - O_i| + |O_i - \overline{O}|\right)^2} \qquad (5\text{-}7)$$

Higher values of d indicate a better agreement of predicted and observed values. Both E and d are considered an improvement over R^2 since unlike R^2, both E and d are sensitive to differences in the means and variances of predicted and observed values (Legates and McCabe, 1999). However, Legates and McCabe (1999) cautioned that E, d, and R^2 are all sensitive to data outliers that are likely to inflate these statistical measures; the sensitivity is due to the squaring of the difference terms in equations 5-6 and 5-7. Consequently, it is likely that there is no single statistical measure that is sufficient for assessing model performance. Therefore, it is recommended that several statistical measures be used when evaluating the performance of any model (Legates and McCabe, 1999). For this study, the following statistical measures were applied to the calibration and evaluation of the model:

1. The mean absolute error (MAE),
2. The root mean square error (RMSE),
3. The Nash-Sutcliffe coefficient (EF),
4. The Index of agreement, (d) and
5. Scatter plots of simulated vs. observed values

Statistical analyses were performed on data for each crop season (fall 2005 to 2006). Fallow periods between crop seasons were not considered for statistical analysis. This was necessary to minimize any simulation bias due to unavailability of data during fallow periods.

Results and Discussion

Simulation runs of ACRU2K.2 indicated that the seepage irrigation process object did not offer major improvements compared to the simple addition of seepage irrigation depth to rainfall. On the other hand, introduction of tile drainage Process object (*PTileDrainage*) showed improvement over ACRU2K.1's simulated WTD. Figure 5-6 shows a 5 cm rainfall event that caused a spike in the simulated WTD for ACRU2K.1 (point e, Fig 5-6 B) that was not seen in the observed WTD. Field data revealed that water was discharge from the field through tile drains during this rainfall event and prevented a sharp rise in the observed WTD; this observation was reflected in the simulated WTD of ACRU2K.2 and was an improvement over ACRU2K.1's simulated WTD.

The sum effect the all modifications applied to ACRU2K.1 (Table 5-2) was the conversion of the top soil layer in ACRU2K.1 into a bedded layer for ACRU2K.2. This conversion was achieved by reducing the soil available storage in the top soil layer to represent that of a set of raised soil beds required for the bedded layer. The soil available storage of the bedded layer was made proportional to the area of field covered by plastic mulched raised bed. Several process objects were modified (Table 5-2) to create the bedded layer in ACRU2K.2. The effect of a bedded layer would be the initiation of ponding as the water table enters the bedded layer of ACRU2K.2; this is in contrast to ACRU2K.1 where no ponding would occur as the water table enters the top soil layer. Hence, the difference between ACRU2K.1 and ACRU2K.2 would be the timing of initial ponding. The significance of this timing would be seen in the occurrence of runoff during rainfall events that cause the water table to rise to the soil surface. It is likely that the occurrence (frequency and volume) off runoff in ACRU2K.2 would be greater than that in ACRU2K.1, which represents the intended effect of bedded vegetable production system in south Florida; and is an improvement for ACRU2K.1. However, no runoff was observed during the calibration and validation period, which hinders actual comparison of runoff volumes between ACRU2K.1 and ACRU2K.2.

Nevertheless, simulation runs for ACRU2K.1 and ACRU2K.2 were compared to determine if there were improvements of ACRU2K.2 over ACRU2K.1. Data for subsurface drainage through tile drains were not included in simulation runs for ACRU2K.1 since no suitable object for tile drainage was found. Visual and statistical comparisons were made between observed and simulated shallow water table depths for versions ACRU2K.1 and ACRU2K.2. Figure 5-6 shows a time series plot of daily water table depths (observed and simulated) above the spodic layer within the model domain for the period October 25, 2005 thru December 31, 2006. The simulated water table depth for both versions varied between 0.2-0.8 m. Irrigation applied range from 1-3 cm per day. Irrigation was applied regularly each day, but was shut off in response to impending rainfall events. The observed WTD appeared to respond sharply to rainfall events that were as little as 0.4 cm. This result is similar to the findings of Jaber et al. (2005), which showed that water table levels in Immokalee Find sands may rise 8 cm in response to a 0.16 cm rainfall event. The response was contributed to the reverse Wieringermeer effect. Similar to the findings of Jaber et al. (2005), the observed WTD appears to respond sharply (within hours) to the start or end of an irrigation event. In the absence of irrigation or rainfall input, fluctuations in the observed WTD appeared to be governed by changes in the pressure head beneath the spodic layer or by the stage of the perimeter canal (Fig. 5-6).

Calibration

ACRU2K.1 and ACRU2K.2 were calibrated for fall 2005 and spring 2006 crop seasons. Calibration was achieved primarily by adjusting two key parameters, i.e., conductance (C_r) and bubble-in-pressure-head (BPH). These parameters were adjusted in an attempt to match the simulated WTDs with the observed WTDs. Emphasis was placed on matching simulated WTDs with peaks in the observed WTD. This was important since runoff under field conditions similar to those described for this study area, occurs only when the water table reaches the soil surface. Adjusting values of C_r and BPH in ACRU2K.1 and ACRU2K.2 was effective in forming the simulated WTD to match the trend seen in the observed WTD. There were several distinct water table peaks in the observed data that were difficult to match, i.e., points a, b, c and d in Figure 5-6. Attempts to match the simulated WTD for ACRU2K.1 and ACRU2K.2 with these observed peaks led to large over-estimation of the simulated WTD. Therefore, simulated WTDs in ACRU2K.1 and ACRU2K.2 that corresponded to these peaks (a, b, c, and d) were matched as close as possible while minimizing the deviation (from the observed mean WTD) for other simulated WTDs.

Figure 5-6 shows that the simulated data for ACRU2K.1 and ACRU2K.2 appear to track relatively well with the observed data. This observation was supported by the mean and standard deviation of the observed and simulated data sets for the calibration period (Table 5-4). The observed mean WTD during the calibration period was 0.51 m with a standard deviation of 0.10 m (Table 5-4). These values compare well with the simulated mean WTD and standard deviation for both versions during the same time period; i.e., 0.52 m and 0.08 m, respectively, for ACRU2K.2; and 0.50 m and 0.01 m, respectively, for ACRU2K.1. Scatter plots in Figure 5-7 show that simulated for ACRU2K.1 and ACRU2K.2 closely match. However, both versions overestimated shallow WTD and underestimated for deeper WTD. The largest departures from observed data occurred when the water table depths were relatively shallow (0.3 to 0.5 m). These simulation errors may indicate that the process objects used in ACRU2K.1 and ACRU2K.2 did not fully represent the soil-water processes that controlled the water table for this range of

WTDs. However, the magnitudes of these simulation errors appeared relatively small in most cases (Fig. 5-6). This was observation was supported by a comparison of the standard deviation of the simulated (σ_s) and observed (σ_o) data, which were found to be similar i.e. $\sigma_{s\text{-ACRU2K.2}}$= 0.08 m, $\sigma_{s\text{-ACRU2K.1}}$= 0.10 m and σ_o = 0.10 m. Overall, both ACRU2K.1 and ACRU2K.2 calibrated well considering the MAE and the RSME were less than 12% of the observed mean WTD. The EF and d values reported in table 5-4 also show that ACRU2K.1 and ACRU2K.2 performed well during the calibration period (EF = 0.65 and d = 0.88 for ACRU2K.2, and EF = 0.73 and d = 0.92 for ACRU2K.1)

Evaluation Run

Compared to the calibration period, the simulated mean during the evaluation period (fall 2006) for both ACRU2K.2 and ACRU2K.1 under predicted the observed mean WTD, (Table 5-6). The observed mean WTD for the evaluation period was 0.48 m and had a standard deviation of 0.04, while the simulated mean was 0.34 and 0.33 m and the standard deviation was 0.12 and 0.10 for ACRU2K.2 and ACRU2K.1, respectively. The underestimations can be also seen visually in the time series (Fig. 5-6A) and scatter plots (Fig. 5-7A) for the evaluation period. The standard deviation of the simulated data for ACRU2K.2 (0.12 m) was three times greater than that of the observed data (0.04 m). Such an increase in the standard deviation indicates that the effect of one or more hydrologically processes (e.g. evaporation or transpiration) may have had an increased effect on the WTD simulated by ACRU2K.2. For instance, the effect of soil evaporation on the WTD in ACRU2K.2 maybe more pronounced since soil evaporation is taken directly from a depth 0.2-0.35 m below the bedded layer. Figure 5-6 shows that the WTD for ACRU2K.1 and ACRU2K.2 was predicted to be in the 0.2-0.5 m depth range for the majority of the evaluation period. In contrast, soil evaporation in ACRU2K.1 was taken from the top soil layer (0-0.2 m) that acts as a buffer zone for any effect on the WTD.

Relatively high standard deviations combined with a reported 34.7% RMSE indicated that ACRU2K.2 underperformed during fall 2006. The negative value reported for the EF (-0.67) was further evidence of ACRU2K.2's underperformance for fall 2006.

Graphical plots (Fig. 5-6B and Fig. 5-7B) and results from the statistical evaluation (Table 5-4) revealed that ACRU2K.1 under performed during the evaluation period. Results from the various methods used to evaluate model performance were very similar to those observed for ACRU2K.2. Although the simulated WTD for ACRU2K.1 showed somewhat less variability compared with ACRU2K.2, these differences were small and appear inconsequential. Nevertheless, the movement of the water table into the bedded layer for ACRU2K.2 (or top layer for ACRU2K.1) would be required to see a notable difference in performance between ACRU2K.1 and ACRU2K.2. Differences in performance would be seen in the frequency and volume of runoff for a given crop season, and would be the result of differences in storage capacity of the top soil layer for ACRU2K.1 and ACRU2K.2.

Results presented above appear to show that both ACRU2K.1 and ACRU2K.2 were unable to discharge sufficient water from soil layers, leading to the underestimation of the WTD. The reason for this underestimation becomes apparent when rainfall data along with observed WTD data are examined for the calibration period (Fig. 5-6). This analysis revealed that there was an apparent lag in the response of the observe WTD to particular rainfall event. Figure 5-6 shows four irregular peaks in the observed WTD (points a, b, c, and d) that did not appear to correspond with one or more rainfall events within the same day (i.e., the WTD appeared to rise on the day after a rainfall event). Also, the simulated WTD's for ACRU2K.1 and ACRU2K.2 at points a, b, c, and d, did not match well with the observed peaks. To further investigate this irregularity, sub-daily values (15-min time step) for water table depths and rainfall depths were examined (Figs.

