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REVISION OF AFSIRS CROP WATER SIMULATION MODEL

SUMMARY

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SUMMARY
(TASK 39)

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TASK 39 - SUMMARY

1. INTRODUCTION

The Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model was developed for Florida's water management districts by University of Florida's Institute of Food and Agricultural Sciences (IFAS) to provide a method to determine allocations for consumptive use permitting programs. The model estimates irrigation requirements for Florida crops, soils, irrigation systems, and climate conditions. The model was last revised in 1990 and the User's Guide (SJ2008-SP16) and Technical Manual (SJ2008-SP17) were created at that time. Much of the information in these documents remains relevant and they will continue to be useful in their present forms until they can be updated. Since the 1990 revision, two significant advances affected the viability of the existing AFSIRS model: 1) additional research on crop water requirements had been conducted and 2) computer technology had significantly changed. In addition, opportunities were identified to improve the estimates and projections of evapotranspiration.

St. Johns River Water Management District (SJRWMD) has worked with the other water management districts and agricultural agencies to evaluate various crop and evapotranspiration (ET) models. In 2000, the Division of Water Supply Management at SJRWMD determined a need to modify the methods used by SJRWMD to collect ET data and to modify the way crop water use is calculated using the AFSIRS model (Jacobs and Satti 2001).

Implementation guidelines were developed as necessary to make those feasible improvements based on the recommendations from contract SD325AA and those recommendations of colleagues within the Florida agencies, as well as professional members of the agricultural and climate communities. Based on these recommendations a series of objectives was identified at the project onset. Over a six-year period (10/1/01 to 9/30/07), 39 specific tasks were identified and completed. The initial goals and tasks are described in detail in the project work plan, *Appendix 1, Revision of AFSIRS Crop Water Simulation Model Work Plan*. This document reviews the original project objectives and summarizes the significant outcomes. Many of the tasks' results were documented separately and submitted to SJRWMD during the study period. As appropriate, these documents are referenced in this summary document and presented as appendices.

2. PROJECT OBJECTIVES

1) Revise and update the ASFIRS software in a Windows format and couple it with SJRWMD GIS/Relational databases. Reporting and planning capabilities will be expanded, and existing climate, crop, irrigation system, and soils databases will be ported to the reporting features using a Visual Basic interface. The user interface and reports will include existing features and new components. Software will be demonstrated to SJRWMD staff for feedback, training of SJRWMD staff will be conducted, and a user manual developed.
2) Identify existing stations in Florida that provide routine meteorological data necessary to calculate reference ET for present and future data requirements. Identify gaps in the network. Communicate the location and measurements of existing stations and potential data gaps to organizations within Florida to include all water management districts (WMDs).

3) Update and expand historical climate databases to include more recent data including daily measurements of incoming solar radiation, wind speed, dew point temperature, and historical maximum and minimum temperatures where data are available.
4) Develop a spatial interpolation scheme for the historical climate database in the SJRWMD region. Approaches may include examination and integration of the FAWN network and remotely sensed precipitation and evapotranspiration data.
5) Review irrigation literature to determine and document efficiencies for Florida irrigation systems. Systems will be defined through a digital library of irrigation system photographs to avoid potential confusion of diverging names.
6) Conduct experiments necessary to determine crop coefficients for several crops. Most likely crop coefficients will be obtained for potatoes, sod, citrus, cabbage, bahia grass (*Paspalum notatum*) and potentially one other crop. Conduct a literature review of crop coefficients in the southeastern U.S. before commencing crop coefficient studies.
7) Compare crop coefficient results from an eddy correlation flux system and a weighing lysimeter system.
8) Compare modeled and measured crop water use for a minimum of one crop using the AFSIRS model. The measured crop water use data set will be developed during the crop coefficient experiments.
9) Coordinate all university personnel involved with the project and report monthly in writing and quarterly through in-person meetings or more frequently as needed.

3. PROJECT RESULTS

Table 1 lists the 39 AFSIRS project tasks and categorizes them as project management, experimentation, or software enhancement. Key results are summarized in the following sections by category. In addition, several peer reviewed publications have resulted from the project. These are briefly identified in the following sections and listed in the references for this document.

3.1 Project Management

The management tasks had no specific deliverables, but supported ongoing communication among the PIs and the SJRWMD project managers. Project managers were John Fitzgerald (2001, 2004-2007), Katherine Pordeli (2001-2003), and Beth Wilder (2003-2004). Principal investigator (PI) Jacobs led the project management activities with support from PI Dukes. Activities included scheduling, directing, and approving project work products, formal recruitment of IFAS staff for support of this project, recruitment of graduate students and post-doctoral researcher scientists, coordination, presentation development, documentation of meetings, project management, and administration. In addition, project management and support regarding the AFSIRS model was provided for complementary projects. Formal interactions among PIs and the project managers included monthly progress report submission, billing and accounting support, routine communications and meetings, and facilitation of transitions between project managers.

Table 1. List of AFSIRS tasks.

Task	Task Name	Category
1	Work Plan	Management
2	AFSIRS Coordination	Management
3	Software – Phase I	Software
4	Facilitate Reference ET Network	Software
5	Instrumentation and Computer Equipment	Management
6	Irrigation Efficiency Literature Review	Software
7	Crop Coefficient Instrumentation Establishment and Evaluation	Management
8	Climate Data Comparison to Reference ET Data	Experimentation
9a	Update Climate DB: Update AFSIRS Historical Climate Database	Software
9b	Review Methods to Enhance Spatial Interpolation of Climate Database	Software
10	AFSIRS Coordination	Management
11	Project Management: Coordination	Management
12	AFSIRS Software Modifications: Complete GIS System	Software
13	AFSIRS Model Enhancements: Implement Spatial Interpolation of AFSIRS Historical Climate Database	Software
14	Experimentation and Analysis: Grass Crop Coefficient (Year 1 of 2)	Experimentation
15	Experimentation and Analysis: Instrumentation II	Experimentation
16	Experimentation and Analysis: Citrus Crop Coefficient: Instrumentation Setup and Site Selection	Experimentation
17	Project Management: Coordination	Management
18	Experimentation and Analysis: Grass Crop Coefficient	Experimentation
19	Experimentation and Analysis: Citrus Crop Coefficient	Experimentation
20	Software Enhancements – Analysis Software Modification and Modular Design	Software
21	Model Enhancements - Software Demonstration and Training	Software
22	Model Enhancements - Sensitivity Analysis of Model Parameters	Software
23	Equipment Replacement - Supplement	Experimentation
24	Project Management: Coordination	Management
25	Experimentation and Analysis: Grass Crop Coefficient (Year 2 of 2)	Experimentation
26	Experimentation and Analysis: Citrus Crop Coefficient (Year 2 of 2)	Experimentation
27	Experimentation and Analysis: Row Crop Coefficient	Experimentation
28	Experimentation and Analysis: Sod Coefficient: Site Selection and Instrumentation Setup	Experimentation
29	Project Management: Coordination	Management
30	Analysis: Grass Crop Coefficient	Experimentation
31	Experimentation and Analysis: Citrus Crop Coefficient (Year 2 of 2)	Experimentation
32	Experimentation and Analysis: Sod Coefficient (Year 1)	Experimentation
33	Software Documentation	Software
34	Project Management: Coordination	Management
35	Experimentation and Analysis: Sod Coefficient (Year 2)	Experimentation
36	Climate Database	Software
37	Crop Coefficients Update	Software
38	GIS-based Water Resources and Agricultural Permitting and Planning System (GWRAPPS) Enhancements	Software
39	Technical Memorandum	Management

3.2 Experimentation

3.2.1 Background

The importance of evapotranspiration (ET) in the hydrologic cycle, irrigation scheduling, and water resources management has long been recognized. It is the main loss of water from the vegetation surface; therefore, accurate estimation of ET is important. However, accurate ET measurement is difficult to obtain. Numerous internal and external factors influence evapotranspiration. The magnitude of ET varies seasonally and diurnally. It is influenced by climate conditions, soil and vegetation surfaces, soil moisture status, crop phenology, growth stage, shading, and ground cover. For irrigated agriculture, ET is traditionally estimated by multiplying the reference evapotranspiration (ET_o) values by crop specific coefficients (K_c). Accurate estimates require knowledge of climate data to calculate ET_o and K_c values for crops. A comparison of a Florida Automated Weather Network (FAWN) climate dataset and an ET_o dataset to identify differences in climate data and calculated ET_o values was conducted (Task 8). The focus of the experimentation tasks was determining crop coefficients for the predominant crops in SJRWMD. Table 2 lists the nine crops, which constitute a total of 88.1% of the acreage under cultivation in SJRWMD.

Table 2. Crops grown in SJRWMD region in 88.1% of the total cropped area.

Crop	Area (Acres)	Percentage of Total
Citrus	113,977	37.4
Pasture	63,628	20.9
Sod	24,414	8.0
Potatoes	20,622	6.8
Sorghum	19,322	6.3
Field Corn	9,084	3.0
Nursery, container	6,359	2.1
Cabbage	6,314	2.1
Nursery, field	4,891	1.6

The University of Florida, in cooperation with SJRWMD, began a study in 2003 to determine crop coefficients (K_c) for three crops, bahiagrass, citrus, and sod. Bahiagrass and sod were selected because of their predominance in SJRWMD and the extremely limited experimental data on different types of grass. Citrus was selected because it is one of the most important agricultural crops in Florida and it requires irrigation to ensure citrus quantity and quality due to low soil water holding capacity of sandy soils. Citrus evapotranspiration and crop coefficients are critical parameters for citrus irrigation scheduling and water management. Florida citrus groves typically are grown in two regions of the state: flatwoods in the southern and coastal region of the state and ridge in the northern and central portion of the state. There was a strong need to determine crop coefficients for mature ridge citrus. Multiple year field experiments were conducted to determine crop coefficients. These measured K_c values were then applied to the AFSIRS software crop database, as well as being used to guide evapotranspiration estimates.

3.2.2 Reference ET

A detailed comparison of a FAWN climate dataset and a reference ET dataset as necessary to understand differences in climate data and calculated reference ET values between the two sites is documented in *Appendix 2, Reference ET Network for the State of Florida*. The validity of the reference ET estimates is a function of both the method and the climate data used in the estimates. Reference evapotranspiration (ET) is defined as “the rate of ET from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water” (Allen et al. 1998). As appears in the definition, the necessary input parameters for the reference ET estimations should be collected from the weather station that is located at the “reference site” having sufficient and valid weather measurements (solar radiation, air temperature, humidity, wind speed) to apply one of the combination-based equations to estimate reference ET. The weather measurements need to be collected at a properly watered and maintained site, otherwise adjustment to air temperature, humidity, and wind speed measurements may be necessary.

In Florida, the standard reference crop is a well-watered grass. The height of the grass reference should be at least 8 and no more than 15 cm. The available climate data are from NOAA and FAWN weather stations that may or may not be properly maintained as reference ET sites. To understand potential climate data differences, climate data from a site meeting reference ET standards were measured and compared to data from a nearby weather station. A “reference weather station” site was established at the Plant Science Research and Education Unit (PSREU) near Citra to collect one year of climate data for reference ET (REF-ET) estimations. The PSREU datasets were compared to those recorded at the FAWN-Citra station. Details of this work appear in *Appendix 3, Comparisons Between the Ref-ET Site and the Fawn Site at the PSREU in Citra, Florida*.

The solar radiation, wind, temperature, relative humidity, and reference ET measurements were compared (Figure 1). Overall, results indicated that there are some discrepancies in climate data collected between the two sites. The measured R_s values for both sites were comparable and reasonable. The daily average wind speeds measured at the FAWN site were usually lower than those measured at the REF-ET site. The lower wind speed values of the FAWN site are probably due to the fact that the wind flow is being intercepted by surrounding tall trees and buildings. No significant differences were observed in air temperatures between the two sites. The daily maximum relative humidity (RH) values at the REF-ET site were usually 100% whereas they rarely exceeded 90% at the FAWN site, most likely indicating calibration issues with the RH temperature probe at the FAWN site. Lower FAWN RH values may also have been caused by the lack of irrigation at the FAWN site. The resulting FAWN site reference ET values were usually slightly higher than the REF-ET site. However, this is largely attributed to differences in calculated net radiation as compared to measured net radiation.

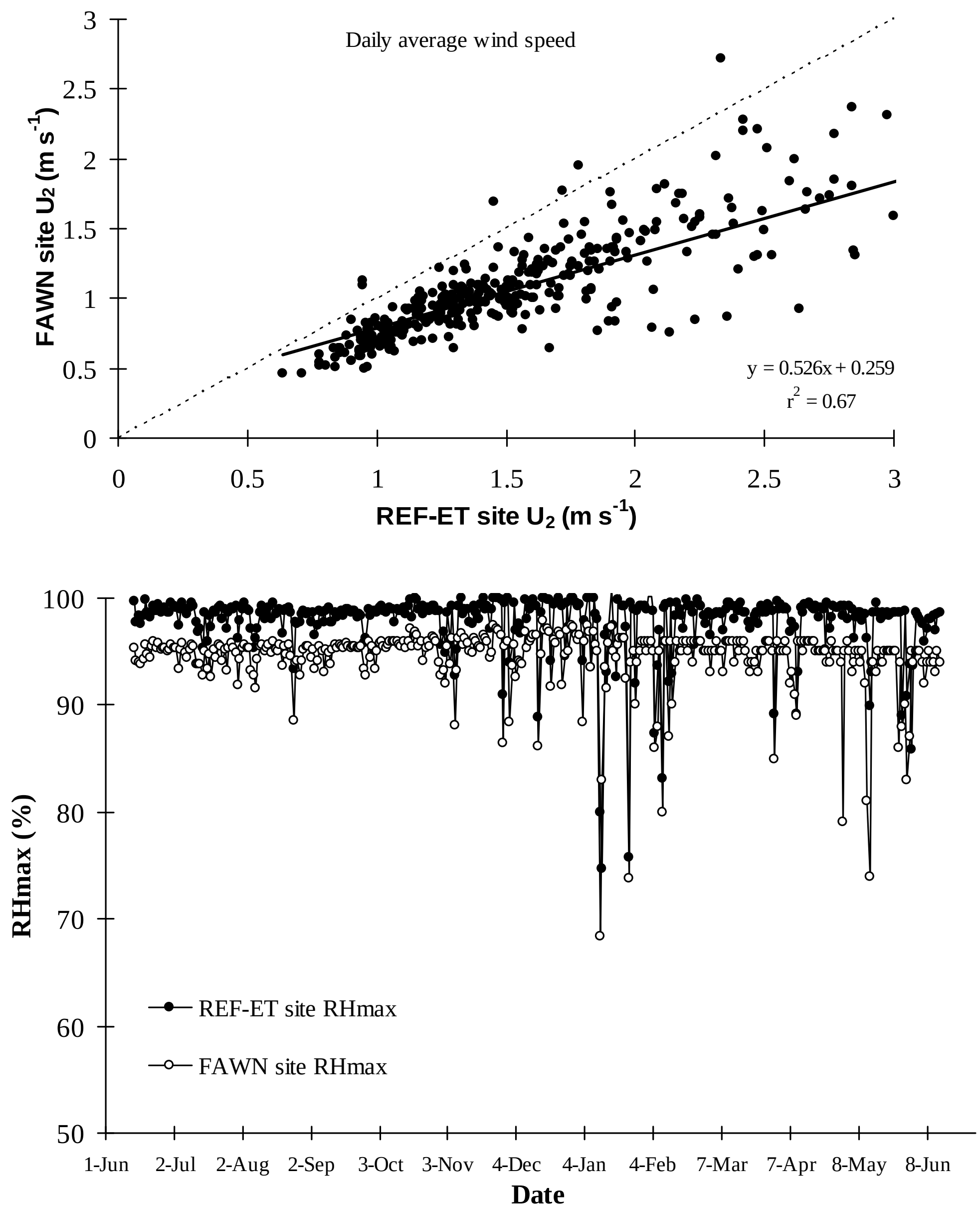
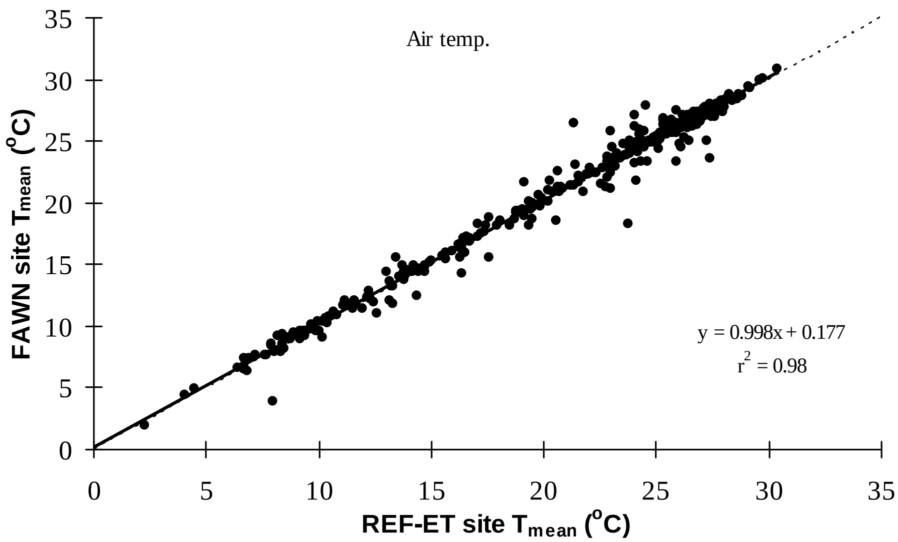


Figure 1. Comparison of climate data and reference ET values at the FAWN-Citra site and at the adjacent PSREU reference weather station.



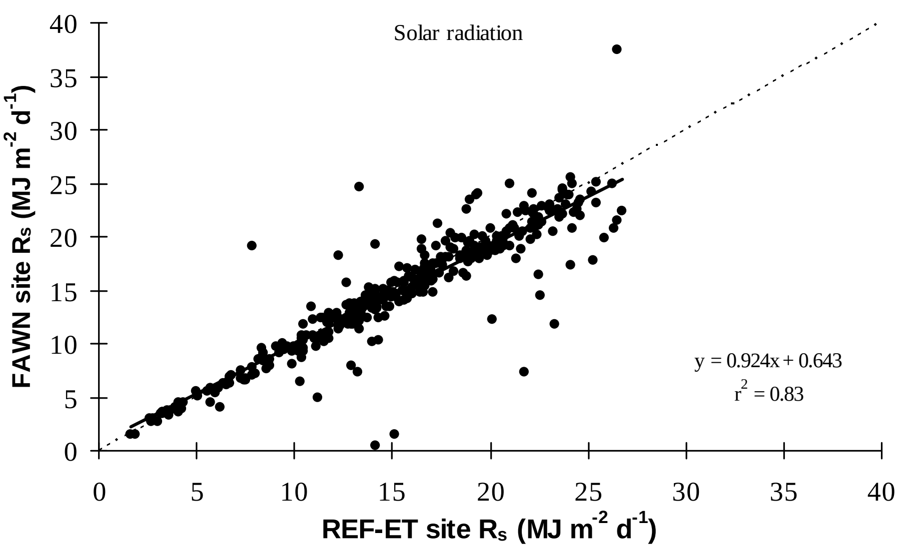
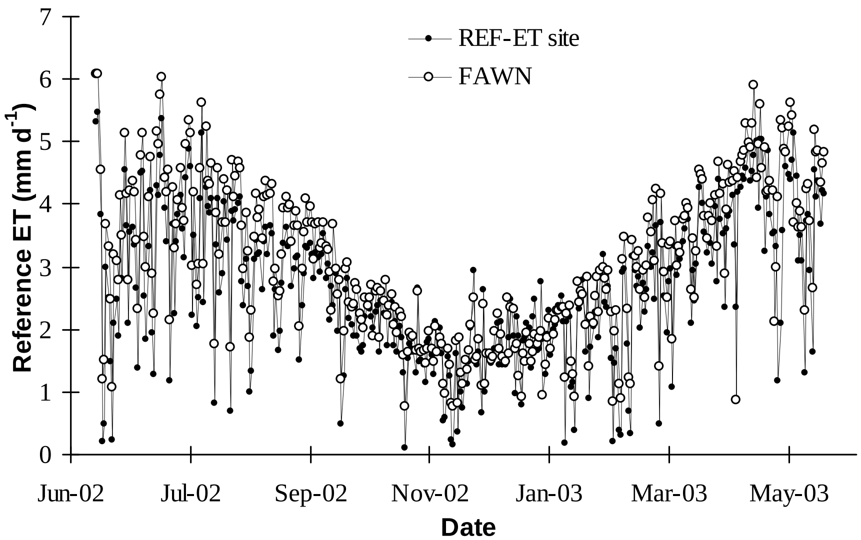


Figure 1 cont. Comparison of climate data and reference ET values at the FAWN-Citra site and at the adjacent PSREU reference weather station.



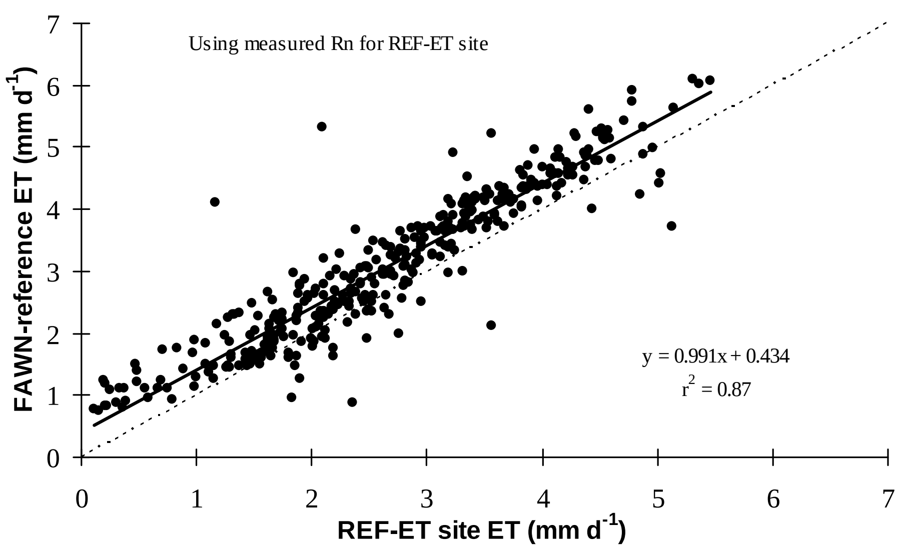


Figure 1 cont. Comparison of climate data and reference ET values at the FAWN-Citra site and at the adjacent PSREU reference weather station.

3.2.3 Crop Coefficients

3.2.3.1 Approach

There are two common ways to determine the evapotranspiration rate, direct and indirect methods. Direct measuring methods include soil water depletion, lysimeter, water balance, energy balance, mass transfer, eddy correlation, combination of energy and heat, and mass transfer (Jensen et al. 1990). Indirect measuring methods relate reference evapotranspiration (ET_o) to a crop coefficient (K_c). The ET_o can be calculated from weather data collected from a well-watered reference crop surface. Many methods have been developed to estimate the ET_o. The most current method has been developed by the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) (ASCE-EWRI 2005). Therefore, crop coefficient development requires both crop evapotranspiration (ET_c) and ET_o estimates for a specific crop and location.

The lysimeter method has been considered the most accurate method for almost one hundred years (Brutsaert 1982). If properly designed, constructed, instrumented, managed, operated and interpreted, lysimeters can provide precise and representative measurements of crop evapotranspiration that integrate environmental factors controlling ET (Allen and Fisher 1990). Lysimeters are categorized as follows: drainage, weighable, and weighing. Weighing lysimeters provide the most accurate data for short time periods (Jensen et al. 1990).

When the AFSIRS project was initiated, the eddy correlation was considered to be a new and innovative method. It had strong documented advantages, including the ability to successfully directly measure evapotranspiration (Sumner 2001; Sumner and Jacobs 2005), to overcome the need to determine each component in the water balance, and to avoid soil surface heterogeneity issues by placing the sensors above the crop canopy. In addition, considerable errors can result from the design and operation of lysimeters.

For the first set of crop coefficients, bahiagrass, a set of lysimeters operated simultaneously with an eddy correlation system. The three large weighing lysimeters, double steel tanks with an inner surface area of 2.32 m^2 and a soil depth of 1.37 m and each equipped with four commercial load cells, were designed, built, installed, and used specifically for the ET_c measurement. Looking at the site from the ground surface, the finished foundation is a monolithic concrete base with three square bases on top and six pipes protruding upward (Figure 2). The finished lysimeter site includes the three large tanks to collect the drainage from each lysimeter, a vacuum container, a vacuum pump and an automatic timer are enclosed in a water-proof cabinet beside the storage tanks mounted to the mobile trailer so that it can be moved for field operations (Figure 3). The weighing lysimeters design and preliminary results are presented in a refereed journal publication (Jia et al. 2006).

The following sections describe the crop coefficient results summarized for the bahiagrass, citrus, and sod. The coefficients are derived using experimental methods that are documented in appendices 4, 5, and 6. In addition, the principal investigators intend to write a peer-reviewed article for each experiment. Any modifications to the crop coefficients resulting from the peer-review process will be conveyed to SJRWMD for use in crop database updates to the GWRAPPS/AFSIRS model.

Figure 2. Lysimeter outer tanks and pressure release pipes.

Figure 3. Lysimeters (foreground) and the automatic vacuum pumping system (in the distance) (looking northeast).

3.2.3.2 Bahiagrass

The methods and resulting crop coefficients for Bahiagrass are documented in *Appendix 4, Crop Coefficients for Grass*. Grass evapotranspiration rates were measured on a nearly continuous basis from November 1, 2003 through April 30, 2006, using three weighing lysimeters and one eddy correlation system (Figure 4). Results include daily measurements of bahiagrass ET_c and ET_o, and monthly crop coefficients. Bahiagrass crop coefficients (K_c) were determined for Nov. 2003 through April 2006 in central Florida. The lysimeter and eddy correlation methods were used to estimate crop evapotranspiration (ET_c) rates. The standardized ET_o equation (ASCE-EWRI 2005) was applied to calculate the ET_o values using weather data from a nearby station. An eddy correlation system was used to directly measure the turbulent fluxes of water vapor (LE) and sensible heat (H) above the crop canopy. The distance between the lysimeters and the eddy stations was 80 m.

Figure 4. Bahia grass lysimeter site (left) and eddy correlation station (right) in August 2005.

Daily K_c values were estimated using the ET_c measured by the lysimeters and the eddy correlation system and the calculated ET_o. Monthly K_c values are shown in Figure 5. The K_c values determined by the eddy correlation method were similar to those determined from lysimeter measurements during the summer season. The largest K_c differences were found in winter time when the grass growth was active inside the lysimeters, but dormant in the surrounding field. Therefore, the monthly K_c values by eddy correlation method were more representative of the actual field condition. As summarized in Table 3, the recommended K_c values in this study were 0.34, 0.36, 0.54, 0.80, 0.89, 0.84, 0.72, 0.68, 0.62, 0.69, 0.65, and 0.46 for January through December.

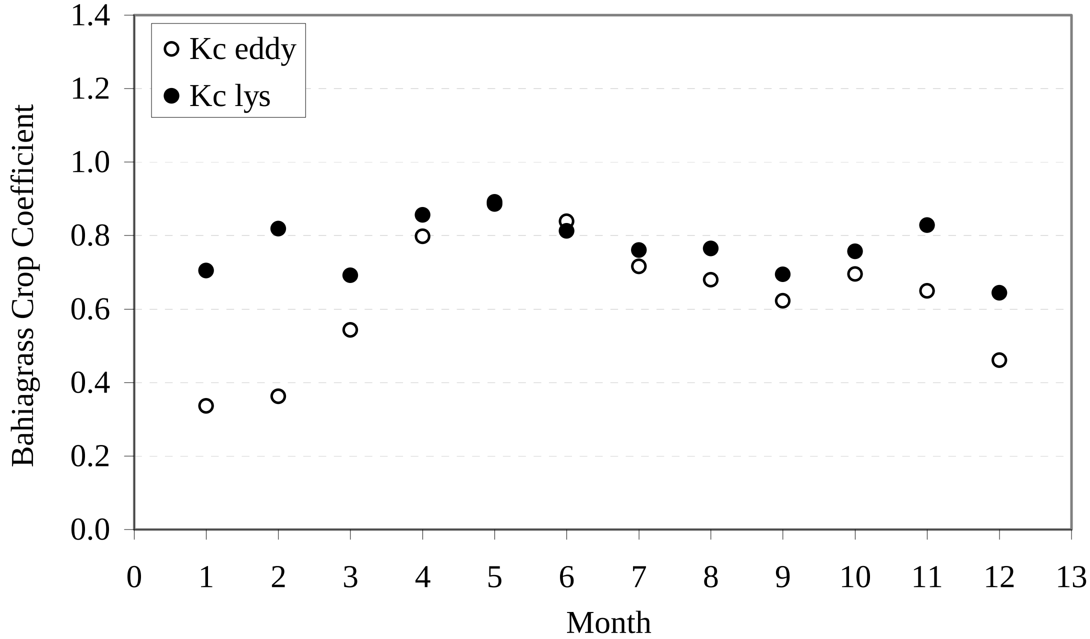


Figure 5. Monthly bahiagrass crop coefficients by eddy correlation (Kc eddy) and lysimeter (Kc lys) methods.

Table 3. Monthly bahiagrass evapotranspiration (ET_c) and crop coefficient (K_c) by lysimeters (lys) and eddy correlation (eddy) method: average (Avg) and standard deviation (Std).

Month	ET_o		ET_c Lys		ET_c eddy		K_c lys		K_c eddy	
	Avg	Std	Avg	Std	Avg	Std	Avg	Std	Avg	Std
1	2.12	0.55	1.54	0.58	0.70	0.24	0.70	0.22	0.34	0.10
2	2.29	0.86	1.97	0.82	0.84	0.40	0.82	0.27	0.36	0.11
3	3.33	0.90	2.44	1.04	1.84	0.70	0.69	0.24	0.54	0.14
4	4.30	0.60	3.74	1.40	3.45	0.79	0.86	0.29	0.80	0.13
5	4.55	1.07	4.04	1.74	4.21	1.33	0.89	0.27	0.89	0.16
6	4.30	0.83	3.56	1.62	3.68	1.17	0.81	0.32	0.84	0.15
7	4.39	0.82	3.39	1.60	3.18	0.89	0.76	0.31	0.72	0.12
8	3.96	0.89	3.07	1.55	2.74	0.99	0.76	0.32	0.68	0.15
9	3.75	0.87	2.75	1.32	2.41	0.85	0.69	0.29	0.62	0.16
10	2.78	0.59	1.98	0.84	1.96	0.58	0.76	0.34	0.69	0.13
11	2.35	0.52	1.99	0.73	1.53	0.47	0.83	0.28	0.65	0.17
12	1.79	0.49	1.20	0.51	0.82	0.32	0.64	0.24	0.46	0.15
Annual	3.20	1.23	2.56	1.48	2.14	1.37	0.77	0.29	0.61	0.22

3.2.3.3 Citrus

The methods and resulting crop coefficients for ridge citrus are documented in *Appendix 5, Crop Coefficients for Citrus*. The citrus experiment in the ridge region was conducted in central Florida, at Weirsdale, Marion County from August 1, 2004, through July 31, 2006 (Figure 6). Citrus evapotranspiration (ET_c) and crop coefficient (K_c) values were estimated using the eddy correlation method. The eddy correlation method is an innovative approach to estimate ET_c by measuring the ET_c above crop canopy. This method can be readily adapted to the tall trees characteristic of a citrus grove. The measured citrus ET_c showed a clear annual cycle similar to radiation energy flux, with a decrease in May due to frequent rainfall events. Citrus crop coefficients were estimated from the ratio of citrus ET_c to ET_o calculated from weather data over a grass reference site. Jia et al. (2007) present the first year ridge citrus results compared to flatwoods citrus in a refereed journal publication. The final results that include all experimental data are shown in Figure 7. The citrus K_c minimum values are 0.70 for dormant conditions from January to March. The citrus K_c peak values are 1.05 from July to November. In December, the K_c value reduction from 1.05 to 0.80 was triggered by a continuous minimum temperature (about a week) below 10^{o}C. Recommended monthly values for ridge citrus are listed in Table 4.

Figure 6. Citrus grove during weather station maintenance at Weirsdale, Florida in August 15, 2005 (looking west).

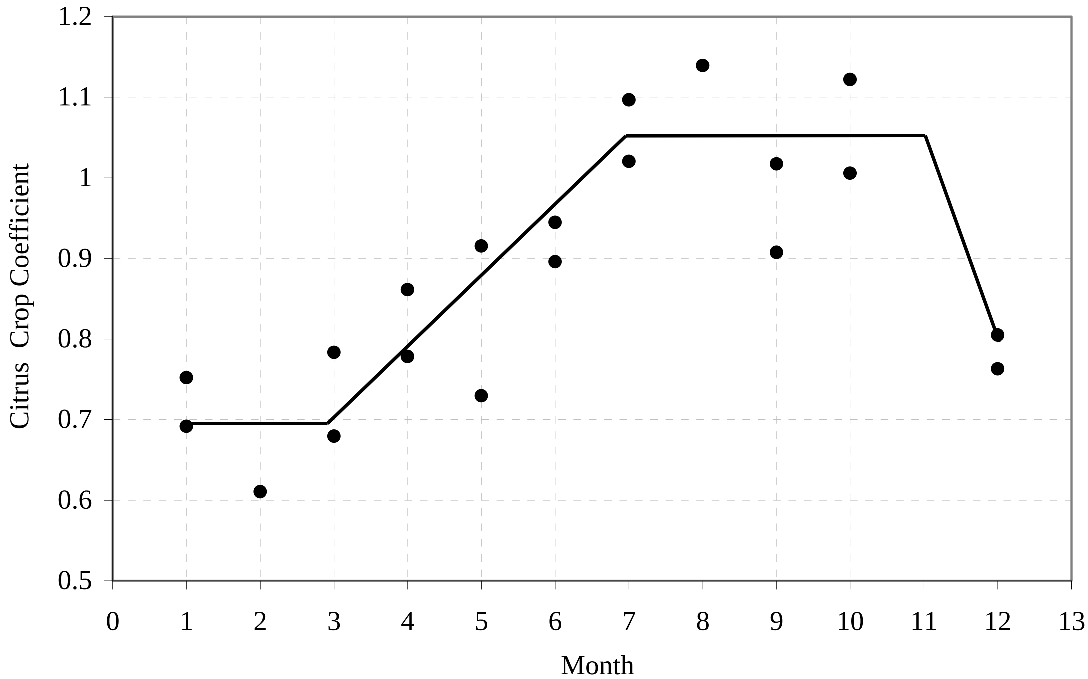


Figure 7. Monthly citrus crop coefficients by eddy correlation method (dots) and recommended K_c values for central Florida ridge citrus region (line).

Table 4. Monthly citrus evapotranspiration (ET_c) and crop coefficient (K_c) by eddy correlation method: average (Avg) and standard deviation (Std). Recommended crop coefficient values have a bold type in the last column.

Month	ET_o (mm/day)		ET_c eddy (mm/day)		K_c eddy		
	Avg	Std	Avg	Std	Avg	Std	K_c
1	2.16	0.56	1.51	0.44	0.72	0.24	**0.70**
2	2.42	0.68	2.01	0.98	0.83	0.34	**0.70**
3	3.16	0.97	2.26	0.79	0.73	0.21	**0.70**
4	4.29	0.63	3.49	0.68	0.82	0.16	**0.80**
5	4.11	1.16	3.83	1.17	0.92	0.13	**0.88**
6	4.01	0.83	3.85	1.42	0.94	0.25	**0.97**
7	4.48	0.73	4.62	1.34	1.02	0.20	**1.05**
8	4.03	0.88	4.41	1.06	1.10	0.19	**1.05**
9	3.77	0.87	3.69	1.28	0.96	0.25	**1.05**
10	2.80	0.59	2.99	0.80	1.06	0.22	**1.05**
11	2.34	0.51	2.45	0.69	1.05	0.26	**1.05**
12	1.75	0.54	1.41	0.60	0.78	0.28	**0.80**
Annual	3.15	1.16	2.90	1.38	0.90	0.27	

3.2.3.5 Sod

The methods and resulting crop coefficients for sod are documented in *Appendix 6, Crop Coefficients for Sod*. The sod experiment was conducted at Strickland Sod Farm, a commercial sod farm, east of Bunnell, Flagler County, Florida (latitude 29° 23' 56" N, longitude 81° 14' 29" W, and the elevation is about 7 m above sea level). The sod plot, where the weather station is located, has 75 ha of St. Augustine grass, about 500 m wide and 1500 m long. The sod was irrigated using a linear move overhead sprinkler. Evapotranspiration and ancillary climate data were measured on a nearly continuous basis from January 1, 2006, through July 31, 2007, using an eddy correlation system (Figure 8). Results include daily measurements of sod evapotranspiration, reference crop evapotranspiration rates and monthly crop coefficients as well as their variations due to the shallow water table.

Figure 8. Sod at Bunnell, Florida in February 14, 2007 (looking northeast).

The crop coefficients were estimated from a dual crop coefficient approach that separates the crop coefficient (K_c) into two coefficients: a basal crop coefficient (K_{cb}) and a soil evaporation coefficient (K_e). Daily K_{cb} values were estimated using the ET_c measured by the eddy correlation system and the calculated ET_o. As summarized in Table 5, K_{cb} values range from 0.67 to 0.83 with the lowest values occurring after harvest. Monthly K_c values are shown in Figure 9. These values likely somewhat underestimate a site's potential evapotranspiration. Thus, a single soil evaporation coefficient of 0.15 was found to reasonably describe the soil evaporation from a wet soil surface and was used to adjust the monthly crop coefficients. This site's coefficient exceeded the FAO56's single soil evaporation coefficient of 0.05. It is recommended that the soil evaporation coefficient be further investigated. The recommended sod K_c values range between 0.88 and 0.98. The lower values reflect the reduced plant transpiration following harvest and the peak values reflect the active growing periods.

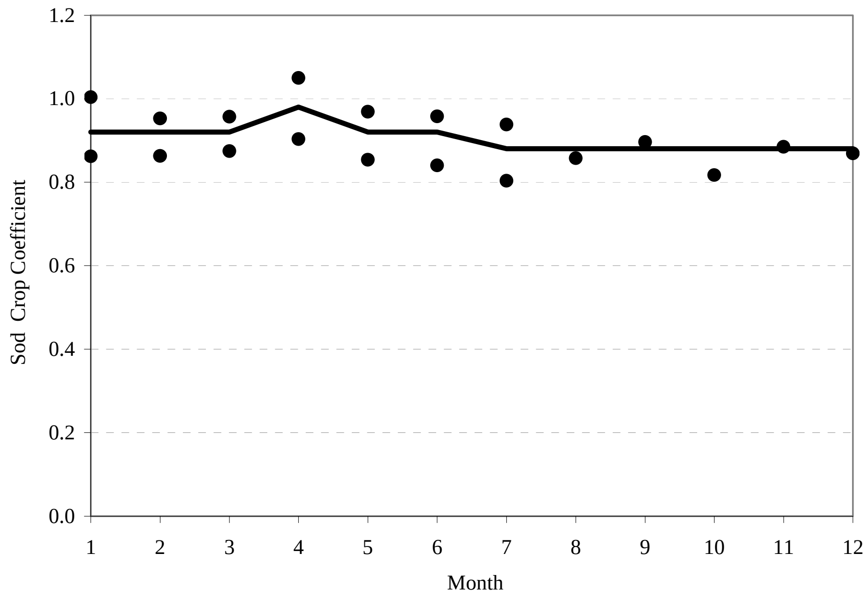


Figure 9. Monthly sod crop coefficients by eddy correlation method (dots) and recommended Kc values for sod grass from January 2006 to July 2007.

Table 5. Monthly sod evapotranspiration (ET_c) and crop coefficient (K_c) by eddy correlation measurements and the dual K_c method. Recommended crop coefficient values have a bold type in the last column.

Month	**ET_o (mm/day)**	**ET_c eddy (mm/day)**	**K_{cb}**	**K_c**
1	2.25	1.74	0.78	**0.92**
2	2.65	2.03	0.76	**0.92**
3	3.66	2.79	0.77	**0.92**
4	4.89	4.01	0.83	**0.98**
5	5.13	3.94	0.76	**0.92**
6	4.91	3.71	0.75	**0.92**
7	4.61	3.36	0.72	**0.88**
8	3.99	2.94	0.71	**0.88**
9	4.03	3.03	0.75	**0.88**
10	3.43	2.27	0.67	**0.88**
11	2.36	1.73	0.73	**0.88**
12	2.11	1.51	0.72	**0.88**
Annual	3.67	2.76	0.74	0.91

3.3 Software

3.3.1 Background

Prior to this project, crop water permitting at SJRWMD was supported using a DOS-based version of the AFSIRS model that was last revised in 1990. The AFSIRS model uses a water balance approach to estimate daily irrigation demand over a historical 30-year period. Daily values are aggregated to weekly, monthly, and annual irrigation requirements. The 2-year, 5-year and 10-year demands are estimated using statistical methods based on the modeled irrigation requirements. The overall goal of the software tasks was to update the software interface and supporting parameter files. Towards that end, the GIS-based Water Resources and Agricultural Permitting and Planning System (GWRAPPS), a GIS-based user-interface, was developed that integrates ArcGIS databases, AFSIRS, and a windows user interface. This software was documented and demonstrated to multiple user groups. Additionally, the approach was peer reviewed for publication (Satti and Jacobs 2004).

During the project, the climate, soils, crop, and irrigation system parameters were systematically reviewed and updated. In order to update the climate database, several preliminary activities were performed including the development of a spatial interpolation scheme, the identification of existing stations in Florida that provide routine meteorological data necessary to calculate reference ET for present and future data requirements, the review of intermediate climate measurements, and the calculation of reference ET using the FAO Penman-Monteith method. With respect to irrigation systems, the irrigation literature was reviewed to determine and document irrigation efficiencies for Florida irrigation systems. Systems were identified with matching irrigation system photographs to avoid potential confusion regarding naming conventions. A preliminary literature review of crop coefficients in the southeastern U.S. was conducted before commencing crop coefficient studies and then formalized at the conclusion of the project.

3.3.2 Model Parameter Updates

3.3.2.1 Sensitivity Analysis of Model Parameters

This study examined the effects of crop coefficients, ET methods, crop root zone depth, and soil water holding capacity on the irrigation requirements. It also determined the most sensitive factors in the regional irrigation requirement with respect to the regional average and farm to farm variability. The methods and results are documented in *Appendix 7, Sensitivity Analysis of Model Parameters* as well as a refereed Journal publication (Satti et al. 2004).

The sensitivity analysis was performed on a regional scale using GWRAPPS. The sensitivity analysis examined four ET methods, five crop coefficient values, three water holding capacities, and five crop root zone depths for two crops. The irrigation requirements were found to be most sensitive to crop coefficients, followed by ET_o method, soil water holding capacity (WHC), and crop root zone depth in that order. Thus, accurate determination of crop coefficients for different crops is vital for efficient irrigation practices. Additionally, irrigation system types and their efficiencies were identified as extremely important to determine the gross irrigation requirement, yet are poorly understood.

3.3.2.2 Irrigation System Parameters

Appendix 8, Types and Efficiencies of Florida Irrigation Systems, is a broadly relevant document that reviews typical Florida irrigation systems as well as their efficiency values. The document describes the concept of irrigation system efficiency, describes irrigation systems typically found in Florida, and presents efficiency values derived from relevant research data and or the literature. Pictures of systems are presented in the body of the document. A summary of attainable efficiencies is provided in Table 6.

Table 6. Florida irrigation systems attainable efficiencies[1] (See Appendix 8, Types and Efficiencies of Florida Irrigation Systems, for details and references.).

Method	Range	Average
Sprinkler		
Solid set	70-80	75
Solid set, container nursery	15-50	20
Portable guns	60-70	65
Traveling guns	65-75	70
Center pivot and lateral move	70-85	75
Periodic move lateral	65-75	70
Residential solid set	10-85	45
Micro		
Surface drip	70-90	85
Subsurface drip	70-90	85
Spray or jet	70-85	80
Bubbler	70-85	80
Surface		
Crown flood	25-75	
Flood	25-75	
Seepage		
Open ditch		
Flow through	20-70	
Tailwater recycle	30-80	
Semi-closed		
Flow through	30-70	
Tailwater recycle	40-80	
Subsurface conduit system	40-80	

[1] Attainable efficiencies do not consider management, only efficiency through design and installation.
[2] Average efficiency not given for surface or seepage systems since this varies with soil hydraulic properties and will be site specific.

3.3.2.3 Climate Database Update

Long-term consistent daily climate data are required for consumptive water use planning and permitting. The climate data provide the basis for understanding the spatio-temporal dynamics of water input and output in the form of precipitation and evapotranspiration. Estimates of ET require temperature, relative humidity, wind speed, and solar radiation. This project supported several activities to develop short-term and long-term climate resources necessary to determine crop water use for permitting and planning. Immediate needs included the development of a climate database for current and future applications that require ET. Towards that end, a review of existing data sources was conducted, best methods of interpolation were characterized, and climate databases were updated at the beginning of the project (1970-1999) and project end (2000-2004). To address the longer term climate development needs requires coordination among organizations within the State of Florida. This project helped to facilitate the development of a coordinated reference ET data system funded by the five WMDs and served by the United States Geological Survey's (USGS) Orlando, Florida office.

The available data sources as of 2003 are reviewed in *Appendix 3. Reference ET Network for the State of Florida.* In summary, Florida climate data are measured and recorded primarily by 6 agencies including IFAS, the WMDs, the National Weather Service (NWS), and USGS. Additional data are available from other sources that have limited stations within the state. The most established network is that of the NWS. This network consists of numerous stations, many with historical records dating from the 1930s and 1940s to present. This network is an excellent resource for historical precipitation and temperature data and 12 stations have historical wind speed and solar radiation data. However, solar radiation data has not been recorded since 1990 by the NWS. Starting in 1998, the FAWN stations provide good coverage throughout the state and have a complete set of instrumentation. Both the South Florida Water Management District and the Southwest Florida Water Management District have recently established a network of stations that monitor all climate variables necessary for ET and precipitation model input within their districts. Figure 4 shows the primary stations that might be used for developing a reference ET network within SJRWMD and the regions of the WMD that have existing consumptive use permits. The central portion of the District appears to be well monitored. The northern and southeastern portions of SJRWMD have significant gaps in coverage. The southeastern portion of SJRWMD is of particular concern given the density of permits.

The methods used to update the climate station data and to characterize the best interpolation approach are documented in *Appendices 9. Climate Database,* and *10. Spatial Interpolation of Climate Database,* respectively. The original AFSIRS climate database provides daily evapotranspiration (ET) and rainfall (P) data from eight locations in and near Florida. The locations are Mobile, Tallahassee, Jacksonville, Daytona Beach, Orlando, Tampa, West Palm Beach, and Miami. The record lengths at these locations range from 18-24 years. The records for these stations and an additional station at Gainesville were extended to include data from 1970 to 1999. Four interpolation methods, Inverse Distance Weighting (IDW), spline, kriging, and trend surface, were compared to estimate ET and precipitation at ungaged sites. The results show that the IDW method performed best for ET interpolation with a denser network required for the precipitation dataset.

The implementation of the above data and methods to interpolate the climate data to a 20 km grid climate product for the ArcGIS software tool are documented in *Appendix 11. Climate Database Implementation*. The updated AFSIRS climate data were used to generate 30 years of daily climate data at 368 locations covering the state of Florida. These locations are spaced at a 20-km resolution. The database was generated using the GWRAPPS climate interpolation utility that employed the inverse distance weighting technique and, for each location, stored the interpolated data in a separate Microsoft Access database. The final AFSIRS 1970-1999 climate database includes daily ET data generated from the NWS nine stations and the 80 daily precipitation stations. The updated reference ET database was generated using the FAO Penman-Monteith method (Allen et al. 1998).

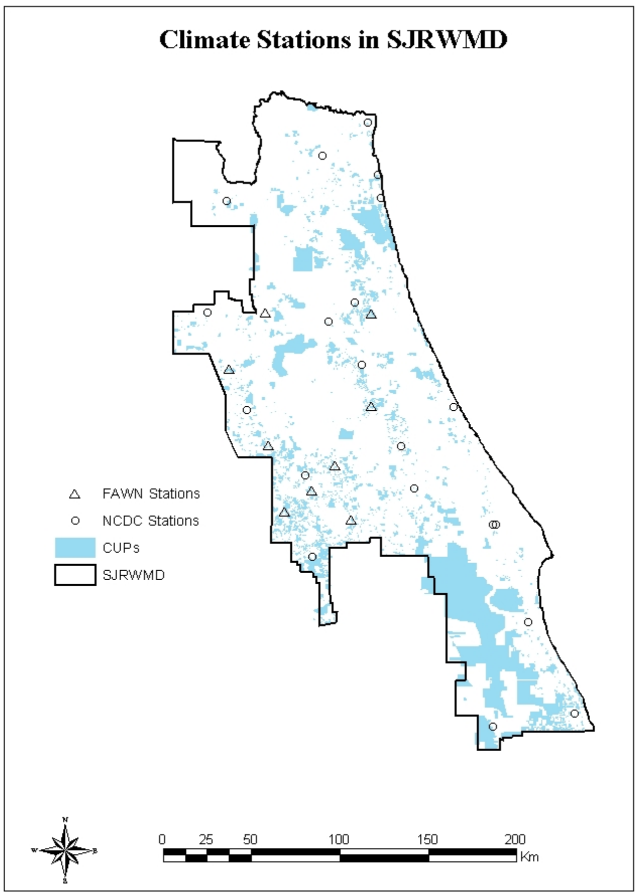


Figure 10. NCDC stations with 30 years of data and FAWN stations and existing consumptive use permits (CUPS) with SJRWMD.

3.3.2.4 Crop Coefficient Parameters

Appendix 12. Crop Coefficient Updates provides a literature review that was used to update crop coefficients relevant to Florida and SJRWMD. The focus was on experiments conducted since 2002 in the Southeastern U.S., including the USGS work being conducted in Florida, and national databases developed by the American Society of Civil Engineers (ASCE) Evapotranspiration Committee. Nine crops that constitute a total of 88.1% of the acreage under cultivation in SJRWMD were reviewed. Reviewed coefficients were used to create an updated crop coefficient file (crop.dat) for the GWRAPPS software. A significant finding was that, aside from those studies conducted during this project, few studies have provided crop coefficients or data necessary to update existing crop coefficients.

3.3.3 AFSIRS Model Enhancements

A key task in the AFSIRS crop water simulation model was the development of a GIS interface to link to the AFSIRS model that takes advantage of GIS tools. The resulting software enhancement is the GIS-based Water Resources and Agricultural Permitting and Planning System (GWRAPPS). GWRAPPS is a decision support system running in a Windows environment that tightly couples ArcGIS with AFSIRS.

The system's framework integrates ArcGIS, AFSIRS, and a user interface developed using object-oriented technology. The GWRAPPS handles the user selection of crop-specific and location-specific information. The GWRAPPS also enables data exchange between the spatial data and the AFSIRS model. The linkages between ArcGIS and AFSIRS include automatic data and control transfer between the two components of the integrated system.

GIS is the front-end tool for preprocessing data and the visualization tool for analyzing the final results. A schematic representation of the integrated system is provided in Figure 11. GIS provides a Graphical User Interface (GUI) for assembling the necessary AFSIRS model input. The user interface, developed using Visual Basic, controls the data and the flow between the integrated system and the AFSIRS model. The interface also provides a visual representation of the spatial distribution of the AFSIRS model results. In addition, GIS provides access to spatial and temporal databases that maintain distributed crop-specific data and climate information.

The user interface, developed using Visual Basic, resides within the GIS and interacts with the user for selecting crop-specific and location-specific data. The user interface accepts input from the user and transfers it to the data access modules. Based on the user input, the data access modules acquire the necessary spatial and non-spatial data from GIS layers and a Relational Database Management System (RDBMS), respectively. Spatial (GIS) and temporal (RDMBS) databases maintain the distributed crop, soils, and climate data. ArcObjects, a Component Object Model (COM) oriented technology, handles the interaction between the spatial information and the user. Spatial information, such as the soil type and the nearest climate location are acquired from the GIS layers. Temporal information such as evapotranspiration and rainfall are acquired from a RDBMS. The translation modules translate the user selected spatial and non-spatial data into AFSIRS compatible input datasets. Linkages between ArcGIS and AFSIRS facilitate automatic control to transfer between the user interface and the AFSIRS model. The AFSIRS model simulates crop water requirements using the generated input datasets and the AFSIRS model data files. The visualization modules display the resultant spatially distributed crop water demand within the GIS framework.

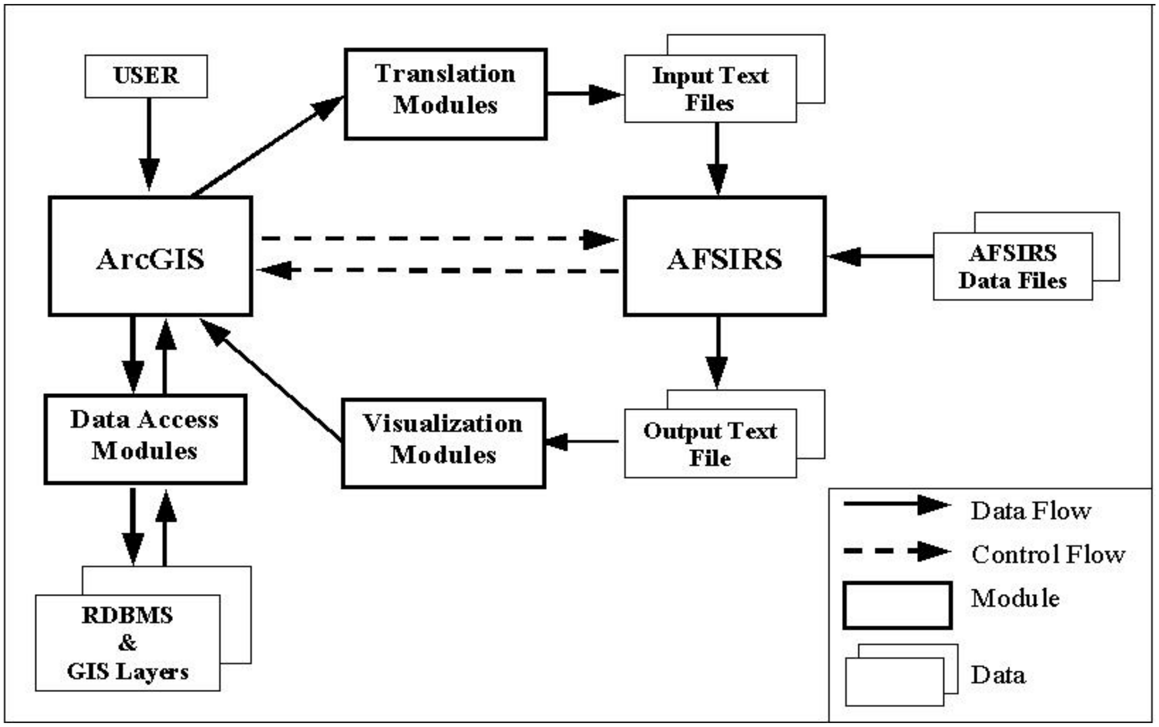


Figure 11. Schematic representation of GWRAPPS.

Additional user support activities were conducted in parallel with software development and transfer. A 1-day technical training course on AFSIRS was presented by Dr. J. Jacobs at SJRWMD on August 15, 2006. Approximately 30 SJRWMD technical staff participated in the course. The presentation was recorded and the presentation materials were archived for future applications.

4. SUMMARY

A number of significant software and database upgrades have been supported through this contract. The University of Florida, in cooperation with the SJRWMD determined coefficients for three major crops that cover a total of 66.3% of the acreage under cultivation in SJRWMD. Crop coefficients were obtained for bahiagrass, citrus, and sod. These experiments significantly improve knowledge regarding water use by predominant crops in SJRWMD and greatly enhance the previously extremely limited experimental data. Other significant crops in SJRWMD are potatoes and sorghum, which cover totals of 6.8% and 6.3% of the acreage under cultivation in SJRWMD, respectively. Few data are available for sorghum water use or irrigation requirements for Florida conditions. Comparison between SJRWMD Benchmark Farms program data and current water demand estimated by the GWRAPPS/AFSIRS model would identify significant discrepancies and help to determine the value of additional information that could be derived through experimental determination of crop coefficients.

GWRAPPS has been operational at SJRWMD for over one year with the revised climate and parameter databases. Users of the GWRAPPS/AFSIRS model should familiarize themselves with the technical aspects of the model in the documentation. One aspect identified during this project that may be relevant is that the model accounts for one dimensional (vertical) water movement, but does not track upward movement of soil water from near surface water tables. Additionally, the GWRAPPS/AFSIRS model does not include leaching, freeze protection, or crop cooling requirements, even though water for these purposes may be applied through an irrigation system. Currently, Florida has a significant water demand for landscape and nursery irrigation. The heterogeneous and multidimensional aspects of this type of water movement and evapotranspiration are not well aligned with the AFSIRS modeling approach. Additional work is necessary to provide a consistent and reliable irrigation water demand estimate for these types of land uses.

Two activities currently are being conducted outside this contract that are relevant to the GRWAPPS/AFSIRS model. The first is a national effort towards reviewing and updating crop coefficients. The second is a Florida project that is generating ET datasets at a daily time step from 1995 to present. With respect to the national effort, in 2002, the ASCE Evapotranspiration in Irrigation and Hydrology committee (ET committee) proposed a Task Committee on the Transferability of Crop Coefficients (Kc committee). This committee has met annually since 2003. The Kc committee is collating peer reviewed journal articles that document experimentally determined crop coefficients and supporting methods and practices. Upon completion of this review, a peer reviewed document will be produced that provides recommendations for crop coefficients. Once this document is complete, it is recommended that SJRWMD compare the ASCE crop coefficient values to their existing dataset and update coefficients as appropriate. While locally determined crop coefficients are preferred to support irrigation requirement estimation, in many cases this may not be feasible or efficient. In these cases, the ASCE recommendations can provide a peer-reviewed set of coefficients to estimate irrigation water requirements.

All of the WMDs in Florida are currently supporting the “Satellite-Based Solar Radiation, Net Radiation, and Potential and Reference Evapotranspiration Estimates Over

Florida" project being conducted by J. Jacobs, University of New Hampshire, J. Mecikalski, University of Alabama, and S. Islam, Tufts University and coordinated by D. Sumner, USGS Orlando. Once completed in December 2007, the project will provide gridded estimates of potential evapotranspiration and ET_o at a 2 km grid scale and a daily time scale from 1995 to 2004 for the entire state of Florida. This 2 km grid matches that grid used for the NEXRAD rainfall data. In addition to providing a 10-yr ET dataset, the project also is developing, documenting, and transferring methods for use by USGS and the WMDs. In the future, it is intended that USGS will update the ET databases on an ongoing basis. It is recommended that the USGS reference ET databases be used to update the GWRAPPS/AFSIRS models' climate data. That said, care should be taken prior to updating the climate database. Climate database changes will modify modeled irrigation water requirements. While ET updates will likely occur on an annual basis, climate database updates for the GWRAPPS/AFSIRS models are recommended less frequently. An update every 5 to 10 years is likely to be adequate to capture significant climate trends and cycles. Any climate database changes should be well documented.

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL

APPENDIX 1
WORK PLAN
(TASK 1)

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL
APPENDIX 1 - WORK PLAN

INTRODUCTION

There historically have been significant differences among the water management districts (WMDs) regarding evapotranspiration (ET) estimates for various crops. Differences exist, for example, between citrus ET estimates at coincident locations made by South Florida Water Management District (SFWMD) versus those estimated by the St. Johns River Water Management District (SJRWMD) and Southwest Florida Water Management District (SWFWMD). The agricultural community, consultants, the Tri-District MOU group, the Water Planning Coordination Group, and the SJRWMD Agricultural Advisory Committee noted these differences during the development of the 1998 Water Supply Assessment.

SJRWMD has worked with agricultural agencies and the other WMDs to evaluate various crop and ET models based on the recommendations of these groups. In 2000, the SJRWMD Division of Water Supply Management determined that according to work done under contract SD325AA (Evaluation of Reference Evapotranspiration Methodologies and AFSIRS Crop Water Use Simulation Model"), there was a need to modify the methods used to collect ET data and the way crop water use is calculated using the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model.

The AFSIRS model was developed for the WMDs by the Institute of Food and Agricultural Sciences (IFAS) to provide a method for determining allocations for consumptive use permitting programs. The model estimates irrigation requirements for Florida crops, considering soils, irrigation systems and climate conditions. Two significant advances have affected the viability of the existing AFSIRS model since was revised in 1990: 1) additional research on crop water requirements has been conducted, and 2) computer technology has changed significantly. Opportunities to improve the estimates and projections of ET for water use permitting and planning purposes also have arisen. This work plan provides the implementation guidelines necessary to make those improvements, based on recommendations in the report from contract SD325AA. Recommendations from colleagues within Florida agencies and from members of the agricultural and climate communities also have been incorporated into the plan. These improvements are to be conducted over a 5-year period as summarized in the final schedule

The work plan may be divided into four types of tasks: managerial, software modification, modeling and data enhancement, and experimentation and analysis. The managerial tasks will provide the support necessary to successfully coordinate and assure the completion of the tasks outlined below. Managerial tasks also will support the interactions between the University of Florida (UF), SJRWMD, and other state agencies with a vested interest in consumptive water use permitting and planning. The software modification tasks are designed to eliminate limitations to the operational use of the AFSIRS software and to expand its applicability beyond permitting. The modeling and data enhancement tasks address the modification of outdated model components, as well as the development of enhancements that will significantly increase.

AFSIRS functionality. It is anticipated that these two types of tasks may be addressed in parallel. Continued cooperation, collaboration, and outreach among the WMDs, and ongoing university research facilitated by project investigators are implicit in this work plan. The experimental and analysis tasks are designed primarily to develop crop coefficients over the duration of the project. Climate and water use data also will be used to validate and enhance the methods used for water use estimation.

TASK REVIEW

Task 1. Project Management

1. *Work Plan*
   A comprehensive work plan will be developed. The work plan will identify tasks, prioritize timing, and develop task descriptions and budgets. This work plan will be developed in cooperation with SJRWMD and other agencies and will include discussion and prioritization of the potential enhancements to the consumptive use permitting process and its application to planning initiatives.

2. *AFSIRS Coordination*
   This task will provide for the coordination of project tasks with other university staff and departments. It will involve scheduling, directing and approving project work products; formal recruitment of IFAS staff for support of this project; recruitment of graduate students and post-doctorial candidates; coordination, presentation development, and documentation of meetings; project management; and administration. Communications with the SJRWMD project manager also will occur on a regular basis.

Task 2. Software Modifications

Software modifications will be conducted in three phases, which will be staggered to introduce significant modifications to the AFSIRS software and to allow consumptive use permitting staff to benefit quickly from new system developments. Transition to the new AFSIRS model should occur after the Phase I software development is complete and the climate database has been updated. The planned revised model will enhance user-interface and reporting capabilities significantly, ease database maintenance and facilitate the inclusion of model enhancements. The model also will be able to operate at regional, as well as farm scales. Model documentation, user support features and training requirements will address the current model and new enhancements.

The completed model will consist of three components: data storage, user interface and reporting, and data analysis. The majority of the data necessary for and resulting from the crop water use analysis will be stored in a relational database management system (RDBMS). Existing climate, crop, irrigation system, and soil databases will be ported to the RDBMS. Spatially distributed data will be maintained in an ArcView/ArcInfo geographic information system (GIS). The user interface and reporting features, existing features and new components, will be developed using a Visual Basic interface. The AFSIRS analysis will be conducted using C++ development tools and existing Fortran code and will be ported to a C++ environment. The

C++ environment will be object-oriented in order to simplify future modifications of the AFSIRS model components.

Phase 1

The first phase of redevelopment commenced with a project scope and the development interface, reporting, and storage modules with SJRWMD personnel. UF developed and presented screen and report "mock-ups" for SJRWMD review. The software plan, which includes detailed scoping and timelines for the final product, was developed in conjunction with and approved by SJRWMD.

The software developments aspects of Phase 1 included the Visual Basic interface and preliminary report development, RDBMS development and data porting, and development of GIS tools necessary to demonstrate the application of AFSIRS to regional water use. Reporting capabilities duplicated currently available tools. UF developed a testing and debugging plan that will be administered by SJRWMD permitting personnel. A temporary RDBMS to ASCII conversion utility was developed during Phase 1 to allow for the continued use of the Fortran analysis model with the new RDBMS. Phase 1 development was completed over a 12-month period.

1. *User Interface Enhancement*
   The AFSIRS software interface is an inflexible DOS based tool. The user interface enhancements include online help, ability to modify system inputs, enhanced reporting requirements and a range of return period predictions (e.g., 5-year, 10-year).

2. *Demonstration of GIS Integration*
   The AFSIRS software needs to be coupled with SJRWMD GIS/relational databases. The GIS databases should include soil types, long-term climate data, water table data, irrigation system data, and land-use data. The land-use and water table data should include present scenarios and future plans. Many of these databases already exist at SJRWMD in an acceptable format. The GIS integration should have the flexibility to use existing and planned layers. In Phase 1, a demonstration version of this system will be developed.

3. *Enhance Reporting Capabilities*
   Modifications to the AFSIRS model should allow for flexible reporting that captures present needs and is easily adaptable to future requirements. Current needs include a more completely documented output that clearly indicates user inputs and a consistent presentation of results for any analysis period, averaged on a daily, weekly, monthly, or annual basis. The output must also be understandable to permitting staff.

4. *Software Demonstration, Training, and User Manual*
   New users require training in and instructional support for the AFSIRS software. A user manual will be created that includes one or more examples of the application of the AFSIRS model. At the completion of Phase 1, a software training session will be provided.

Phase 2

The primary goals of Phase 2 are to finalize the GIS portion of the software and to port the Fortran code to an object-oriented development environment. Phase 2 also will integrate the model and data enhancements described in the next section. As the software is extended to address planning needs, additional training, user, and technical documentation will be developed.

1. *Analysis Software Modification and Modular Design*
   A Windows based compiler that has or is compatible with a visual interface will be used. The program currently uses a DOS based interface that was developed using the Fortran computer language and is incompatible with newer MS Windows-based compilers. The current software cannot be modified easily to include technical or user interface ranges, so a revised system should be developed in an object-oriented framework that will allow for easy update or replacement of model components. .

2. *Full GIS Integration*
   The AFSIRS software will be coupled with SJRWMD GIS/Oracle databases. The GIS databases should include soil types, long-term climate data, water table data, irrigation system, crop acreages, and land-use data. The land-use and water table data should include present and future planning scenarios. Many of these databases already exist at SJRWMD in an acceptable format. The GIS integration should have the flexibility to use existing and planning layers. Accessing regional data at scales larger than an individual farm is important for planning purposes. For example, Suwannee River WMD and North West Florida WMD have used AFSIRS to estimate current and future agricultural water requirements by county and region.

3. *Spatial Interpolation of Climate*
   Water requirements for users located away from a National Oceanic & Atmospheric Administration (NOAA) weather station are estimated by parameters established through interpolating results from two or more stations. Florida's coastal regions have significantly different climate regimes from the inland regions. An appropriate and consistent tool for interpolating climate databases to small, specifically defined areas, such as local farms, is essential to implement AFSIRS at a local scale and will be developed as an integrated part of the system.

4. *Software Demonstration and Training*
   A half-day software training session will be provided for the SJRWMD planning personnel. The user documentation will be enhanced to include any additional modifications or example scenarios relevant to planning.

Phase 3

Phase 3 provides for additional software development to meet additional needs that will emerge over the project horizon in response to the planned new software developed and the additional information gathered under Tasks 3 and 4. Preliminary targets for this phase include:

1. *Integration of Crop Coefficients to Provide a Single Tool*
   SJRWMD determines agricultural and turf grass allocations for consumptive use permits using both AFSIRS and *Blaney-Criddle supplemental irrigation requirements: 30-year mean: Technical memorandum,* (SJ87-SP4). A single tool would reduce confusion, increase confidence, and provide a more uniform and defensible approach for permitting. This integration is contingent upon successfully characterizing the AFSIRS parameters for crops permitted using SJ87-SP4.

2. *Linkage of Crop Models*
   Numerous experiments and modeling tools are in development in the southeastern United States to characterize water demands of specific crops and plants. Current initiatives in Florida likely will develop additional information on landscapes and golf courses. This task provides the opportunity to integrate these new developments.

3. *Irrigation Management Tool*
   AFSIRS must be extended so it can be used as a management tool or benchmark. This will allow rainfall and climate data to be input in a shorter time period for comparison with actual irrigation use.

Task 3. Model and Data Enhancements

Climate Data Enhancement

Facilitate Reference ET Network

The spatial distribution of climate databases is quite sparse. The NOAA databases should be combined with other climate resources to create an expanded database. The successful development of these resources requires coordination. The university will facilitate the development of a coordinated system, which should include a description of current and potential data sources, those that can be modified, agencies responsible for the meteorological data, necessary revisions, and recommendations for future expansions.

Update and Expand Historical Climate Databases

The AFSIRS climate databases include approximately 25 years (1951–76) of daily precipitation and potential ET data. The climate databases are for a series of locations that include Mobile, Alabama; and Tallahassee, Jacksonville, Gainesville, Daytona Beach, Orlando, Tampa, West Palm Beach, and Miami. The databases should be updated to include recent daily data (1976 to 2000) from the NOAA weather stations identified above. The precipitation values may be obtained directly from the NOAA weather stations. The daily potential ET values for the climate database are calculated quantities. Based on the *Evaluation Of Reference Evapotranspiration Methodologies And AFSIRS Crop Water Use Simulation Model* report results, the updated reference ET databases should use the FAO Penman-Monteith method. This method requires daily measurements of incoming solar radiation, wind speed, dew point temperature, and maximum and minimum temperature data.

Enhance Spatial Interpolation of AFSIRS Historical Climate Database

The AFSIRS climate database's spatial distribution is quite sparse. Water requirements for users located away from a NOAA weather station are estimated by interpolating results from two or more stations. Florida's coastal regions have significantly different climate regimes from the inland regions. A consistent tool for interpolating climate databases to local farms is essential for implementing AFSIRS at a local scale. The NOAA databases should be complemented by other climate resources to create an expanded climate database. Approaches may include examination and integration of the Florida Automated Weather Network (FAWN) network, and remotely sensed precipitation and ET data. The integration methodology should establish a statistically robust and consistent framework to couple additional climate data with the existing database and develop spatially interpolated climate parameters.

Model Enhancement Priorities

Conduct Sensitivity Analysis of Model Parameters

Model and data-needs modifications should be based on an understanding of the relative importance of model parameters, with respect to irrigation requirements. Conducting a sensitivity analysis is a preliminary step to prioritizing model and data needs. Parameters of interest include crop coefficients, ET methods, soil properties, and crop properties.

Irrigation Component

Irrigation systems play a significant role in the determination of gross irrigation requirement. Significant variability in the systems, efficiencies, and application approaches, however, are not well addressed. The AFSIRS model should be enhanced to better characterize irrigation systems.

A literature review was conducted to determine and document irrigation efficiencies for Florida irrigation systems. A digital library of irrigation system photographs was compiled to provide clear definitions of the systems. Based on this review, irrigation evaluations may be conducted for those systems for which data is either suspect or does not exist.

The current irrigation options are: 1) Irrigate to field capacity, 2) Irrigate to fixed depth, and 3) use deficit irrigation. Landscape and golf courses automatically irrigate to a fixed depth, However, the scheduling of automatic irrigation may not coincide with the AFSIRS irrigation timing. An option for scheduled irrigation would more realistically simulate water needs, as well as provide information on water losses for scheduled systems and improved scheduling.

Model Enhancement Opportunities

Additional priorities likely will arise as a result of the sensitivity study, the experimental work, and the analyses of models and climate. The following is a preliminary list of additional model enhancements that might be conducted. Other items may be added to this category, based on research in the early part of this study and input from SJRWMD.

1. *Water Table Interaction*
   The current AFSIRS model does not include water table effects on crop water requirements. This is a major limitation of the current AFSIRS model. Inclusion of the water table interactions should improve the ability to predict water requirements in regions with near-surface water tables. Possible approaches to addressing this issue include semi-empirical relationships or integration of existing models.

Table 7. *Additional Water Requirements*
Additional water requirements for fertigation, chemigation, and freeze protection need to identified and quantified.

Table 7. *Improved Soil Information*
Water use estimates are highly sensitive to the range of soil parameters based on the Natural Resource Conservation Service (NRCS) soil survey. Improved data are necessary for the most widely observed soils and those with the greatest range of parameters.

Task 4. Experimentation and Analysis

Task 4 seeks to advance through experimentation the knowledge of specific crops' water use and the appropriate characterization of climate variables as necessary to force the long-term simulations of crop water use. Toward this goal, UF will purchase and deploy experimental instrumentation necessary to develop an experimental dataset. This dataset subsequently will be analyzed to characterize crop coefficients and to identify necessary climate corrections. The results will be implemented through Task 2 into the AFSIRS software. The main components necessary to successfully complete this task are outlined below.

1. *Instrumentation and Computer Equipment*
   This task provides for the purchase of equipment necessary to perform current and future modification of the AFSIRS crop model. Instrumentation includes computer equipment and software, two combination eddy flux and meteorology systems, and a reference ET station. Funds also are allocated to support the installation and construction of three lysimeters at the IFAS Plant Science Research and Education Unit (PSREU). This component may be subdivided across multiple years.

2. *Crop Coefficient Instrumentation Establishment and Evaluation*
   This task provides for the development and validation of parallel crop coefficient monitoring systems. The two systems are an eddy-correlation flux system and a weighing lysimeter system. A literature review was conducted and an instrumentation and installation plan was developed for the weighing lysimeter. All instrumentation will be ordered, installed, and constructed as needed. Instrumentation will be set up initially at the IFAS PSREU .

   A pilot study of the instrumentation will be conducted using a grass crop. A post-doctoral researcher is responsible for initial data collection and methodology evaluation. The researcher will manage the eddy correlation equipment, the reference ET weather station and the weighing lysimeters. This person also will set up collection and storage methodology to assure data integrity and prevent accidental data loss. Data collection during this period will be checked for quality and instruments will be calibrated, if necessary. Any problems identified with the methodology will be addressed during this phase.

3. *Crop Coefficient Determination*
Timing and prioritization of crop coefficient determinations were established by SJRWMD and UF**.** The coefficients were prioritized based on a review of the acreage and the available crop coefficient data for priority row crops and grasses. Each crop will be studied for a minimum of two years. The project currently includes two sets of instruments necessary to measure ET: an eddy correlation system (EC1) and a series of three lysimeters. The purchase of a second eddy correlation system (EC2) is planned, using funds from the upcoming fiscal year. These three sets of instrumentation will be available to conduct crop coefficient studies over the next four years (years 2 to 5 of the AFSIRS contract).

   The first crop study will measure grass ET using EC1 and the lysimeters. In addition to obtaining a grass crop coefficient, the relationship between the actual ET, as measured by the lysimeter and by EC1, will be characterized. This will be done as necessary to make corrections to the EC measurements in the other crop coefficient studies. A subcomponent of this grass study may include quantification of irrigation demand under deficit irrigation.

   Crop coefficients will be obtained for potatoes, sod, citrus, and cabbage. An additional crop with a single-year study may be possible. Table 1 summarizes the crops, the study years, the instrumentation, and the study location. Cooperators necessary for the upcoming citrus and sod study locations will be identified jointly by SJRWMD and UF. A final review of previous crop studies in Florida, Georgia, Alabama, South Carolina, and North Carolina will be conducted before commencing experimentation.

Crop	Study Years	Instrumentation	Location
Bahia Grass	2 and 3	EC1 and Lysimeter	PSREU
Potato	4 and 5 (Spring)	Lysimeter	PSREU
Cabbage	4 and 5 (Fall)	Lysimeter	PSREU
Citrus	3 and 4	EC2	TBA
Sod (St. Augustine)	4 and 5	EC1	TBA

Table 1. Crop coefficient study plan

4. *Climate Data Comparison to Reference ET Data*
The validity of the reference ET estimates is a function of both the method and the climate data used in the estimates. The differences between the Penman and Penman-

Monteith methods are quite small, as demonstrated in the report results ("Evaluation of Reference Evapotranspiration Methodologies and AFSIRS Crop Water Use Simulation Model"). There is considerable confidence, therefore, in the ability to provide a reasonable reference ET estimate, given appropriate model inputs. The appropriateness of existing weather stations to provide climate data that meet reference ET standards, however, needs to be established. The reference crop is typically grass or alfalfa under well-watered conditions. The standard reference crop in Florida is grass. The height of the grass reference should be at least 8 cm and no more than 15 cm.

The available climate data are from NOAA weather stations that may or may not be properly maintained as reference ET sites. This task will compare climate data from a site that meets reference ET standards with a nearby weather station. The preliminary site selection is the PSREU. This site maintains a FAWN climate station in a location that does not meet reference ET standards and also has field sites that can be maintained to reference standards. This research supports the analysis and comparison between the FAWN and reference ET data sets.

5. *Eddy Flux and Lysimeter Comparison*
   The experiment's design is in keeping with the best experimental methods applied to crop coefficient research. Critical issues addressed for the successful determination of crop ET using lysimeters, according to the agricultural engineering standards, include fetch, lysimeter design and construction, and operations. An advantage of the experimental facility is the multiple lysimeters that may be used to characterize the variability of results. The eddy flux instrumentation is rapidly emerging as a reasonably priced, portable, and robust method to estimate ET. It is particularly valuable to those crops that may not be measured readily in lysimeters due to long establishment periods or size problems. It is critical that experiments conducted with either the lysimeter measurements or the eddy correlation measurements result in the same crop coefficient values. The bahia grass crop coefficient will be measured simultaneously using both instruments to ensure successful application of the eddy flux systems in citrus and sod. The results will be analyzed and procedures will be developed for the application of the eddy flux instrumentation to the citrus and sod crop coefficient studies.

6. *Water Use Estimation and Analysis*
   Limited comparisons of the AFSIRS-modeled water budget exist. Model validation and correction are critical components to ensure that appropriate water is allocated. This task provides for the development of several datasets of crop water use that may be analyzed in comparison to the AFSIRS model in order to identify and correct model discrepancies and to ensure that the model results are robust. Additional datasets that may be included in an expanded comparison are the Benchmark Farms water use data (citrus, fern, potato, and sod) and data from other ongoing field experiments in Florida and Georgia.

	Year 1		**Year 2**		**Year 3**		**Year 4**		**Year 5**	
Task	1-6	7-12	1-6	7-12	1-6	7-12	1-6	7-12	1-6	7-12
Managerial										
Work Plan	X	X								
Coordination	X	X	X							
Software Modifications										
Phase I	X	X								
Phase II				X	X					
Phase III						X	X	X		
Model/Data Enhancements										
Reference ET Network	X	X								
Update Climate DB		X	X							
Climate Spatial Interpolation		X	X	X	X					
Sensitivity Analysis			X							
Irrigation		X			X	X	X			
Additional Enhancements							X	X	X	X
Experimentation and Analysis										
Instrumentation and Computer I	X	X	X							
Instrumentation and Computer II				X						
Instrumentation Estab. And Eval.		X	X	X						
Develop Bahia Grass Coefficient			X	X	X	X	X			
Develop Potato Coefficient							X		X	X
Develop Cabbage Coefficient								X		X
Develop Citrus Coefficient					X	X	X	X	X	
Develop Sod Coefficient							X	X	X	X
Reference ET Comparison			X	X						
Eddy Flux vs. Lysimeter Comparison				X	X					
Water Use Estimation Comparison							X	X	X	X

Table 2. Proposed tasks and timeframes

REVISION OF AFSIRS CROP WATER SIMULATION MODEL

APPENDIX 2
REFERENCE ET NETWORK FOR THE STATE OF FLORIDA
(TASK 4)

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL
APPENDIX 2 - REFERENCE ET NETWORK FOR THE STATE OF FLORIDA

Climate data have the capacity to save businesses and taxpayers millions of dollars annually, reduce energy consumption, educate the next generation of citizens, make an incalculable contribution to research projects every year, and even save lives. Weather forecasting, agriculture, education, emergency management, scientific research, and the energy and transportation industries are only a handful of the entities that are enhanced through the effective and timely availability of meteorological data.

Long-term, consistent, daily climate data are required for consumptive water-use planning and permitting. Climate data provide the basis for understanding the spatio-temporal dynamics of water input and output in the form of precipitation and evapotranspiration (ET). Estimates of reference ET require temperature, relative humidity, wind speed and solar radiation. Accurate estimates of precipitation require dense networks.

A review of existing data sources was conducted toward the goal of developing a climate database for current and future applications that require reference ET. This report documents the findings of this review and includes a detailed description of the existing data sources, a summary of strengths and weaknesses of these sources, and an outline for enhancing the existing data network.

Climate Data Sources for the State of Florida
The data sources considered for preparing a comprehensive climate dataset for the state of Florida are the following (in alphabetical order):

1. *Florida Automated Weather Network (FAWN)*
2. *Georgia Automated Environmental Monitoring Network (GAEMN)*
3. *Kennedy Space Center (KSC)*
4. *National Weather Service (NWS)*
5. *South Florida Water Management District (SFWMD)*
6. *Southwest Florida Water Management District (SWFWMD)*
7. *St. Johns River Water Management District (SJRWMD)*
8. *The Nature Conservancy (TNC)*
9. *United States Geological Survey (USGS)*

The climate data that is available from the above sources ultimately would be utilized to prepare a spatially well-distributed long-term climate database of ET and rainfall (P) for the GIS-based Water Resources and Agricultural Permitting and Planning System (GWRAPPS). As direct measurement of ET is not common, climate information necessary to estimate ET from empirical methods will be collected. This information will include daily minimum and maximum temperatures, wind speed, relative humidity, and solar radiation.