5-8 A through D). Figures 5-8 A through D show that peaks a, b, c, and d were caused by rainfall that occurred on the second half of the previous day. As a result, the observed WTD's initial response to the rainfall event(s) occurred towards the end of the day and carried over into the following day. Consequently, when 15-min values for the WTDs are averaged to obtain daily values, WTDs for the day of the rainfall event only represents a portion of water table's response; the remaining portion of the water table's response is seen in the daily average WTD for the following day (Figures 5-8 A through D). Therefore, a jump in the water table level appears to occur for no apparent reason when daily WTDs were considered. For example, in Figures 5-8 A, B, C and D; the observed WTD jumps from 0.54 to 0.37 m, 0.55 to 0.37 m, 0.56 to 0.43 m, and 0.51 to 0.44 m, respectively. In an effort to match these peaks during the calibration period, the conductivity of the restrictive (spodic) layer was reduced to provide the best chance to match simulated WTDs for ACRU2K.1 and ACRU2K.2 with points a, b, c, and d in the observed WTDs. It is likely that manipulation of the conductivity parameter, which directly controls deep seepage, only served to sensitize both models to a sharp rise in the water table that were a result of a rainfall event, or the start of an irrigation period. It is notable that during the calibration period, rainfall was variable while irrigation was relatively stable. Periods of irrigation that were relatively stable (uniform application for a couple day or more) allowed the simulated WTD to closely track the observed WTD, and is a result of deep seepage having greater influence over the position of the simulated WTD. This point is demonstrated in Figure 5-6, particularly during the later part of November 2005 and most of December 2005. However, during the evaluation period, irrigation was relatively unstable while experiencing several rainfall events of varying depths. Since there were no extended periods in which irrigation was relatively stable, the simulated WTD for ACRU2K.1 and ACRU2K.2 was unable recover from the first sharp rise experienced in the simulated WTDs. As a result, ACRU2K.1 and ACRU2K.2 underestimated the observed WTDs.

Underestimations of the observed WTD mention above could also be the result of the previous assumption that the drainage canal had a negligible effect on the model domain. However, this assumption appears to be sound for the reasons discussed below. The effect of the canal level is minimized by the presence of a geotextile barrier between the model domain and the canal. Since the barrier extends from the soil surface down to the spodic layer, lateral flows that would have normally occurred between plots and the canal (above the spodic layer) were likely minimized. It is unlikely that water travelled within the spodic layer and entered into the canal since its K_{sat} is much less than the over and underlying soil horizons (up to 100 times less). Also, the floor of the canal did not cut into the spodic layer, which would have increased drainage from the spodic layer. Hence, it is evident that the spodic layer would have supported relatively small flows of water toward the drainage canal. However, it is possible that deep seepage from each plot could have been directed toward the canal by a hydraulic gradient developed across the bottom of the spodic layer and the floor of the canal. Figure 5-6 shows that a hydraulic gradient existed (e.g. first half of calibration period) that could have created water flow from beneath the spodic layer into the canal. As a result, it is possible that water could have been indirectly drained from the model domain by the canal. However, water within the canal was retained by a set of flashboards during each crop season, and water was only removed by a throw-out pump (Figure 5-2) during rainfall events that threatened to flood experimental plots. Since the pump was never used to remove water from the canal during calibration and evaluation periods, it is likely that the effect of the canal on the subsurface input-outputs for the model domain was minimal.

Spatial variability in the WTD within each plot may also partly affect the calibration and evaluation of ACRU2K.2. The shape of the water table assumes two basic forms during the growing season. The first is a relatively level surface that extends throughout the entire plot when seepage irrigation is off. The second occurs during irrigation and is series of peaks and troughs beneath irrigation ditches (Figure 5-9). Measurements of the WTD are regularly made at a single point in experimental plots during the growing season. Since single point measurements of WTD are taken, it is difficult to capture the shape of the actual WTD. As a result, an error maybe introduced when determining the average WTD. A possible consequence of this measurement error is the erroneous assertion that the observed WTD reaches the field surface.

Future Work

ACRU2K.2 can be further improved by addressing the issues identified above that introduced uncertainty (or errors) in model predictions discussed previously. These problems may be addressed by implementing the concepts outlined below. These concepts will improve ACRU2K.2's ability to evaluate water dynamics for vegetable crops grown on plastic mulch raised beds in south Florida.

- ACRU2K.2's time step may be shortened from a daily time step to a 1-hour or 15-minute time step, and an infiltration equation (e.g. Green-Ampt) can be introduced so that the distance travelled by water percolating down to the water table is monitored the model. For rainfall inputs, the appropriate case for the Green-Ampt model would be a rainfall rate that is less than the K_{sat} of the infiltrated soil layer. Therefore, rainfall that infiltrates the soil surface will be vertically distributed toward the water table in a timely manner, which is more representative of field conditions. As a result, rainfall that enters the soil profile will not be added instantly to the water table by the model. Instead, water added to the soil surface will take some time to reach the water table.

- ACRU2K.2 may also be adjustment, without changing the daily time step, by introducing an infiltration PProcess that determines the depth of the wetting front of infiltrated water within a day. A loop statement may be used to infiltrate water on a 15-minute or 1-hour bases given the duration and intensity of the rainfall event at the soil surface within a day. At the end of the rainfall event the PProcess would output the depth to which water infiltrates the soil profile. With this information the model can determine if the wetting front of the infiltrated water interacts with the water table within a given day.

- A procedure for seepage irrigation can be introduced that is similar to the rainfall input outlined above. However, the appropriate case for the Green-Ampt model would be: irrigation rate is greater than the K_{sat} of the infiltrated soil layer. This case will allow the ponding of water to occur on the soil layer that receives irrigation. An assumption must then be made in ACRU2K.2 that water ponded by this procedure does not contribute to runoff since irrigation water is retained by a ditch.

- Introduction of equations that calculate the flow of water through different control structures (e.g. weirs or flumes) should be added to PTileDrainage object, which directly calculate the discharge from drain tiles embedded in the field. Subsurface drainage from drain tiles should be directly related to the water table depth in the field. Such a relation would give a more accurate representation of how the water table responds to subsurface drainage from a set of drain tiles. To achieve this, an equation (or a series of command statements with equations) would be introduced that takes into account the dimensions of the control structure along with the height of the water table (in the field) over the control structure.

Summary and Conclusion

A lumped model (ACRU 2K.1) for simulating water dynamics in shallow water table environments was modified and evaluated to simulate water dynamics in a plastic mulch raised bed system for vegetable production in south Florida. The updated model, ACRU2K.2, was calibrated using data collected during the fall 2005 and spring 2006 crop seasons; and evaluated using data from fall 2006.

The model domain consisted of a 0.24-hactare plot that was hydrologically isolated from its surroundings by an impermeable barrier; within this plot a 0.1-hctare portion was bedded. The model domain extended from the bed surface to 2.48 m below the spodic layer. The bed surface was created by reducing the soil available storage in the top soil layer to represent that of a set of raised soil beds required for the bedded layer. The soil available storage of the bedded layer was made proportional to the area of field covered by plastic mulched raised bed.

The design of ACRU2K.2 followed an object oriented method that utilized ACRU2K.1's extensibility. This extensibility permitted the use of Process and Data objects used in ACRU2K.1 to be used by ACRU2K.2 with the introduction of new Data objects and modification to the code structure. Next, ACRU2K.2 was calibrated to simulate WTDs in the model domain described above. Graphical and statistical methods were used to evaluate the performance of ACRU2K.2. Calibration and evaluation results of ACRU2K.1 were compared with ACRU2K.1 to evaluate the benefits of model modifications.

Calibration results indicated that both ACRU2K.1 and ACRU2K.2 performed well. The mean of the observed water table depth (0.51 m) was similar to that of ACRU2K.1 (0.50 m) and ACRU2K.2 (0.52 m). Values for the RMSE, NS and d were 10.4, 0.73 and 0.92, respectively, for ACRU2K.1; and 11.9, 0.65 and 0.88, respectively, for ACRU2K.2. However, simulation results for the evaluation period (visual and statistical) revealed considerable differences in predicted and observed WTD. The mean of the observed WTD (0.48 m) during the evaluation period was notably different from values simulated by ACRU2K.1 (0.33 m) and ACRU2K.2 (0.34 m). Values for the RMSE, NS and d were 33.0, -6.0 and 0.63, respectively, for ACRU2K.1; and 34.7, -6.7 and 0.62 respectively, for ACRU2K.2.

Results revealed that both ACRU2K.1 and ACRU2K.2 performed similarly for the model domain considered, and both models underestimated the observed WTDs. ACRU2K.2 had limited improvement in simulating water dynamics of plastic mulch bed systems. The similar performance of both models was a result of the observed WTD never entering the soil's top layer. The top soil layer of ACRU2K.1 and ACRU2K.2 has different soil storage capacities and would require the interaction of the water table with the bedded layer to create any notable difference in model performance. An evaluation of sub daily time step data revealed that both models were unable to correctly simulate a water table's response (sharp rise and slow descent) to a rainfall/irrigation event occurring during the latter half of a day. This problem arises when the duration of the WTD descent includes the midnight hour, creating a water table peak during the following day that has no corresponding hydrologic input to explain its presence. The inability of each model to respond to certain water table fluctuation may be a fundamental flaw in their hydrological response time. This is especially a problem given the high K_{sat} and shallow WTD condition associated with vegetable production systems of south Florida

Overall, results indicate that a lumped model can be modified to simulate hydrological processes within a bedded layer system, but it is insufficient to accurately depict the hydrological response of the shallow water table environment. Further modifications are necessary to address the high Ksat and shallow WTD condition associated with vegetable production systems of south Florida. A sub daily time step combined with infiltration equations are needed for future improvements in ACRU2K.2.

A

B

Figure 5-1. A topographical comparison between (A) a level field, and (B) a bedded field for the vegetable production system.