1. FAWN
The Institute of Food and Agricultural Services (IFAS) established FAWN in 1997. These stations measure all the climate variables necessary for estimating ET. There currently are 21 stations all over Florida. FAWN stations do not provide long-term climate data, but are potential sources for climate data for recent years (the past one to four years), and the years to come. Data are available free of charge. Additional stations will be added to expand the FAWN network to 32 stations.

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	Belle Glade	FAWN	1997		26.6680	-80.6320
2	Putnam Hall	FAWN	2001		29.6961	-81.9832
3	Citra	FAWN	2000		29.4097	-82.1704
4	Alachua	FAWN	1999		29.8027	-82.4108
5	Hastings	FAWN	1999		29.6932	-81.4448
6	Oklawaha	FAWN	1998		29.0202	-81.9690
7	Pierson	FAWN	1998		29.2226	-81.4490
8	Tavares	FAWN	1997		28.7893	-81.7479
9	Umatilla	FAWN	1997		28.9194	-81.6310
10	Okahumpka	FAWN	1997		28.6822	-81.8861
11	Avalon	FAWN	1997		28.4731	-81.6486
12	Brooksville	FAWN	2000		28.6347	-82.2848
13	Apopka	FAWN	1997		28.6422	-81.5493
14	Lake Alfred	FAWN	1997		28.1019	-81.7114
15	Dover	FAWN	1998		28.0170	-82.2340
16	Bradenton	FAWN	1998		27.4501	-82.4818
17	Ona	FAWN	1998		27.3975	-81.9400
18	Fort Lauderdale	FAWN	2001		26.0867	-80.2417
19	Fort Pierce	FAWN	1998		27.4261	-80.4020
20	Homestead	FAWN	1997		25.5092	-80.4987
21	Immokalee	FAWN	1997		26.4623	-81.4403

Table 1. FAWN stations

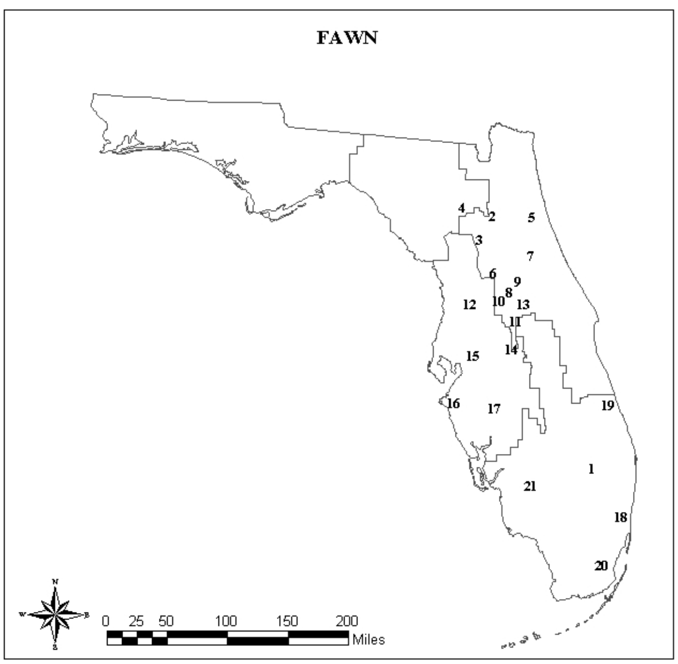

Figure 1. FAWN stations
Additional information: http://fawn.ifas.ufl.edu

2. GAEMN

The University of Georgia College of Agriculture and Environmental Sciences established the GAEMN in 1991. Each station monitors air temperature, relative humidity, rainfall, solar radiation, wind speed, wind direction, and soil temperature at 2-, 4-, and 8-inch depths. The GAEMN currently monitors 50 stations. Eleven stations in southern Georgia, however, can provide better spatial distribution of climate data in the northern Florida region. Data is not available free of charge.

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	Alma	GAEMN	1993		31.5600	-82.5100
2	Arlington	GAEMN	1997		31.3530	-84.6310
3	Attapulgus	GAEMN	1992		30.7612	-84.4853
4	Brunswick	GAEMN	1999		31.1832	-81.4829
5	Cairo	GAEMN	1997		30.8519	-84.2353
6	Camilla	GAEMN	1997		31.2802	-84.1944
7	Dixie	GAEMN	1998		30.7946	-83.6674
8	Nahunta	GAEMN	2002		31.1798	-82.0085
9	Newton	GAEMN	1999		31.2239	-84.4779
10	Tifton	GAEMN	1991		31.4833	-83.5333
11	Valdosta	GAEMN	1997		30.8243	-83.3153

Table 2. GAEMN stations

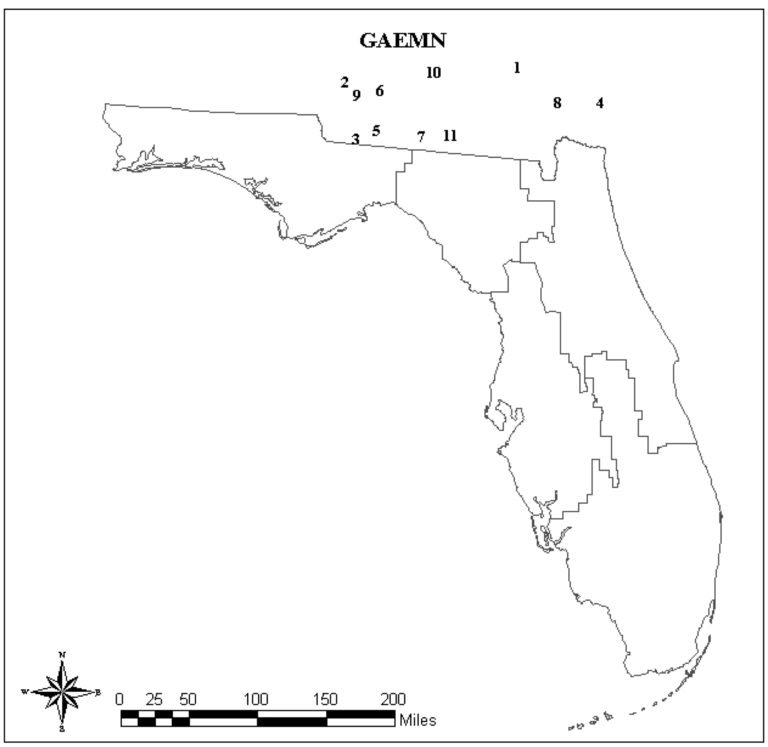

Figure 2. GAEMN stations

Additional information: http://www.griffin.peachnet.edu/bae/

3. KSC

KSC maintains two eddy flux towers at the space center. All the data necessary for estimating ET are measured at each site standard. These stations also are relatively new.

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	KSFC 1	NASA			28.6085	-80.6715
2	KSFC 2	NASA			28.4583	-80.6709

Table 3. KSC stations

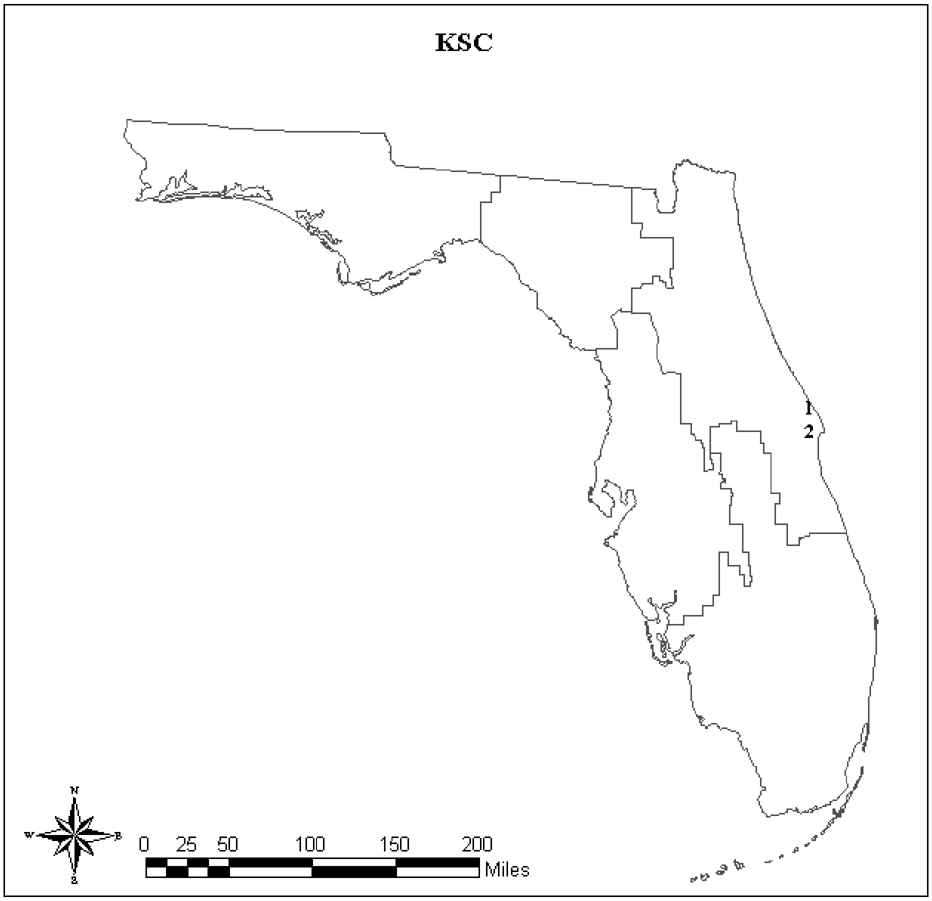

Figure 3. KSC stations

Additional information: http://public.ornl.gov/ameriflux/Participants/Sites/index.cfm

4. NWS
The National Climatic Data Center (NCDC) of the NWS has 257 stations in the state of Florida. Not all stations are in operation currently. Emphasis was given to stations that had continuous data for at least 30 years (1960-1990). Eighty-six stations matched this criterion. Temperature and precipitation data are available at these stations. This is the primary source for long-term temperature and rainfall data.

Information about solar radiation or wind speed can be obtained from 12 stations in the state. The solar radiation and wind speed data, however, is available only through 1989. Solar radiation measurements have not been conducted from 1990 to present at any NCDC-maintained stations. The following stations are not included in the previous list:

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	Arcadia	NWS	1931		27.2333	-81.8500
2	Avon Park 2 W	NWS	1931		27.6000	-81.5333
3	Babson Park 1 ENE	NWS	1955	1992	27.8500	-81.5167
4	Bartow	NWS	1931		27.9000	-81.8500
5	Belle Glade Exp Stn	NWS	1924		26.6500	-80.6333
6	Brooksville Chin Hill	NWS	1931		28.6167	-82.3667
7	Bushnell 2 E	NWS	1944		28.6667	-82.0833
8	Canal Point USDA	NWS	1953		26.8667	-80.6167
9	Chipley 3 E	NWS	1948		30.7833	-85.4833
10	Clermont 7 S	NWS	1948		28.4500	-81.7500
11	Clewiston US Engineers	NWS	1948		26.7500	-80.9167
12	Crescent City	NWS	1931		29.4333	-81.5000
13	Cross City 2 WNW	NWS	1948		29.6500	-83.1667
14	Daytona Beach	NWS	1948		29.2167	-81.0333
15	De Funiak Springs	NWS	1931		30.7333	-86.0667
16	Deland 1 SSE	NWS	1931		29.0167	-81.3000
17	Desoto City 8 SW	NWS	1955		27.3667	-81.5167
18	Devils Garden	NWS	1956		26.6000	-81.1333
19	Everglades	NWS	1931		25.8500	-81.3833
20	Federal Point	NWS	1931		29.7500	-81.5333
21	Fernandina Beach	NWS	1948		30.6667	-81.4667
22	Fort Drum 5 NW	NWS	1948		27.5833	-80.8333
23	Fort Green 12 WSW	NWS	1955		27.5667	-82.1333
24	Fort Lauderdale	NWS	1948		26.1000	-80.2000
25	Fort Lauderdale Beach	NWS	1952		26.1333	-80.1000
26	Fort Pierce	NWS	1931		27.4667	-80.3500
27	Glen St Mary 1 W	NWS	1931		30.2667	-82.1833
28	Hialeah	NWS	1948		25.8333	-80.2833
29	High Springs	NWS	1948		29.8333	-82.6000
30	Hillsborough Rvr St Pk	NWS	1948		28.1500	-82.2333
31	Inverness 3 SE	NWS	1948		28.8000	-82.3167

ID	Station	Source	Start Year	End Year	Latitude	Longitude
32	Jacksonville Beach	NWS	1948		30.2833	-81.4000
33	Jasper	NWS	1952		30.5167	-82.9500
34	Kissimmee 2	NWS	1948		28.2833	-81.4167
35	La Belle	NWS	1948	2001	26.7500	-81.4333
36	Lake Alfred Exp STN	NWS	1905	2000	28.1000	-81.7167
37	Lake City 2 E	NWS	1931		30.1833	-82.6000
38	Lisbon	NWS	1958		28.8667	-81.7833
39	Live Oak	NWS	1952		30.2333	-82.9667
40	Madison	NWS	1931		30.4500	-83.4167
41	Mayo	NWS	1949		30.0500	-83.1667
42	Milton Exp STN	NWS	1948		30.7833	-87.1333
43	Monticello 3 W	NWS	1948		30.5333	-83.9167
44	Moore Haven Lock 1	NWS	1930		26.8333	-81.0833
45	Mountain Lake	NWS	1948		27.9333	-81.6000
46	Myakka River State Park	NWS	1948		27.2333	-82.3167
47	Naples	NWS	1948		26.1667	-81.7833
48	Niceville	NWS	1948		30.5333	-86.5000
49	Ocala	NWS	1948		29.2000	-82.0833
50	Okeechobee	NWS	1948		27.2000	-80.7667
51	Ortona Lock 2	NWS	1948		26.7833	-81.3000
52	Palatka	NWS	1948		29.6500	-81.6667
53	Panacea 3 S	NWS	1948		29.9833	-84.3833
54	Parrish	NWS	1948		27.6167	-82.3500
55	Perrine 4 W	NWS	1958		25.5833	-80.4333
56	Perry	NWS	1948		30.1000	-83.5667
57	Plant City	NWS	1931		28.0167	-82.1333
58	Pompano Beach	NWS	1948	2001	26.2333	-80.1500
59	Royal Palm Ranger STN	NWS	1949		25.3833	-80.6000
60	Saint Leo	NWS	1931		28.3333	-82.2667
61	Sanford Experiment STN	NWS	1956		28.8000	-81.2333
62	St Petersburg	NWS	1948	1998	27.7667	-82.6333
63	Steinhatchee 6 ENE	NWS	1958	2001	29.7167	-83.3000
64	Stuart 1 S	NWS	1948		27.1667	-80.2333
65	Tamiami Trail 40 mi Bend	NWS	1948		25.7667	-80.8167
66	Tarpon Springs SWG PLNT	NWS	1948		28.1500	-82.7500
67	Tavernier	NWS	1948		25.0000	-80.5167
68	Titusville	NWS	1939		28.6167	-80.8333
69	Titusville	NWS	1939		28.6167	-80.8167
70	Usher Tower	NWS	1956		29.4167	-82.8167
71	Venice	NWS	1948		27.1000	-82.4333
72	Wauchula	NWS	1948		27.5500	-81.8000
73	Wewahitchka	NWS	1956		30.1167	-85.2000
74	Winter Haven	NWS	1948		28.0167	-81.7333

Table 4. NWS stations without solar radiation or wind speed

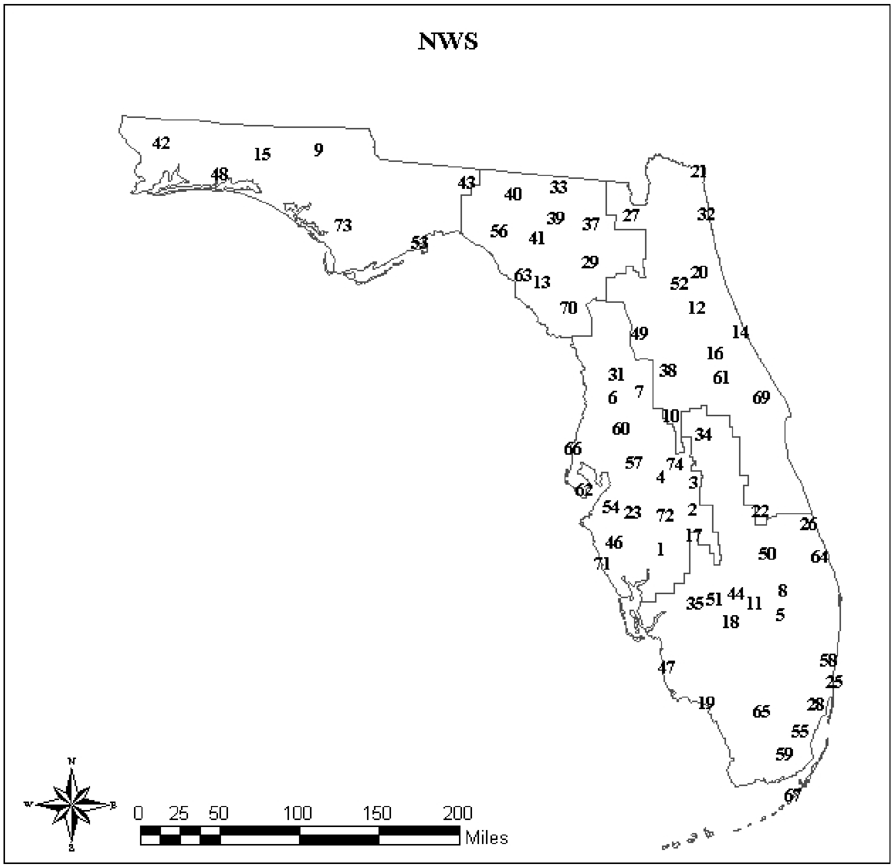

Figure 4. NWS stations

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	Mayport NS	NWS	1959		30.4000	-81.4167
2	Orlando Intl. Airport	NWS	1952		28.4333	-81.3333
3	Gainesville Regional Airport	NWS	1960		29.7000	-82.2833
4	Fort Myers Page Field	NWS	1931		26.5833	-81.8667
5	Key West Intl Airport	NWS	1948		24.5500	-81.7500
6	Melbourne Regional Airport	NWS	1948		28.1167	-80.6500
7	Vero Beach Municipal Airport	NWS	1948		27.6500	-80.4167
8	West Palm Beach Intl. Airport	NWS	1948		26.6833	-80.1000
9	Miami Beach	NWS	1948		25.7833	-80.1333
10	Crestview Bob Sikes Airport	NWS	1948		30.7833	-86.5167
11	Jacksonville Intl Airport	NWS	1948		30.5000	-81.7000
12	Pensacola Regional Airport	NWS	1948		30.4833	-87.1833

Table 5. NWS stations that monitor solar radiation and wind speed

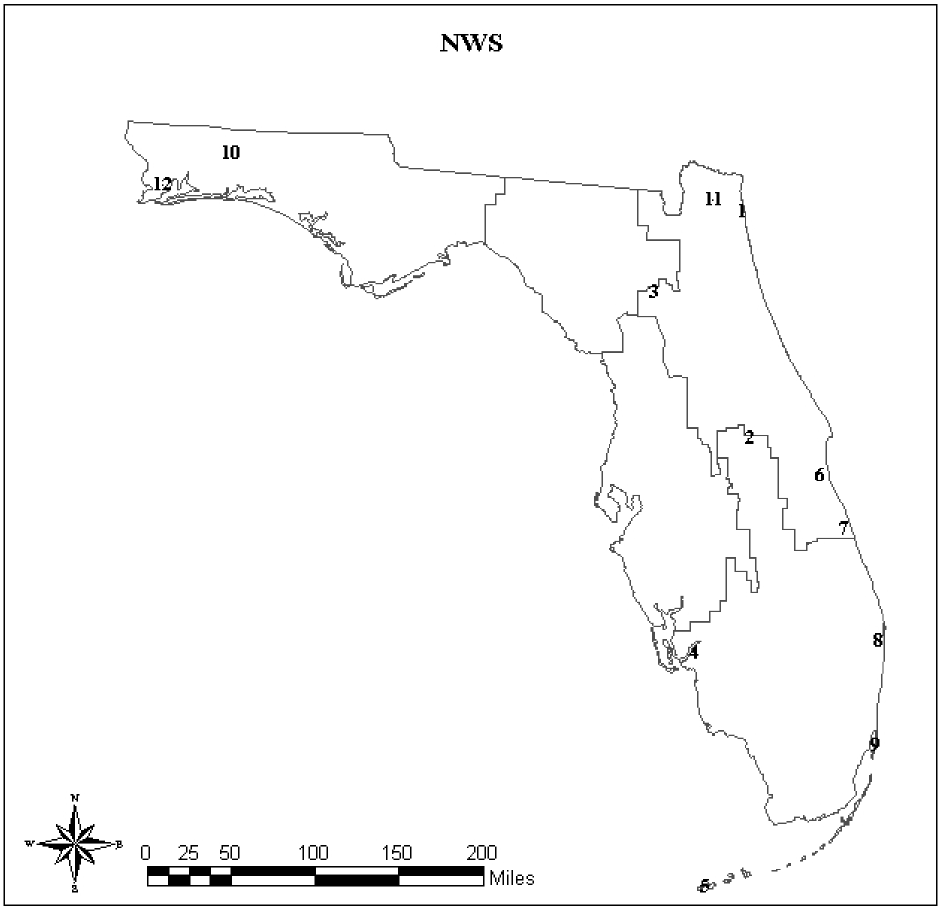

Figure 5. NWS stations that monitor solar radiation and wind speed

Additional information: http://www.ncdc.noaa.gov

5. SFWMD

The SFWMD has numerous stations monitoring meteorological data. All data are available online for download. Information about all the variables measured at one station, however, is not easily available. The following list includes the stations that collect solar radiation. Additional effort is in progress to collect station information with the variables measured.

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	12512	SFWMD	1988		26.9567	-80.9724
2	12522	SFWMD	1989		26.8218	-80.7834
3	13080	SFWMD	1990		26.9017	-80.7893
4	15084	SFWMD	1991		25.2246	-80.5401
5	15469	SFWMD	1992		27.4014	-81.1148
6	15479	SFWMD	1992		28.1400	-81.3515
7	15490	SFWMD	1992		26.7898	-81.3028
8	15501	SFWMD	1992		26.1720	-80.8273
9	15512	SFWMD	1992		26.7351	-80.8953

10	15880	SFWMD	1994		26.6226	-80.4389
11	16024	SFWMD	1994		27.1396	-80.7890
12	16256	SFWMD	1994		25.6109	-80.5098
13	DO527	SFWMD	1996		26.6570	-80.6298
14	DU554	SFWMD	1993		26.4990	-80.2223
15	FF840	SFWMD	1997		28.0483	-81.3995
16	FI267	SFWMD	1997		27.2903	-80.2537
17	GO853	SFWMD	1997		27.0287	-80.1653
18	GE348	SFWMD	1997		26.3320	-80.8800
19	GG624	SFWMD	1998		26.3359	-80.5367
20	MX243	SFWMD	2000		26.2970	-81.4384
21	LJ292	SFWMD	2000		27.3143	-81.0222

Table 6. SFWMD stations

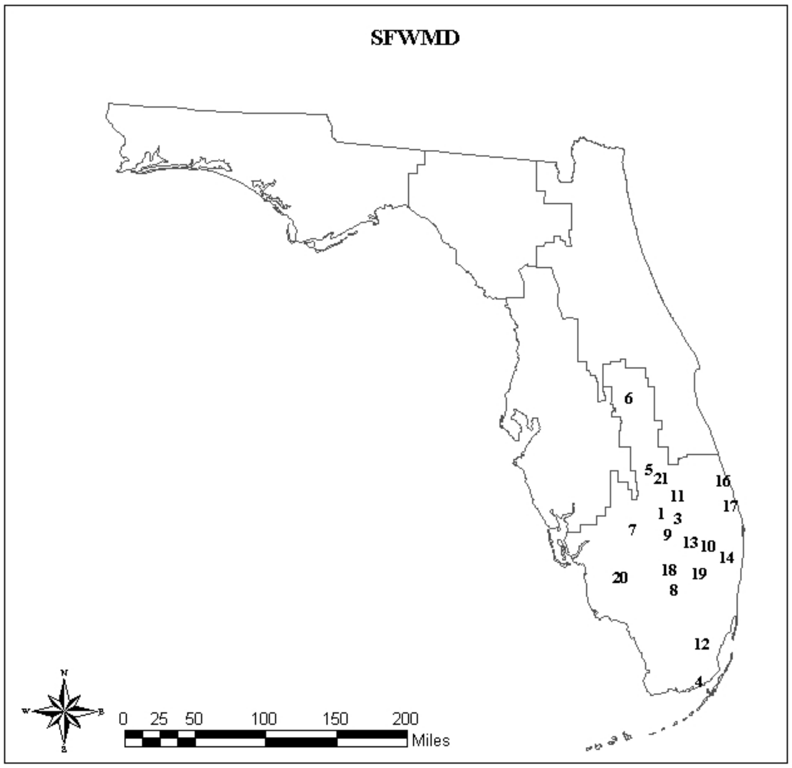

Figure 6. SFWMD stations

Additional information: http://www.sfwmd.gov/org/ema/dbhydro/

6. SWFWMD

The SWFWMD maintains 10 stations that collect all the data required for estimating ET. These stations were established in 1998. Additional stations that measure rainfall are being investigated.

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	Peace River Wt Plant	SWFWMD	1998		27.0889	-82.0045
2	Dover ET	SWFWMD	1998		28.0150	-82.2323
3	Floral City	SWFWMD	1998		28.7578	-82.2756
4	Lake Como	SWFWMD	1998		28.1822	-82.4698
5	Inglis	SWFWMD	1998		29.0253	-82.6153
6	Brooksville HQ	SWFWMD	1998		28.4719	-82.4440
7	Bowling Green	SWFWMD	1998		27.6386	-81.8359
8	Wildwood	SWFWMD	1998		28.8630	-82.0337
9	Avon Park ROMP	SWFWMD	1998		27.6045	-81.4801
10	Bushnell ET	SWFWMD	1998		28.6903	-82.1043

Table 7. SWFWMD stations

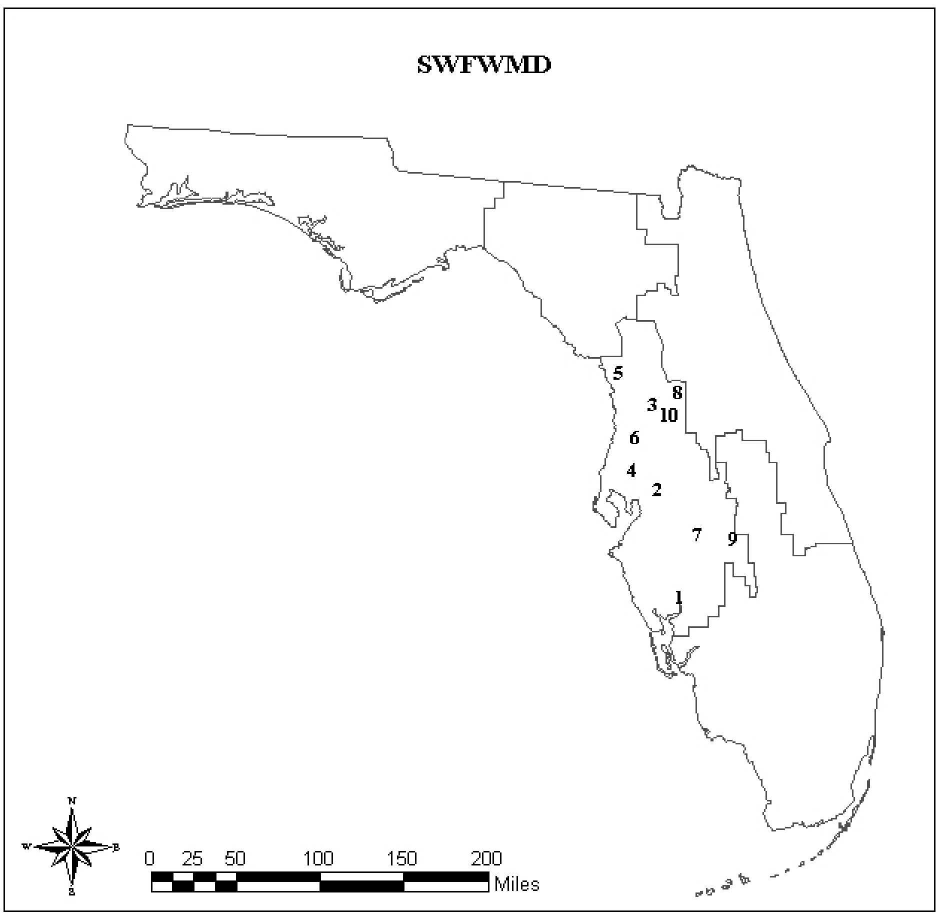

Figure 7. SWFWMD stations

7. SJRWMD

The SJRWMD has about 80 stations well distributed throughout the District. Almost all of these stations are rainfall-measuring stations. Only a few stations (fewer than five) measure temperature and/or relative humidity and/or pan ET.

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	Alachua FG	SJRWMD	1998		29.6847	-82.2869
2	Astronaut High Sch	SJRWMD	2002		28.6258	-80.8497
3	Black Ck	SJRWMD	1996		29.9680	-81.7972
4	Black Ck Maxville	SJRWMD	1996		30.2060	-81.9907
5	Black Ck Middleburg	SJRWMD	1996		30.0602	-81.8489
6	Blue Cypress Marsh	SJRWMD			27.6953	-80.7114
7	Bostwick Rain	SJRWMD	1990		29.7356	-81.6443
8	Bryceville Fire Dept	SJRWMD	2002		30.3969	-81.9364
9	Buckman Lock	SJRWMD	2002		29.5458	-81.7292
10	Bull Ck 1 Crabgrass	SJRWMD	1994		28.1158	-81.0070
11	C-58	SJRWMD	1978		27.9701	-80.8967
12	Callahan Rain	SJRWMD	1998		30.5744	-81.8273
13	Charlotte St	SJRWMD	1994		28.6824	-81.3554
14	Chesser Well	SJRWMD	2002		29.6322	-81.9886
15	Codys Corner	SJRWMD	1991		29.3440	-81.3100
16	DHQ	SJRWMD	1991		29.6642	-81.6943
17	Duda Farm Bahaya	SJRWMD			28.2739	-80.8092
18	Eddy FT	SJRWMD	1993		30.5432	-82.3437
19	Egans Ck	SJRWMD	1998		30.6863	-81.4473
20	Elkton	SJRWMD	1993		29.7752	-81.4431
21	Eureka L&D	SJRWMD	1998		29.3776	-81.8929
22	Forest Rd 88	SJRWMD	1991		29.1850	-81.7730
23	Gold Head SP	SJRWMD	1991		29.8200	-81.9567
24	Groveland FT	SJRWMD	1989		28.6894	-81.8959
25	Hell Cat Bay	SJRWMD	1994		29.5971	-81.5271
26	I FAS	SJRWMD	1996		28.6547	-81.5544
27	Jax Beach WP	SJRWMD	1998		30.2672	-81.3959
28	Kiwanis Park	SJRWMD	1996		28.3605	-80.6765
29	Lk Apopka Cntr	SJRWMD	1990		30.7913	-81.9664
30	Lk Apopka Dedc Twr	SJRWMD	1997		28.6620	-81.6844
31	Lk Ashby	SJRWMD	1986		28.9334	-81.1036
32	Lk Harris Bayou	SJRWMD	1996		28.8256	-81.8245
33	Lk Joanna	SJRWMD	1989		28.8345	-81.6460
34	Lk Louisa SP	SJRWMD	1998		28.4285	-81.7166
35	Lk Lowery	SJRWMD	1996		28.1154	-81.6712
36	Lk Norris	SJRWMD	1992		28.9485	-81.5438
37	Losco Rd	SJRWMD	1996		30.1723	-81.5801
38	MacClenny Rn	SJRWMD	1998		30.3209	-82.1707
39	Marvin Jones Rd	SJRWMD	1994		29.4135	-81.6183
40	Melbourne Wickham Rd	SJRWMD	1988		28.1461	-80.6708
41	Mickler Landing	SJRWMD	1997		30.1619	-81.3577
42	Mill Ck	SJRWMD	1991		29.9541	-81.4924

ID	Station	Source	Start Year	End Year	Latitude	Longitude
43	Mosquito Ctrl Dist	SJRWMD	1997		29.5481	-81.2079
44	National Weather Srv	SJRWMD	2002		30.4836	-81.7019
45	Normandy Village	SJRWMD	1996		30.2923	-81.7723
46	Oak Hill	SJRWMD	1996		28.7775	-80.8856
47	Orange Lake WS	SJRWMD	1997		29.4776	-82.1266
48	Orange Lk Boardman	SJRWMD	1996		29.4620	-82.1918
49	Ormond Beach Rain	SJRWMD	1998		29.2894	-81.0731
50	Osceola Landfill	SJRWMD	1992		28.7873	-81.0876
51	Palm Bay Public Wrks	SJRWMD	1979		27.9981	-80.7008
52	Palm Bay STP	SJRWMD	1994		28.0261	-80.5975
53	Palmetto Branch	SJRWMD	1990		29.7163	-81.8203
54	Pierson Ap	SJRWMD	1993		29.2470	-81.4635
55	Pine Island Rn	SJRWMD	2000		28.4939	-80.7214
56	Pine Oaks	SJRWMD	1998	1998	29.2230	-82.1634
57	Playalinda	SJRWMD	1996		28.9068	-80.8208
58	Pritchard Rd	SJRWMD	1996		30.3719	-81.7765
59	Putnam Hall	SJRWMD			29.6958	-81.9831
60	S of Blue Sprgs Repl	SJRWMD	2002		28.9203	-81.3411
61	S-157	SJRWMD	1971		27.8306	-80.5397
62	S-164	SJRWMD	1976		28.3406	-80.9338
63	S-251	SJRWMD			27.6956	-80.6436
64	S-96	SJRWMD	1981		27.8167	-80.7033
65	Sam Tilton Farm	SJRWMD	1995		29.4860	-81.3497
66	Silver Pond Wells	SJRWMD	1991		29.3786	-81.5260
67	SJR US Winder	SJRWMD	1997		28.2360	-80.8600
68	Smith Lk Bellview	SJRWMD	1988		29.0555	-81.9923
69	SR40 and 11	SJRWMD	2000		29.2250	-81.3205
70	SR46 at SR46A	SJRWMD	1994		28.8129	-81.4617
71	St. Augustine Shores	SJRWMD	1997		29.7996	-81.3136
72	St. Johns WCD	SJRWMD	1988		27.6401	-80.6769
73	St. Marys WMA	SJRWMD	1998		30.7832	-81.9530
74	Stokeslanding St. Aug.	SJRWMD	1995		30.0065	-81.3596
75	Storey Ranch	SJRWMD	1989		28.5572	-81.1330
76	Sunny Hill Weather	SJRWMD	1996		29.0052	-81.8327
77	Tiger Bay Rn	SJRWMD	1999		29.1423	-81.1265
78	Vero Beach Ap	SJRWMD	1996		27.6554	-80.4043
79	Winnemissett Lk	SJRWMD	2002		29.0275	-81.2558
80	Yeehaw Junction	SJRWMD	1995		27.6967	-80.8958

Table 8. SJRWMD stations

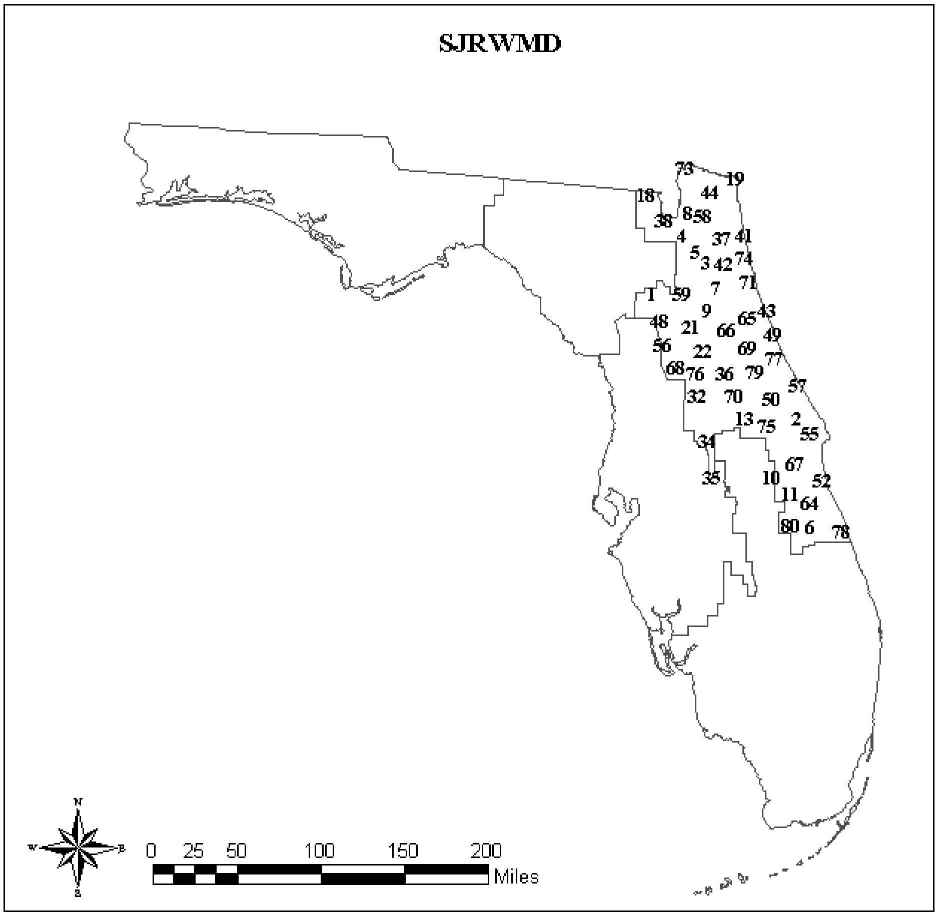

Figure 8. SJRWMD stations

8. TNC

The TNC maintains five stations that collect necessary climate data for estimating ET. These stations have been in operation since 1994. The TNC has six stations in central Florida. The stations are too close together to be discernable when looking at a WMD scale, and therefore can be treated as a single location. They collected ET and wind speed until October 2001, and rainfall and temperature data currently are being measured.

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	Main (original location)	TNC	1994	1999	28.1093	-81.4332
2	Main (current location)	TNC	1999		28.1280	-81.4229
3	Far North	TNC	1994		28.1389	-81.4436
4	North	TNC	1994		28.1137	-81.4121
5	Central	TNC	1994		28.0718	-81.4132
6	South	TNC	1994		28.0366	-81.3865

Table 9. TNC stations

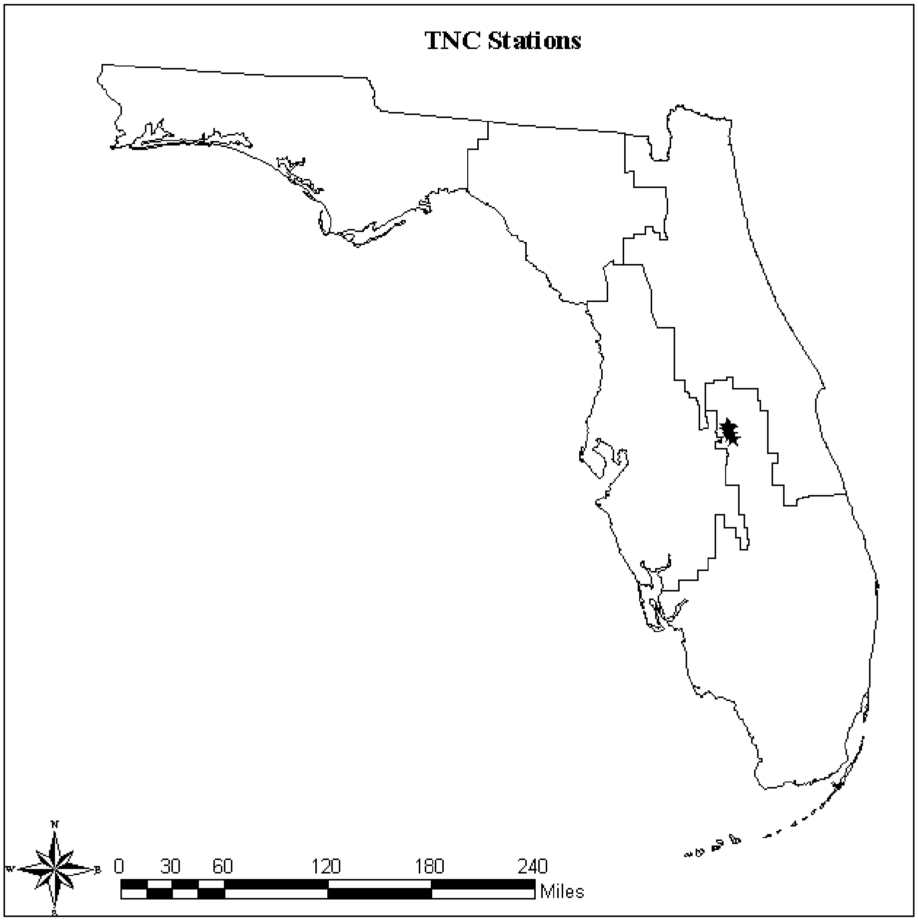

Figure 9. TNC stations

9. USGS

The USGS maintains nine stations that collect climate information necessary to estimate ET in the Everglades region. The monitoring began in 1996.

ID	Station	Source	Start Year	End Year	Latitude	Longitude
1	1	USGS	1996		26.6528	-80.4089
2	2	USGS	1996		26.6278	-80.4367
3	3	USGS	1996		26.5222	-80.3369
4	4	USGS	1996		26.3167	-80.3853
5	5	USGS	1996		26.2614	-80.7322
6	6	USGS	1996		25.7472	-80.5019
7	7	USGS	1996		25.7472	-80.7031
8	8	USGS	1996		25.3533	-80.6353
9	9	USGS	1996		25.3597	-80.7667

Table 10. USGS stations

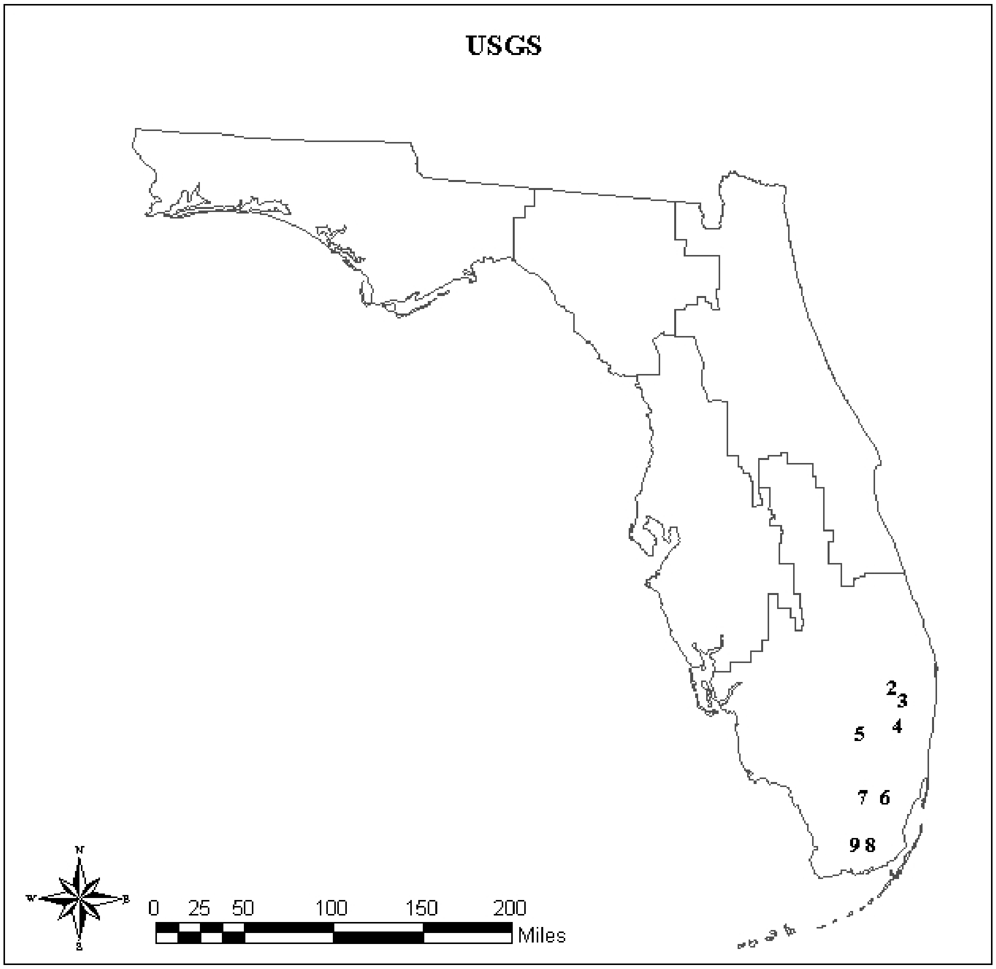

Figure 10. USGS stations

Additional information: http://sofia.usgs.gov/projects/evapotrans/

SUMMARY OF STATIONS

Florida climate data are measured and recorded primarily by six agencies, including the IFAS, the WMDs, the NWS, and the USGS. Additional data are available from other sources that have limited stations within the state. The most established network is that of the NWS. This network consists of numerous stations, many with historical records dating from the 1930s and 1940s to the present. This network is an excellent resource for historical precipitation and temperature data. In addition, the network has 12 stations with historical wind speed and solar radiation data. Solar radiation data, however, has not been recorded by the NWS since 1990. The other climate stations are much newer. Most of these stations have less than 10 years of historical data. The FAWN stations provide good coverage throughout the state, as well as a complete set of instrumentation. The stations, however, have 5 years of data at most. Both SFWMD and SWFWMD have recently established a network of stations that monitor all data necessary for ET and precipitation data within their districts.

The SJRWMD has an extensive monitoring network. This network, however, predominantly collects rainfall data. The SJRWMD does not support any climate stations that have the data necessary to estimate reference ET. Within the SJRWMD boundary, there is very good daily precipitation data. There are only approximately nine FAWN stations, however, that are gathering the datasets necessary to estimate ET. The location of the FAWN stations does not provide coverage of the coastal regions or the southern portion of the district. The extended NWS stations are located primarily at the boundary of the SJRWMD and lack the instrumentation necessary to estimate ET.

Figure 11 shows the primary stations that might be used for developing a reference ET network within the SJRWMD and the regions of the WMD that have existing consumptive use permits. The NCDC stations have long-term climate data, but they provide only temperature and precipitation data. The FAWN network provides all necessary data but is limited to recent years and primarily supports inland locations. The central portion of the SJRWMD appears to be well monitored, but the northern and southeastern portions have significant gaps in coverage. The southeastern portions are of particular concern given the density of permits.

In summary, the Florida network of meteorological data is maturing. In the 1990s, several agencies recognized the need for robust climate data and implemented continuous monitoring stations. The FAWN network is an excellent statewide resource that provides near real-time and historical data at no charge to all sectors. The SFWMD and SWFWMD have developed a denser network of climate stations within their districts. The value of the current network increases with increasing longevity. Sustained support of these stations is critical for the development of future historical databases. In addition, collaboration in locating and assembling datasets is highly recommended. Finally, the significant coverage gaps within the SJRWMD boundaries need to be addressed prior to providing high-quality estimates of ET for application to hydrologic studies, water-use permitting, and planning.

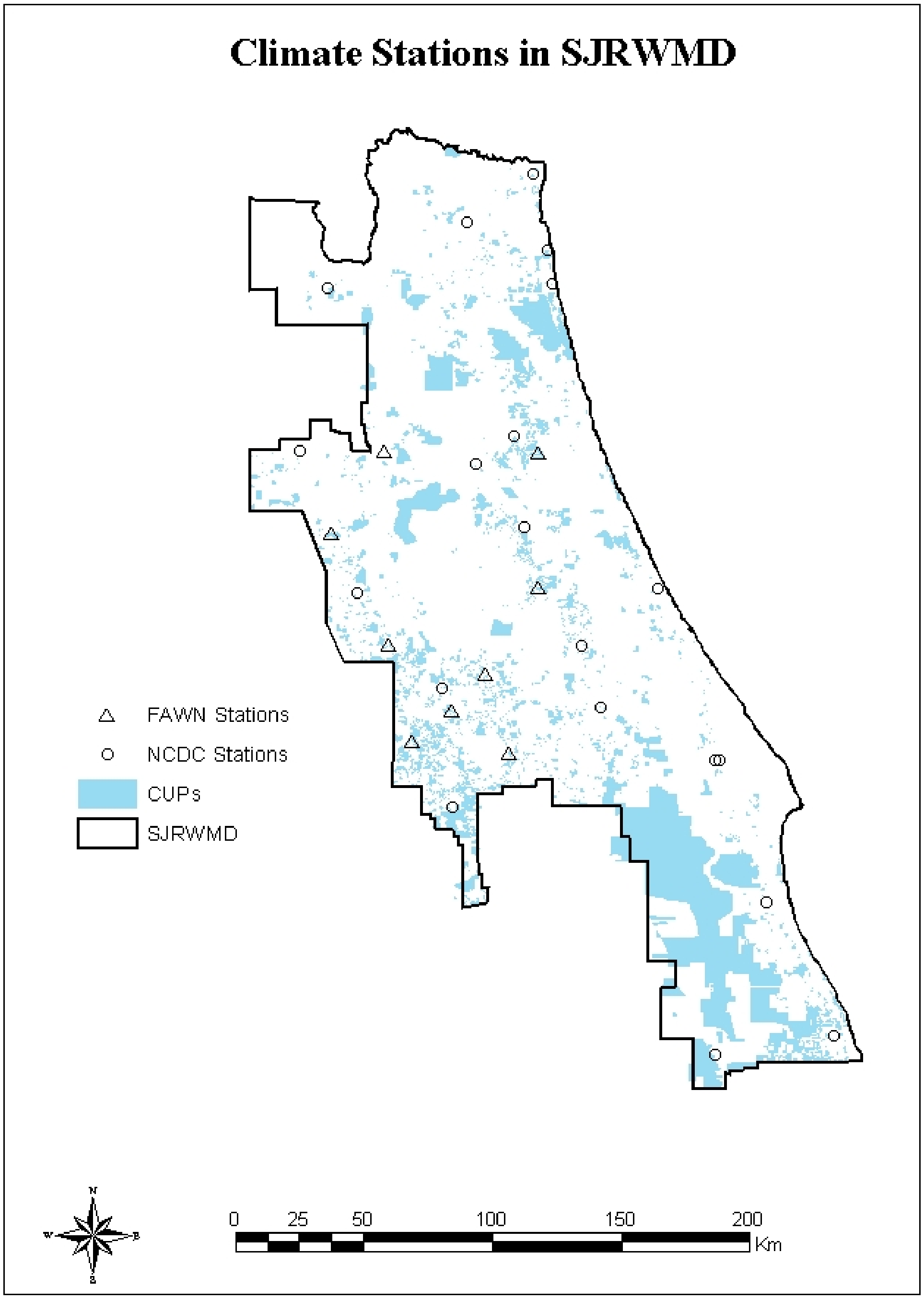

Figure 11. NCDC stations with 30 years of data, FAWN stations, and existing consumptive use permits (CUPs) within the SJRWMD

APPENDIX

NETWORK CONTACT INFORMATION

Florida Automated Weather Network
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Smithsonian CO2 Site
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National Weather Service
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South Florida Water Management District
Web site: http://www.sfwmd.gov/org/ema/dbhydro/index.html

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REVISION OF AFSIRS CROP WATER SIMULATION MODEL

APPENDIX 3
CLIMATE DATA AND REFERENCE EVAPOTRANSPIRATION COMPARISONS BETWEEN THE REFERENCE EVAPOTRANSPIRATION SITE AND THE FLORIDA AUTOMATED WEATHER NETWORK SITE AT THE PLANT SCIENCE RESEARCH AND EDUCATION UNIT IN CITRA, FLORIDA
(TASK 8)

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University of Florida
Gainesville, Florida

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Palatka, Florida

2003

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FIGURES

TABLE

COMPARISONS BETWEEN THE REF-ET SITE AND THE FAWN SITE AT THE PSREU IN CITRA, FLORIDA

INTRODUCTION

Reference evapotranspiration (ET) is defined as "the rate of ET from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m-1 and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water" (Allen et al., 1998). The necessary input parameters for the reference ET estimations should be collected from the "reference site" weather station that has sufficient and valid weather measurements (solar radiation, air temperature, humidity, wind speed) to apply one of the combination-based equations to estimate reference ET. The weather measurements, therefore, should be collected at a properly watered and maintained site. Otherwise, adjustment to air temperature, humidity, and wind-speed measurements may be necessary.

The Institute of Food and Agricultural Sciences (IFAS) at the University of Florida has 32 weather stations throughout Florida that record climate data. These datasets are published at the FAWN Web site (http://fawn.ifas.ufl.edu) at 15-minute intervals. This is an extraordinarily useful service to academics, researchers, and the public. The quality and integrity of the climate data that are collected at these sites, however, need to be checked against those collected at the reference site to evaluate whether the FAWN sites reflect the reference site.

REF-ET site at PSREU

A reference weather station site was established as a task objective at the PSREU near Citra to collect climate data for reference ET estimations and to compare these datasets with those recorded at the FAWN-Citra station. This research briefly outlines the analyses and comparisons between the FAWN and REF-ET site datasets. Climatic data for one year (June 14, 2002, through June 14, 2003) at 15-minute intervals and the computed reference ET data for the FAWN and REF-ET sites were provided to SJRWMD digitally.

The REF-ET site at PSREU was set up in early June 2002, and the climate data recordings were started on June 14, 2002. The weather station was set up on a seven-hectare Bahia-grass field that is irrigated with a linear-move irrigation system. Irrigation schedule is based on the soil-water content measurements made at the nearby REF-ET station. The site is irrigated, on average, at least twice a week in the absence of rainfall. The field is fertilized about twice a year to maintain healthy, vigorous growth. The grass is mowed approximately two or three times a month to maintain a 0.12-meter height as closely as possible to meet the criteria of reference crop (grass) height, based on the reference ET definition (Allen et al., 1998). The weather station has a fetch distance of about 200 meters in all directions for unobstructed wind flow (Figure 1). The site is far from any major highways, tall trees, or buildings and is surrounded by hundreds of hectares of irrigated agricultural fields.

Figure 1. REF-ET site at the PSREU

The climate variables collected at the REF-ET site include solar radiation, net radiation, air temperature, relative humidity, wind speed and direction, atmospheric pressure, and rainfall. Some soil data are collected to use them for maintaining the site's grass under non-stressed (reference) conditions. The soil data include soil water content (every 0.15 meters down to 1.20 meters), soil matric potential at four different depths (0.15, 0.30, 0.45, and 0.60 meters), soil temperature at 0.02-, 0.04-, 0.06-, and 0.10-meter depths, and soil heat flux at 0.06 meters (two sensors) from the soil surface. Climate and soil data are recorded every 15 minutes, with the exception of the soil matric potential which is recored three times per week. The instrumentation information (name, model, height, etc.) for the site is given in Table 1.

FAWN site

The FAWN station is located at the north entrance (main gate) of the PSREU. The climate variables measured at the site include solar radiation, air temperature, relative humidity, wind speed and direction, and rainfall. The only soil property measured at the site is the soil temperature at a 0.10-meter depth. The instrumentation information (name, model, height, etc.) for the station is given in Table 1. The site is not irrigated, mowed on a regular basis, or fertilized. The station is very close to Highway 318 (Figure 2A). Some of the climate variables measured at the station (i.e., wind speed and direction, temperature, and humidity) may be negatively influenced by the nearby traffic. The station does not have the required minimum fetch distance because it also is very close to the main PSREU office buildings and is surrounded by the tall trees (Figure 2B). These factors, therefore, also may negatively affect some of the climate variables (e.g., solar radiation, wind speed, soil and air temperatures, and relative humidity) measured at the site. Solar radiation and wind speed probably will be affected more than the other variables.

Figure 2A. Proximity of FAWN site to Highway 318

Figure 2B. Proximity of FAWN site to PSREU office buildings and tall trees

Variable	REF-ET Site	FAWN Site	Sensor Height-depth (m)
Net radiation	NR-LITE net radiometer	NM*	0.7
Solar radiation	LI200X Pyranometer	LI200 Pyranometer	2.0
Air temp. and hum.	HMP45C probe	HMP probe	1.5
Rainfall	TE525 Tipping bucket	TE525 Tipping bucket	2.0
Wind speed and dir.	Vaisala Model 425 Ultrasonic	Handar 425A Ultrasonic	2.0
Soil heat flux	HFT3 soil heat flux plate	NM	0.06
Soil temperature	0.5-mm thermocouples	Soil thermometer	0.02, 0.04, 0.06, 0.10
Soil water content	CS616 TDR	NM	with 0.15 intervals to 1.20
Pressure	CS105 barometric pres. sensor	NM	0.60
Soil matric pot.	Tensiometers	NM	0.15, 0.30, 0.45, 0.60

(*) Not measured

Table 1. Instrumentation information for the two weather station sites (REF-ET and FAWN)

REF-ET Site Versus FAWN Climate Data Comparisons

The daily average and/or cumulative values of rainfall, solar radiation, wind speed, and air temperature are plotted in Figures 3A, B, C, and D, respectively, in order to quantify and analyze the differences in climate variables between the REF-ET site and the FAWN site.

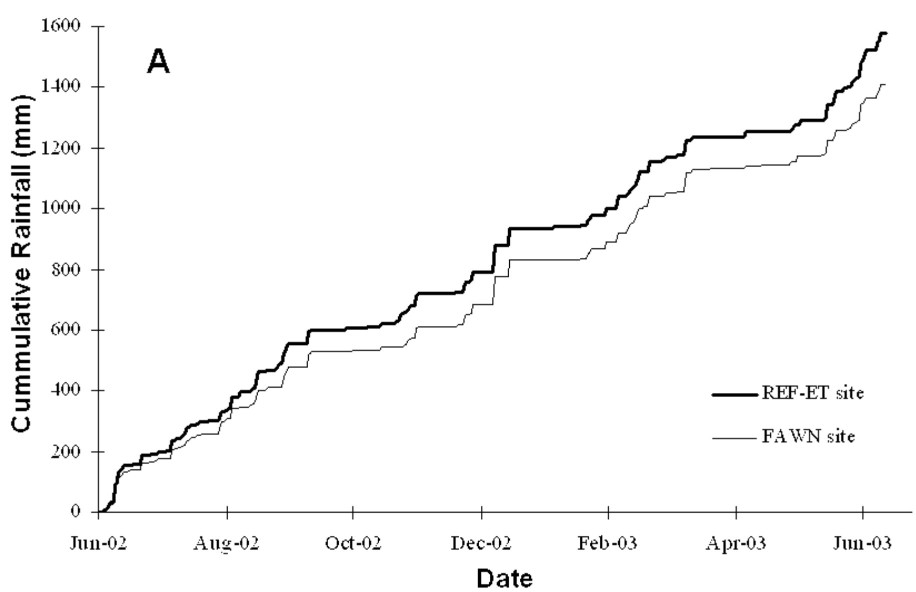

Figure 3A. Cumulative rainfall at FAWN versus REF-ET site

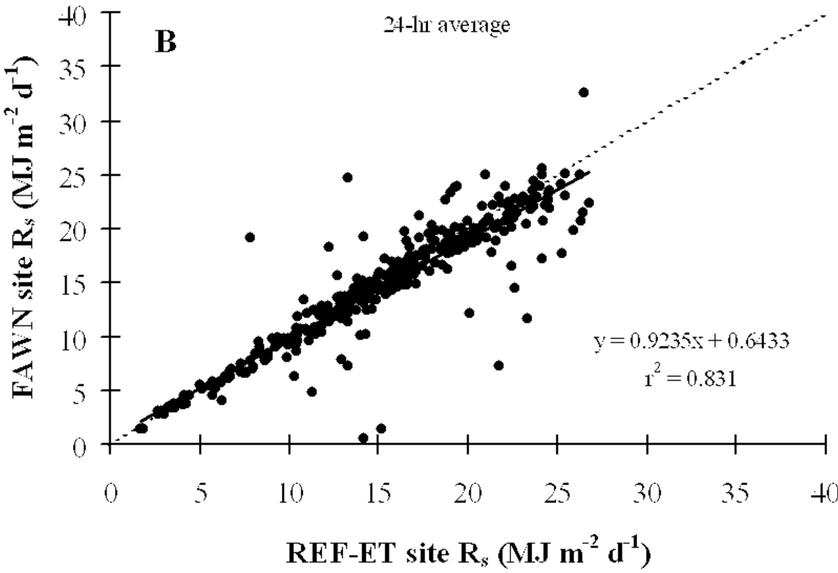

Figure 3B. Solar radiation at FAWN versus REF-ET site

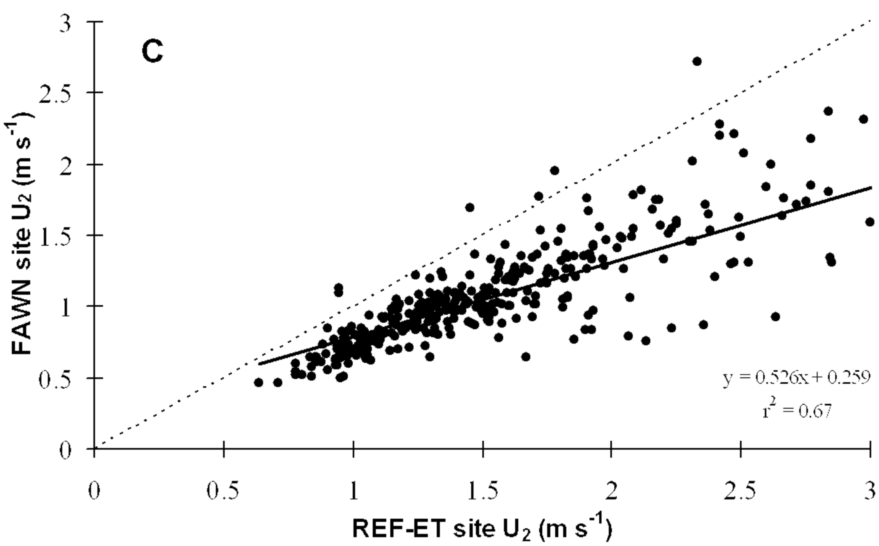

Figure 3C. Daily average wind speed at the REF-ET versus FAWN site

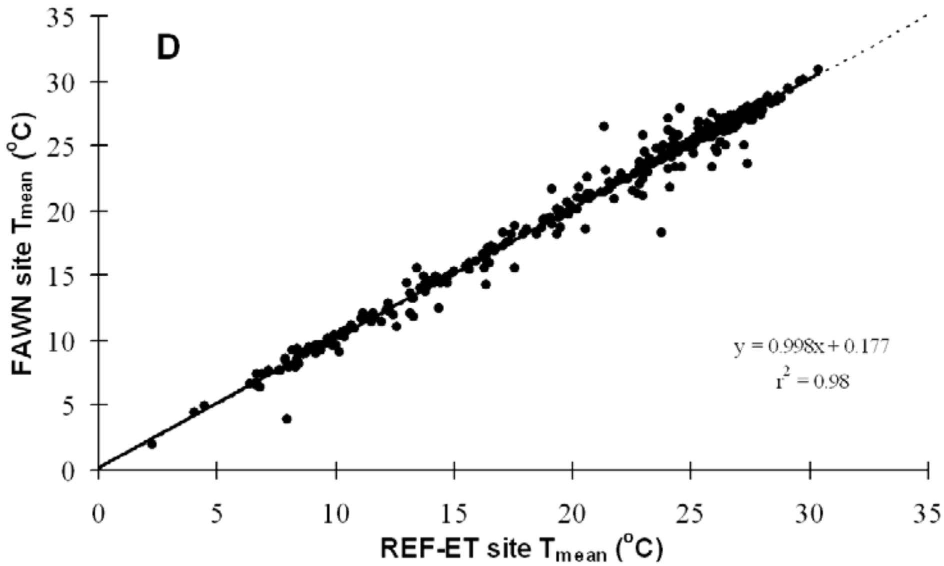

Figure 3D. Daily air temperature at the REF-ET versus FAWN site

The values shown in Figures 3A through D were plotted from June 14, 2002, through June 14, 2003 for all variables except cumulative rainfall for which June 14, 2002 through July 2, 2003 values were used. Some considerable differences in climate data are apparent between the two sites. The cumulative rainfall measured at the REF-ET site, for example, was approximately 170 millimeters higher (1,580 mm versus 1,410 mm) than the FAWN site. A second rain gauge was installed mid-distance between the two sites to verify that the rain gauge at the REF-ET site was measuring the correct rainfall. Rainfall was measured from August 10, 2002, through December 25, 2002. The second rain gauge gave the exact readings as the one installed at the REF-ET site during this test period, indicating a problem with the FAWN station rain gauge or the location of the rain gauge.

A detailed solar radiation data quality analysis was conducted on the solar radiation data for the two sites. The clear-sky solar radiation (Rso) envelopes were computed for the Citra location and graphed against measured Rs data for the two sites (Figures 4A and B). The Rso values represent the maximum solar radiation value that can reach the earth in clear-sky conditions. The measured Rs in clear-sky conditions should not exceed computed Rso. The computed Rso versus measured Rs values in both locations gave good results, indicating that the measured Rs values in both sites are accurate.

The daily average wind speeds measured at the FAWN site usually were lower than those measured at the REF-ET site (Figure 3C). The standard height for the wind-speed measurements for reference ET estimations is 2.0 meters. The wind speed was measured at a 10-meter height, however, to account for the tall trees and the surrounding buildings at the FAWN station. The FAWN wind-speed values were converted to 2.0 meters, using the standard procedures outlined in the Food and Agriculture Organization of the United Nations *Irrigation and Drainage* Paper No. 56 (FAO56; Allen et al., 1998), according to the following equation:

$$U_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)}$$

where U_2 is the wind speed at 2-m above ground surface (m s-1), uz is the measured wind speed at z-m above ground surface (m s-1), and z is the height of measurement above ground surface (m).

The lower wind-speed values of the FAWN site probably are due to the tall trees and buildings intercepting the wind flow. No considerable differences were observed in air temperatures between the two sites (Figure 3D).

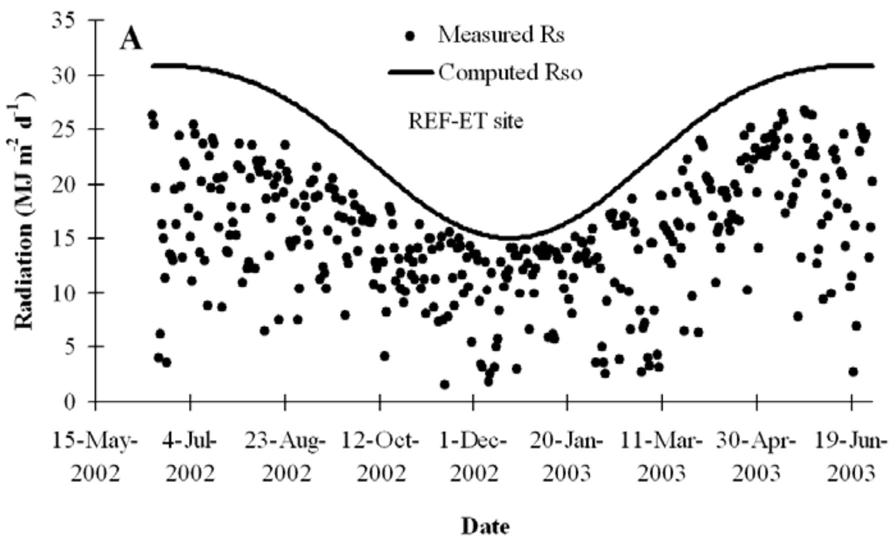

Figure 4A. Measured Rs versus computed Rso envelopes for the REF-ET sites

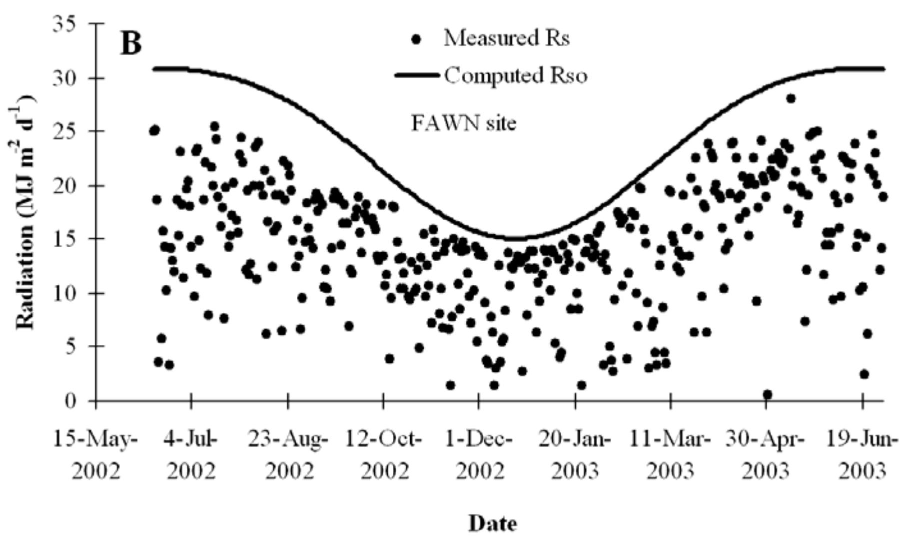

Figure 4B. Measured Rs versus computed Rso envelopes for the FAWN sites

The relative humidity comparisons between the two sites are given in Figure 5. The daily maximum humidity values at the REF-ET site usually are 100 percent, whereas they rarely exceed 90 percent at the FAWN site, which most likely indicates calibration issues with the RH-temperature probe at the FAWN site. Lower RH values at the FAWN site also might indicate that the FAWN site is not irrigated and might have more arid conditions, as compared to the REF-ET site.

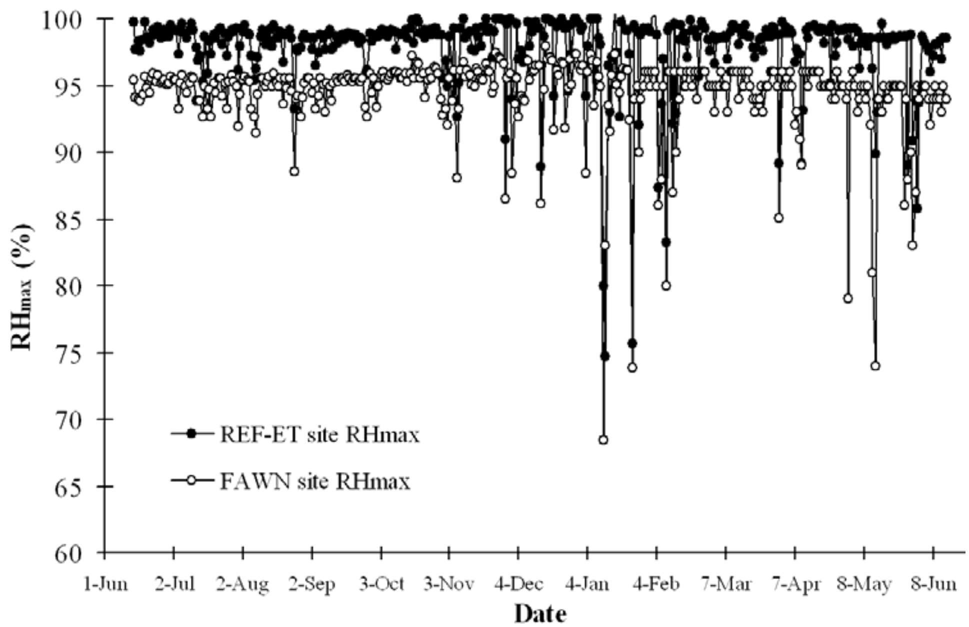

Figure 5. Daily comparisons of RHmax between the REF-ET and FAWN site

REF-ET Site Versus FAWN Reference ET Comparisons

The daily values of REF-ET were calculated according to procedures outlined in FAO56 and the following equation:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

where

ET_o = reference ET (mm d-1)
$\triangle$ = slope of vapor pressure curve (kPa oC-1)
R_n = mean daily net radiation (MJ m-2 d-1)
G = soil heat flux density (MJ m-2 d-1)
γ = psychrometric constant (0.0671 kPa oC-1)
T = mean daily air temperature at 2-m height ((Tmax + Tmin) /2, oC)
U_2 = wind speed at 2-m height (m s-1)
e_s = saturation vapor pressure (kPa)
e_a = actual vapor pressure (kPa)
e_s - e_a = saturation vapor pressure deficit (kPa)

Figure 6 shows the daily patterns of the reference ET for both sites. The peak months in north-central Florida usually are May-June; the December-January period has the lowest ET rates. The reference ET in both sites varied from 0.2 mm d-1 in winter to 6 mm d-1 in summer (June).

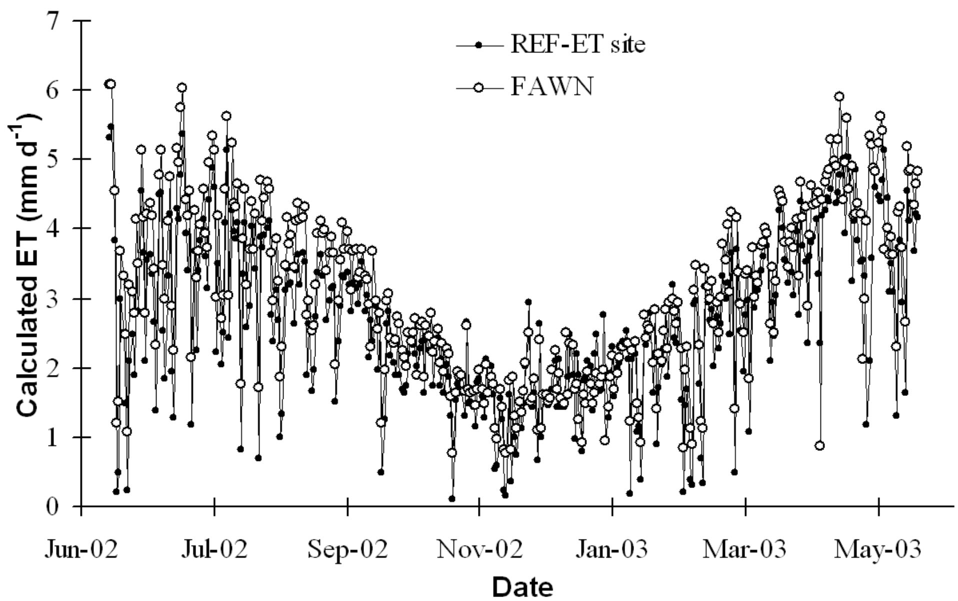

Figure 6. Daily pattern of reference ET as a function of day at the two sites

The FAWN station does not measure net radiation. The REF-ET site reference ET values (shown in Figure 6) were computed using the measured net radiation (R_n) values, whereas the FAWN site reference ET values were computed using the estimated R_n values, according to the following equation:

$$R_n = R_{ns} - R_{nl}$$

where

R_n = net radiation (MJ m-2 d-1)
R_{ns} = incoming net short-wave radiation (MJ m-2 d-1)
R_{nl} = outgoing net long-wave radiation (MJ m-2 d-1).

The daily values of R_{ns} and R_{nl} are computed using the procedures outlined in Allen et al. (1998). The reference ET values for both sites were graphed in Figure 7 with a 1:1 line to better quantify the over- or under-estimations. The FAWN site reference ET values in Figure 7 usually are higher than the REF-ET site, due to the over-estimations of the daily Rn values. The REF-ET site, therefore, holds an important advantage over the FAWN site with the measured Rn values.

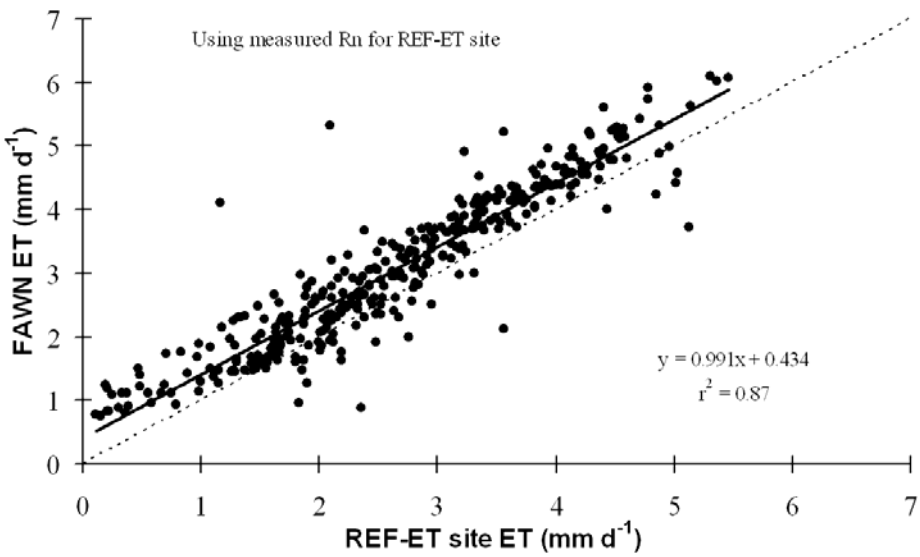

Figure 7. Daily reference ET comparisons for the FAWN and REF ET sites

Results indicated considerable discrepancies between the two sites in the climate data collected. The quality-check analyses on the measured climate dataset at the REF-ET site are done routinely. The agricultural settings of the REF-ET site is adequate, based on the standards set by the American Society of Civil Engineers, Evapotranspiration Task Committee. The instruments used at the site are checked and/or sent for calibration about once a year.

The climate data and the reference ET comparisons shown so far are done on a daily-average basis. The standardized Penman-Monteith (Allen et al., 1998) was used to estimate the daily reference ET values for both sites. The standardized Penman-Monteith equation, however, gives the most accurate daily reference ET values, when the hourly values of the ET are computed and summed for a given day. The hourly reference ET computations require measured soil heat-flux values. This variable is not measured at the FAWN site. It is possible that these and other variables might be considerably different when hourly or shorter period (15-minute) values are considered, even though there was not a considerable difference in air temperature between the two sites on a daily basis. The air temperature and solar radiation values measured with 15-minute intervals in both sites are plotted in Figures 6 and 7, respectively, to test this hypothesis.

It is clear from Figures 8 and 9 that the settings and surroundings (tall trees, buildings, the highway, and dry, non-irrigated conditions) would have significant negative effects if the reference ET estimations were made on an hourly basis, rather than on a daily average basis. Differences in the climate variables measured at the FAWN site from those at the REF-ET site will be reduced when the daily average values are computed. The final reference ET value, therefore, will not be affected as much as it would have been if hourly reference ET values were to be computed. The air temperature values at the FAWN site, for example, usually are higher than those measured at the REF-ET site. This is due to the dry, non-irrigated conditions of the FAWN site. The settings and the climate data collected at the FAWN site can be judged as moderate in quality.

Findings suggested that the station’s location should be at a more appropriate site, where sensors can intercept free wind flow and other climate variables. This would improve the quality of the climate variables collected at the FAWN station and would make reference ET estimations on a daily basis more accurate. Findings also indicated, however, that the FAWN station can be judged as a poor-quality weather station if the reference ET estimations are made on an hourly basis.

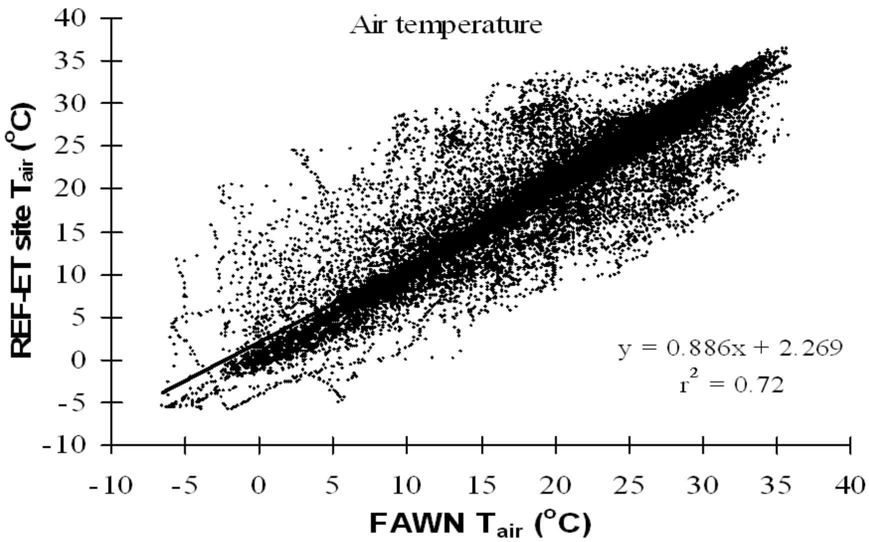

Figure 8. Air temperature (measured every 15 minutes) comparisons for the FAWN and REF-ET sites

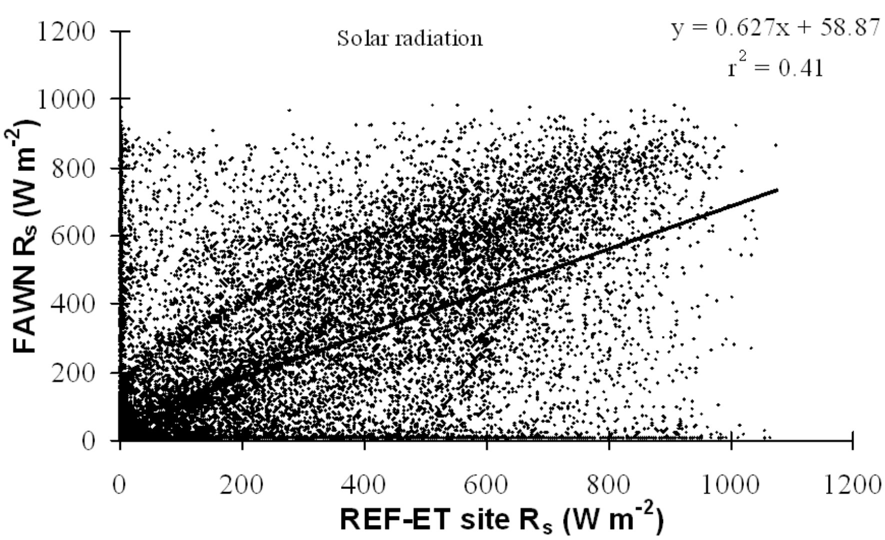

Figure 9. Solar radiation (measured every 15 minutes) comparisons for the FAWN and REF-ET sites

REFERENCE

Allen, RG., Pereira, L.S., Raes, D., and Smith, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrig. and Drain. Paper No. 56. Rome, Italy. 300 pp.

REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL

APPENDIX 4
CROP COEFFICIENTS FOR GRASS
(TASKS 7, 14, 18, and 25)

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ABSTRACT

Bahiagrass (*Paspalum notatum*) crop coefficients (K_c) were determined for Nov. 2003 through April 2006 in central Florida. The lysimeter and eddy correlation methods were used to estimate crop evapotranspiration (ET_c) rates. The standardized reference evapotranspiration (ET_o) equation (ASCE-EWRI 2005) was applied to calculate the ET_o values using weather data from a nearby station. Three relatively large weighing lysimeters, double steel tanks with an inner surface area of 2.32 m^2 and a soil depth of 1.37 m and each equipped with four commercial load cells, were used for the ET_c measurement. An eddy correlation system was used to directly measure the turbulent fluxes of water vapor (LE) and sensible heat (H) above the crop canopy. The distance between the lysimeters and the eddy stations was 80 m.

Daily K_c values were estimated using the ET_c measured by the lysimeters and the eddy correlation system and the calculated ET_o. The K_c values determined by the eddy correlation method were similar to those determined from lysimeter measurements during the summer season. The largest K_c differences were found in winter when the grass growth was active inside the lysimeters, but dormant in the surrounding field. Therefore, the monthly K_c values by eddy correlation method were more representative of the actual field condition. The recommended K_c values in this study were 0.34, 0.36, 0.54, 0.80, 0.89, 0.84, 0.72, 0.68, 0.62, 0.69, 0.65, and 0.46 for January through December.

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL
APPENDIX 4 - CROP COEFFICIENTS FOR GRASS

INTRODUCTION

The importance of evapotranspiration (ET) in the hydrologic cycle, irrigation scheduling and water resources management has long been recognized. In agricultural applications, evapotranspiration is a fundamental and important process. It is the main loss of water from the vegetation surface; therefore, accurate estimation of ET is important. However, accurate ET measurement is difficult to obtain. Numerous internal and external factors influence evapotranspiration. The magnitude of ET varies seasonally and diurnally. It is influenced by climate conditions, soil and vegetation surfaces, soil moisture status, crop phenology, growth stage, shading, and ground cover.

There are two common ways to determine the evapotranspiration rate, direct and indirect methods. Direct measuring methods include soil water depletion, lysimeter, water balance, energy balance, eddy correlation, combination of energy and heat, and mass transfer (Jensen et al. 1990). Indirect measuring methods relate reference evapotranspiration (ET_o) to a crop coefficient (K_c). The ET_o can be calculated from weather data collected from a well-watered reference crop surface. Many methods have been developed to estimate the ET_o. The most current method has been developed by the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) (ASCE-EWRI 2005). Crop coefficient development requires both crop evapotranspiration (ET_c) and ET_o estimates for a specific crop and location.

The lysimeter method has been considered the most accurate method for almost one hundred years (Brutsaert 1982). If properly designed, constructed, instrumented, managed, operated and interpreted, lysimeters can provide precise and representative measurements of crop evapotranspiration that integrate environmental factors controlling ET (Allen and Fisher 1990). Lysimeters are categorized as follows: drainage, weighable, and weighing. Weighing lysimeters provide the most accurate data for short time periods (Jensen et al. 1990).

The eddy correlation is a new and innovative method. It has been used successfully to directly measure evapotranspiration (Sumner 2001; Sumner and Jacobs 2005). This method overcomes the need to determine each component in the water balance. It also avoids soil surface heterogeneity issues by placing the sensors above the crop canopy. The temporal resolution of ET measurements is less than 1 hour.

Purpose and scope

The University of Florida (UF), in cooperation with the St. Johns River Water Management District, began a study in 2003 to determine major crop coefficients (K_c) in central Florida. Crop coefficients are to be obtained for three crops, bahiagrass, citrus, and sod. The measured K_c values are used to improve the Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS) software, as well as, to provide guidance in evapotranspiration estimates.

This report summarizes the experimental design and results for the bahiagrass experiment. Bahiagrass evapotranspiration rates were measured on a nearly continuous basis from November 1, 2003 through April 30, 2006, using three weighing lysimeters and one eddy correlation system. Results include daily measurements of bahiagrass ET_c, ET_o, and monthly crop coefficients.

DESCRIPTION OF THE STUDY AREA

Location

The experimental site is located at the University of Florida, Plant Science Research and Education Unit (PSREU), near Citra in Marion County, Florida (Fig. 1). The PSREU is between Gainesville and Ocala, in central Florida (Fig. 2). The PSREU facility has a total area of 636 hectares (ha) and is approximately 4.9 kilometers in length and 1.3 kilometers in width. The total available land for research is 445 ha.

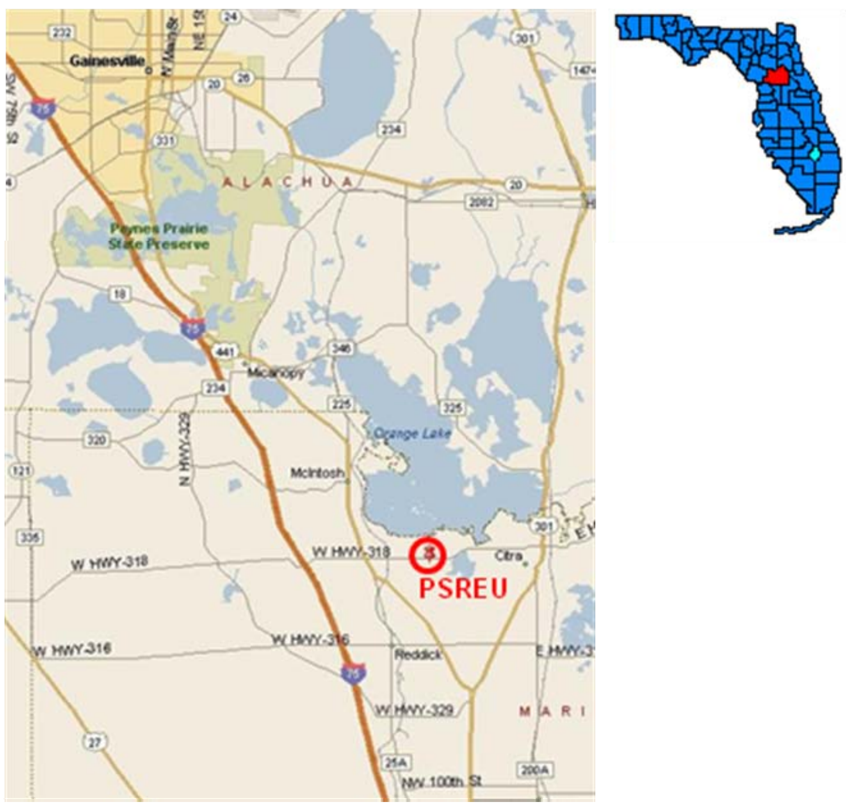


Figure 1. Location of the Plant Science Research and Education Unit (http://plantscienceunit.ifas.ufl.edu/directions.htm).

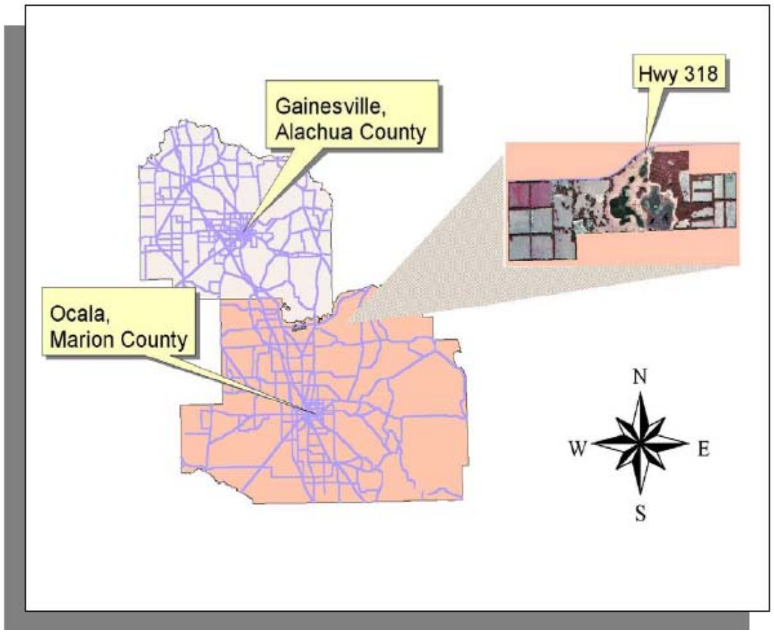


Figure 2. Geographic location of the PSREU (Tischler et al. 2004).

The PSREU Phase 1 field, where the lysimeters are located, is divided into six large blocks for experiments, each one with an area of 20 to 30 ha (Fig. 3). The lysimeter site is located in the middle of block 6, a 23 ha grass plot. The location has at least 230 m of fetch distance in all directions. In the same field, Eddy1 is located 80 m away from the lysimeters and includes an eddy correlation system and a meteorology station. Ref-ET is the second weather station and is located in block 4 about 500 m away from the lysimeters. A Florida Automated Weather Network (FAWN) weather station is located near the entrance to the PSREU. All stations are in bahiagrass fields. The weather data at Eddy1 are used to calculate reference evapotranspiration. The other two stations provide measurements that are used to provide any missing values. The geographic location at the lysimeter site is latitude 29.41° N and longitude 82.17°W with an elevation of approximately 20 m above sea level. The eddy correlation site has a slightly lower elevation than the lysimeters, due to its natural topography.

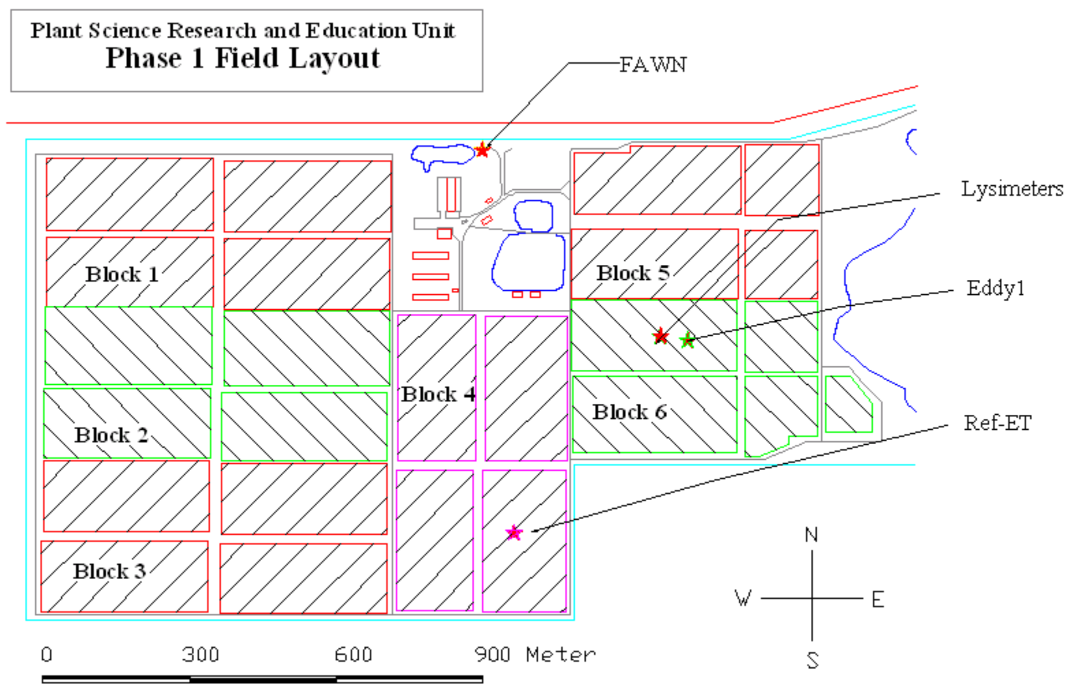


Figure 3. PSREU field layout with weather stations (modified from http://plantscienceunit.ifas.ufl.edu/images/location/p1.jpg) (Jia et al. 2006).

Climate

The climate in central Florida is humid subtropical, with an average annual rainfall of 1,350 mm (Purdum 2002). Most of the rainfall (60%) occurs from June to September. Afternoon thunderstorms are frequent during this period, and it rains on most days. Annual average evapotranspiration is estimated to be 945 mm, which is 70% of the total rainfall (Purdum 2002).

Meteorological variables are also measured at the experimental site by the FAWN station. Table 1 lists monthly average values for air temperature (T_{ave}), relative humidity (RH_{avg}), solar radiation (R_s), wind speed (Wsp), and wind direction (W_{dir}) and average monthly rainfall calculated from five years of FAWN data from Oct. 2000 to Apr. 2006. The average annual temperature is 20.0^{o}C, with a maximum monthly temperature of 35.4^{o}C in July and a minimum temperature of - 4.1^{o}C in January. The average annual rainfall for this 5.5 year period is 1171 mm. The average annual wind direction at the PSREU is 180^{o}. The prevalent wind direction is from the southwest or southeast.

Table 1. Weather variables at the PSREU by FAWN from Oct. 2000 to Apr. 2006. T_{ave}, RH_{ave}, R_s, W_{spd}, and W_{dir} are average daily values. Rain is the average total rainfall for a given month. T_{max} and T_{min} are the daily maximum and minimum temperatures.

Month	T_{ave} (^{o}C)	T_{min} (^{o}C)	T_{max} (^{o}C)	RH_{avg} (%)	Rain (mm)	Rs (W/m^2)	W_{sp} at 10 m (m/s)	W_{dir} at 10 m (degree)
1	12.55	-4.09	27.48	74	35.7	127	1.64	204
2	14.62	-0.93	28.46	75	89.8	139	1.64	185
3	17.61	0.67	30.33	71	91.7	183	1.79	191
4	20.43	4.61	31.82	69	45.7	231	1.56	188
5	23.89	11.11	34.74	70	58.9	239	1.52	177
6	25.84	18.64	35.27	79	189.8	204	1.34	172
7	26.59	20.09	35.36	80	151.5	205	1.07	182
8	26.36	20.05	34.74	82	160.8	189	0.98	173
9	25.39	17.00	34.22	80	174.3	169	1.61	149
10	21.48	7.28	32.06	79	64.3	153	1.27	160
11	17.49	1.52	30.13	77	42.8	133	1.34	180
12	12.87	-2.78	27.28	77	65.7	115	1.56	195
Annual	**20.0**	**-4.09**	**35.36**	**76**	**1171**	**172**	**1.45**	**180**

Vegetation

Bahiagrass (*Paspalum notatum* Flugge) was originally introduced from Brazil as a pasture grass on sandy soils. Since then it has been used as a turf grass in humid regions (Trenholm et al. 2003). It is a popular low maintenance lawn grass for infertile soils. Bahiagrass is a warm-season grass, which has a higher degree of stomatal control with lower potential evapotranspiration rates than a cool-season grass (Jensen et al. 1990). Bahiagrass was previously established as a pasture area in Block 6. The grass fields are mowed as needed to ensure a 12 cm grass height, as defined in the reference evapotranspiration concept in ASCE-EWRI guidelines (ASCE-EWRI 2005).

Soils

The soil type at this site is the Arredondo-Gainesville association (Thomas, et al. 1979), which is nearly level to sloping, well drained soils, with some sand to a depth of more than 100 cm, loamy below, and others sandy throughout. Tischler (2003) stated that the soils at the field are Sparr, Millhopper, or Adamsville, where Sparr is a poorly drained loamy, siliceous, subactive, hyperthermic Aquic Arenic Paleudult; Millhopper is loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults; and Adamsville is hyperthermic, uncoated Aquic Quartzipsamment. The water table is deeper than 2 m year round, and depth to bedrock is greater than 1.5 m (Thomas et al. 1979). The measured bulk density of the soil for the lysimeter site at 15, 30, 45, 60, 75, 90, and 105 cm depths are 1.36, 1.39, 1.41, 1.42, 1.43, 1.42, and 1.43 g/cm^3, respectively. The Sparr, Millhopper, and Adamsville fine sands are composed of 94% to 97% sand and 2% to 5% silt in the upper 100 cm (Carlisle et al. 1989). The field capacity at this site is about 8-10% of soil volumetric content, and soil water holding capacity is 6-8%. This is a very loose sandy soil and it presented challenges during construction due to soil instability and a perched water table (Jia et al. 2006).

METHODS FOR MEASUREMENT AND ESTIMATION OF EVAPOTRANSPIRATION

Evapotranspiration is the combined process by which water is transferred from the earth’s surface to the atmosphere; evaporation of liquid water from the soil surface and water intercepted by plants, plus transpiration by plants (Jensen et al. 1990). Potential ET refers to evapotranspiration of a disease-free crop, grown in very large fields, not short of water and fertilizer (Doorenbos and Pruitt 1977). Actual ET will depend on many other factors, such as climate, soil water conditions, groundwater table, salinity, etc. In this study, the grass has been maintained well-watered and well fertilized to avoid stress conditions.

Two methods, lysimeter and eddy correlation, were used to estimate the ET_c for the study period, when weather permitted, from November 1, 2003 to April 30, 2006. Daily ET_c and monthly ET_c values were estimated using the lysimeter and eddy correlation methods. Daily and monthly crop coefficients were developed using the reference evapotranspiration calculated by the ASCE-EWRI method (ASCE-EWRI 2005).

Lysimeter method

Background and theory

The history of lysimeters can be tracked back to the 17th century, but the first reported weighing lysimeter in U.S. was the Coshocton lysimeter (Harrold and Dreibelbis 1958). Since then, weighing lysimeter use has increased. The design and construction of lysimeters vary based on research goals. Marek et al. (1988) summarized all the U.S. lysimeters used for evapotranspiration research from 1937 to 1986. The calibration, data quality control, data interpretation, and evapotranspiration calculation procedures were also documented by Bushland lysimeter researchers (Dusek et al. 1987; Howell et al. 1995). Crop evapotranspiration rates developed by lysimeters have been used as standard values in the United Nations Food and Agriculture Organization *Crop Water Requirements* Paper no. 24 (FAO24) (Doorenbos and Pruitt 1977) and Irrigation and Drainage Paper no 56 (FAO56) (Allen et al. 1998), where the two guidelines have been standard references for ET research around the world.

A lysimeter is a tank containing a soil profile and plants of interest. By monitoring the change in water storage in the lysimeters, along with other components in the water balance (e.g., precipitation, irrigation, and drainage), the actual evapotranspiration rate can be obtained over the measurement interval. Resultant measurements can provide daily evapotranspiration values for grass to within 0.05 mm or 1% of accuracy (Allen and Fisher 1990), and to 0.43 mm per day over three growing seasons for shallow-rooted crops (Martin et al. 2001).

Lysimeters provide a direct ET measurement by estimating a soil water balance in the lysimeter. The crop evapotranspiration rate is determined by monitoring the change in weight, or equivalently, the change in water storage (ΔS) in each tank. The water budget equation, which expresses the conservation of mass in each lysimeter, can be written as follows:

$$\Delta S = P + I - ET_c - D - RO \qquad (1)$$

where ΔS is the water storage change over time, P is the rainfall, I is the irrigation amount, ET_c is the evapotranspiration loss, D is deep percolation as drainage, and RO is surface runoff. All terms can be expressed in units of water depth relative to the surface of the tank.

The design, construction, and operation of lysimeters are complicated. A summary of lysimeter development and design by Howell et al. (1991) indicates that evapotranspiration accuracy is influenced by the measurement duration, lysimeter shape, weighing mechanism, and construction materials as well as site maintenance. Allen and Fisher (1990) further stated that environmental considerations related to lysimeter design and data corrections could cause the evapotranspiration results to be impractical to use, or lead to inaccurate conclusions. These considerations include accurate estimation of evaporative, vegetative, and lysimeter rim areas and differences between soil moisture content inside and outside the lysimeters. In humid environments, such as in Florida, the design and construction of lysimeters is particularly challenging due to shallow water tables, loose soil structure, and frequent precipitation events. The detailed description of the lysimeters design, construction, calibration, operation and cost analysis used in this study was addressed by Jia et al. (2006).

The amount of precipitation and drainage were measured as well as the time of occurrences (events). The calculation of crop evapotranspiration was based on the weight change recorded by the lysimeter load cells. Therefore, equation (1) can be rearranged as follows

$$ET_c = -\Delta S' \qquad (2)$$

where the ΔS' indicates the weight decrease due to the crop evapotranspiration loss when there is no maintenance or precipitation events.

Instruments

The Citra, Florida lysimeters consist of a large concrete base, three small concrete bases, one for each lysimeter, double tanks reinforced with square steel tubing, an in-situ weighing system, automatic pumping and drainage systems, a data acquisition system, a soil moisture monitoring system, water table monitoring, and a lightning protection system (Jia et al. 2006). The lysimeter construction consists of foundation, tank fabrication, and tank installation and instrumentation setup. The details about the lysimeter foundation and tank construction are described by Jia et al. (2006). After construction, the soil profile was reconstructed inside the lysimeters. A 15 cm layer of coarse sand was placed at the bottom of each lysimeter to provide a storage reservoir for gravity drainage. The soil was repacked in 15 cm increments and tamped approximate to the original bulk density for each layer.

Each lysimeter consists of two tanks. The outer tank is 1.78 x 1.78 x 2.02 m, located on the foundation and extends to the soil surface. The inner tank is 1.52 x 1.52 x 1.37 m and sits inside the larger outer tank. Between the two tanks, four single-ended shear beam SBS-10K load cells (Measurement Specialists, Inc., Huntsville, Ala.) are installed so that the inner tank that holds the soil and crop can be weighed. The load cells are bolted to the tops of steel channels which are welded across two I-beams for stability. All the lysimeter mass, including the steel lysimeter, soil, plants, and soil moisture probes, is supported by the four load cells in each tank (fig. 4).

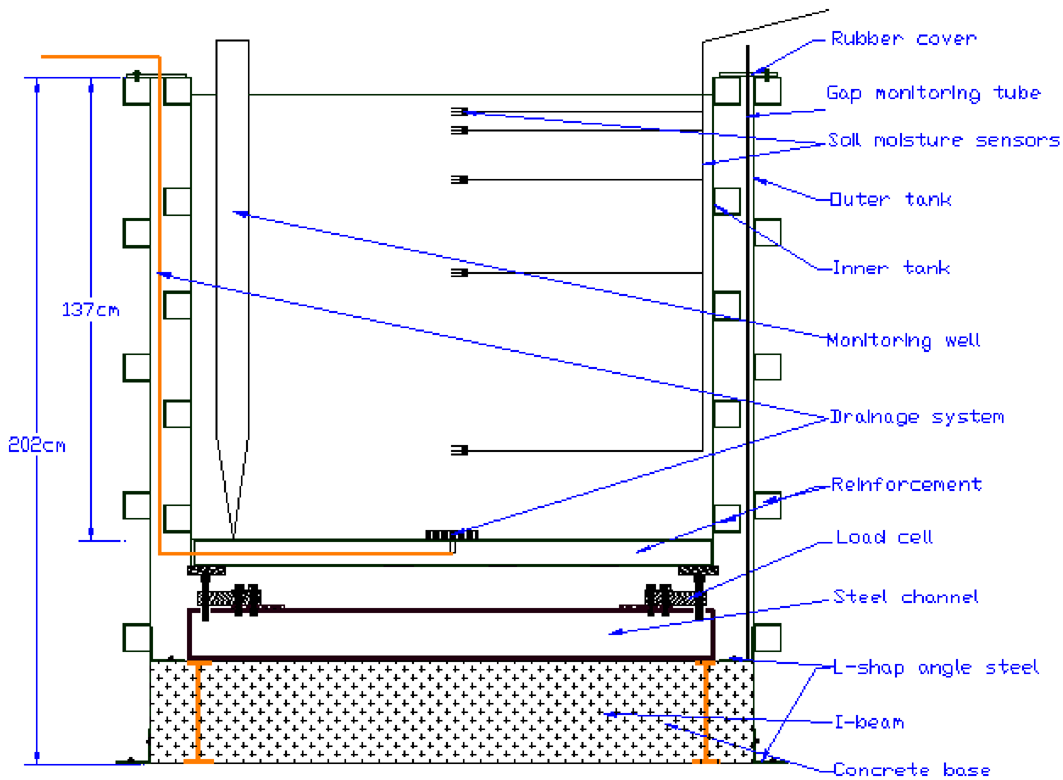


Figure 4. Cross-section view of lysimeters with monitoring well, soil moisture sensors, and load cells (Jia et al. 2006).

The load cells are temperature-compensated, stainless steel cantilever-type that give a linear change in resistance in response to an applied weight. Each load cell is capable of measuring 4,536 kg (10,000 lb). The rated excitation signal is 5 V DC/AC and the full-scale output is 3.0 mV/V. The temperature-compensated range is from -10°C to 50°C, and the safe load limit is 150% of rated capacity. A CR23X datalogger (Campbell Scientific, Inc., Logan, Utah), programmed for a four-wire full bridge, is used to record the voltage output from the lysimeter load cells every minute and outputs average voltage values every 30 min to a data file. A lightening protection system connecting each load cell to the datalogger was installed after an incident occurred in August 2003. A severe storm damaged one load cell in each tank. In September 2003, the bad load cells were replaced and grass was reestablished. The data used in this report exclude the first initial period and use the continuous measurements from November 2003.

Two 15 cm diameter permeable ceramic plates (Filtros, Ltd., East Rochester, N.Y.) are used in each tank to extract the water accumulated in the bottom of each lysimeter. Two copper tubes were connected to the ceramic plates, attached to the inner tank, and attached above the ground surface. The outlets were connected to the vacuum pump through external plastic tubing for pumping the drainage from the lysimeters. In June 2004, the pumping system was changed from pumping one lysimeter at a time to pumping all lysimeters simultaneously by connecting the tanks in parallel. An automated pumping system was installed in October 2004. Pumping was then typically scheduled at night or early morning, when ET_c is minimal. Each lysimeter has a monitoring well. Weekly or semi-weekly measurements of the water table were used as a reference for lysimeter pumping. Pumping was also scheduled for an individual lysimeter when the water table measurements result in differences among the lysimeters.

A PVC pipe, 1.8 m long, was inserted through the center of the gap between the inner and outer tanks to the bottom of the foundation on 22 April 2005. The access pipe was used to pump overflow between the tanks caused by extreme rainfall events, such as hurricanes. During these events, lysimeter monitoring was disabled. Thus, losing drainage to the lysimeter tanks interstitial space did not affect the crop water use calculations.

Before Feb. 2006, the cover used for the 4.7 cm gap between the two tanks was a rubber sheet, 0.5 cm thick and 18 cm wide. The rubber was bolted on the outer tank rim and left the other side free to ensure free vertical movement of the inner lysimeters. Small amounts of precipitation falling on the rubber cover flowed away from the cover to the outside field. However, when large rainfall events occurred, some water drained into the gap between the two tanks. Thus the load cells were immersed in water for substantial periods of time after large storm events such as hurricanes in the fall of 2004. After Feb. 2006, the covers for the gap were changed to rigid recycled plastic (plywood) frames. No runoff occurred between the inner and outer tanks after installation of the new covers.

Calibration

The calibration of lysimeters establishes a linear relationship between the measured voltage of the load cells and the equivalent weight of the tank. The calibration is used to convert voltage changes to lysimeter water storage changes. The lysimeter calibration was performed once a year. Four calibrations have been conducted at the time of this writing. The resulting regression coefficients were applied for the period before next calibration. The coefficients by lysimeter and calibration date are listed in table 2. The linear regression equation is represented as $y = ax + b$, where y is the applied load in mm of water (mm of H_2O), x is the measured voltage output in mV, a is the calibration slope (mm of H_2O/mV), and *b* is the intercept (mm of H_2O). The first three calibrations were performed by adding weight to the lysimeters.

Table 2. Lysimeter calibrations by date and lysimeters tank.

Date	Tank 1			Tank 2			Tank 3		
	a	b	R^2	a	b	R^2	a	b	R^2
6/10/2003[a]	2616.10	-373.428	0.999978	2611.91	-450.60	0.999990	2616.10	-401.05	0.999998
1/28/2004[b]	2620.31	-2959.98	0.980395	2454.57	-2750.95	0.987809	2734.62	-2972.35	0.999637
1/19/2005[b]	2771.83	-2901.44	0.999903	2725.47	-2812.59	0.999966	2650.14	-2698.37	0.999993
3/10/2006[c]	673.52	-2698.75	0.999972	672.13	-2784.29	0.999965	682.31	-2784.49	0.999939

[a:] the calibration was conducted when there is no soil in the tank, so the interception is much smaller.
[b:] the calibration was conducted with full grass cover.
[c:] the calibration was conducted with bare soil between total load cell readings in mV and the change of mm of water, so the slope of the curve is much smaller because the values on the x-axis (total voltage) is smaller than before (average voltage).

The fourth calibration included both an increase and decrease of loading following Howell et al.’s (1995) procedure, while the previous lysimeter calibrations included only increases of loading. Both load increases and decreases with small weights and large weights were tested. There were 82 data points recorded during the calibration process for each lysimeter. Two scales, one is 1000 kg (+/- 0.01kg) and the other is 2000 g (+/- 0.1 g) were used to weigh three groups of weights. The smallest group (GI) was paper bags filled with 100 g to 1000 g soils. The second group (GII) was plastic containers filled with 1 kg to 3 kg of water. The largest group (GIII) was iron weights at about 24 kg each (fig. 5).

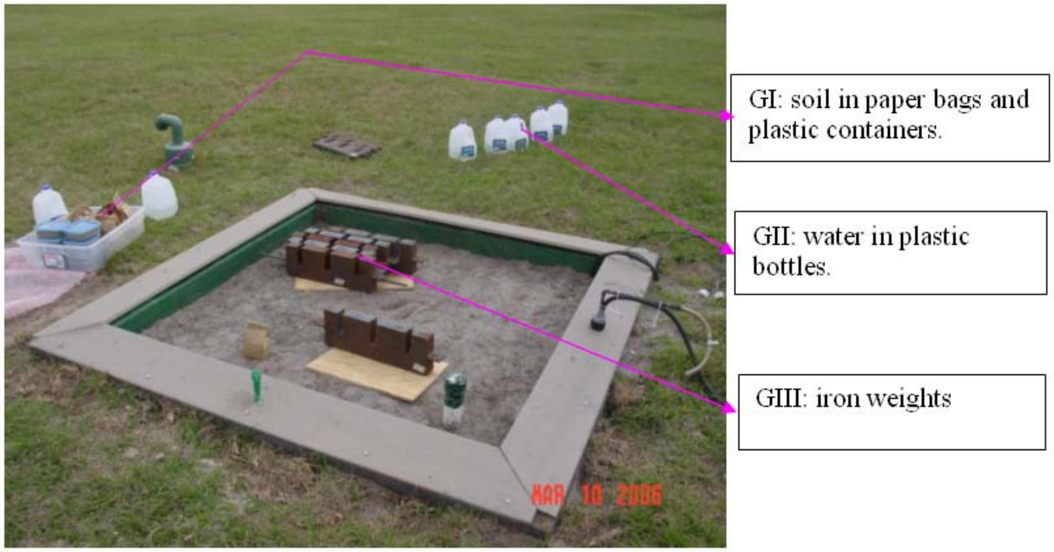
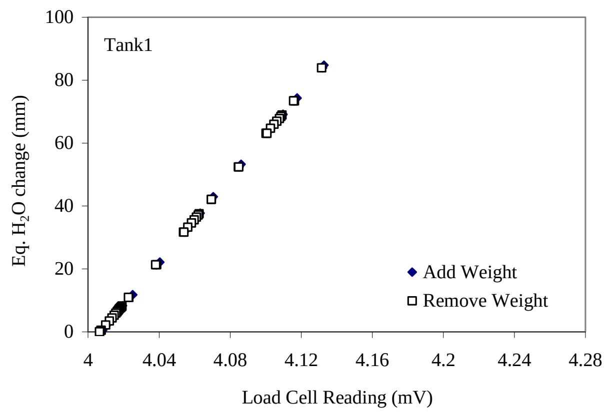
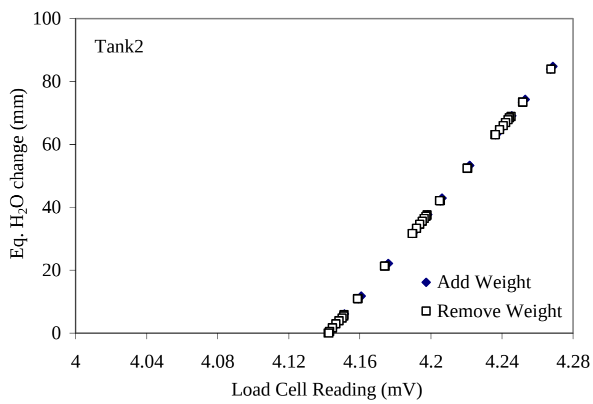


Figure 5. Lysimeter calibration on March 10, 2006.

During the calibration process, the GI small weights were added to the lysimeters one at a time and the voltage changes were recorded before and after the addition of weight. Then the GII group of weight was added to the lysimeter. After the lysimeter readings stabilized, normally 1-2 minutes, the voltage was recorded. Then the weights were removed from the lysimeters, in an opposite sequence as they were added to the lysimeter. Once all the weights were removed and the readings stabilized, the third and heaviest group of weight, GIII, was added to the lysimeter, one at a time. One weight in the GIII group (24 kg) is equivalent to 10.3 mm of water and the total 8 weights are equivalent to 82.7 mm of water. This weight is about the maximum rainfall occurrence in this region for typical rain events excluding hurricanes. The process was repeated until all the GIII weights were added to the lysimeter and the GI and GII were added and removed between the GIII weights. The last step was to remove the GIII weights, one at a time, from the lysimeter. The calibration was conducted for one lysimeter at a time and it took more than 10 hours to finish the calibration for all three lysimeters. Because the calibration took a day to accomplish, the weather conditions may have varied during the whole calibration procedure. The output readings were recorded for each weight increase. The weight change was plotted against the total millivolt output in each lysimeter. The results are shown in Figure 6 for all three tanks.





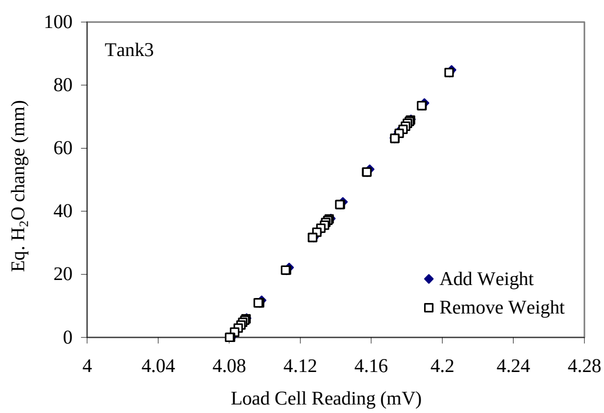


Figure 6. Equivalent water depth (mm) vs. total load cell reading (mV) from lysimeter calibration results on March 10, 2006.

With the manufacturer stated load cell accuracy of 0.02%, this calibration shows that the expected accuracy is about 0.12 mm equivalent depth of water over the lysimeter area (5.8 Mg average lysimeter weight) (Jia et al. 2006).

Lysimeter operation

The weighing lysimeters were put into operation on 28 May 2003. However, the site was not completely established with bahiagrass sod and collecting data until July 2003. On 4 August 2003, a severe thunderstorm resulted in a power surge that damaged at least one load cell in each lysimeter tank. The load cells were replaced, and each load cell was connected to a surge arrestor (model E280-6v, Citel, Inc., Miami, Fla.) to prevent further lightning damage. The repaired lysimeters began operation again on 13 October 2003. In April 2005, due to herbicide damage to the bahiagrass the lysimeters were resodded. In February 2006, 2 load cells in Tank1 and one load cell in Tank2 were replaced due to degradation of the load cells. The sod was reestablished and the lysimeters became operational again on 10 April, 2006.

Rainfall and irrigation at the lysimeter site were monitored by a tipping bucket, a Hobo event logger (Onset Computer, Bourne, MA.) and a manual rain gauge. The manual rain gauge readings were recorded two to three times per week during the summer. Both instruments are installed at a 60 cm height and are subject to overhead irrigation. A third tipping bucket rain gauge is located 80 m away from the lysimeter site at 3 m height. Total rainfall depth from all rain gauges was compared to the increase in lysimeter weight during storm events. However, only the two rain gauges near the lysimeters were used for precipitation depth measurement.

The standard site operation procedure to maintain conditions in the lysimeters comparable to those of the surrounding area is described in detail by Jia et al. (2006). In summary, the soil moisture, soil structure, and soil conditions were kept identical to outside the lysimeters. The grass height and grass variety were maintained at the same level as outside conditions. Pumping was scheduled to maintain a well-drained water table level and similar soil water content. The grass height was measured during the normal field visits. When the grass height was predicted to reach 15 cm, a mowing was scheduled. In the summer time, it was normally mowed every 10 days. Water table height was also measured during field visits. When the water table was above 30 cm, or if there was more than 20 mm of precipitation, pumping was scheduled from 1 to 2 and from 3 to 4 in the morning following the field visit. Drainage was measured by graduated cylinder.

Data collection and processing

Data collection at the lysimeter site included all components of the mass balance described in eq. 1 required to determine evapotranspiration. The lysimeters are considered to be the control volume of interest. The change of water mass in the lysimeters was calculated from the changes in output voltage from the load cells using the calibration equations. Inputs to the lysimeters are precipitation and irrigation. These inputs were recorded as weight increases in the lysimeters and verified by the readings from the Hobo event logger and the manual rain gauge. Outputs from lysimeters are evapotranspiration and drainage. The volume of drainage was measured manually following pumping events and converted to units of weight. The weight loss from the soil and crop surface due to evapotranspiration was measured and recorded as the precipitation minus drainage and change in the lysimeter mass.

Field data were subjected to routine quality assurance and quality control procedures. After the data were downloaded in the field, a preliminary screening was performed to diagnose errors. Data were analyzed on a monthly basis. During the 10 min or 30 min measurement interval, there were frequently small oscillations in load cell voltage, even during the nighttime. This might have been due to wind effects, or vibrations recorded by the load cells. Small amounts of signal noise were smoothed by using a curved equation (Allen et al. 1994).

Eddy correlation method

Background

Eddy correlation measures actual evapotranspiration using measurements of the turbulent atmosphere. The average vertical movement of water is measured using a high frequency sampling of the atmosphere's water specific humidity and vertical wind speed averaged over 30-minute periods.

The eddy correlation station is used to directly measure actual evapotranspiration using an energy-budget approach (Tanner and Greene 1989; Twine et al. 2000). It is a proven approach for estimating evapotranspiration from various types of vegetation (Sumner 1996, 2001; Gholz and Clark 2002; Jacobs and Sumner 2005). This method overcomes uncertainties due to soil surface conditions and crop growth stages by measuring water vapor fluxes above the crop canopy.

In Belgium, Pauwels and Samson (2006) measured evapotranspiration rates for a wet sloping grassland using eddy correlation method. Their results were in good agreement with those measured using the Bowen ratio method during a 2.5 years study (R^2=0.89). In Spain, the evapotranspiration of an olive orchard was measured by the eddy correlation method. For periods with no rainfall, ET measured by the soil water balance method and the eddy correlation method agreed within 10% (Testi et al. 2004). Comparison of citrus transpiration measured by sap flow and evaporation by eddy correlation method also showed good agreement (< 10% difference) (Rana et al. 2005).

The sensible and latent heat fluxes were measured using a CSI CSAT3 3-D Sonic Anemometer and a CSI KH20 Krypton Hygrometer. The anemometer measures the three directional wind speeds and the hygrometer measures the vapor density of the air above the grass canopy. Fluctuations in wind speed, virtual air temperature, and vapor density were sampled at 10 Hz frequency and 30-minute average covariances were calculated to estimate the latent and sensible heat fluxes. Flux and atmospheric measurements were recorded by a CR23X datalogger.

The latent heat fluxes were corrected for temperature-induced fluctuations in air density (Webb et al. 1980) and for the hygrometer sensitivity to oxygen (Tanner and Greene 1989). Sensible heat fluxes were corrected for differences between the sonic temperature and the actual air temperature (Schotanus et al. 1983). Both the sensible and latent heat fluxes were corrected for misalignment with respect to the natural wind coordinate system (Baldocchi et al. 1988). The Bowen-ratio method was used to close the surface energy balance relationship (Twine et al. 2000).