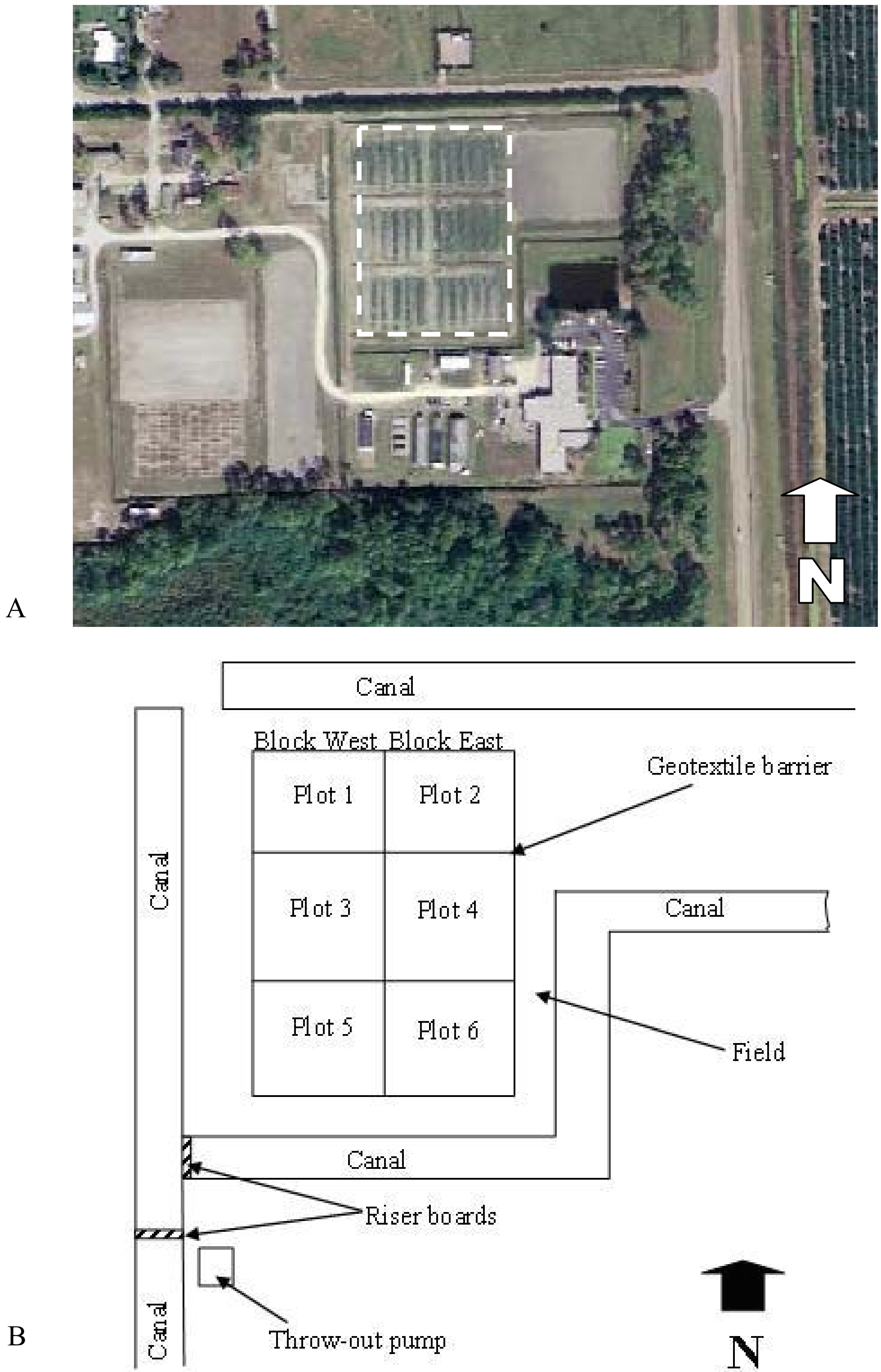


Figure 5-2. Layout of experimental plots. A) Image of experimental plots developed in a field at the South West Florida Research and Education Center. B) Schematic (not to scale) of experimental plots. Dotted line in Figure 5-2A delineates the study area's six plots.

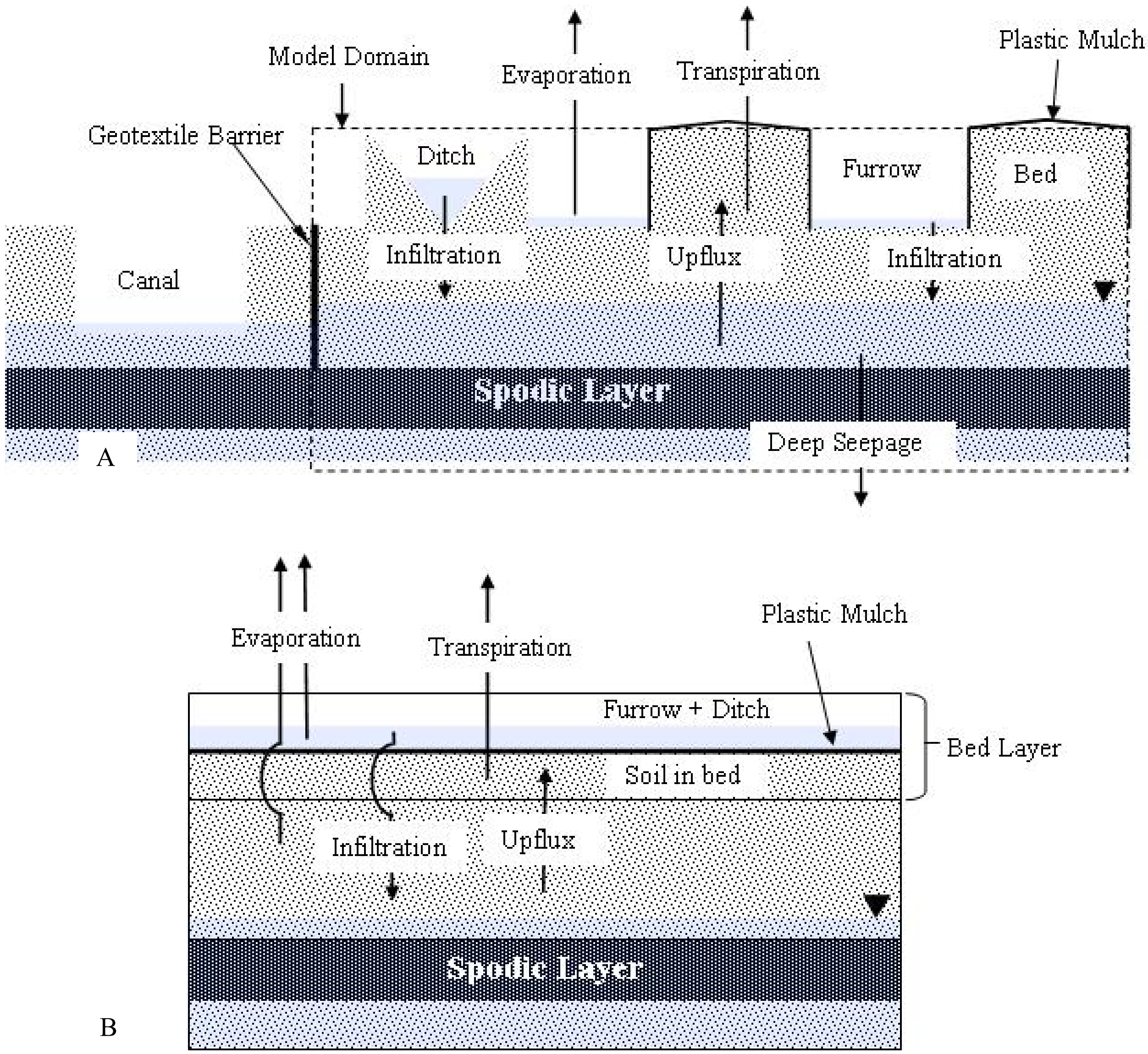


Figure 5-3. Diagrams that show the difference between the actual soil profile and conceptual soil profile used in ACRU2K.2. A) Simplified soil profile for a bedded vegetable field. B) An abstraction of the bedded vegetable field used to design ACRU2K.2. Crop beds were considered as one homogeneous unit and bedded layer is the same height as actual crop beds, but with reduce soil water storage capacity. Solid shaded areas represent water within a layer. Some features are exaggerated for clarity.

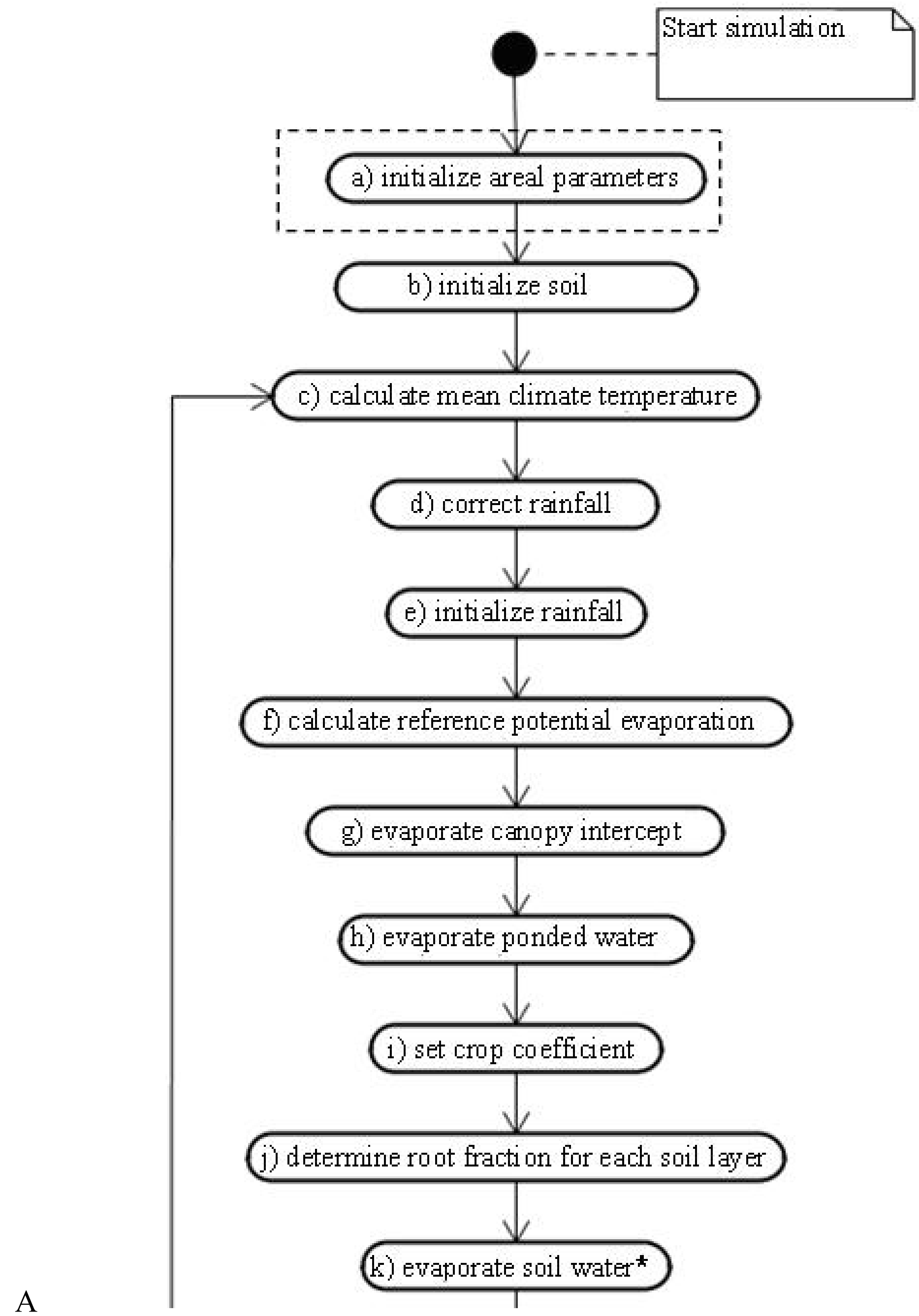
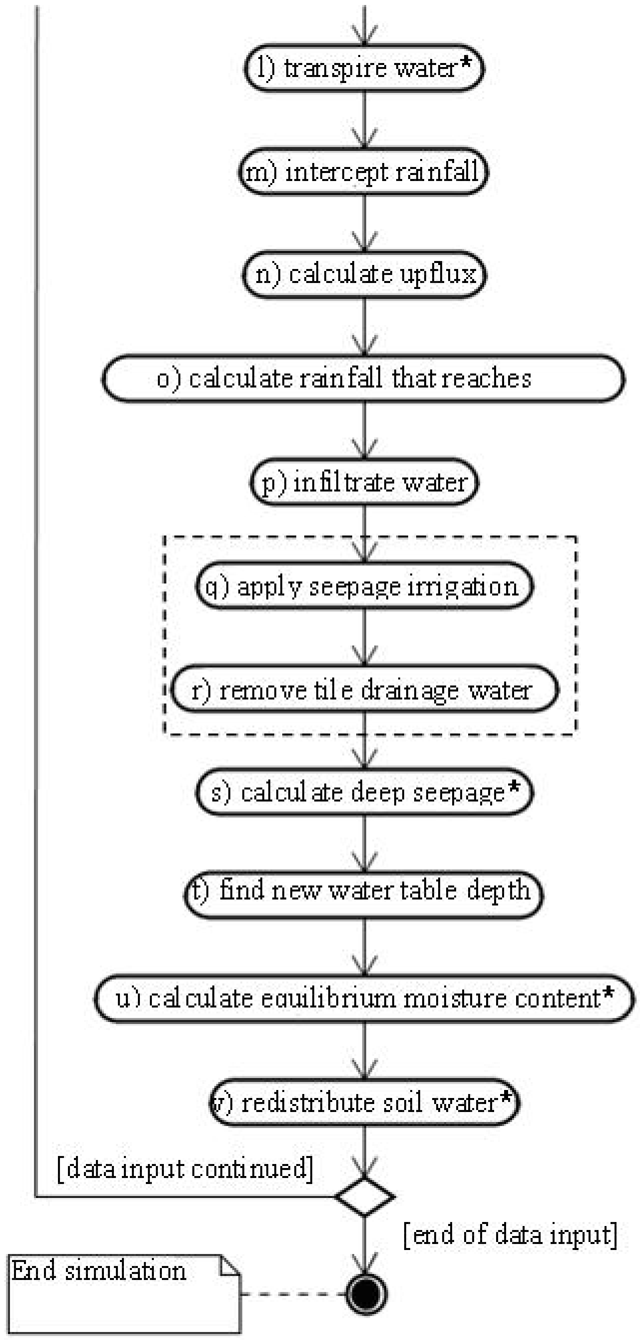