During certain periods, evenings and early mornings having dew formation and after rainfall, the hygrometer measurements were not available due to water on the lens. The data analysis was conducted for daytime measurements, as the dew formation frequently limited the evening measurements. The limited availability of nighttime ET measurements due to humid conditions suggests that nighttime ET is negligible. Nighttime ET is likely to be significant only if standing water is present. Daytime periods after rainfall were excluded in the analysis.

Missing periods were modeled using the atmospheric data in the Priestley-Taylor method (Priestley and Taylor 1972) adjusted in order to determine total daily ET. Sumner (1996) noted that the Priestley-Taylor approach performed superior to Penman-Monteith for successional vegetation in central Florida.

Instruments

An eddy correlation system consists of two major instruments, the CSI CSAT3 3D Sonic Anemometer and KH20 Krypton Hygrometer. As discussion in detail by Jia et al. (2005), the sonic anemometer measures wind speed and the speed of sound using three pairs of nonorthogonal sonic transducers. A high frequency resolution enables the sensor to detect any changes that may be induced by wind fluctuations. By capturing the covariance of vertical wind speed fluctuations, as well as temperature and vapor density changes (using the Krypton hygrometer), the anemometer measurements are used to calculate the sensible and latent heat fluxes, which are components of the energy balance. The measurement of the path length is 10.0 cm vertically and 5.8 cm horizontally. The transducer path angle is 60 degrees from horizontal. Each transducer has a 0.64 cm diameter. The anemometer was set up facing the prevailing wind to minimize the negative effect by the anemometer arms and other supporting structures. After the anemometer was installed, the head of the instrument was adjusted so that the apparatus was level and parallel to the grass surface. The anemometer, like other ultrasonic anemometers, is incapable of measuring wind speed when water droplets are present on the transducers. As soon as the water droplets evaporate or are removed, the sensor automatically makes measurements. The frequency of the CSAT3 is 10 Hz with output averaged every 30 min.

The Krypton Hygrometer is normally mounted 10-15 cm from the center of the CSAT3, with the source tube (the longer tube) on the top and the detector tube (the shorter tube) on the bottom. The KH20 tubes were tilted to reduce water accumulation on the lenses. The measurement of vapor density is based on the attenuation of ultraviolet radiation emitted from the source tube to the detector tube, with a path distance of 1 cm. The output voltage of the hygrometer is proportional to the attenuated radiation, which is in turn related to vapor density fluctuations. The KH20 source and detector tube windows become scaled (weakened) with time, especially when exposed to a moist environment. The emitted signal will drop with time; therefore, distilled water is carefully used to clean the lenses at least once each week at the Eddy1 Station to restore the strength of the signal. The fluctuations of the signal are used in calculating the vapor density fluctuations, as long as the signals are not near zero or negative, the data is still useful. The frequency of the hygrometer is 10 Hz with an average output every 30 min.

The net radiation is measured by a Kipp & Zonen NR-LITE net radiometer. It measures the net radiation by balancing the solar and far infrared (long wave) radiation. The net radiation is the difference between the incoming and outgoing radiation. The upward facing sensor measures the incoming solar and far infrared radiation. The downward facing sensor measures the outgoing solar and far infrared radiation reflected by the surface. The sensor surfaces are coated with Teflon to ensure good sensor stability, long life and easy maintenance. Measurements require corrections at higher wind speed (> 5 m/s) conditions.

There is no external power needed for the operation of the instrument since the sensor measures high accuracy temperature differential, which is proportional to the net radiation. To provide both the lower and upper sensors with the same field view of 180 degrees and the same sensitivity, the sensor was balanced and leveled at installation.

The CSI HFT3 soil heat flux plate has a thickness of 3.91 mm and a diameter of 38.2 mm. Its measurement range is ± 100 W/m^2, and signal range is ± 2.4 mV with an accuracy of ± 5%. The plate is a thermopile and measures temperature gradients across the plate below the soil surface. The plate requires no maintenance.

Methods

In addition to being a component of the water balance, evapotranspiration is also a component of the energy budget equation. Evapotranspiration is the only term common to both the water budget and energy budget. The energy budget equation is

$$R_n = LE + H + G \qquad (3)$$

where R_n is the net radiation, in watts per square meter, H is the sensible heat flux into the atmosphere, in watts per square meter, G is the soil heat flux into ground, in watts per square meter, and LE is the latent heat flux, in watts per square meter. L is the latent heat of vaporization (2450 J/g at 20^oC) and E is the water evaporated, in grams per square meter per second.

The eddy correlation method measures the turbulent fluxes of vapor and heat above the canopy surface. The eddy correlation fluxes are calculated and recorded in a 30-min temporal resolution. Assuming the net lateral advection of vapor transfer is negligible, the latent heat flux (evapotranspiration) can be calculated from the covariance between the water vapor density (ρ_v) and the vertical wind speed (w) as

$$LE = \lambda \overline{w'\rho_v'} \qquad (4)$$

where LE is the latent heat flux (W/m^2), λ is the latent heat of vaporization (J/kg), ρ_v' is the fluctuation in the water vapor density (kg/m^3), and w' is the fluctuation in the vertical wind speed (m/s). The overbar represents the average of the period and the primes indicate the deviation from the mean values during the averaging period.

Sensible heat flux can be calculated from the covariance of air temperature and the vertical wind speed as

$$H = \rho_a C_p \overline{w'T'} \qquad (5)$$

where H is the sensible heat flux (W/m^2), ρ_a is the air density (kg/m^3), C_p is the specific heat of moist air (J/kg/^{o}C), and T' is the fluctuation in the air temperature (^{o}C).

The fine wire thermocouples (0.01 mm diameter) were not included in the eddy correlation system. The air temperature fluctuations, measured by the sonic anemometer, are corrected for air temperature fluctuations in estimation of sensible heat fluxes. The correction is for the effect of wind blowing normal to the sonic acoustic path. The simplified formula by Schotanus et al. (1983) is as follows:

$$\overline{w'T'} = \overline{w'T_s'} - 0.51\left(\overline{T + 273.15}\right)\overline{w'q'} \qquad (6)$$

where w'T' is rotated covariance of wind speed and sonic temperature (m ^{o}C/s), T is air temperature (^{o}C), and q is the specific humidity in grams of water vapor per grams of moist air.

Estimation of turbulent fluxes is highly dependent on the accuracy of the vertical wind speed measurements. Measurement of wind speed in three orthogonal directions with sonic anemometer requires a refined orientation with respect to the natural coordinate system through mathematic coordinate rotations (Sumner 2001). The vector of wind has three components (*u*, *v*, *w*) in three coordinate directions (x, y, z). The z-direction is oriented with respect to gravity, and the other two are arbitrary. Tanner and Thurtell (1969) and Baldocchi et al. (1988) provide procedures to transform the initial coordinate system to the natural coordinate system. Described in detail by Sumner (2001), the coordinate system is rotated by an angle η about the z-axis to align *u* into the x-direction on the x-y plane, and then rotated by an angle θ about the y-direction to align w along the z-direction. The results force $\bar{v}$ and $\bar{w}$ equal to zero, and $\bar{u}$ is pointed directly to the airstreams. When θ was greater than 10 degrees, the turbulent flux data should be excluded based on the assumption that spurious turbulence was the cause of the excessive amount of the coordinate rotation.

$$\cos\theta = \sqrt{\frac{\left(u^2 + v^2\right)}{\left(u^2 + v^2 + w^2\right)}} \qquad (7a)$$

$$\sin\theta = \frac{w}{\sqrt{\left(u^2 + v^2 + w^2\right)}} \qquad (7b)$$

$$\cos\eta = \frac{u}{\sqrt{\left(u^2 + v^2\right)}} \qquad (7c)$$

$$\sin\eta = \frac{v}{\sqrt{\left(u^2 + v^2\right)}} \qquad (7d)$$

The latent heat and sensible heat fluxes are computed from the coordinate rotation-transformed covariance as follows:

$$\left(\overline{w'\rho_v{}'}\right)_r = \overline{w'\rho_v{}'}\cos\theta - \overline{u'\rho_v{}'}\sin\theta\cos\eta - \overline{v'\rho_v{}'}\sin\theta\sin\eta \qquad (8)$$

$$\left(\overline{w'T_s{}'}\right)_r = \overline{w'T_s{}'}\cos\theta - \overline{u'T_s{}'}\sin\theta\cos\eta - \overline{v'T_s{}'}\sin\theta\sin\eta \qquad (9)$$

After the coordinate rotation, the final latent heat flux can be estimated from equation (4) with the corrections for air density (OC_1) (Webb et al. 1980) and for oxygen (OC_2) (Tanner and Greene 1989) given as

$$OC_1 = \frac{\overline{\rho_v}\,\overline{H}}{\overline{\rho C_p}\left(\overline{T + 273.15}\right)}\lambda \qquad (10)$$

$$OC_2 = \frac{FK_o\,\overline{H}}{K_w\left(\overline{T + 273.15}\right)}\lambda \qquad (11)$$

where F is the factor used in krypton hygrometer correction that accounts for molecular weights of air and oxygen, and atmospheric abundance of oxygen, equal to 0.229 g $^oC/J$, K_o is the extinction coefficient of hygrometer for oxygen, estimated as 0.0045 $m^3/g.cm$, K_w is the extinction coefficient of hygrometer for water, from the manufacture is 0.149 $m^3/g.cm$.

The Priestley-Taylor (PT) approach (1972) is used to estimate any missing 30-min LE values as follows

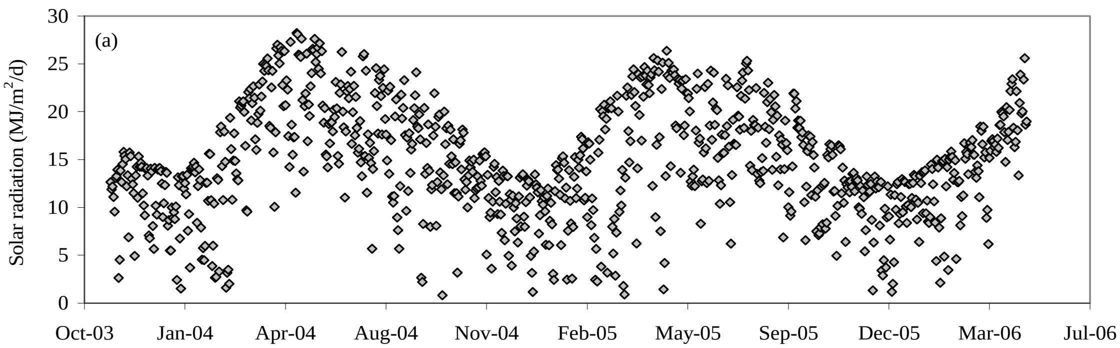
$$LE = \alpha\frac{\Delta(R_n - G)}{\Delta + \gamma} \qquad (12)$$

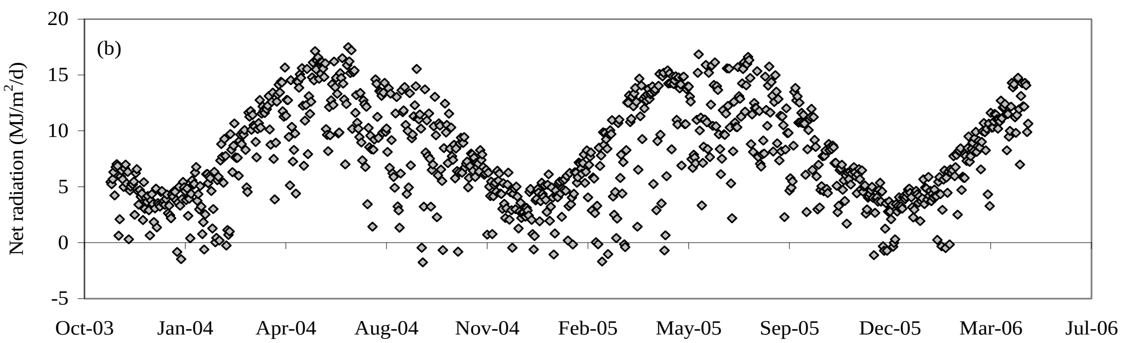
where α is empirical coefficient introduced to the original theoretical equation. Δ is the slope of saturation (kPa/^{o}C) and γ is the psychrometric constant in kPa/^{o}C. In this study, the empirical coefficient α was estimated from the measured LE values, and a monthly average α value was used in the calculations.

RESULTS

Meteorological conditions

Daily average solar radiation (R_s, $MJ/m^2/d$), net radiation (R_n, $MJ/m^2/d$), temperature (T, ^oC), relative humidity (RH, %), vapor pressure deficient (VPD, kPa), and wind speed at 2 m height (U_2, m/s) are plotted in Figure 7. The solar radiation and net radiation are high in the summer and low in the winter, with peak radiation values occurring in May for both years. Starting in June, the incoming and net energy decreased due to increased cloud cover and frequent afternoon rainfall. The lowest radiation energy values occurred during December and January.





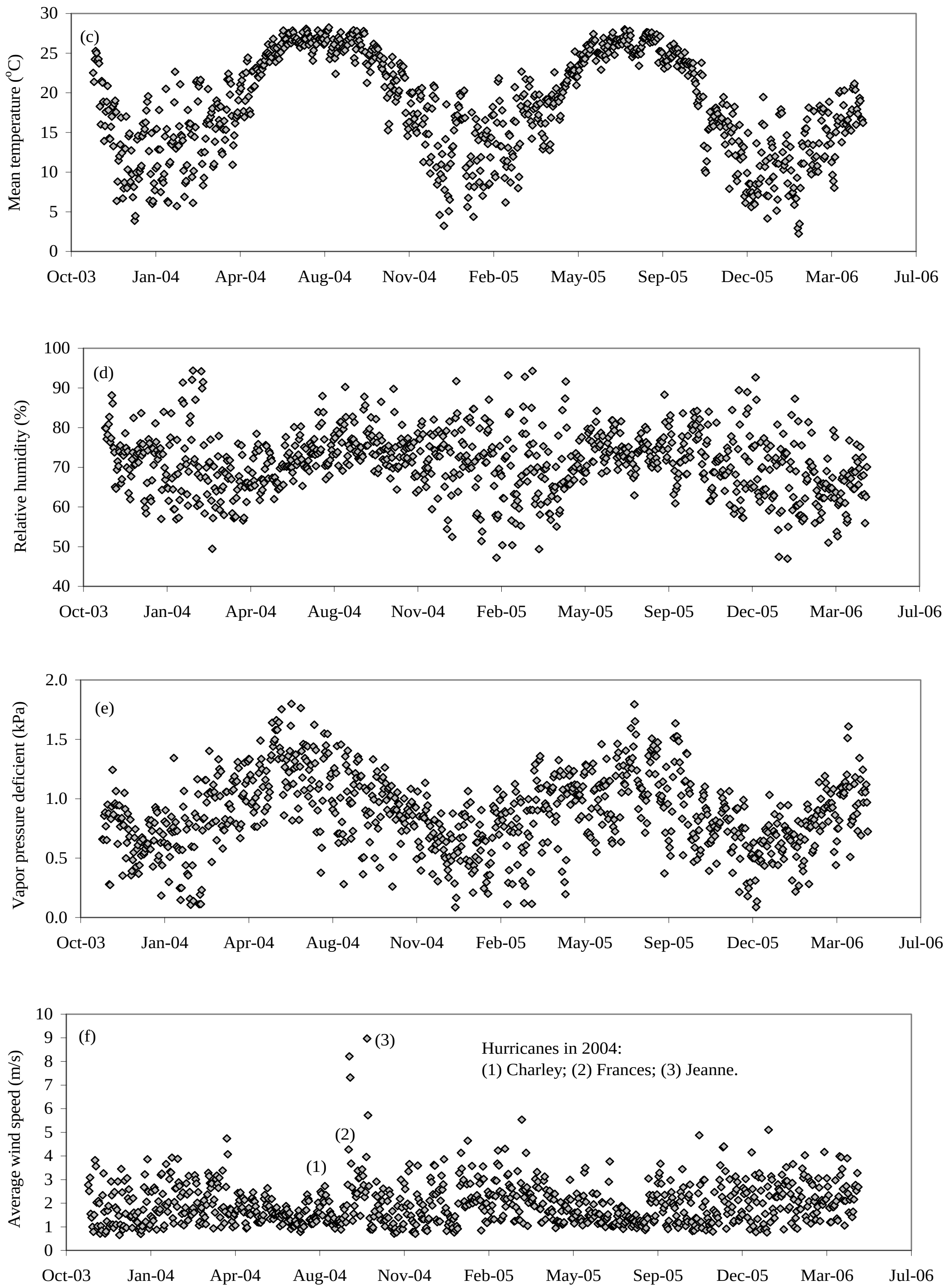


Figure 7. Daily average climate variables, (a) solar radiation, (b) net radiation, (c) temperature, (d) relative humidity, (e) vapor pressure deficient, and (f) wind speed at 2 m height from November 2003 to April 2006 at Citra, Florida.

The mean temperature at the experimental site follows an annual trend similar to the radiation change, higher in the summer and low in the winter. However, due to frequent rainfall, there is not a consistent relationship between solar radiation and temperature. The highest temperature values are from June to September. The lowest temperatures occur from December to March. The highest temperature variability also occurs in the winter months. For example, the mean temperature was 17.6^{o}C on Nov. 28, 2004 and decreased to 6.4^{o}C on the next day (Nov. 29) (Figure 7c).

The average relative humidity also has an annual pattern, higher in the summer than the rest of the year with the lowest values in the winter. In the summer, the average RH ranges from 70 to 90%, however, in the winter months, from November to March, there is higher RH variability, low near 50% and high above 90%.

The vapor pressure deficient (VPD), calculated from temperature and relative humidity, shows a clear annual cycle, with the highest in June and July and the lowest in January. The VPD variations are more consistent throughout the year than temperature and relative humidity.

Normally, the conditions are windier during the spring from February to May and calmer in the summer. In the fall of 2004, three hurricanes occurred at the experimental site, which are marked in Figure 7f. The hurricanes increased the average wind speed during the fall of 2004. As the wind speeds were higher in the spring of 2005 than the spring in 2004, the annual average wind speed values were comparable in 2004 and 2005.

Reference crop evapotranspiration

Reference crop evapotranspiration (ET_o) is defined as " the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (ASCE-EWRI 2005). The most recent standard method was established by the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) and was used in this study. This method requires solar radiation, temperature, relative humidity, and wind speed as the input data collected from a weather station. The detailed equations are also documented in the previous report (Jia et al. 2005). Before calculating the ET_o, all climate data were processed through the standard data quality check (ASCE-EWRI 2005).

Figure 8 shows the daily ET_o rates during the study period. The ET_o values differed in 2004 and 2005. The 2004 ET_o values (1243 mm) were 5% higher than the 2005 ET_o values (1180 mm). Maximum and minimum temperature and solar radiation values in 2004 exceeded those in 2005 by 3.3%, 5% and 6%, respectively.

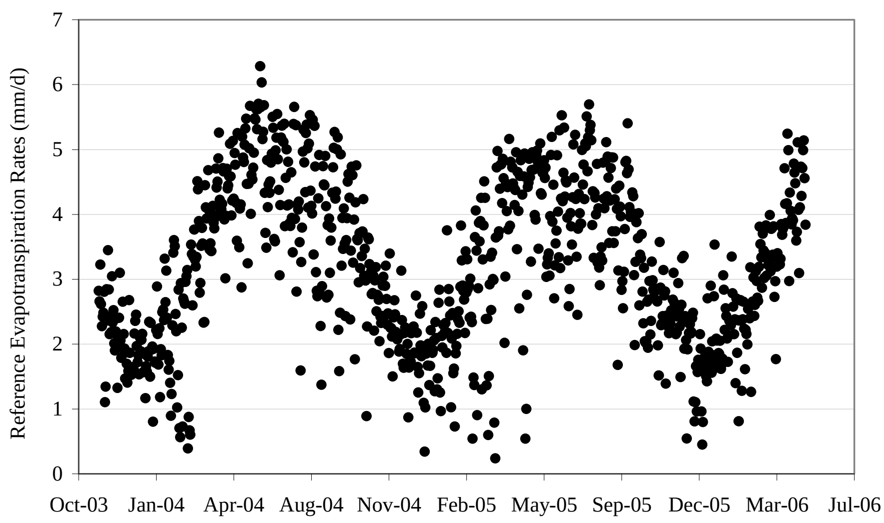


Figure 8. Reference crop evapotranspiration rates from November 2003 to April 2006.

Lysimeter evapotranspiration measurements

Bahiagrass evapotranspiration rates were measured from November 1, 2003 to April 30, 2006. During the study period, there are two major missing periods, 28 days in April of 2005 and 52 days in March/April of 2006 due to lysimeter maintenance. When pumping, precipitation, or mowing activities occurred, the daily ET_c rates might not be reliable and were reviewed prior to being used to calculate ET_c and crop coefficients. For example, the periods immediately following significant rainfall events often had high ET_c values. To provide preliminary estimates, monthly K_c values were calculated using only data measured when no pumping, precipitation, or mowing occurred (47% of the study period). To identify potentially erroneous K_c values, daily K_c values for days with pumping, precipitation, or mowing activities were calculated. These values were compared to the mean monthly values estimated from days with no activity. Measurement spikes exceeding 1.5 times average monthly K_c were excluded from the final K_c calculations. Of 912 days during the study period, 764 days (84%) of the daily ET_c values were used for the final analysis. The average daily ET_c rates from the lysimeters are shown in Figure 9.

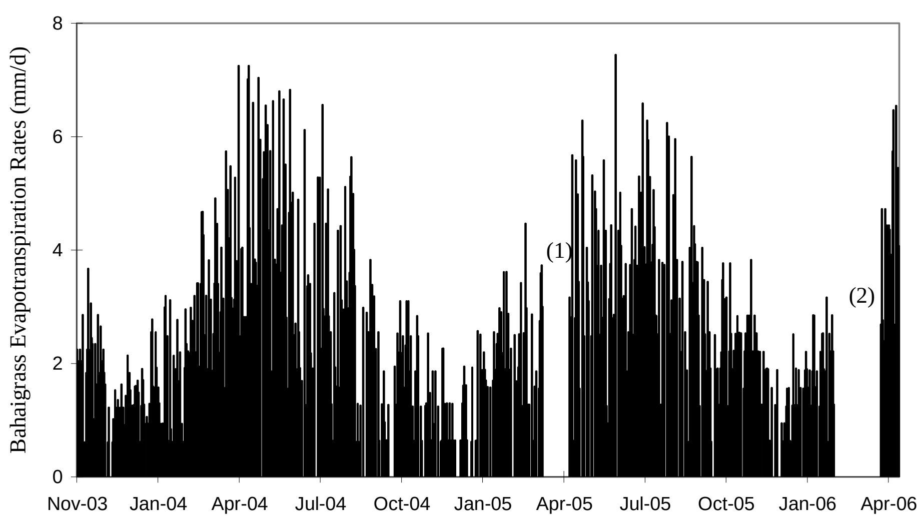


Figure 9. Daily bahiagrass evapotranspiration rates at Citra, Florida from November 2003 to April 2006. The ET_c measurements were missing from (1) 4/1/05 - 4/28/05 and (2) 2/17/06 - 4/9/06 due to field maintenance.

Monthly ET_c rates were calculated as the average from all three lysimeters. A comparison of these values to the reference crop evapotranspiration rates is shown in Figure 10. The results show that the lysimeter ET_c values have a similar annual cycle as the ET_o values and change simultaneously with the ET_o.

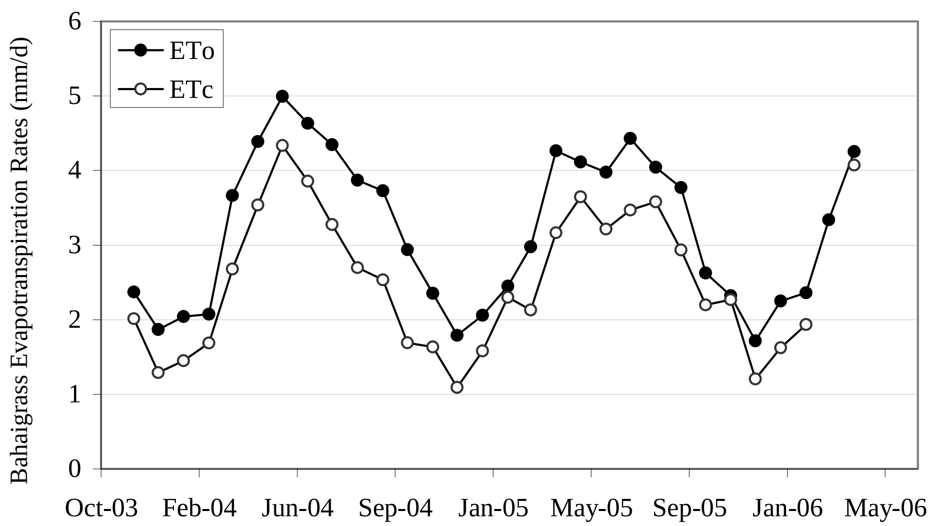


Figure 10. Monthly bahiagrass ET_c values from lysimeters and calculated ET_o values during the study period, November 2003 to April 2006 at Citra, Florida.

Eddy correlation evapotranspiration measurements

Energy fluxes

Figure 11 shows the daily average daytime energy fluxes at the experimental site. The total available energy (Net radiation (R_n) – soil heat flux (G)) were calculated for daytime only, corresponding to the daytime values when the latent heat flux (LE) and the sensible heat flux (H) were measured. The LE and H measurements were not consistently available during the nighttime.

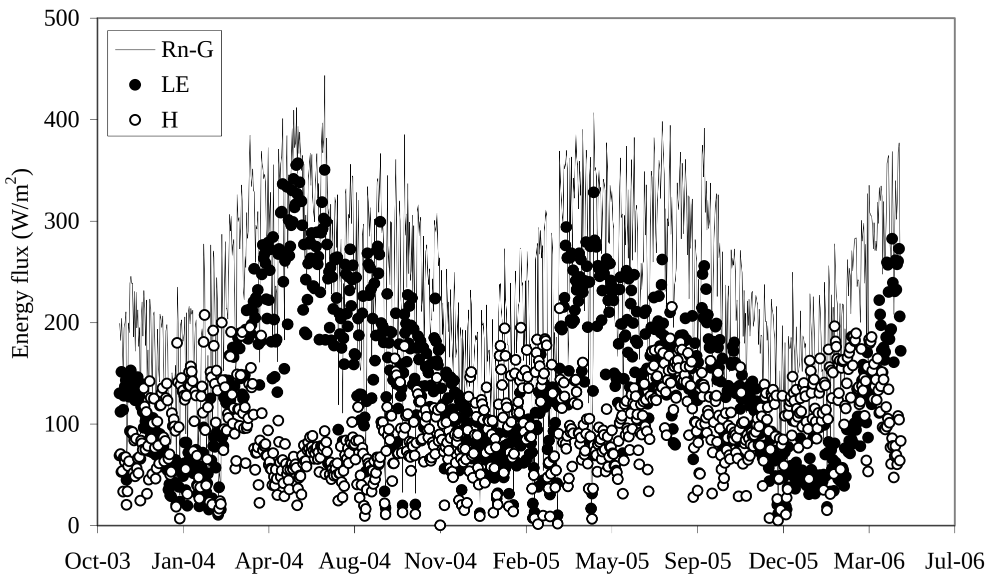


Figure 11. Daily average daytime energy fluxes at Citra, Florida from November 2003 to April 2006.

LE shows an annual cycle similar to the R_n – G, higher in the summer and lower in the winter, which implies that the evapotranspiration process depends on the available energy and changes simultaneously with the energy at the land surface. The H values have a different pattern than the LE and R_n-G. They are fairly consistent values throughout the year with slightly higher values in the winter than the summer. As expected, both LE and H are below the R_n-G during the entire study period. The LE values were greater than the H from April to September, indicating a large fraction of energy being used for grass evapotranspiration – energy used for changing the phase of water from liquid to vapor under isobaric-isothermal condition (ASCE 1996). During the rest of the months in the fall or spring, the LE and the H values were about the same.

The evaporative ratio, LE/R_n, and the Bowen ratio, H/LE, are plotted in Figures 12 and 13, respectively. These ratios were relatively consistent on a day-to-day basis, but varied seasonally. The fraction of net radiation used for evapotranspiration, LE/R_n, ranged from 20% in January to above 80% in May and June, and had a clear annual cycle in 2004. However, in 2005, the LE/R_n ratio did not show a clear annual pattern, possibly due to differences from the meteorological variables. The Bowen ratio, H/LE, was smaller in the summer months, indicating the grass has adequate soil moisture supply and is actively transpiring. In the winter months, December to March, the Bowen ratio was greater than 1, indicating a reduction in the relative use of available energy for crop evapotranspiration.

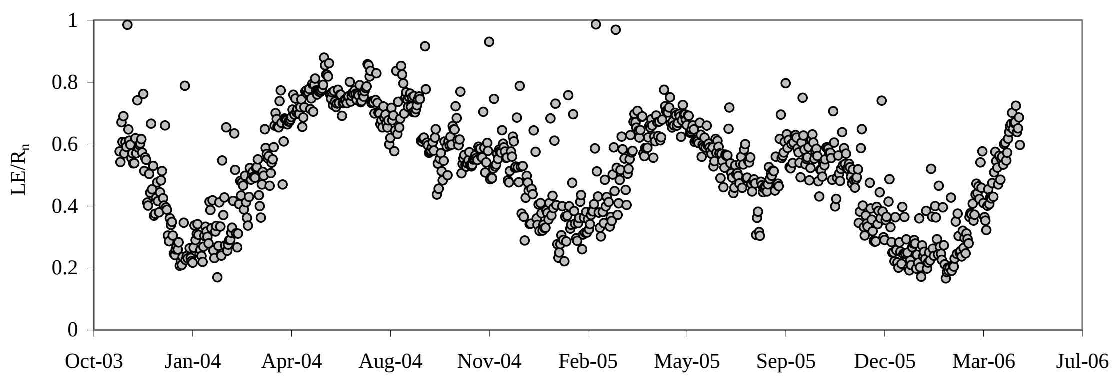


Figure 12. Ratio of daytime latent heat flux (LE) to daytime net radiation (R_n) over grass reference at Citra, Florida from November 2003 to April 2006.

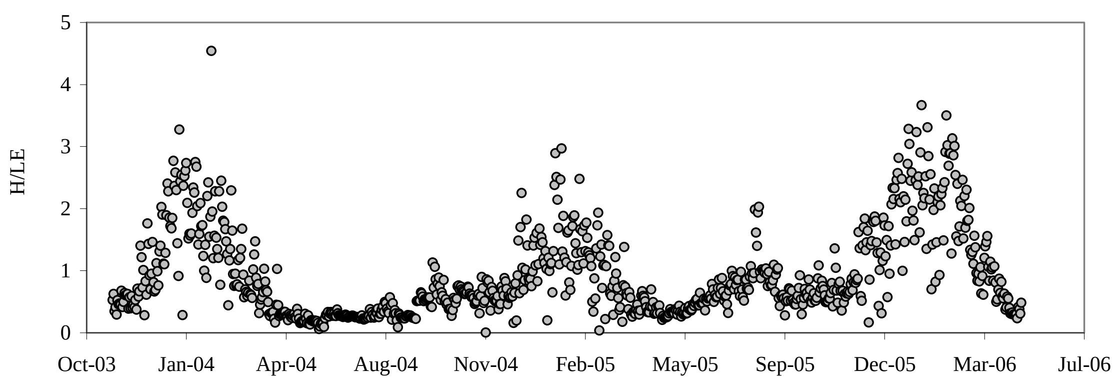


Figure 13. The Bowen ratio (ratio of daytime sensible heat flux (H) to daytime latent heat flux (LE)) over grass surface at Citra, Florida from November 2003 to April 2006.

Table 3 summarizes the monthly average values for daytime energy fluxes. The R_n and the LE values were highest in April and lowest in January. For the whole study period, the net radiation partitioned 55% into latent heat flux, 36% into sensible heat flux and 9% into soil heat flux.

Table 3. Monthly values of daytime energy fluxes (R_n = net radiation, LE= latent heat flux, H=sensible heat flux, and G=soil heat flux) and ratios of LE/R_n, H/R_n, G/R_n, and H/LE over grass surface at Citra, Florida from November 2003 to April 2006.

Month	R_n	LE	H	G	LE/R_n	H/R_n	G/R_n	H/LE
1	195	57	108	31	0.33	0.54	0.13	1.93
2	208	64	112	33	0.34	0.52	0.14	1.74
3	287	124	123	40	0.47	0.41	0.12	1.02
4	348	217	93	38	0.63	0.27	0.11	0.45
5	344	251	62	31	0.75	0.17	0.08	0.25
6	321	219	83	20	0.68	0.26	0.06	0.40
7	311	193	93	25	0.63	0.29	0.07	0.50
8	295	171	102	23	0.60	0.33	0.07	0.67
9	281	161	98	22	0.60	0.36	0.04	0.61
10	253	142	86	25	0.56	0.34	0.09	0.62
11	221	120	79	22	0.56	0.35	0.09	0.70
12	180	70	85	25	0.42	0.47	0.11	1.30
Annual	**271**	**149**	**94**	**28**	**0.55**	**0.36**	**0.09**	**0.85**

All energy fluxes are in W/m^2 and ratios have no units.

Evapotranspiration rates

The daily average evapotranspiration rates by the eddy correlation method are plotted in Figure 14. Evapotranspiration differed by year with 2004 having higher summer values than 2005. The differences reflect the relatively higher rainfall during the summer 2004 compared to the summer 2005. Monthly ET_c values by eddy correlation method are highly related to the ET_o values (Figure 15).

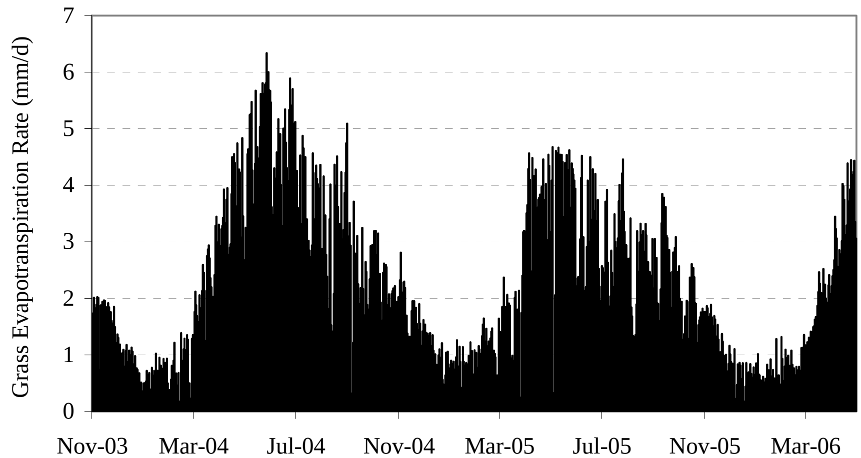


Figure 14. Daily grass evapotranspiration rates estimated by eddy correlation method at Citra, Florida from November 2003 to April 2006.

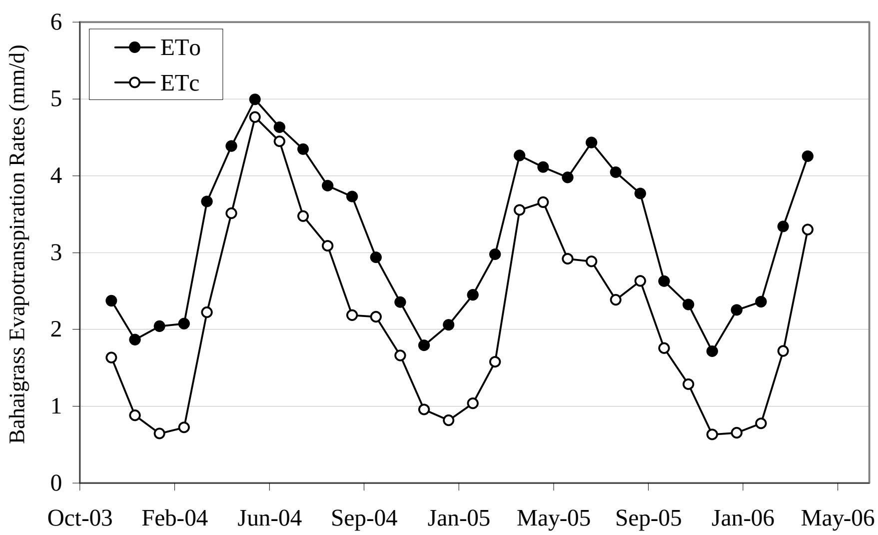


Figure 15. Monthly bahiagrass ET_c by eddy correlation vs. calculated ET_o values during the study period from November 2003 to April 2006 in central Florida.

Lysimeter and eddy correlation comparison

Figure 16 compares the daily ET_c values by the two methods, eddy correlation and lysimeters, using the procedures described above. During most of the season, the values by the two methods had similar trends; however, the lysimeter method measurements tended to vary more than those by the eddy correlation method. The maximum daily ET_c values measured by the eddy correlation method were approximately 6 mm/day. Daily values measured by the lysimeters exceeded 7 mm/day on several days.

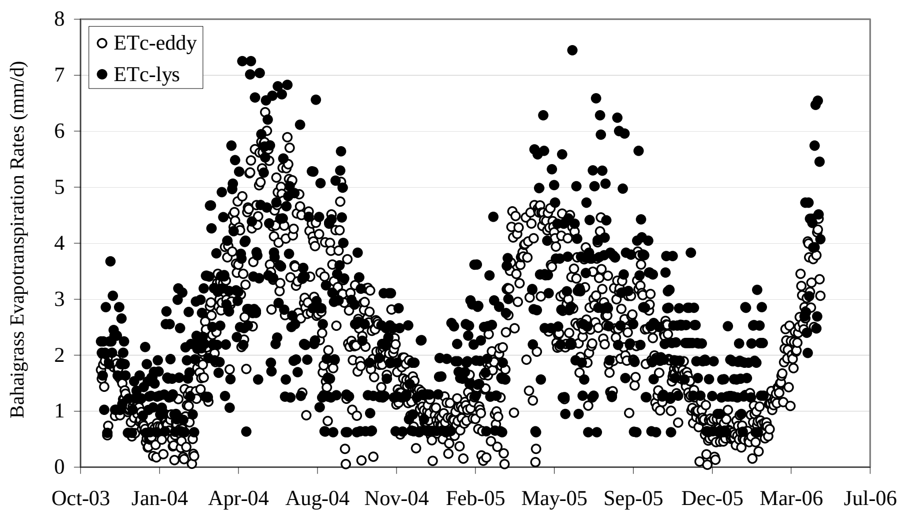


Figure 16. Daily grass ET_c rates by lysimeters and eddy correlation methods at Citra, Florida from November 2003 to April 2006.

Figure 17 shows the grass ET_c rates by the lysimeters and eddy correlation methods and ET_o rates by month. Monthly measured ET_c values never exceeded the ET_o values. Eddy ET_c values were typically lower than the lysimeters values during the winter and early spring. Summer values were comparable, with the eddy measurements being slightly higher than the lysimeters measurements in 2004 and slightly lower in 2005.

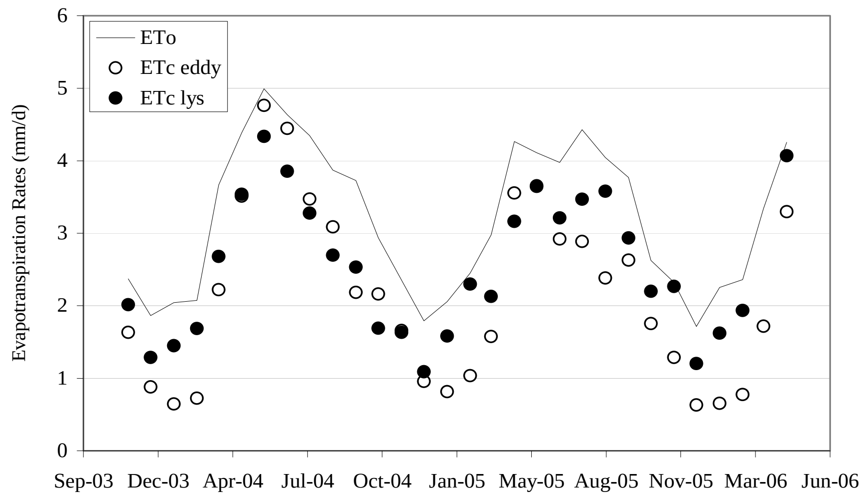


Figure 17. Monthly grass ET_c rates by lysimeters and eddy correlation methods and ET_o rates at Citra, Florida from November 2003 to April 2006.

Bahiagrass crop coefficients were calculated from the ratio of actual measured crop ET to reference crop ET. Figure 18 compares the individual monthly K_c values from the lysimeters and the eddy correlation method. The results show that the lysimeters typically had higher crop coefficients during the winter and spring. Average monthly crop coefficients (Figure 19) are reasonably similar from both methods during the growing season, April to October. However, the lysimeter's K_c values were much higher than the eddy K_c values for the remainder of the year.