Figure 5-4. Diagram used in the design of ACRU2K.2. A) A UML activity diagram that shows the series of activities used to run the simulation. B) Continuation of the activity diagram. New activities added are outlined with a dotted rectangular boxed. Asteric (*) shows an original activity that was modified.



B

Figure 5-4. Continued

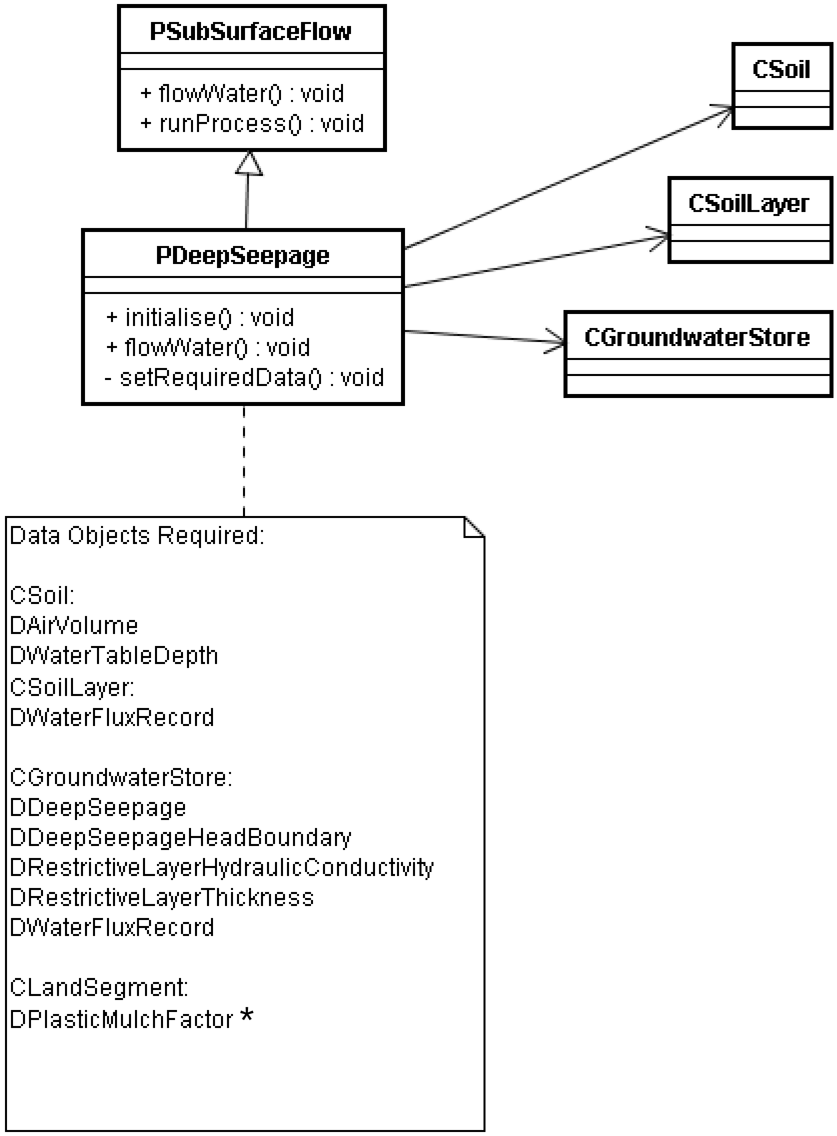


Figure 5-5. Example of an interaction diagram used in the design phase of ACRU2K.2. Asterisk (*) shows a DDate object added to the Class.

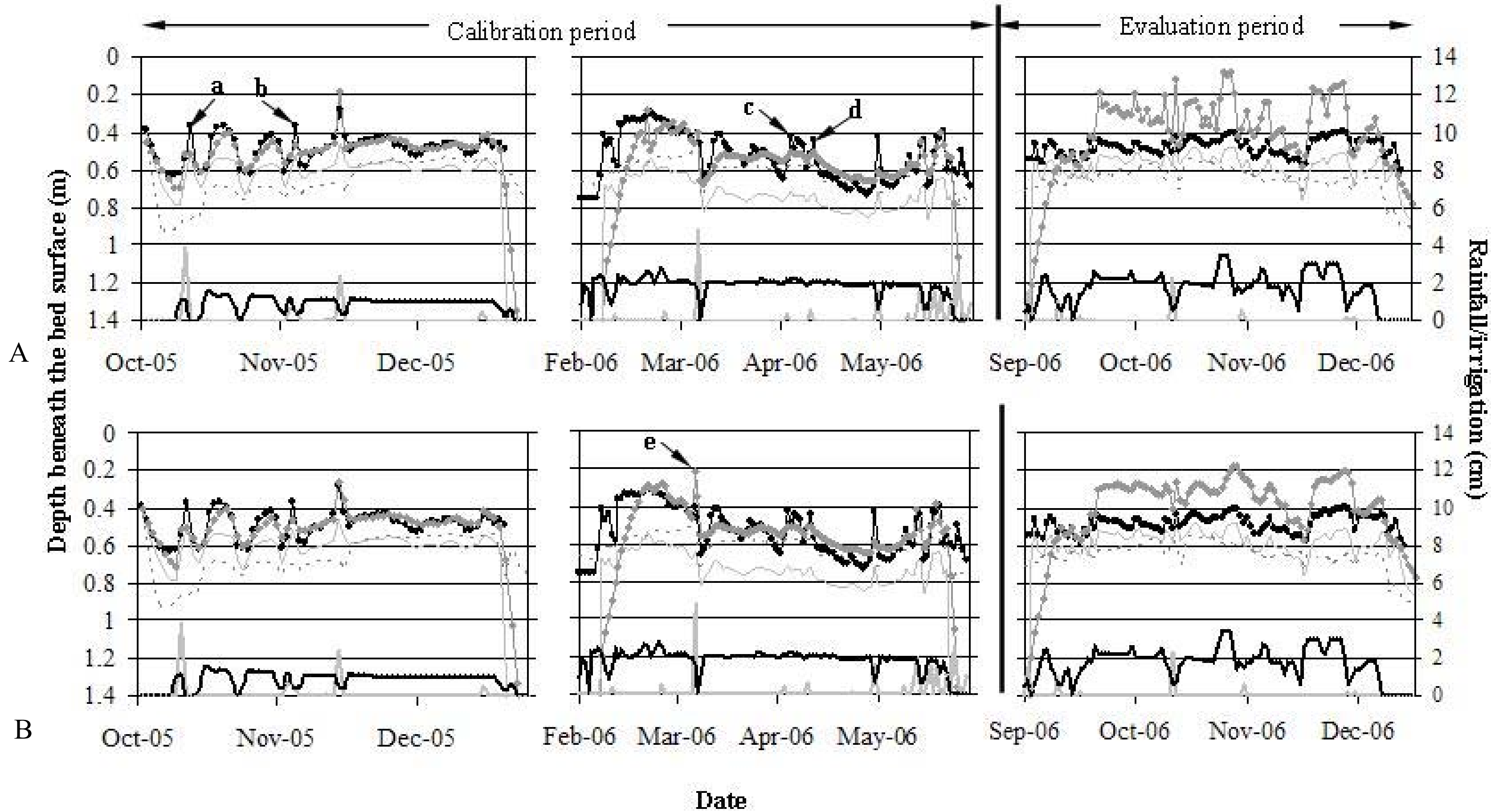
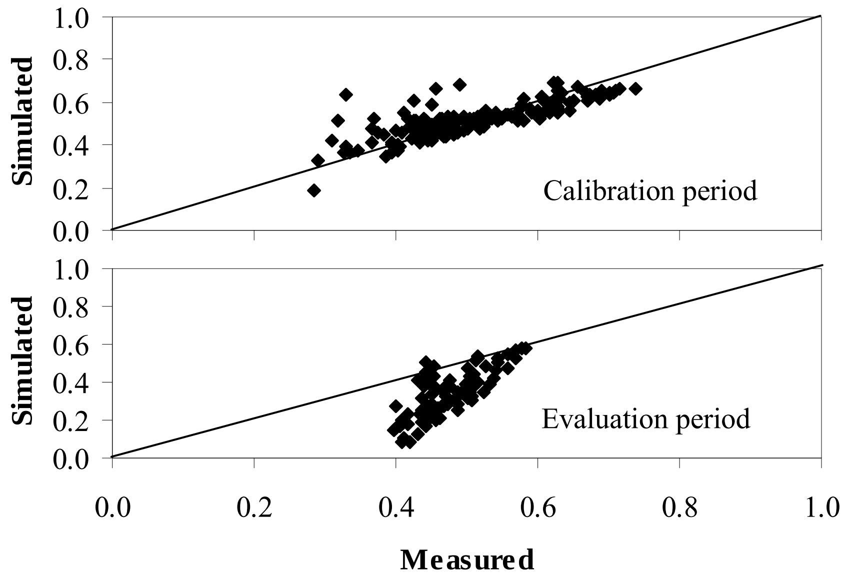
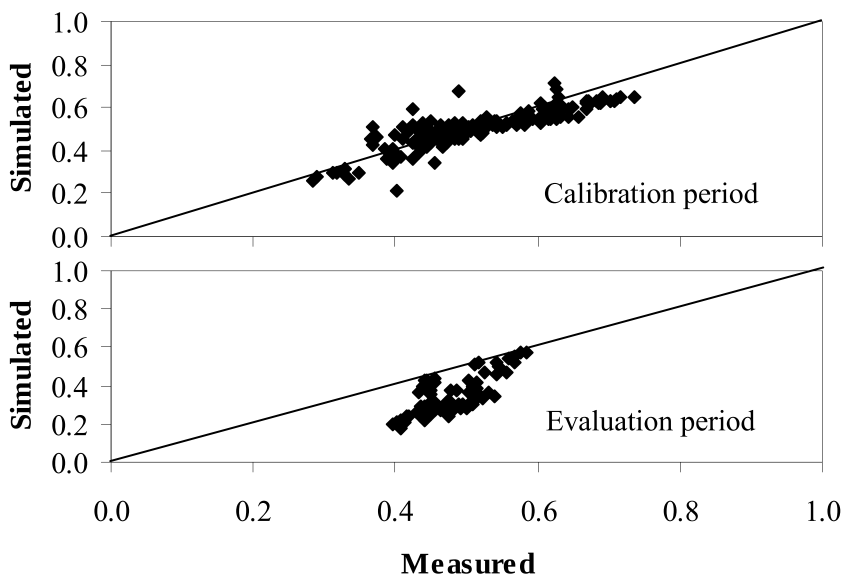


Figure 5-6. Calibration and evaluation runs for model versions. A) ACRU2K.2, and B) ACRU2K.1. Each plot displays the observed and simulated water table depth (WTD) below the bed surface, the water table depth observed below the spodic layer, and the depth (below the bed surface) to water level the perimeter canal.