Ideally, the monthly K_c values by the two methods should be the same because the two stations were only 80 m apart and all the field activities were applied to maintain the two sites identical. However, as indicated in the results, the K_c values were different, especially in the winter months. In Appendix 1, photos at the lysimeter site and in the surrounding field are paired for each month from November 2003 to April 2006. The photos show that the grass grew differently in the winter time. Inside the lysimeter, the grass was green and vivid.

In the field surrounding the lysimeter, the grass was dormant and yellowish. Soil temperature measurements indicate that the average temperature for seven days in February

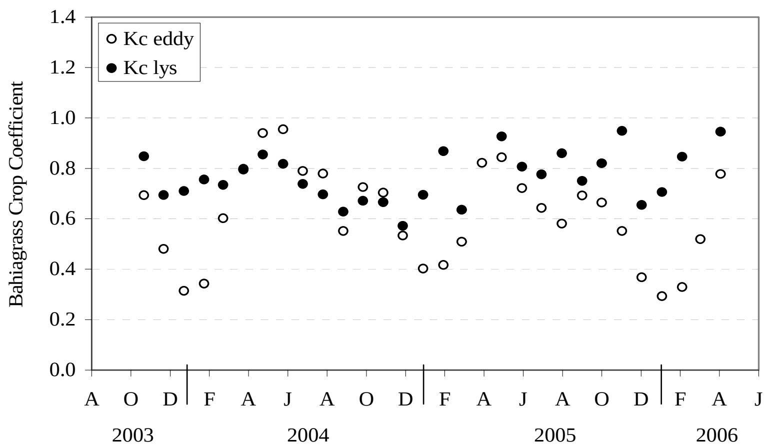


Figure 18. Monthly bahiagrass crop coefficients by eddy correlation (Kc eddy) and lysimeter (Kc lys) from November 2003 to April 2006.

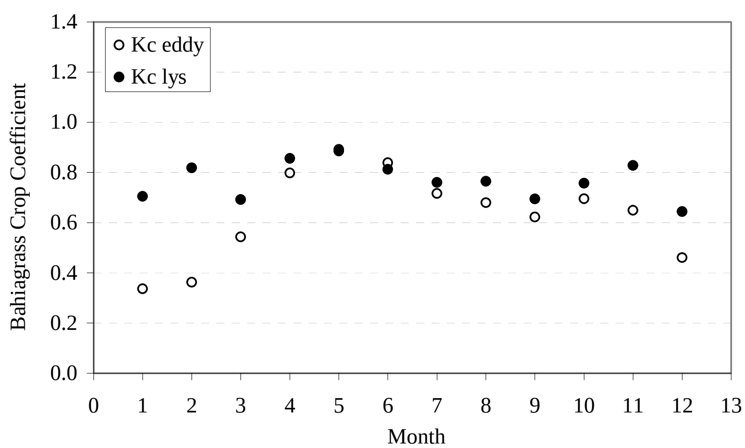


Figure 19. Monthly bahiagrass crop coefficients by eddy correlation (Kc eddy) and lysimeter (Kc lys) methods.

2006 inside the lysimeters was 0.86°C (10 cm depth) and 1.43°C (20 cm depth) higher than the surrounding field. Overall, the micro-environment (soil moisture, soil temperature, nutrient, texture, etc.) inside the lysimeter seems to favor grass growth because even during the summer time, the grass inside the lysimeter grew faster than the grass outside. For example, the grass height inside the lysimeter was 7.5 cm and 16 cm on August 11 and 19, 2005, respectively, yielded a grass growth rate 1.06 cm/d. In the surrounding field, the grass was 7.5 cm and 12.5 cm on August 11 and 19, respectively, yielded a grass growth rate 0.62 cm/d. These observed differences between the lysimeters and surrounding field suggest that the differences between the monthly K_c values by the two methods are probably due to differences in grass growth. The grass inside the lysimeters had a favorable microenvironment resulting in a longer active growing season and higher winter transpiration values than the surrounding grass. The grass in the surrounding field represents a more realistic field environment and thus is recommended as the source for the K_c values. During the summer time, even though the grass growth showed some differences, the crop coefficients by the two methods were similar, implying that the eddy correlation method is working correctly and comparable with the lysimeter method, thus corresponding with the objectives of the research.

Table 4 summarizes the ET_o, ET_c and K_c values by month and method. During the wintertime, the relatively wet and warm tank conditions maintained an actively transpiring grass that was not representative of the surrounding conditions. Thus, the lysimeter values provide insight as to values under much wetter and warmer conditions. The eddy K_c values in December, January, February, and March are representative of dormant grass conditions consistently observed during the experiment. During the summertime, the lysimeter results are similar to those values measured by the eddy correlation system and support the values measured by the eddy correlation system. However, the lysimeters had higher day-to-day variations than the eddy correlation system due to necessary maintenance such as pumping and variable drainage patterns within the three lysimeters. The eddy correlation system provided consistent reliable measurements of evapotranspiration and crop coefficients. Thus, the recommended coefficients for bahiagrass are those derived using eddy correlation system measurements.

Table 4. Monthly bahiagrass evapotranspiration (ET_c) and crop coefficient (K_c) by lysimeters (lys) and eddy correlation (eddy) method: average (Avg) and standard deviation (Std). Recommended crop coefficient values have a bold type.

Month	**ET_o**		**ET_c Lys**		**ET_c eddy**		**K_c lys**		**K_c eddy**	
	Avg	**Std**	**Avg**	**Std**	**Avg**	**Std**	**Avg**	**Std**	**Avg**	**Std**
1	2.12	0.55	1.54	0.58	0.70	0.24	0.70	0.22	**0.34**	0.10
2	2.29	0.86	1.97	0.82	0.84	0.40	0.82	0.27	**0.36**	0.11
3	3.33	0.90	2.44	1.04	1.84	0.70	0.69	0.24	**0.54**	0.14
4	4.30	0.60	3.74	1.40	3.45	0.79	0.86	0.29	**0.80**	0.13
5	4.55	1.07	4.04	1.74	4.21	1.33	0.89	0.27	**0.89**	0.16
6	4.30	0.83	3.56	1.62	3.68	1.17	0.81	0.32	**0.84**	0.15
7	4.39	0.82	3.39	1.60	3.18	0.89	0.76	0.31	**0.72**	0.12
8	3.96	0.89	3.07	1.55	2.74	0.99	0.76	0.32	**0.68**	0.15
9	3.75	0.87	2.75	1.32	2.41	0.85	0.69	0.29	**0.62**	0.16
10	2.78	0.59	1.98	0.84	1.96	0.58	0.76	0.34	**0.69**	0.13
11	2.35	0.52	1.99	0.73	1.53	0.47	0.83	0.28	**0.65**	0.17
12	1.79	0.49	1.20	0.51	0.82	0.32	0.64	0.24	**0.46**	0.15
Annual	**3.20**	**1.23**	**2.56**	**1.48**	**2.14**	**1.37**	**0.77**	**0.29**	**0.61**	**0.22**

Values during the actively growing season are supported by previous studies on grass in the southeastern U.S.. For a non-irrigated pasture in central Florida, Sumner and Jacobs (2005) determined that the crop coefficients were 0.47 in Jan. and 0.92 in July, using eddy correlation method for the ET_c and FAO56 for the ET_o. The K_c values during the winter months were higher than our recommended values, possibly due to the grass difference, while the natural grass was tall and Citra grass was maintained short. Carrow (1995) compared K_c values for seven grass species used in the Southeast U.S. using a soil water balance method for ETc and modified Penman Monteith method for ET_o. The K_c values for the five warm season grasses ranged from 0.49 for a common bermudagrass in June to 1.24 for a common centipede grass in September.

SUMMARY AND CONCLUSIONS

A study was conducted which measured bahiagrass evapotranspiration rates from November 1, 2003 through April 30, 2006, using three weighing lysimeters and one eddy correlation system. Meteorological factors necessary to calculate reference ET were also measured. The experiment was conducted at the Institute of Food and Agricultural Sciences (IFAS), Plant Science Research Education Unit (PSREU). The results include daily measurements of bahiagrass ET_c, ET_o, and monthly K_c values. The lowest average monthly ET_c value (0.70 mm/day) occurred in January. The highest average monthly value (4.21 mm/day) occurred in May. Recommended monthly crop coefficient values were derived from those measured by the eddy correlation system. Crop coefficients ranged from 0.34 in January to 0.89 in May.

ACKNOWLEDGEMENT

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APPENDIX A

Figure A1. Grass at the lysimeter site (left) and the eddy correlation station (right) in January 2006.

Figure A2. Grass inside the lysimeter (left) and in the surrounding field (right) in February 2005.

Figure A3. Grass in the lysimeter (left) and in the surrounding field (right) in March 2005.

Figure A4. Grass at the lysimeter site (left) and in the surrounding field (right) in April 2006. Notice that the cover frame of the lysimeter has been changed since February 2006.

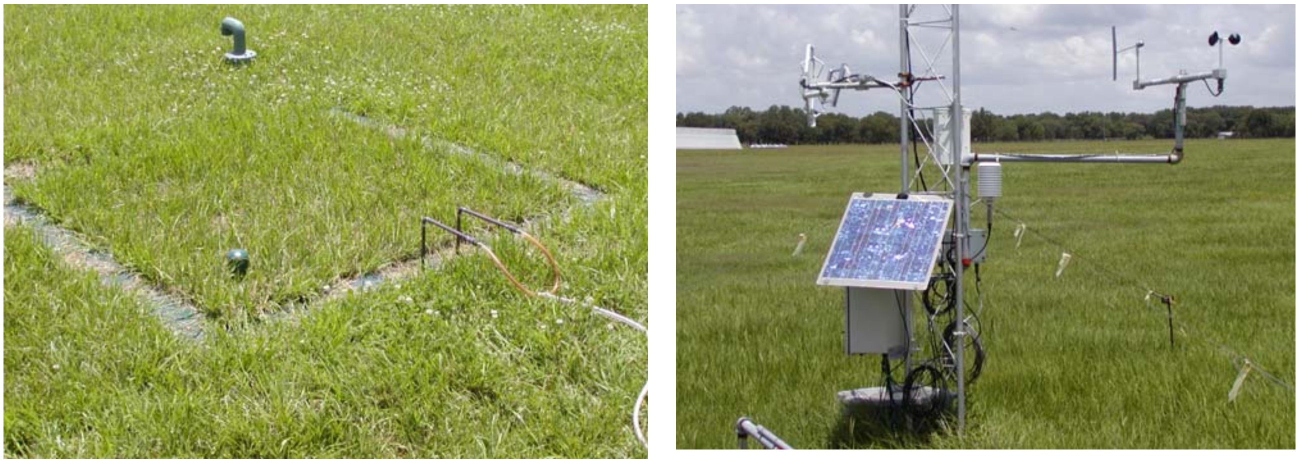

Figure A5. Grass at the lysimeter site (left) and the eddy correlation station (right) in May 2004.

Figure A6. Grass at the lysimeter site (left) and the eddy correlation station (right) in June 2005.

Figure A7. Grass at the lysimeter site (left) and the eddy correlation station (right) in July 2005. Notice that the eddy correlation station was just mowed.

Figure A8. Grass at the lysimeter site (left) and at the eddy correlation station (right) in August 2005.

Figure A9. Grass in the lysimeter (left) and in the surrounding field (right) in September 2004.

Figure A10. Grass inside the lysimeter (left) and at the eddy correlation station (right) in October 2005.

Figure A11. Grass inside the lysimeter (left) and in the surrounding field (right) in November 2004.

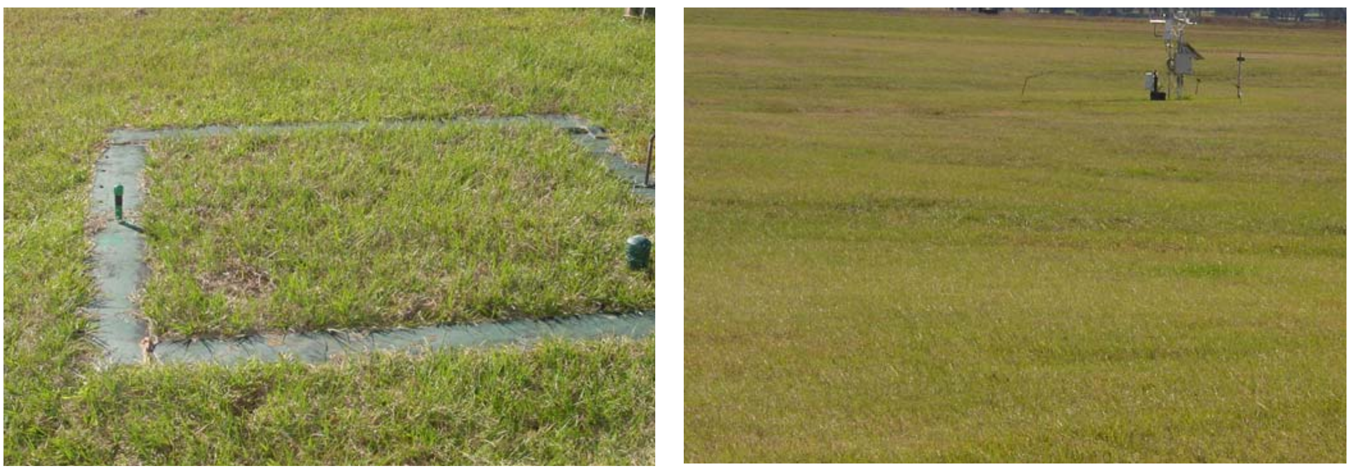

Figure A12. Grass in the lysimeter (left) and near the eddy correlation station (right) in December 2005.

REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL

APPENDIX 5
CROP COEFFICIENTS FOR CITRUS
TASKS 7, 14, 18, and 25

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ABSTRACT

Citrus is one of the most important agricultural crops in Florida. It accounts for 80% of the citrus production in the United States. Irrigation is required to ensure citrus quantity and quality due to low soil water holding capacity sandy soils commonly found in Florida. Citrus evapotranspiration and crop coefficients are critical parameters for citrus irrigation scheduling and water management. Florida citrus groves are typically grown in two sets of conditions in two regions of the state: flatwoods in the southern and coastal region of the state and ridge in the northern and central portion of the state. In this study, an experiment in the ridge region was conducted in central Florida, at Weirsdale, Marion County from August 1, 2004 through July 31, 2006. Citrus evapotranspiration (ET_c) and crop coefficient (K_c) values were estimated using the eddy correlation method. The eddy correlation method is an innovative approach to estimate ET_c by measuring it above crop canopy. This method can be readily adapted to the trees characteristic of a citrus grove. The measured citrus ET_c showed a clear annual cycle similar to radiation energy flux, with a decrease in May due to frequent rainfall events. Citrus crop coefficients (K_c) were estimated from the ratio of citrus ET_c to reference evapotranspiration (ET_o) calculated from weather data over a grass reference site. The citrus K_c values are 0.70 for dormant conditions from January to March. The citrus K_c peak values are 1.05 from July to November. In December, a K_c value reduction from 1.05 to 0.80 was triggered by a continuous minimum temperature (about a week) below 10^oC.

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL
APPENDIX 5 - CROP COEFFICIENTS FOR CITRUS

INTRODUCTION

The importance of evapotranspiration (ET) in the hydrologic cycle, irrigation scheduling and water resources management has long been recognized. In agricultural applications, evapotranspiration is a fundamental and important process and is the main loss of water from the vegetation and soil surface. Therefore, accurate estimation of ET is important in agricultural water management. However, accurate ET measurement is difficult to obtain due to numerous factors. The magnitude of ET varies seasonally and diurnally. It is influenced by climate conditions, soil and vegetation surfaces, soil moisture status, crop phenology, growth stage, shading, and ground cover.

There are two common ways to determine the evapotranspiration rate, direct and indirect methods. Direct measuring methods include soil water depletion, lysimeter, water balance, energy balance, mass transfer, eddy correlation, and combination of energy and heat (Jensen et al. 1990). Indirect measuring methods relate reference evapotranspiration (ET_o) to a crop coefficient (K_c). The crop coefficient multiplied by the reference ET value yields the crop ET. ET_o can be calculated from weather data collected from a well-watered reference crop surface. Many methods have been developed to estimate ET_o and the most current method has been developed by the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) (ASCE-EWRI 2005). Crop coefficient development requires both crop evapotranspiration (ET_c) and ET_o estimates for a specific crop and location.

Eddy correlation is a new and innovative method. It has been used successfully to directly measure evapotranspiration (Sumner 2001; Sumner and Jacobs 2005). This method overcomes the need to determine each component in the energy balance. It also avoids soil surface heterogeneity issues by placing the sensors above the crop canopy. The temporal resolution of ET measurement is less than 1 hour.

Purpose and scope

The University of Florida (UF), in cooperation with the St. Johns River Water Management District, began a study in 2003 to determine major crop coefficients (K_c) in central Florida. Crop coefficients are to be obtained for three crops, bahiagrass, citrus, and sod. The measured K_c values are used to improve the Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS) software, as well as, to provide guidance in evapotranspiration estimates.

This report summarizes the experimental design and results for the citrus experiment. Citrus evapotranspiration rates were measured on a nearly continuous basis from August 1, 2004 through July 31, 2006, using an eddy correlation system. Results include daily measurements of citrus evapotranspiration and reference crop evapotranspiration rates as well as monthly crop coefficients.

DESCRIPTION OF THE STUDY AREA

The experimental site is located in the central ridge area of Florida, east of Weirsdale in Marion County, Florida (latitude 28^o 59’ 54” N, longitude 81^o 51’ 46” W) at about 23 m above sea level) (Figure 1, Appendix A). The citrus grove has 95 ha of various citrus varieties. The weather station is located near the center of the grove, where ‘Parson Brown’ variety of sweet orange (citrus sinensis (L) Osbeck) is grown (Figure 2). Trees were planted in 1989 and spacing is 3.8 meters between trees and 7.7 m between rows (340 trees/ha). Rows run north to south on level fields. The space between rows is maintained as bare soil through tillage (Figure 3). Near the tower, the trees are mature and their height is maintained at 5 to 6 m by annual hedging. The shortest distance from the eddy flux station to the northwest edge of the grove, where oak trees are growing, is 170 m. The soil type at the site is Candler fine sand (Thomas et al. 1979), which is nearly level to strongly sloping, excessively drained and well drained sandy soils, and with thin sandy loam lamellae at a depth of 1.5-2.0 m. The water table is greater than 2.0 m below the surface. Roots are found primarily in the upper 1 m of the soil.

A second weather station is located at the Plant Science Research and Education Unit (PSREU), near Citra, Marion County, Florida (Fig. 1). This weather station was chosen as the reference evapotranspiration site for citrus crop coefficient development. It is located in the middle of 23 ha bahiagrass field (Jia et al. 2006) and the shortest distance to the side of the field is 230 m.

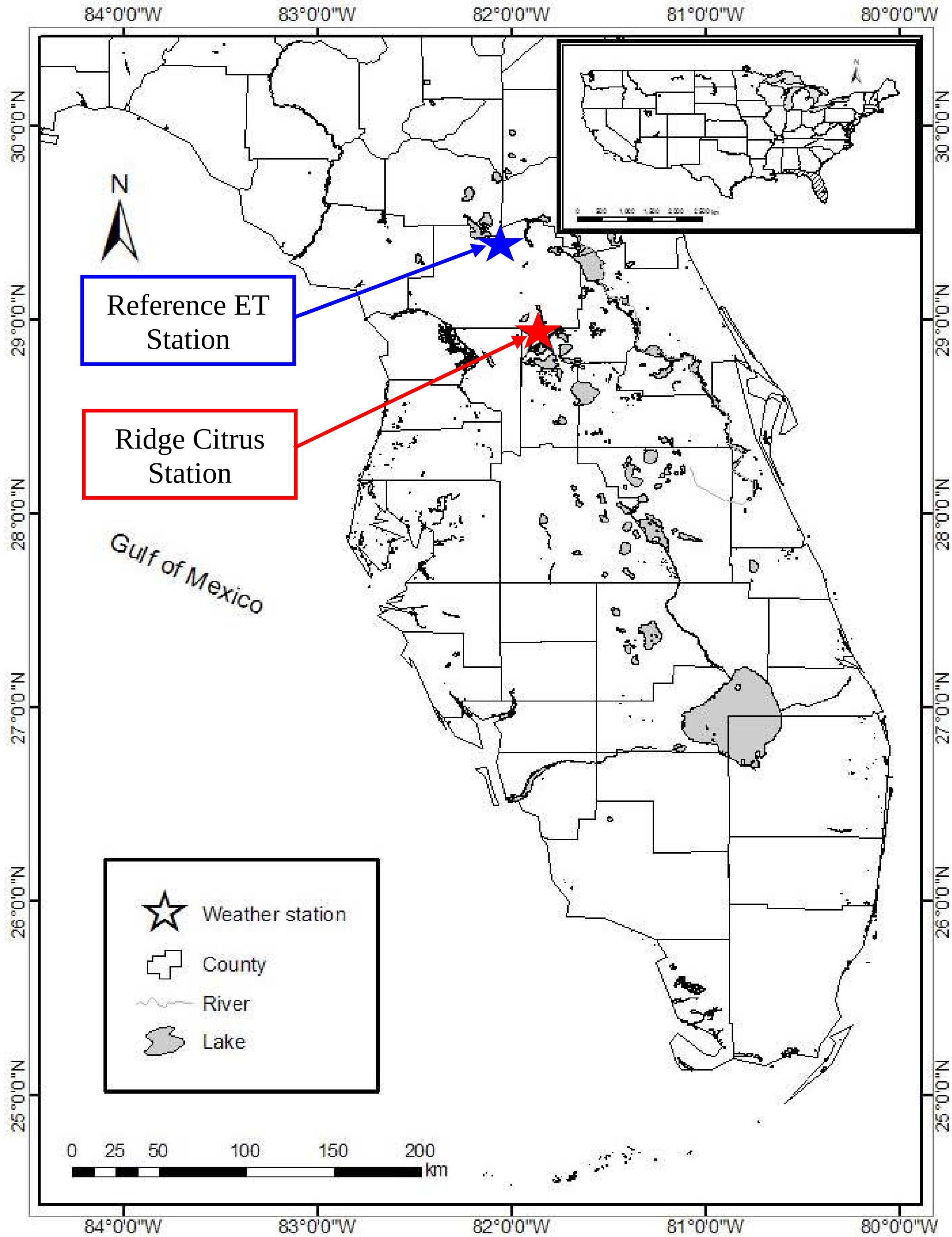


Figure 1. Experimental sites.

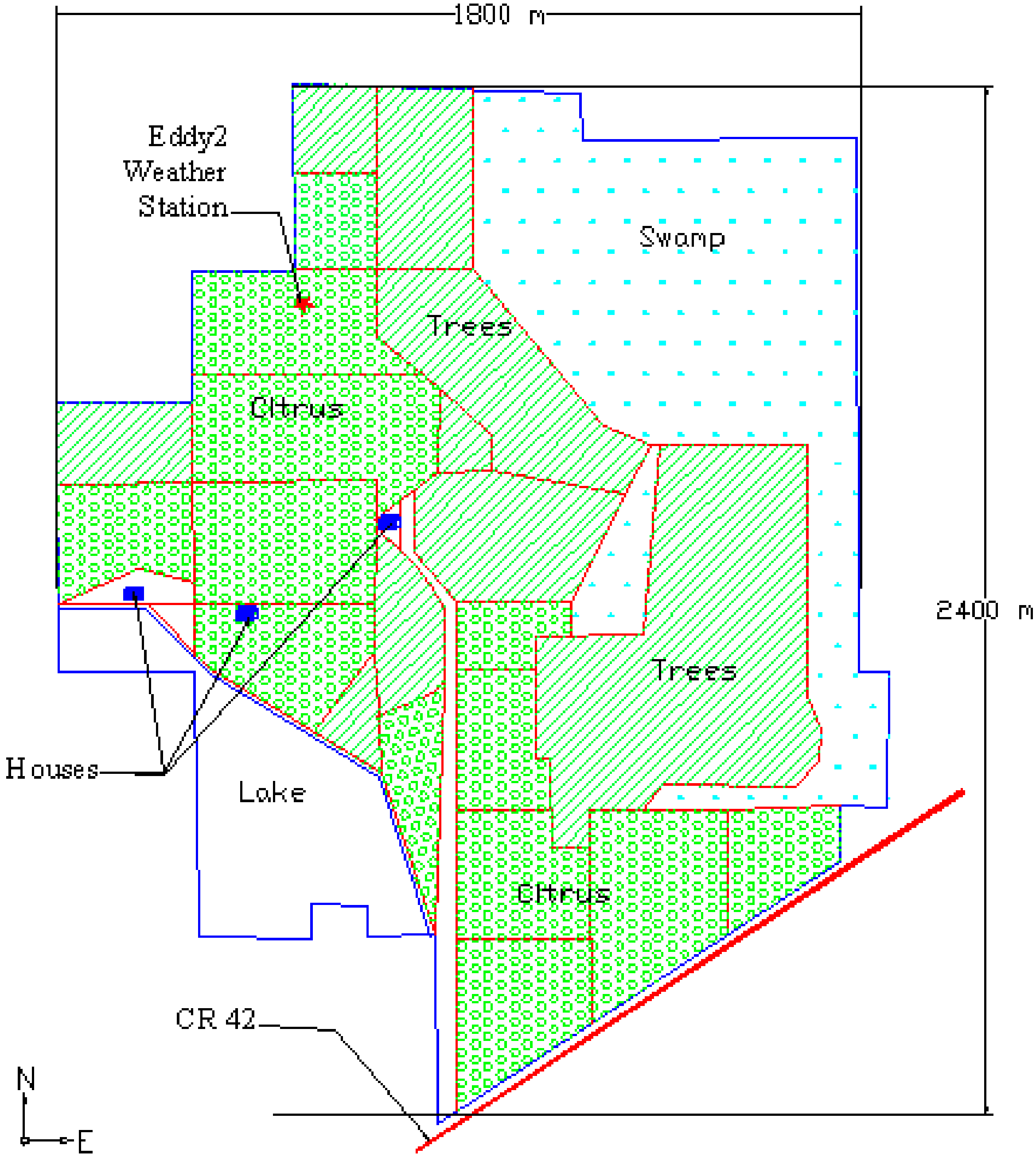


Figure 2. Location of weather station in the citrus grove.

Figure 3. Photo of ground cover in the citrus grove on December 9, 2005 (from south to north direction).

The climate in this central region of Florida is humid subtropical, with an average annual rainfall of 1,350 mm (Purdum 2002). Most of the rainfall (60%) occurs from June to September. Afternoon thunderstorms are frequent during this period and it rains on most days. Annual average evapotranspiration is estimated to be 945 mm, which is 70% of the total rainfall (Purdum 2002).

Meteorological variables are also measured near the experimental site by a Florida Automated Weather Network (FAWN) station. Table 1 lists monthly average values for air temperature (T_{ave}), relative humidity (RH_{avg}), solar radiation (R_s), wind speed (W_{sp}), and wind direction (W_{dir}) and average monthly rainfall calculated for 6.6 years of FAWN data from January 1999 to July 31 2006. The average annual temperature is 20.9^{o}C, with a maximum monthly temperature of 38.2^{o}C in August and a minimum temperature of – 5.0^{o}C in January. The average annual rainfall for this 6.6 year period is 1160 mm. The prevalent wind direction is from the southwest or southeast.

Table 1. Weather variables near the weather station from Florida Automated Weather Network from Jan. 1999 to Aug. 2006. T_{ave}, $RH_{ave,}$ R_s, W_{spd}, and W_{dir} are average daily values. Rain is the average total rainfall for a given month. T_{max} and T_{min} are the daily maximum and minimum temperatures.

Month	T_{ave} (°C)	T_{min} (°C)	T_{max} (°C)	RH_{avg} (%)	Rain (mm)	R_s (W/m^2)	W_{sp} at 10 m (m/s)	W_{dir} at 10 m (degree)
1	13.39	-5.00	29.59	75	43.4	139	1.06	189
2	15.27	-3.00	30.41	75	71.4	156	1.12	178
3	18.25	-2.14	33.34	71	93.9	195	1.29	182
4	21.08	1.57	34.70	69	47.2	264	1.29	180
5	24.34	6.55	37.65	69	59.9	269	1.29	170
6	25.80	14.80	37.61	78	218.1	215	1.12	154
7	26.51	17.86	37.91	80	195.9	227	1.23	169
8	26.34	17.59	38.16	80	91.9	225	1.01	165
9	25.39	14.53	36.95	81	187.9	187	1.34	146
10	21.87	4.84	34.00	78	58.1	168	1.47	133
11	18.08	-4.24	31.84	77	36.9	148	1.28	158
12	13.80	-3.50	30.17	77	56.3	125	1.02	175
Annual	**20.89**	**-5.00**	**38.16**	**76**	**1161**	**196**	**1.21**	**167**

METHODS FOR MEASUREMENT AND ESTIMATION OF EVAPOTRANSPIRATION

Evapotranspiration is the combined process by which water is transferred from the earth's surface to the atmosphere; evaporation of liquid water from the soil surface and water intercepted by plants, plus transpiration by plants (Jensen et al. 1990). Potential ET refers to evapotranspiration of a disease-free crop, grown in very large fields, not short of water and fertilizer (Doorenbos and Pruitt 1977). Actual ET will depend on many other factors, such as climate, soil water conditions, methods of irrigation, and cultural practices.

In this study, the eddy correlation was used to estimate ET_c using two-years of data. Daily ET_c and monthly ET_c values were estimated. Daily and monthly crop coefficients were developed using the reference evapotranspiration calculated by the ASCE-EWRI method (ASCE-EWRI 2005).

Eddy correlation method

Background

Eddy correlation measures actual evapotranspiration using measurements of the turbulent atmosphere. The average vertical movement of water is measured using a high frequency sampling of the atmosphere's water specific humidity and vertical wind speed averaged over 30-minute periods.

The eddy correlation station is used to directly measure actual evapotranspiration using an energy-budget approach (Tanner and Greene 1989; Twine et al. 2000). It is a proven approach for estimating evapotranspiration from various types of vegetation (Sumner 1996 2001; Gholz and Clark 2002; Sumner and Jacobs 2005). This method overcomes uncertainties due to soil surface conditions and crop growth stages by measuring water vapor fluxes above the crop canopy.

In Belgium, Pauwels and Samson (2006) measured evapotranspiration rates for a wet sloping grassland using eddy correlation method. Their results were in good agreement with those measured using the Bowen ratio method during a 2.5 year study (R^2=0.89). In Spain, the evapotranspiration of an olive orchard was measured by the eddy correlation method. For periods with no rainfall, ET measured by the soil water balance method and the eddy correlation method agreed within 10% (Testi et al. 2004). Comparison of citrus transpiration measured by sap flow and evaporation by eddy correlation method also showed good agreement (< 10% difference) in southern Italy under Mediterranean climate (Rana et al. 2005).

Instruments

An eddy correlation system consists of two major instruments, the CSI CSAT3 3D Sonic Anemometer and KH20 Krypton Hygrometer. As discussed in detail by Jia et al. (2005), the sonic anemometer measures wind speed and the speed of sound using three pairs of nonorthogonal sonic transducers. A high frequency resolution enables the sensor to detect any changes that may be induced by wind fluctuations. By capturing the covariance of vertical wind speed fluctuations, as well as temperature and vapor density changes (using the Krypton hygrometer), the anemometer measurements are used to calculate the sensible and latent heat fluxes, which are components of the energy balance. The measurement of the path length is 10 cm vertically and 5.8 cm horizontally. The transducer path angle is 60 degrees from horizontal. Each transducer has a 0.64 cm diameter. The anemometer was set up facing the prevailing wind to minimize the negative effect by the anemometer arms and other supporting structures. After the anemometer was installed, the head of the instrument was adjusted so that the apparatus was level and parallel to the citrus canopy. The anemometer is incapable of measuring wind speed when water droplets are present on the transducers. As soon as the water droplets evaporate or are removed, the sensor automatically makes measurements. The frequency of the CSAT3 is 10 Hz with output averaged every 30 min.

The Krypton hygrometer is normally mounted 10-15 cm from the center of the CSAT3, with the source tube (the longer tube) on the top and the detector tube (the shorter tube) on the bottom. The KH20 tubes were tilted to reduce water accumulation on the lenses. The measurement of vapor density is based on the attenuation of ultraviolet radiation emitted from the source tube to the detector tube, with a path distance of 1 cm. The output voltage of the hygrometer is proportional to the attenuated radiation, which is in turn related to vapor density fluctuations. The KH20 source and detector tube windows become scaled (weakened) with time, especially when exposed to a moist environment. The emitted signal will drop with time; therefore, distilled water is carefully used to clean the lenses every two weeks at the eddy covariance station to restore the strength of the signal. The fluctuations of the signal are used in calculating the vapor density fluctuations, as long as the signals are not near zero or negative, the data is still useful. The frequency of the hygrometer is 10 Hz with an average output every 30 min.

The sensible and latent heat fluxes were measured using a CSI CSAT3 3-D Sonic Anemometer and a CSI KH20 Krypton Hygrometer. The anemometer measures the three directional wind speeds and the hygrometer measures the vapor density of the air above the citrus canopy. Fluctuations in wind speed, virtual air temperature, and vapor density were sampled at 10 Hz frequency and 30-minute average covariances were calculated to estimate the latent and sensible heat fluxes. Flux and atmospheric measurements were recorded by a CR23X datalogger.

The latent heat fluxes were corrected for temperature-induced fluctuations in air density (Webb et al. 1980) and for the hygrometer sensitivity to oxygen (Tanner and Greene 1989). Sensible heat fluxes were corrected for differences between the sonic temperature and the actual air temperature (Schotanus et al. 1983). Both the sensible and latent heat fluxes were corrected for misalignment with respect to the natural wind coordinate system (Baldocchi et al. 1988). The Bowen-ratio method was used to close the surface energy balance relationship (Twine et al. 2000).

Missing periods were modeled using the atmospheric data in the modified Priestley-Taylor method (Priestley and Taylor 1972) with a monthly averaged alpha value to determine total daily ET. Sumner (1996) stated that the Priestley-Taylor approach performed superior to Penman-Monteith for successional vegetation in central Florida.

The net radiation is measured by a Kipp & Zonen NR-LITE net radiometer. It measures the net radiation by balancing the solar and far infrared (long wave) radiation. The net radiation is the difference between the incoming and outgoing radiation. The upward facing sensor measures the incoming solar and far infrared radiation. The downward facing sensor measures the outgoing solar and far infrared radiation reflected by the surface. The sensor surfaces are coated with Teflon to ensure good sensor stability, long life and easy maintenance. Measurements require corrections with wind speed conditions. There is no external power needed for the operation of the instrument since the sensor measures the high accuracy temperature differential, which is proportional to the net radiation. To provide both the lower and upper sensors with the same field view of 180 degrees and the same sensitivity, the sensor was balanced and leveled at installation.

The CSI HFT3 soil heat flux plate has a thickness of 3.91 mm and a diameter of 38.2 mm. Its measurement range is ± 100 W/m^2, and signal range is ± 2.4 mV with an accuracy of ± 5%. The plate is a thermopile and measures temperature gradients across the plate below the soil surface. The plate requires no maintenance.

The weather station was set up in June 2004 and data from August 1, 2004 to July 31, 2006 were used in the analysis. Table 2 lists instrumentation used in the study. Other meteorological and environmental variables measured include air temperature, relative humidity, wind speed and wind direction, soil heat flux, soil temperature, rainfall, net radiation and incoming solar radiation. All the above ground instruments were mounted to a 1.5 m frame (Figure 4). This frame and the instruments were lifted to the top of an antenna tower (8 meter tall) by movable carriage (Figure 5). The source area of an eddy correlation measurement is generally to extend an upwind distance of about 100 times the sensor height above the canopy (Campbell and Norman 1998). With this criterion and a sensor height of 7.28 meters (average 1.5 m above canopy), the source areas are dominated by citrus trees.

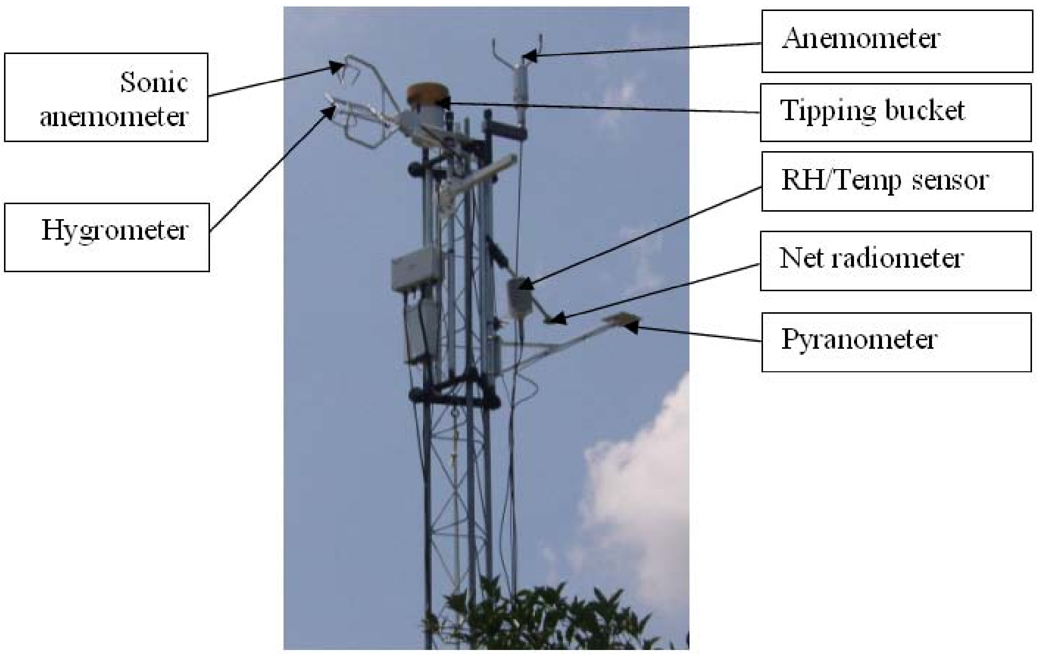


Figure 4. Instrument layout at the weather station between 6.5 – 8 m height above ground surface (from northeast to southwest direction).

Figure 5. Photo of the winch for lifting up the instrument carriage on August 2, 2005 (from northwest to southeast direction).

Table 2. Study instrumentation in the experiment

Measurement	Instrument	[2]Height (m)
Evapotranspiration	CSI[1] 3D sonic anemometer	7.3
Evapotranspiration	CSI KH20 krypton hygrometer	7.3
Air temperature/relative humidity	Vaisala HMP45C probe	6.6
Net radiation	Kipp & Zonen NR-Lite net radiometer	7.0
Incoming solar radiation	Li-Cor LI200X pyranometer	7.0
Wind speed/direction	Vaisala WS425 ultrasonic wind sensor	8.0
Soil heat flux	CSI HFT-3 soil heat flux plates (2)	-0.08
Soil temperature	Soil thermocouple probes (2)	-0.02, -0.06
Rainfall	Texas Elec. TE525WS tipping bucket	7.55
Datalogging	CSI 23X and 10X dataloggers	0.5
	12 volt deep-cycle battery	0
	20 watt solar panel	1

1. CSI: Campbell Scientific, Inc.

2. Negative height is depth below land surface.

Methods

In addition to being a component of the water balance, evapotranspiration is also a component of the energy budget equation. Evapotranspiration is the only term common to both the water budget and energy budget. The energy budget equation is

$$R_n = LE + H + G \qquad (1)$$

where R_n is the net radiation, in watts per square meter, H is the sensible heat flux into the atmosphere, in watts per square meter, G is the soil heat flux into ground, in watts per square meter, and LE is the latent heat flux, in watts per square meter. L is the latent heat of vaporization (2450 J/g at 20^{o}C) and E is the water evaporated, in grams per square meter per second.

The eddy correlation method measures the turbulent fluxes of vapor and heat above the canopy surface. Eddy correlation fluxes are calculated and recorded in a 30-min temporal resolution. Assuming the net lateral advection of vapor transfer is negligible, the latent heat flux (evapotranspiration) can be calculated from the covariance between the water vapor density (ρ_v) and the vertical wind speed (w) as

$$LE = \lambda \overline{w'\rho_v'} \qquad (2)$$

where LE is the latent heat flux (W/m^2), λ is the latent heat of vaporization (J/kg), ρ_v' is the fluctuation in the water vapor density (kg/m^3), and w' is the fluctuation in the vertical wind speed (m/s). The overbar represents the average of the period and the primes indicate the deviation from the mean values during the averaging period.

The sensible heat flux can be calculated from the covariance of air temperature and the vertical wind speed as

$$H = \rho_a C_p \overline{w'T'} \qquad (3)$$

where H is the sensible heat flux (W/m^2), ρ_a is the air density (kg/m^3), C_p is the specific heat of moist air (J/kg/^{o}C), and T' is the fluctuation in the air temperature (^{o}C).