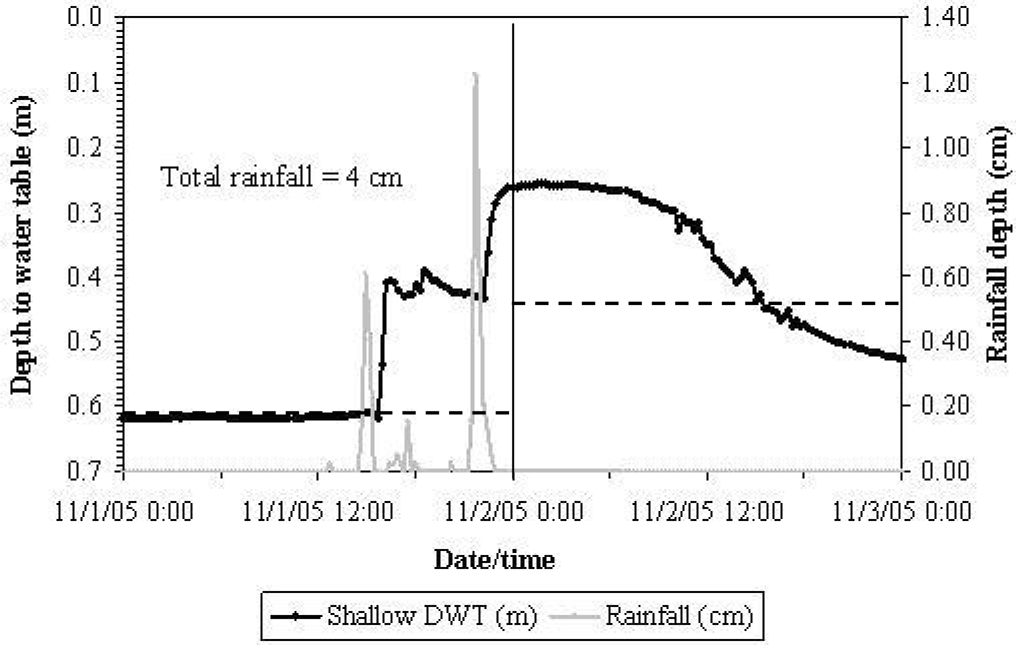


A

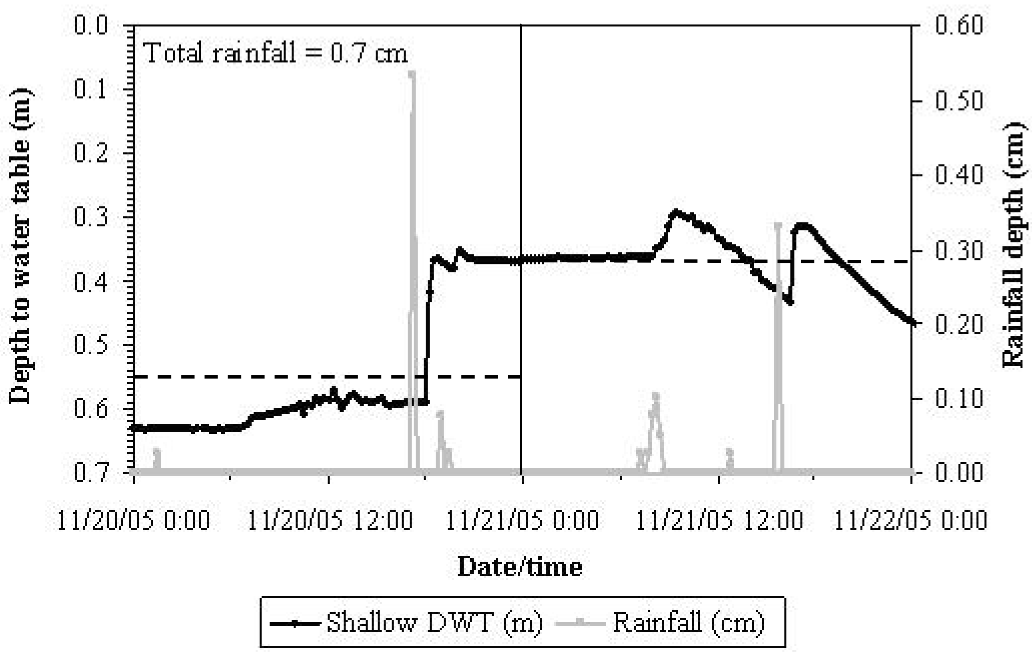


B

Figure 5-7. Scatter plots of observed and simulated shallow water table depths during the calibration (fall 2005 and spring 2006) and evaluation periods (fall 2006) for both model versions: A) ACRU2K.1 and B) ACRU2K.2.

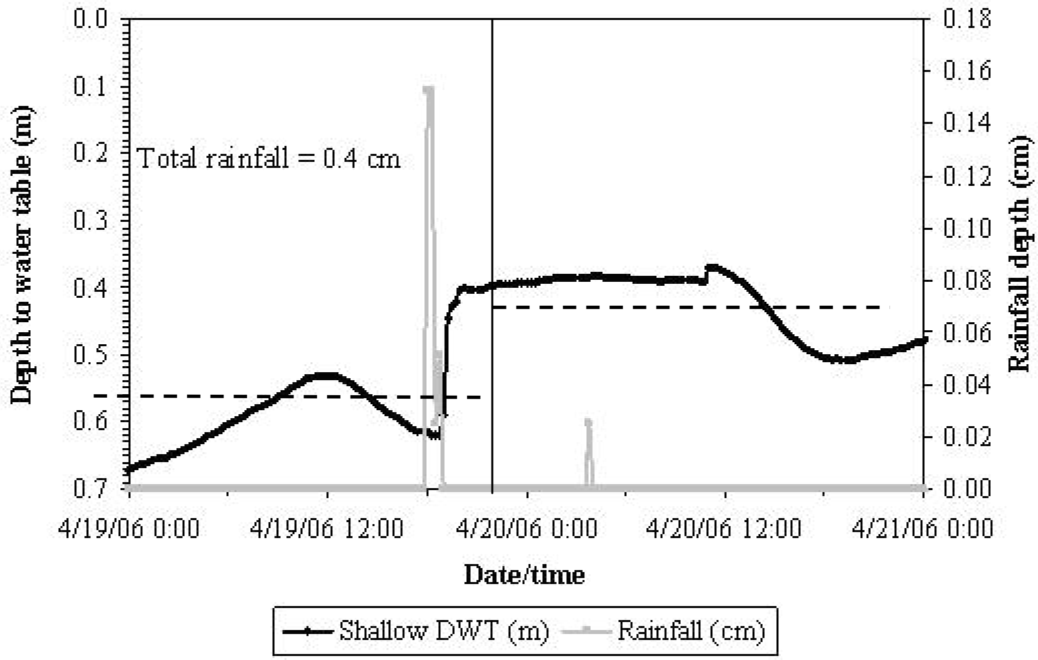


A

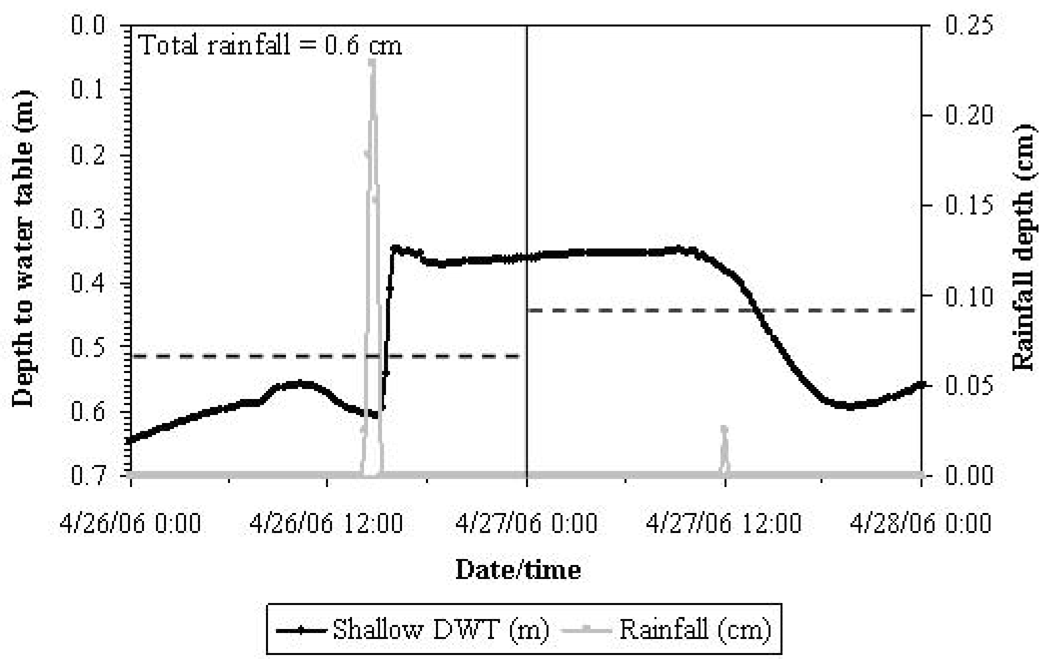


B

Figure 5-8. Rainfall and depth to water table in plot 1 for four 2-day periods (i.e., points a, b, c, and d in Figure 5-6). A) November 1 to 2, 2005 corresponds to point (a). B) November 20 to 21, 2005 corresponds to point (b). C) April 19 to 20, 2006 corresponds to point (c). D) April 26 to 27, 2006 corresponds to point (d). Dotted lines show daily average depth to water table.



C



D

Figure 5-8. Continued

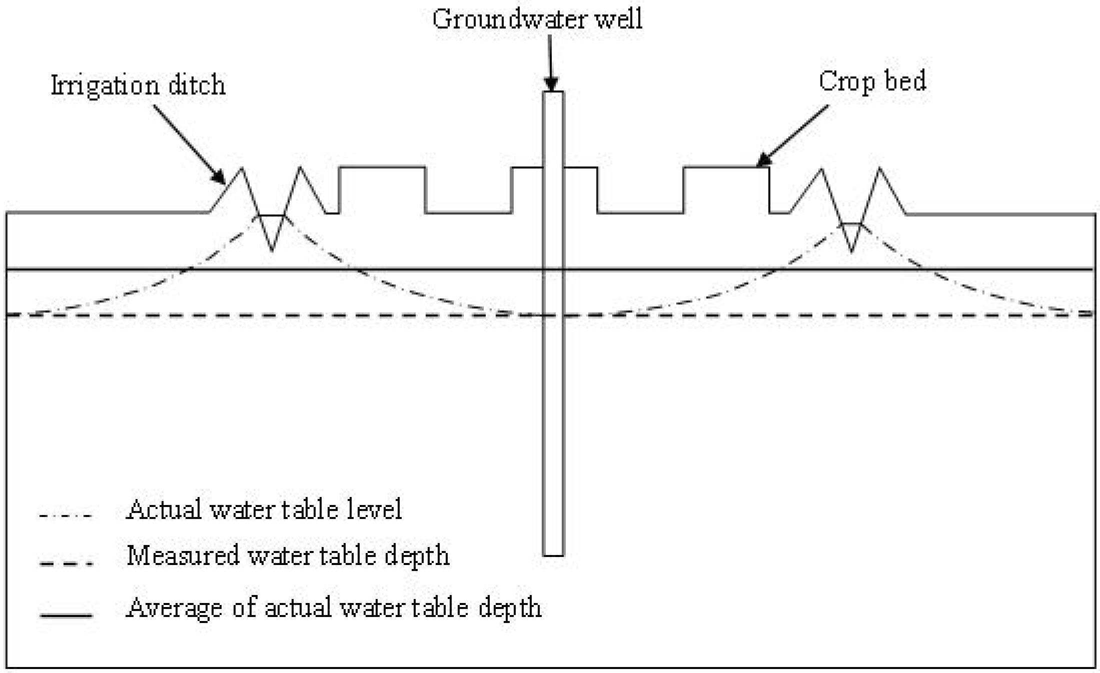


Figure 5-9. Spatial variation of water table level beneath a seepage irrigated field with raised crop beds.

Table 5-1. Process objects used to execute activities for ACRU2K.2

Activity[x]	Process object	Process	Action
a	PInitialiseUFBeddedLayerOptionHWT	Get areal dimensions for crop beds	Added
b	PInitialiseSoilUFOptionHWT	Get soil layer dimensions and create soil profile. Set soil moisture content	Modified
k	PAcruHWTRitchieSoilEvap	Calculate and remove evaporation depth from soil storage	Modified
l	PHWTCropCoefTrans	Calculate and remove transpiration from soil storage	Modified
p	PStorageLimitedInfilltration	Calculate and add infiltration to soil storage	Modified
q	PSeepageIrrigation	Get seepage irrigation and add to soil storage	Added
r	PTileDrainage	Get tile drainage and remove from soil storage	Added
s	PDeepSeepage	Calculate deep seepage and remove from soil storage	Modified
t,u	PFindNewWaterTableDepth	Calculate and set water table depth for the next day	Modified
v	PStorageLimitedRedistribution	Redistribute soil water above the new water table depth	Modified

[x]Description of actives are provided in Figure 5-4

Table 5-2. Physical characteristics representative of Immokalee fine sand

	Depth			
Physical character	0-20cm	20-100 cm	100- 130 cm	>130 cm
Sand%	97.2	98.7	88.7	88.7
Silt%	2.5	0.8	5.5	4.7
Clay%	0.3	0.5	5.8	6.6
Bulk Density (g/cm^3)	1.3	1.44	1.37	1.36
K_{sat} (m/s)	4.39×10^{-5}	5.67×10^{-5}	5.56×10^{-7}	1.39×10^{-5}

Table 5-3. Statistic measures for observed and simulated shallow water table depths for the calibration and evaluation periods

		ACRU2K.2		ACRU2K.1	
Data	Statistical measure	Calibration	Evaluation	Calibration	Evaluation
Observed	Mean (m)	0.51	0.48	0.51	0.48
	Standard Deviation (m)	0.10	0.04	0.10	0.04
Simulated	Mean (m)	0.52	0.34	0.50	0.33
	Standard Deviation (m)	0.08	0.12	0.10	0.10
	Mean absolute error (m)	0.05	0.14	0.04	0.14
	Root mean square error (%)	11.9	34.7	10.4	33.0
	Nash Sutcliffe coefficient	0.65	-6.7	0.73	-6.0
	Index of agreement	0.88	0.62	0.92	0.63

CHAPTER 6
SUMMARY AND CONCLUSION

Agricultural best management practices (BMPs) are generally recommended for a variety of crops with the aim of improving surface and ground water quality while maintaining economic viability. However, there are many BMPs whose effects have not been quantified. A three-year (spring 2004-fall 2006) monitoring and modeling study was conducted in southern Florida to evaluate the effects of a water-nutrient BMP on vegetable crops grown on plastic-mulched raised beds on water use and quality, yield, and farm income.

Three water-nutrient treatments were randomly applied among six hydrologically isolated 0.6 ac plots that were planted with tomato (fall)-watermelon (spring) rotations. One of the innovative aspects of this study was the hydrologic isolation of individual plots to prevent the mixing of groundwater nutrients between treatments. Tomato and watermelon crops, grown in rotation, were selected for their high cash value and high acreage in south Florida. The experimental plots were characterized by sandy soils, poor drainage and a low conductivity spodic layer (approximately 0.91 m beneath the soil surface). Water-nutrient management strategies compared were: 1) high fertilizer rate and moisture content (HR) with seepage irrigation, which represents the current water and nutrient input by vegetable producers in south Florida, 2) recommended fertilizer rate and moisture content (RR) within seepage irrigation, and 3) same as RR but with subsurface irrigation (RR-SD).

The HR treatment parameters were based on results of a survey conducted on vegetable growers in south Florida. The experimental design was a randomized complete block design consisting of three treatments and two replications. Response variables tested were crop yield, plant biomass, leaf tissue nitrogen (N), phosphorus (P) and potassium (K), and concentrations of N and P species in soil (suction lysimeter and core samples) and groundwater (shallow and deep). To characterize nitrogen leaching and dynamics, an intensive soil core sampling study involving samples (10 cm) taken from the bed surface down to a 40 cm depth was conducted. Soil core sampling was conducted during a single season (spring 2006) for two treatments (HR and RR). Soil N concentrations were also measured using suction lysimeters for all treatments during the entire study period. Hydrological parameters monitored were water use, soil moisture content, water table depth, and drainage. Climatic data monitored included rainfall and other variables for estimating potential evapotranspiration (ET). Groundwater quality measurements were taken form shallow wells (above the spodic layer) and deep wells (below the spodic layer). Economic data were collected on fertilizer and fruit prices, as well as cost on fertilizer application, harvesting and marketing cost. Partial budget analysis was used to determine if there was any benefit in implementing a particular treatment. Statistical techniques (i.e., ANOVA and Tukey's test) were use to determine the presence of any treatment effects for the field data. Yield data were analyzed by crop type while water quality was analyzed for the entire duration of study.

The hydrologic data were used to evaluate a modified model to simulate water dynamics for plastic mulch bed systems. Lumped hydrological models do not adequately represent crop bed environments. Hence, an existing model, ACRU2K.1, that was used to simulate water dynamics for high water table conditions under pasture land uses of south Florida, was modified to simulate crop bed environment (ACRU2K.2). The ACRU2K.1 version was selected for its extensibility (i.e., its ability to add/ change components without altering the main program structure). General modifications made to ACRU2K.1 included: changes to how infiltrated water was routed from the soil surface, changes to water available for evaporation, and incorporation of tile drainage and seepage irrigation objects. Model performances for ACRU2K.1 and

ACRU2K.2 were compared using the measured water table depth data. Statistical techniques (e.g., Nash Sutcliffe Coefficient and Index of Agreement) were used to evaluate the performance of the models simulation output.

Results for the watermelon crop showed that there was no treatment effect ($P < 0.05$) for watermelon yield during spring 2004 (HR = 84961 kg/ha, RR = 60302 kg/ha, RR-SD = 53240 kg/ha). However, watermelon yield for the HR treatment was significantly higher than the RR treatments during a relatively wet spring 2005 (HR = 38669 kg/ha, RR = 21632 kg/ha, RR-SD = 23986 kg/ha). Yield differences were attributed to an unusually wet crop season during spring 2005 (34.1 cm) compared with an average spring crop season (31 cm); in particular, a 6.4 cm rainfall event occurred two days after transplant. Unusually wet conditions increased nutrient leaching and were likely responsible for plant nutrient deficiencies detected by leaf tissue analysis. Leaf tissue analysis revealed that the HR treatment typically had higher N and K contents compared with RR and RR-S throughout spring 2005. The N content from the leaf tissue analysis was at or above the sufficiency range for each of the three treatments throughout the study period. The K content from the leaf tissue analysis was at or above the sufficiency range until week 9 for HR and week 7 for RR ad RR-SD. Plant biomass (total dry weight) result showed that HR (457 g/m^2) was numerically greater than RR (223 g/m^2) and RR-SD (203 g/m^2) for spring 2005. Economic analysis (Hendricks et al., 2007) showed that the value of yield increases for HR (compared with RR and RR-SD) observed during spring 2005 covered the additional cost for both the 2004 and 2005 spring crop season. Overall, HR seemed to perform better than RR and RR-SD for watermelon with unusually wet condition. In addition, there appeared to be a strong economic motivation for higher fertilizer rates particularly during wet years.

Results for tomatoes produced during fall 2004, 2005, 2006 and spring 2006 showed no statistical significant differences between the treatments for fruit yield. However, there were numerical differences in fruit yield with HR producing higher yields than RR or RR-SD during some crop seasons, and RR or RR-SD (compared with HR) produced higher yield during other seasons. Also, no statistical significant differences were detected between any of the three treatments for plant biomass during spring and fall 2006. Generally speaking N, P and K concentrations in leaf tissue were found to be above the sufficiency range for tomatoes in all treatments. There were some instances when P or K (or both) concentrations in the RR treatments fell below their sufficiency ranges at 10 weeks, or more, after day of transplant. Economic analyses of the tomato yield data for this study revealed that HR frequently generated more revenue than RR on a seasonal basis. Added cost for increased fertilizer N use in HR compared with RR would easily be compensated for by a one percent increase in yield. However, RR was able to generate nearly identical revenues compared with HR by end of the study period. Differences in crop revenue for HR and RR were highly dependent on a combination of yield and current market prices reported at the time of harvest. Since market prices can fluctuate widely, it is difficult for this study to determine if one treatment has a revenue advantage over the other.

Core sampling data showed total soil N in the RR treatments was significantly lower in all soil layers sampled (except the bottom layer), when compare to the HR treatment. An in-depth analysis of the results revealed that soil NO_x-N (0-10 and 10-20 cm) and NH_4-N (10-20 cm) concentrations within the crop bed were significantly higher ($P<0.05$) for the HR treatment compared with the RR treatments. Total kjeldahl N (TKN) concentrations were significantly higher ($P<0.05$) for the HR treatment (vs. the RR treatments) within the crop bed (0-10 and 10-

20 cm) and below the crop bed (20-30 cm). In general, core sampling data showed that soil N concentrations in HR created a higher potential for nutrient leaching from the crop bed compared with RR treatment. Results from the suction lysimeter data supported the results from core sampling data. Estimated N leaching losses, based on measured soil N from core samples, showed that N leaching losses from HR were 60% higher than from RR. Total P estimates for soil and plant showed that the potential for P leaching from RR was lower than HR.

Groundwater N concentrations (all analytes) in shallow wells were significantly higher in the HR compared with the RR treatments. Groundwater total N concentration was 38 mg/L for HR treatment; 16 and 21 mg/L for the RR and RR-SD treatments, respectively. Similarly, groundwater total P concentration was 3090 μg/L for HR treatment and, 2098 and 2048 μg/L for the RR and RR-SD treatments, respectively. These results reflected the higher soil nutrient concentrations, and N and P leaching, observed in the HR treatment compared with the RR treatment. However, groundwater N concentrations in the deep wells showed no significant differences between treatments.

Calibration and evaluation results for ACRU2K.1 and ACRU2K.2 showed that both versions performed similarly. Model evaluation results showed that the root mean square error, Nash Sutcliffe coefficent, and an index of agreement were 33.0%, -6.0 and 0.63, respectively, for ACRU2K.1 and 34.7%, -6.7 and 0.62, respectively for ACRU2K.2. Both versions of the model under performed as indicated by a negative EF value. The under performance by both models appeared to be the result of ACRU's daily time-step. ACRU's daily time-step was unable to accurately capture a water table's response to rainfall events. High water table conditions combined with a high saturated hydrologic conductivity results in a sharp rise in the water table level that are not captured in ACRU's daily time step. In addition, observed water table depths did not enter the bedded layer of soil during this study period, which limited the evaluation of ACRU2K.2 for runoff predictions.

The following conclusions were drawn from the data presented in this study:

- Plant performance for watermelon was greater with higher rates of fertilizer and higher soil moisture content in 2005 but not in 2004. The ability to detect significant differences was enhanced by higher rainfall in the 2005 season compared with 2004, indicating the importance of maintaining adequate levels of nutrients in the root zone of a seepage irrigated crop. This study suggests that growers may need to apply higher fertilizer levels particularly during wet years; however, because of the lack of statistical differences in 2004, more study is warranted.

- No yield or monetary advantage was apparent (over four crop seasons) when higher fertilizer-water inputs were applied to seepage irrigated tomatoes on plastic mulch in southern Florida. This study has to be conducted over an extended period of time with a large number of replications to determine the presence of a treatment effect, if any, for yield and farm income. Such an effort is not practical.

- Water use for tomato and watermelon production, under normal weather conditions, may be reduced without adversely affecting crop yield. While it is possible to reduce water use under furrow irrigation, the use of a sub surface drip system proved to be a more efficient method of reducing water used (> 50%) for viable crop production.

- Shallow groundwater quality is improved with the application of the RR treatment compared with the HR treatment. Lower fertilizer and moisture contents in the RR treatment (compared with HR) resulted in reduced nutrient (N and P) leaching that led to lower groundwater N and P concentrations. As a result, canals, streams and rivers will receive less N and P in edge of field drainage from bedded fields that use recommended fertilizer-water inputs (RR) with seepage irrigation.

- The ACRU2K.1 model can be modified to represent the hydrology of plastic mulch bedded field conditions in south Florida. However, the daily time step property of ACRU2K.1 proved to be limiting for the performance of ACRU2K.2. Sub-daily time step simulations are required for ACRU2K.2 to better represent the dynamic nature of the artificially high (< 60 cm) water table conditions associated with seepage irrigated vegetable production systems in south Florida.

In an effort the address Total Maximum Daily Loads required by the Florida Watershed Restoration Act (FWRA) (1999) and enacted by the Florida Department of Environmental Protection, several BMP manuals have been compiled that were based on studies pursued by UF/IFAS. These studies evaluated crop performance with crop nutrient and water requirements, and the results have been used to make fertilizer-water recommendations for optimum crop yield. However, water quality and yield impacts have not been evaluated in these fertilizer-water studies. Hence, no study has shown a link between nutrient management practices and their effect on environmental quality and farm profitability. As a result, fertilizer-water recommendations made by UF/IFAS are, at best, termed “Interim Measures” and not BMPs (Mylavarapu, 2003).

This study provides a first-ever link between fertilizer-water BMPs, water quality and yield for watermelon and tomato produced on plastic mulched crop beds. This study showed that under average weather conditions, groundwater quality can be improved with the use of recommended rates (RR) without adversely impacting yield and farm income. With this evidence, fertilizer-water recommendations (published in the Vegetable Production Guide for Florida) made to FDACS for watermelon and tomato production can be termed a BMP under average weather conditions.

The information provided by this study will be helpful in convincing vegetable producers in south Florida who have been reluctant in accepting the selected recommended water nutrient management strategies. Increased acceptance of recommended water and nutrient practices, by vegetable producers, is likely to result in the improvement of surface and groundwater quality in south Florida.

APPENDIX A
MEASURED SOIL PHOSPHORUS, POTASSIUM, MAGNESSIUM, CALCIUM AND PH

Table A-1. Soil pH and Mehlich-1 extractable phosphorus, potassium, magnesium and calcium concentrations measured in soil samples (0-20 cm) taken during the study period for each treatment

Mehlich-1 Extractable	Treatment	Date								
		6/11/2004	10/22/2004[z]	2/3/2005	6/3/2005	7/8/2005	11/10/2005[z]	1/9/2006	7/13/2006	2/13/2007
Phosphorus (ppm)	HR	77.44	83.19	74.33	62.11	55.50	71.56	126.51	93.50	119.70
	RR	64.91	72.64	67.33	68.67	59.00	43.25	89.00	48.50	53.58
	RR-SD	62.11	78.60	68.33	62.73	50.50	43.63	79.93	63.50	56.42
Potassium (ppm)	HR	n/a[y]	n/a[y]	112.33	n/a[y]	8.50	n/a[y]	346.00	25.50	176.85
	RR	n/a[y]	n/a[y]	47.00	n/a[y]	0.00	n/a[y]	82.33	7.50	46.42
	RR-SD	n/a[y]	n/a[y]	42.00	n/a[y]	0.00	n/a[y]	107.33	20.50	38.86
Magnisium (ppm)	HR	n/a[y]	n/a[y]	39.00	n/a[y]	14.00	n/a[y]	146.00	31.00	122.75
	RR	n/a[y]	n/a[y]	28.67	n/a[y]	11.00	n/a[y]	79.67	21.00	99.57
	RR-SD	n/a[y]	n/a[y]	40.67	n/a[y]	12.50	n/a[y]	96.00	33.50	98.26
Calcium (ppm)	HR	n/a[y]	n/a[y]	447.00	n/a[y]	305.50	n/a[y]	1123.00	419.00	571.40
	RR	n/a[y]	n/a[y]	462.67	n/a[y]	365.50	n/a[y]	936.00	322.00	500.80
	RR-SD	n/a[y]	n/a[y]	457.33	n/a[y]	347.00	n/a[y]	973.33	459.00	525.20
pH		n/a[y]	n/a[y]	6.00	n/a[y]	6.50	n/a[y]	5.6-6.1	6.50	6.8-7.3

[y]n/a = not analyzed. [z]Samples taken shortly after planting.

APPENDIX B
UNIFIED MODELING LANGUAGE (UML) DIAGRAMS FOR HYDROLOGIC PROCESSES MODIFIED IN THE MODEL

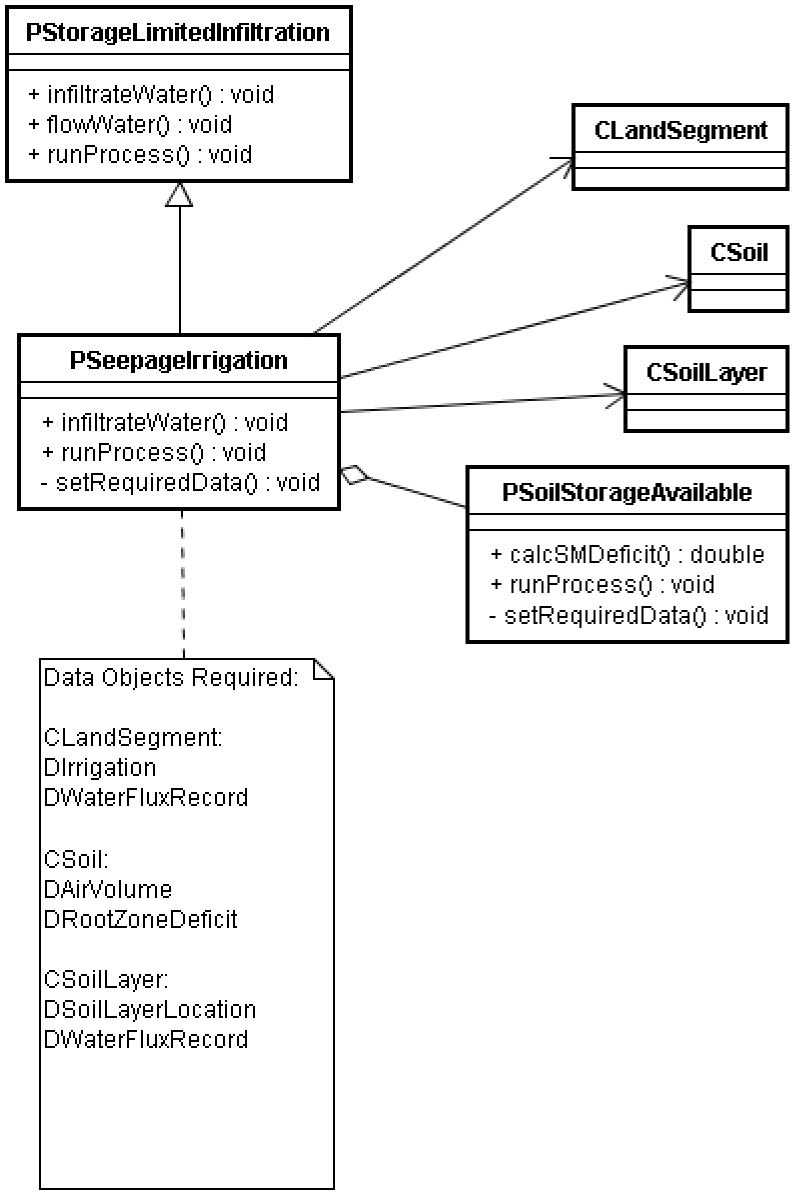


Figure B-1. PSeepageIrrigation interaction diagram.

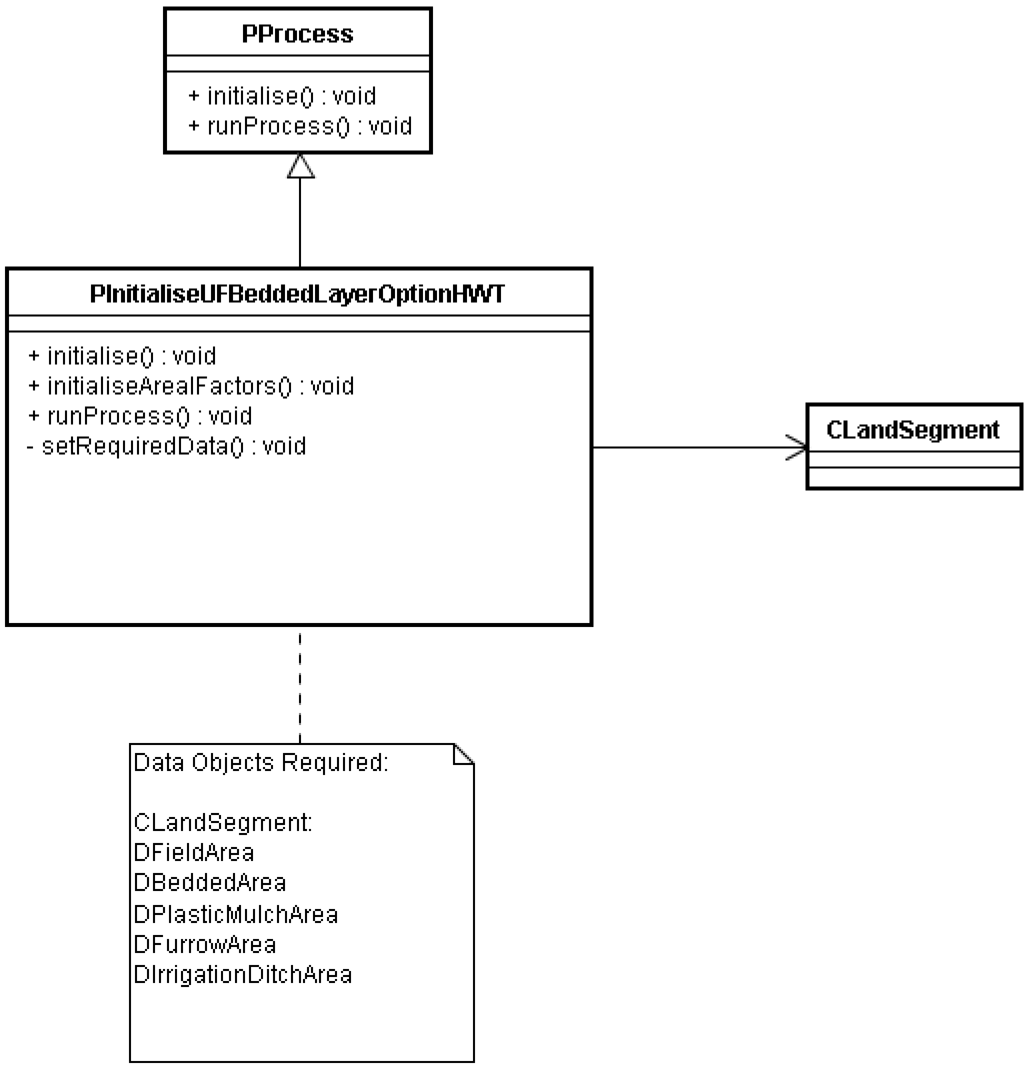


Figure B-2. PInitialiseUFLBeddedLayerOptionHWT interaction diagram.

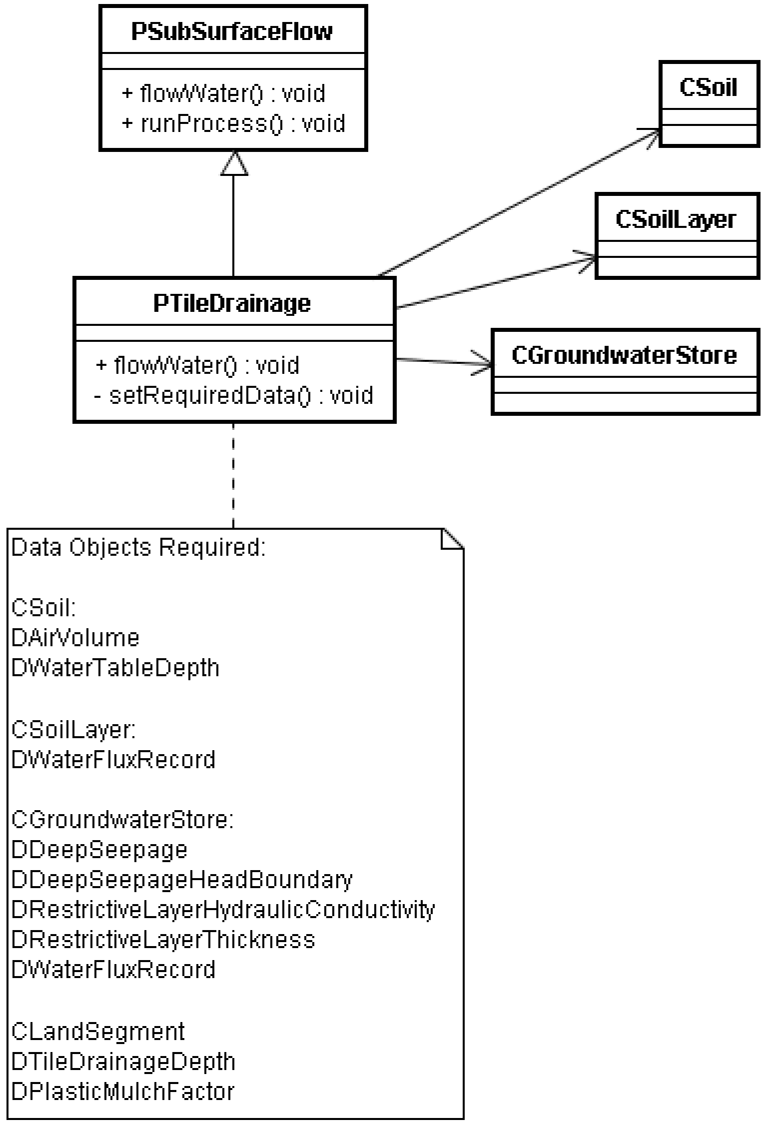


Figure B-3. PTileDrainage interaction diagram.

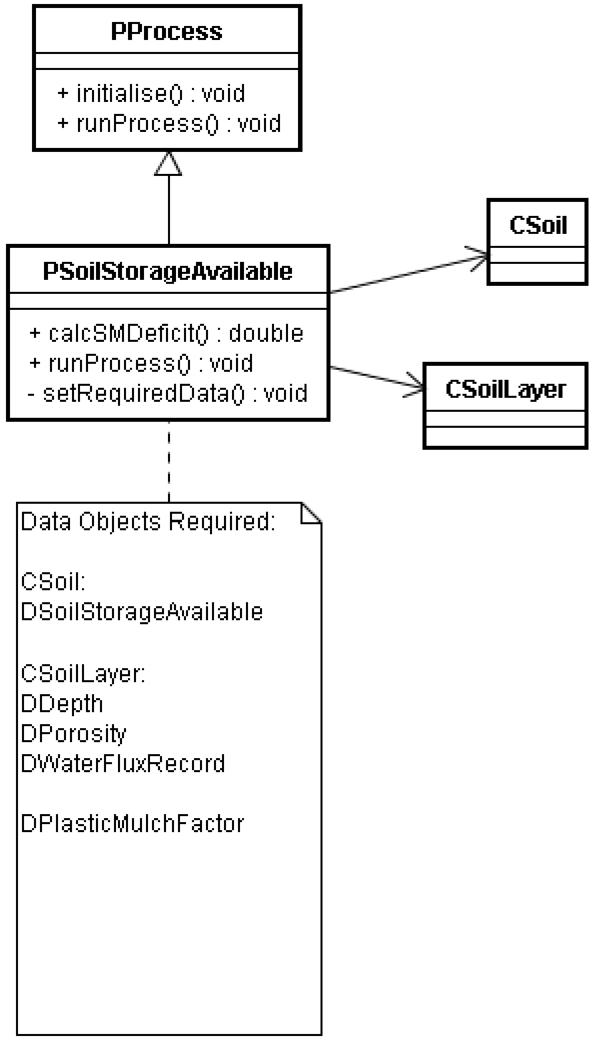


Figure B-4. PSoilStorageAvailable interaction diagram.

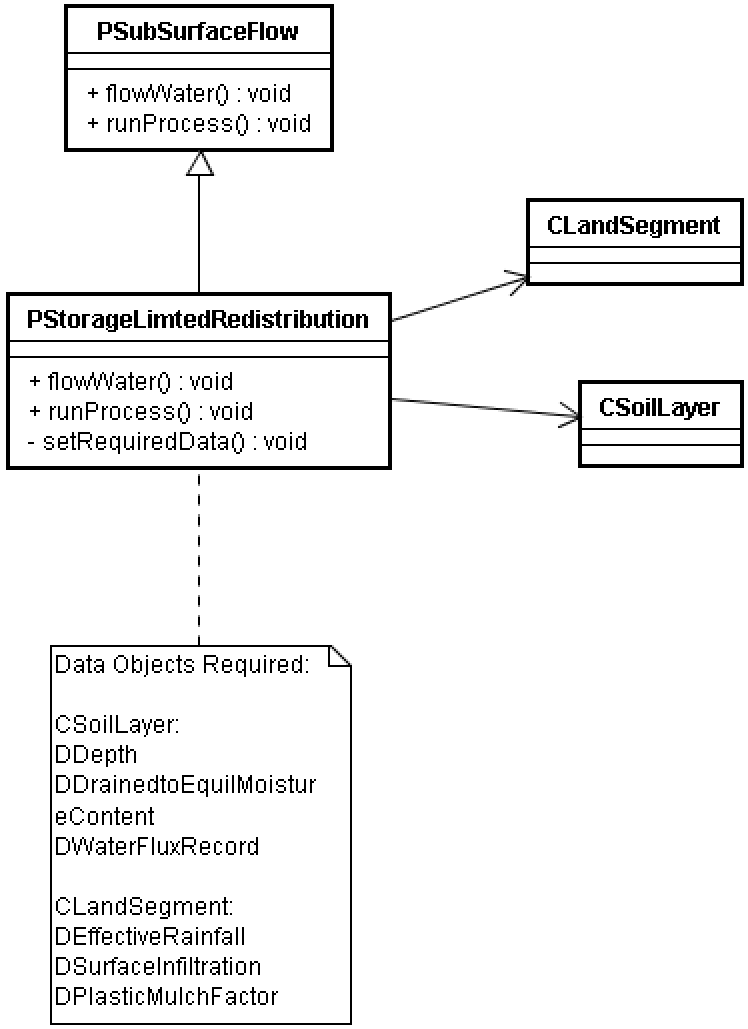


Figure B-5. PStorageLimitedRedistribution interaction diagram.

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BIOGRAPHICAL SKETCH

Gregory Samuel Hendricks was born and grew up on the Island of Jamaica. He is the last of four children of Mr. and Mrs. Joseph S. Hendricks. Gregory's primary education was completed at Mona Preparatory School. His secondary education was completed at Jamaica College. Gregory went on to complete his Bachelor of Science at the University of the West Indies at Mona, Kingston, Jamaica, majoring in the field of electronics. Gregory developed a passionate interest concerning the well being of the natural environment, which led him to the completion of his second Bachelor of Science degree at the Florida Agricultural and Mechanical University, majoring in the field of agricultural engineering. Gregory continued in this field at the University of Florida by pursuing his Master of Engineering degree. After completing his Master of Engineering degree, Gregory pursued his Doctor of Philosophy in the field of agricultural engineering at the University of Florida. Ultimately, his life's goal is to be able to contribute meaningfully to the solutions of the ever-increasing water quality problems presently experienced by society (home and abroad) and in the distant future.