The fine wire thermocouples (0.01 mm diameter) were not included in the eddy correlation system. The air temperature fluctuations, measured by the sonic anemometer, are corrected for air temperature fluctuations in estimation of sensible heat fluxes. The correction is for the effect of wind blowing normal to the sonic acoustic path. The simplified formula by Schotanus et al. (1983) is as follows:

$$\overline{w'T'} = \overline{w'T_s'} - 0.51\left(\overline{T + 273.15}\right)\overline{w'q'} \qquad (4)$$

where w'T' is rotated covariance of wind speed and sonic temperature (m ^{o}C/s), T is air temperature (^{o}C), and q is the specific humidity in grams of water vapor per grams of moist air.

Estimation of turbulent fluxes is highly dependent on the accuracy of the vertical wind speed measurements. Measurement of wind speed in three orthogonal directions with sonic anemometer requires a refined orientation with respect to the natural coordinate system through mathematic coordinate rotations (Sumner 2001). The vector of wind has three components (*u*, *v*, *w*) in three coordinate directions (x, y, z). The z-direction is oriented with respect to gravity, and the other two are arbitrary. Tanner and Thurtell (1969) and Baldocchi et al. (1988) provide procedures to transform the initial coordinate system to the natural coordinate system. Described in detail by Sumner (2001), the coordinate system is rotated by an angle η about the z-axis to align *u* into the x-direction on the x-y plane, and then rotated by an angle θ about the y-direction to align w along the z-direction. The results force $\bar{v}$ and $\bar{w}$ equal to zero, and $\bar{u}$ is pointed directly to the airstreams. When θ was greater than 10 degrees, the turbulent flux data should be excluded based on the assumption that spurious turbulence was the cause of the excessive amount of the coordinate rotation.

$$\cos\theta = \sqrt{\frac{\left(u^2 + v^2\right)}{\left(u^2 + v^2 + w^2\right)}} \tag{5a}$$

$$\sin\theta = \frac{w}{\sqrt{\left(u^2 + v^2 + w^2\right)}} \tag{5b}$$

$$\cos\eta = \frac{u}{\sqrt{\left(u^2 + v^2\right)}} \tag{5c}$$

$$\sin\eta = \frac{v}{\sqrt{\left(u^2 + v^2\right)}} \tag{5d}$$

The latent heat and sensible heat fluxes are computed from the coordinate rotation-transformed covariance as follows:

$$\left(\overline{w'\rho_v{}'}\right)_r = \overline{w'\rho_v{}'}\cos\theta - \overline{u'\rho_v{}'}\sin\theta\cos\eta - \overline{v'\rho_v{}'}\sin\theta\sin\eta \tag{6}$$

$$\left(\overline{w'T_s{}'}\right)_r = \overline{w'T_s{}'}\cos\theta - \overline{u'T_s{}'}\sin\theta\cos\eta - \overline{v'T_s{}'}\sin\theta\sin\eta \tag{7}$$

After the coordinate rotation, the final latent heat flux can be estimated from equation (2) with the corrections for air density (Cor_Webb) (Webb et al., 1980) and oxygen (Cor_O_2) (Tanner and Greene 1989) given as

$$Cor\_Webb = \frac{\overline{\rho_v}\,\overline{H}}{\overline{\rho}\overline{C_p}\left(T + 273.15\right)}\lambda \tag{8}$$

$$Cor\_O_2 = \frac{FK_o \overline{H}}{K_w (T + 273.15)} \lambda \qquad (9)$$

where F is the factor used in krypton hygrometer correction that accounts for molecular weights of air and oxygen, and atmospheric abundance of oxygen, equal to 0.229 g $^oC/J$, K_o is the extinction coefficient of hygrometer for oxygen, estimated as 0.0045 $m^3/g.cm$, K_w is the extinction coefficient of hygrometer for water, from the manufacture is 0.149 $m^3/g.cm$.

The modified Priestley-Taylor (PT) approach (1972) is used to estimate any missing 30-min LE values as follows

$$LE = \alpha \frac{\Delta (R_n - G)}{\Delta + \gamma} \qquad (10)$$

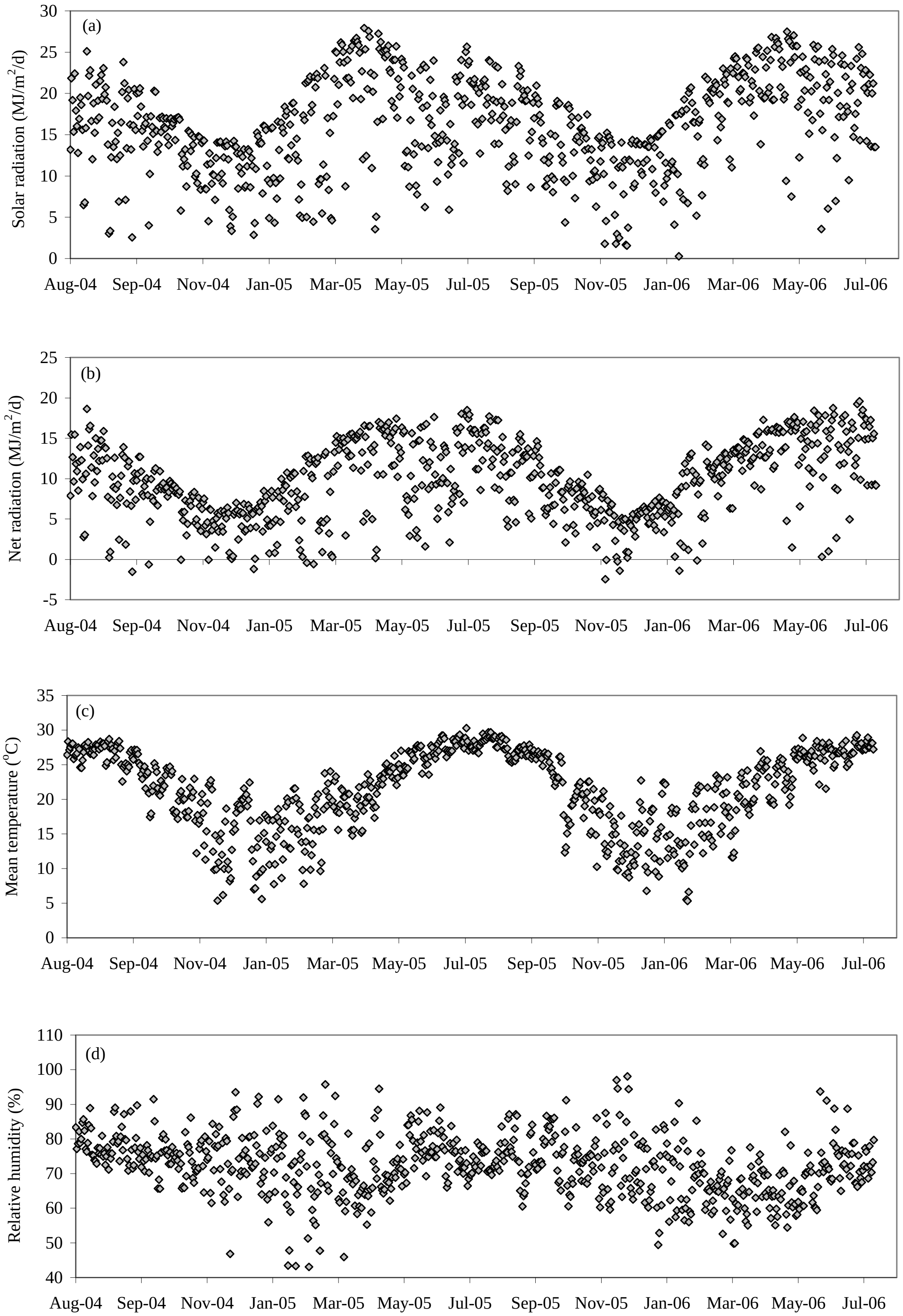
where α is an empirical coefficient introduced to the original theoretical equation. Δ is the slope of saturation (kPa/^{o}C) and γ is the psychrometric constant in kPa/^{o}C. The empirical coefficient α was estimated from the measured LE values, and a monthly average α value was used in the calculations. Among the total 730 days, 186 days (25%) were estimated by the PT approach.

RESULTS

Meteorological conditions

Daily average solar radiation (R_s, MJ/m^2/d) (Figure 6a), net radiation (R_n, MJ/m^2/d) (Figure 6b), temperature (T, ^{o}C) (Figure 6c), relative humidity (RH, %) (Figure 6d), vapor pressure deficit (VPD, kPa) (Figure 6e), and wind speed at 2 m displacement height (U_2, m/s)

(Figure 6f) from August 2004 to July 2006 at Weirsdale, Florida are shown below .



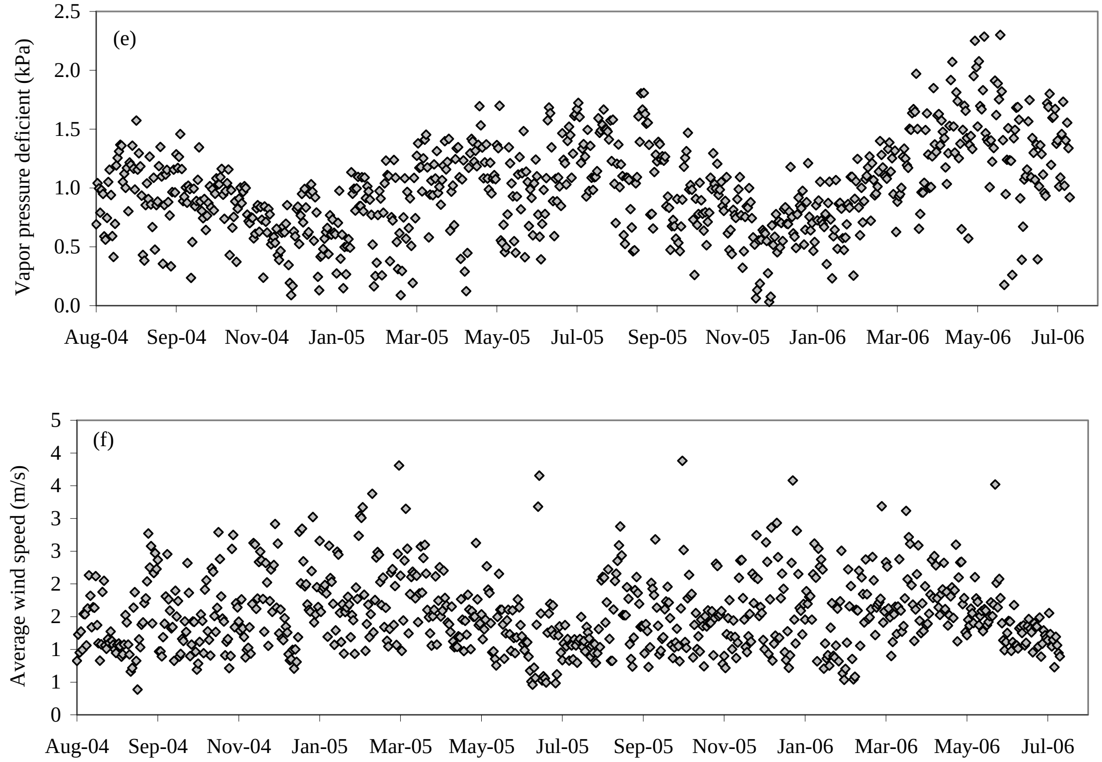


Figure 6. Daily average climate variables, (a) solar radiation, (b) net radiation, (c) temperature, (d) relative humidity, (e) vapor pressure deficit, and (f) wind speed at 2 m displacement height from August 2004 to July 2006 at Weirsdale, Florida.

The solar radiation and net radiation were high in the summer and low in the winter, with peak radiation values occurring in April and May for both years. Starting in June, the incoming and net energy decreased due to increased cloud cover and frequent afternoon rainfall. The lowest radiation energy values occurred during December and January. A strong relationship existed between the measured R_s and R_n, with a fitting equation $R_n = 0.7845\ R_s - 3.0606$ and a $R^2 = 0.92$.

The mean temperature at the experimental site followed an annual trend similar to the radiation energy, higher in the summer and lower in the winter. However, there was no clear relationship between the temperature and the radiation. The highest temperature was in August and lowest temperature was in December. The highest temperature variability occurred in December.

The vapor pressure deficit (VPD), calculated from temperature and relative humidity, showed an annual cycle, higher in the summer and lower in the winter months. The highest VPD occurred in May, when temperature was high and relative humidity was low. The VPDs in 2006 were higher than the VPDs in 2005 during the same period. This might be due to the decreased humidity, such as in May, when the conditions were drier in May 2006 than in 2005. The VPD increased from 1.12 kPa (2005) to 1.58 kPa (2006), while the RH decreased from 72% (2005) to 64% (2006).

The relative humidity and wind speed did not show a clear pattern during the study period. This was probably due to the location of the station, which was in the central ridge area and surrounded by tall, heterogeneous tree canopies. Wind was normally out of the southwest, while the citrus was located in the north to south orientation. The anemometer was located at 8.0 m high, above the citrus canopy height 5.5-6.0 m, but probably below the oak tree height. The tall oak trees near the citrus grove might reduce the wind speed during the infrequent periods when wind was out of the northwest. Additionally, the ridge location might cause local patterns that differed from lower elevation stations. A comparison of wind measurement data from four nearby weather stations showed considerable variability among the stations.

Reference crop evapotranspiration

Reference crop evapotranspiration (ET_o) is defined as “ the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (ASCE-EWRI 2005). The most recent standard method was established by the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI) and was used in this study. This method required solar radiation, temperature, relative humidity, and wind speed as the input data collected from a weather station. The detailed equations were also documented in the previous report (Jia et al. 2005). Before calculating the ET_o, all climate data were processed through the standard data quality check (ASCE-EWRI 2005).

The daily ET_o rates during the study period are shown in Figure 7. The ET_o values differed from one year to the other (Jia et al. 2006).

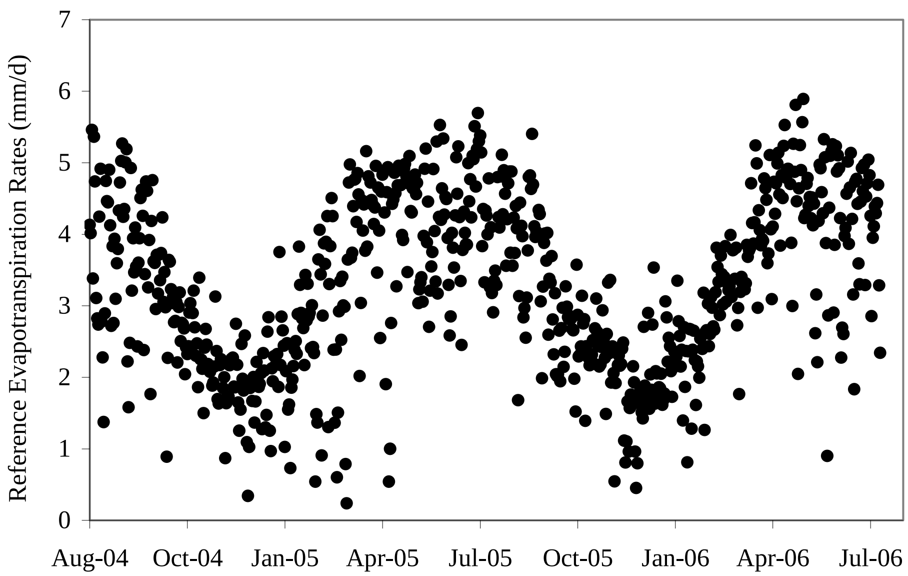


Figure 7. Grass reference evapotranspiration rates at Citra, Florida from August 2004 to July 2006.

In the ASCE-EWRI (2005), the weather data required for the calculation of reference evapotranspiration should be collected from the environment within the area for which an estimate of ET is required. In the American Society of Agricultural and Biological Engineers (ASABE) standard for automatic weather station setup (ASABE 2005), an agricultural weather station should be sited in level, open terrain representative of the local agricultural environment. The station should be free from any influence of obstacles such as buildings, trees, small hills as well as away from paved or graveled areas (highways) and large open water surfaces. The fetch distance requirement for a weather station was traditionally recommended to be 100 times the height of the measurement above ground surface (for a short grass). Considering all the requirements together, the grass site was the best option for the reference ET calculation. The second station which met most of the requirements was the station in the citrus grove. However, instead of grass reference surface, it had a homogenous citrus surface and represented the local environment. The reference ET rates using data collected at the citrus surface ($ET_{o,\ citrus}$) were compared to the ET_o from the grass surface (Figure 8). Though the two stations were 45 km apart, the $ET_{o,\ citrus}$ was 5% higher than the ET_o. Given this similarity and the grass standard required for a reference site, the ET_o from the grass surface was used as the reference ET value.

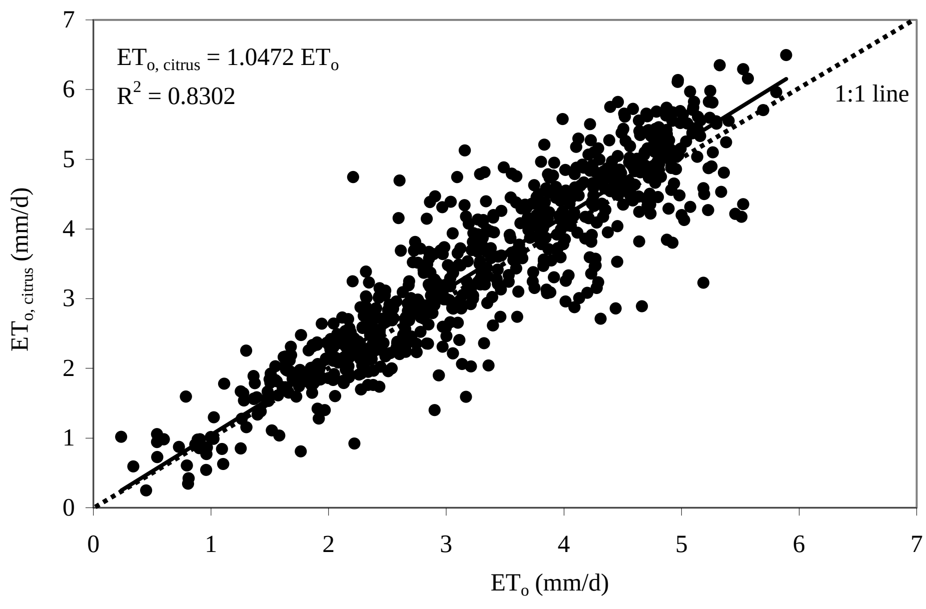


Figure 8. Citrus reference ET rates ($ET_{o,\ citrus}$) vs. grass reference ET rates (ET_o) from August 2004 to July 2006.

Eddy correlation evapotranspiration measurements

Energy fluxes

Figure 9 shows the daily average daytime energy fluxes at the experimental site. The total available energy (Net radiation (R_n) – soil heat flux (G)) were calculated for daytime only, corresponding to the daytime values when the latent heat flux (LE) and the sensible heat flux (H) were measured. The LE and H measurements were not consistently available during the nighttime.

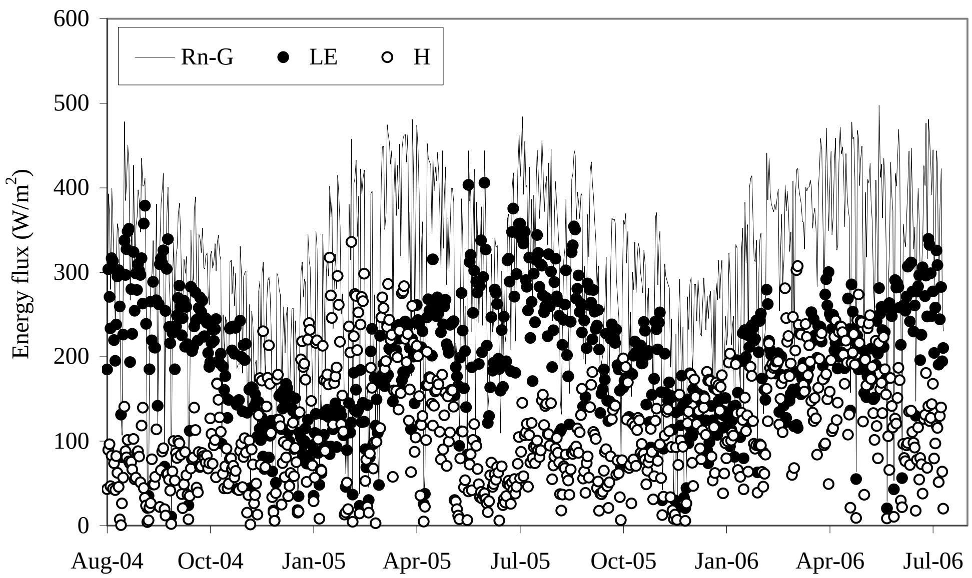


Figure 9. Daily average daytime energy fluxes at Weirsdale, Florida from August 2004 to July 2006.

LE showed an annual cycle similar to the R_n-G, higher in the summer and lower in the winter, which implied that the evapotranspiration process depended on the available energy and changed simultaneously with the energy at the land surface. In the spring, the difference between the R_n-G values and the LE values was larger than in the fall, which indicated that more available energy was used for ET in the fall than in the spring. The highest R_n-G values occurred in April, and starting from May, the R_n-G magnitudes were gradually reduced, corresponding to the start of the rainy season. In July, once the sky became clear, both the R_n-G and the LE values increased.

The H values had a different pattern than either the LE, or the R_n-G values. The H values were higher in the beginning of the year, from January to May, and lower in the summer months. As expected, both LE and H were below the R_n-G during the entire study period. The LE values were greater than the H during the growing season, indicating a large fraction of energy being used for evapotranspiration – energy used for changing the phase of water from liquid to vapor under isobaric-isothermal condition (ASCE 1996). During the rest of the months in the fall or spring, the LE and the H values were about the same.

The evaporative ratio, LE/R_n, and the Bowen ratio, H/LE, are plotted in Figures 10 and 11, respectively. These ratios were relatively consistent on a day-to-day basis, but varied seasonally. The fraction of net radiation used for evapotranspiration, LE/R_n, ranged from 50% in March to 80% in September. The Bowen ratio, H/LE, was smaller in the summer months, indicating the citrus had adequate soil moisture supply and was actively transpiring. In the winter months, January to March, the Bowen ratio was close to or greater than 1, indicating a reduction in the relative use of available energy for crop evapotranspiration.

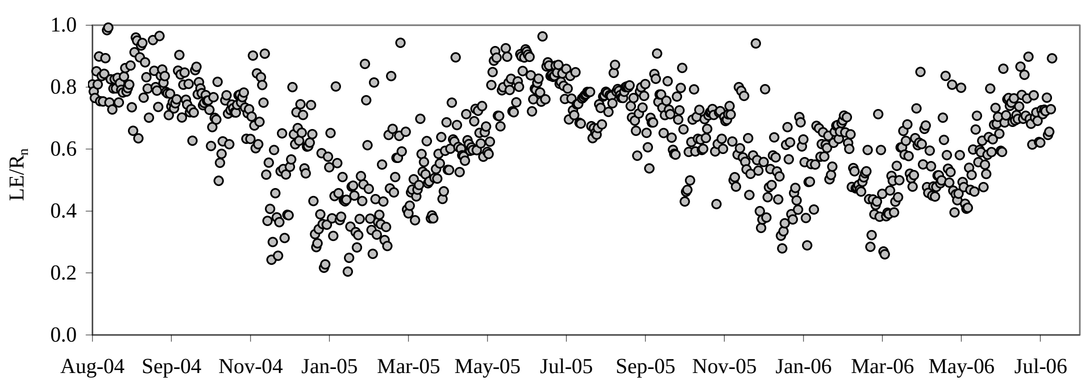


Figure 10. Ratio of daytime latent heat flux (LE) to daytime net radiation (R_n) over citrus surface at Weirsdale, Florida from August 2004 to July 2006.

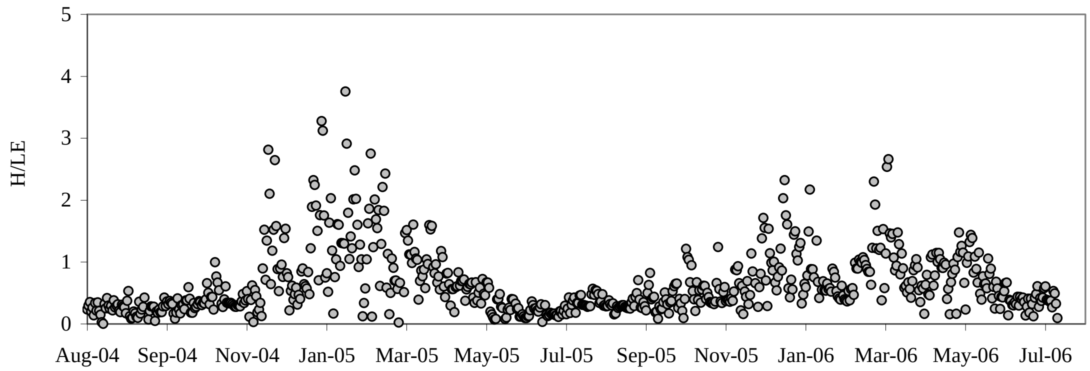


Figure 11. The Bowen ratio (ratio of daytime sensible heat flux (H) to daytime latent heat flux (LE)) over citrus surface at Weirsdale, Florida from August 2004 to July 2006.

Table 3 summarizes the monthly average values for daytime energy fluxes. The R_n values were highest in April and lowest in December, and the LE values were highest in August and lowest in December. For the whole study period, the net radiation partitioned 65% into latent heat flux, 33% into sensible heat flux and 2% into soil heat flux.

Table 3. Monthly values of daytime energy fluxes (R_n = net radiation, LE= latent heat flux, H=sensible heat flux, and G=soil heat flux) and ratios of LE/R_n, H/R_n, G/R_n, and H/LE over citrus surface at Weirsdale, Florida from July 2004 to August 2006.

Month	**R_n**	**LE**	**H**	**G**	**LE/R_n**	**H/R_n**	**G/R_n**	**H/LE**
1	245	116	121	8	0.52	0.46	0.02	1.10
2	285	148	128	8	0.54	0.43	0.02	0.97
3	334	149	174	10	0.50	0.47	0.03	1.16
4	401	215	177	9	0.55	0.43	0.02	0.85
5	373	210	155	8	0.59	0.40	0.02	0.74
6	312	226	84	2	0.75	0.24	0.01	0.36
7	345	264	77	4	0.78	0.21	0.01	0.29
8	348	268	84	-4	0.78	0.23	-0.01	0.31
9	305	239	68	-1	0.80	0.20	0.00	0.28
10	289	207	79	3	0.73	0.26	0.01	0.39
11	273	186	80	7	0.69	0.28	0.02	0.43
12	214	113	92	9	0.58	0.38	0.05	0.83
Annual	**310**	**195**	**110**	**5**	**0.65**	**0.33**	**0.02**	**0.64**

All energy fluxes are in W/m^2 and ratios have no units.

Evapotranspiration rates

The daily average evapotranspiration rates by eddy correlation method are plotted in Figure 12. The evapotranspiration rates showed a clear annual pattern that decreased in May, corresponding to the radiation energy flux changes. The highest daily ET_c (6.94 mm) occurred on July 21, 2005 and the lowest (0.06 mm) on December 25, 2004.

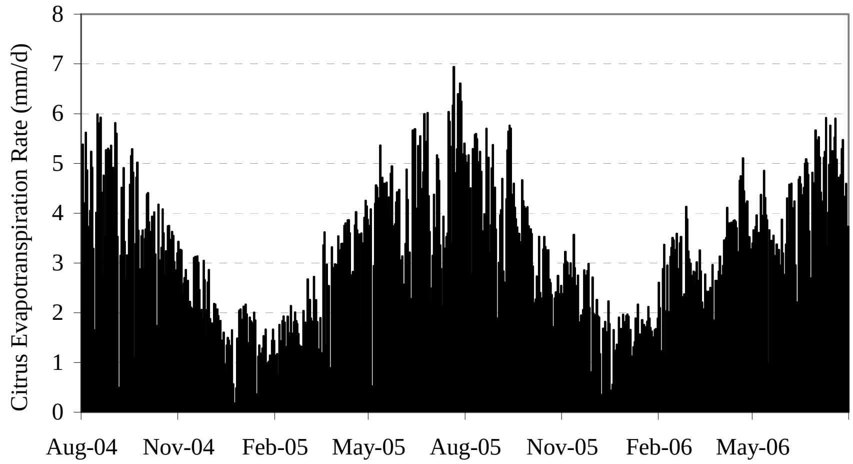


Figure 12. Daily citrus evapotranspiration rates estimated by eddy correlation method at Weirsdale, Florida from August 2004 to July 2006.

The ET and rainfall values differed between the two study years (Figure 13). Rainfall exceeded ET_c during most summer months. There were two extremely wet months, August and September 2004, due to hurricanes. The 2005 growing season was very wet with rainfall exceeding the ET_c from March to July. However, the same period during 2006 had little rainfall until June. The citrus production (observed from the fruit numbers in the spring times) were also lower during this 2006 period.

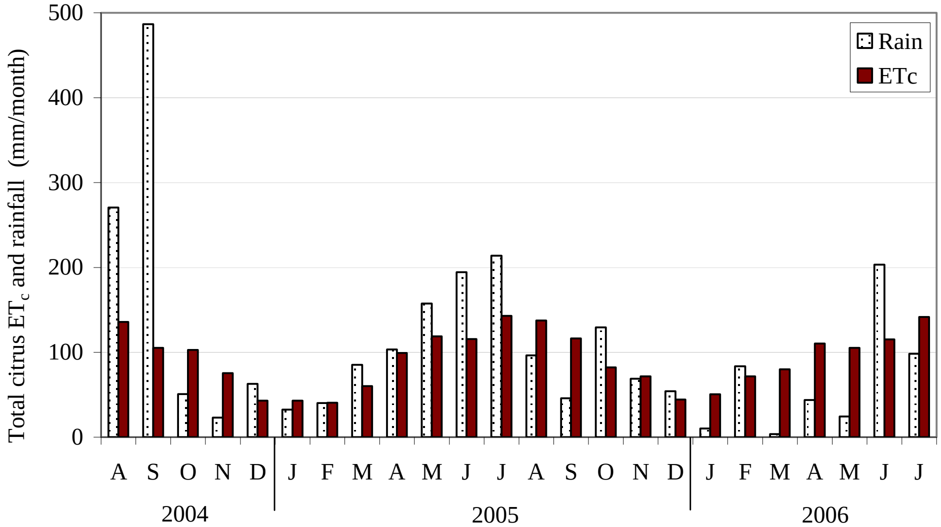


Figure 13. Total monthly citrus evapotranspiration rates and rainfall at Weirsdale, Florida from August 2004 to July 2006.

Figure 14 shows the citrus ET_c rates by the eddy correlation method and the ET_o rates by month. The two values showed a similar annual cycle, higher in the summer and lower in the winter. The ET_c values were typically lower than the ET_o values during most months.

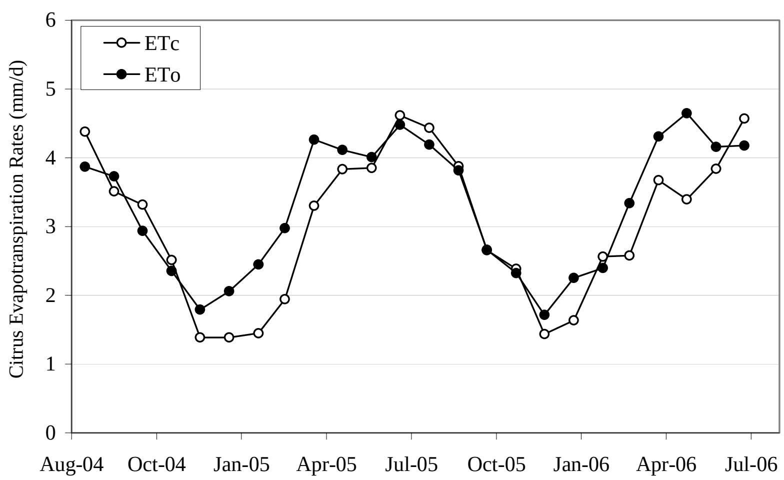


Figure 14. Monthly citrus ET_c by eddy correlation vs. calculated ET_o values during the study period from August 2004 to July 2006 in central Florida.

Citrus crop coefficients

Citrus crop coefficients were calculated as the ratio of the actual measured citrus ET_c to grass ET_o. Figure 15 shows the monthly K_c values from August 2004 to July 2006. Values for Nov. 2004, Aug. and Nov. 2005, and Feb. 2006 are distinguished using pink dots. For these months, the K_c values relied heavily on values estimated using the PT approach because of sensor failures at the weather station that resulted in less than 50% of the days providing measured values. K_c values were generally larger in summer and fall and smaller in winter months. The K_c values were different between years, especially during the winter and spring time. This suggested that the differences in the weather conditions captured a range of plant water response for this season. From July to November, the K_c values were consistently high. The winter decrease in the K_c values was relatively sudden in December. In contrast, the spring transition was quite gradual and occurred over a four month period.

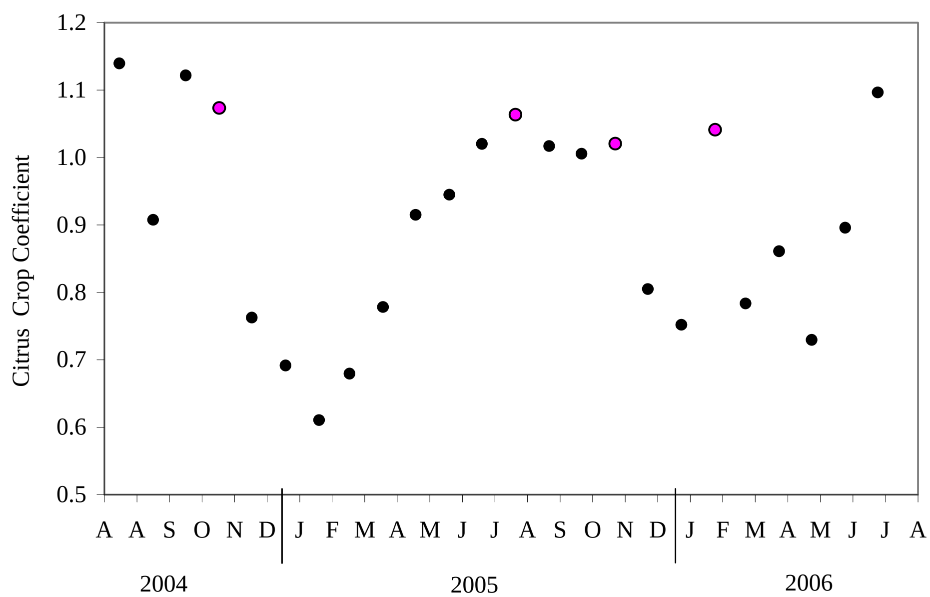


Figure 15. Monthly citrus crop coefficients by eddy correlation from August 2004 to July 2006. The black dots are K_c values measured by the eddy correlation method and the pink dots are K_c values estimated by the Priestley-Taylor approach.

Oswalt (2006) reported that citrus trees ceased active growth when temperature reached certain low threshold and became dormant. During this continued quiescence period at lower temperatures, citrus fruits increased in sugars and amino acids with decreases in starch levels within plant tissues. Tissue moisture decreased along with increases in the stability and binding of cell water. Rouse and Wiltbank (1972) stated when daily minimum temperatures continuously fall below 10°C in central Florida, citrus trees became dormant. In this study, a continuous lower temperature (T_{min} < 10°C) occurred on December 14, 2004 and December 11, 2005. Upon reaching this temperature threshold, the citrus K_c values dropped. After this period, though the citrus leaves were still green and the oranges were colorful, the K_c values showed no consistent difference till next March or April. In addition, irrigation was not normally supplied during this dormant period. The daily K_c values and the daily minimum temperatures as well as the 10°C threshold line are shown in Figure 16.

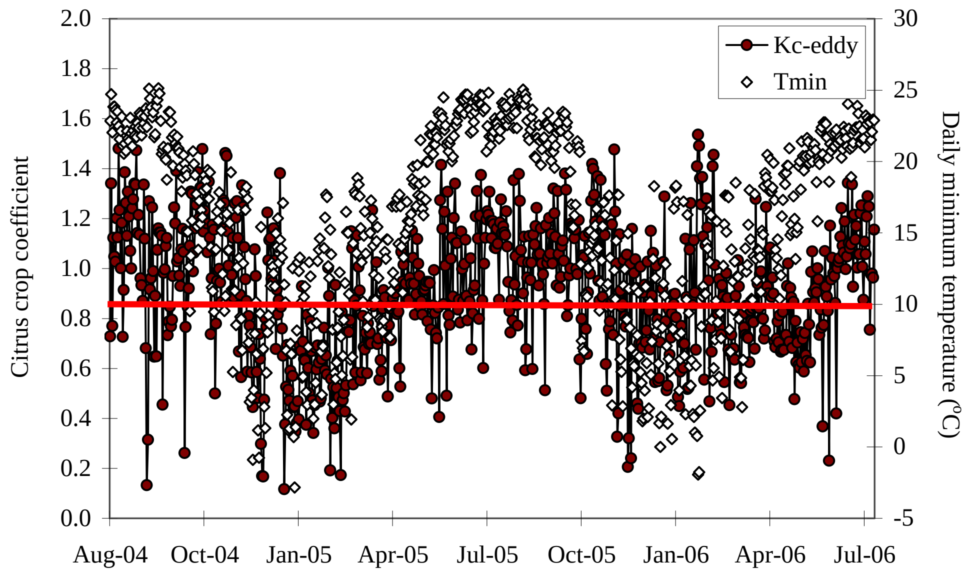


Figure 16. Citrus crop coefficients versus minimum daily temperature at Weirsdale, Florida from August 2004 to July 2006. The red line is 10°C threshold temperature.

Figure 17 summaries the individual monthly K_c values and recommends seasonal K_c values for the citrus at the experimental location. The K_c values for the four months that were estimated by the PT approach were not included in Fig. 17.

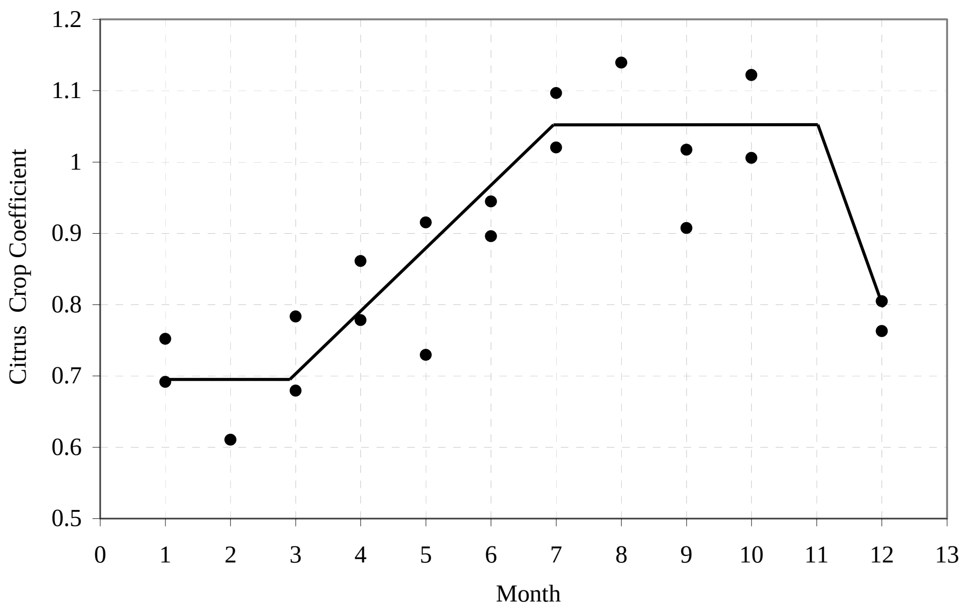


Figure 17. Monthly citrus crop coefficients by eddy correlation method (dots) and recommended K_c values for central Florida ridge citrus region (line).

Table 4 summarizes the ET_o, ET_c and K_c values by month. The K_c values in January, February, and March are representative of dormant citrus conditions, consistently observed during the experiment. The K_c values from July to November represent the peak citrus growing period. The K_c values from April to June are representative of crop development stage. The recommended K_c values for the two years of study period are 0.70 for dormant season and 1.05 for peak season.

Table 4. Monthly citrus evapotranspiration (ET_c) and crop coefficient (K_c) by eddy correlation method: average (Avg) and standard deviation (Std). Recommended crop coefficient values have a bold type in the last column.

Month	**ET_o (mm/day)**		**ET_c eddy (mm/day)**		**K_c eddy**		
	Avg	**Std**	**Avg**	**Std**	**Avg**	**Std**	**K_c**
1	2.16	0.56	1.51	0.44	0.72	0.24	**0.70**
2	2.42	0.68	2.01	0.98	0.83	0.34	**0.70**
3	3.16	0.97	2.26	0.79	0.73	0.21	**0.70**
4	4.29	0.63	3.49	0.68	0.82	0.16	**0.80**
5	4.11	1.16	3.83	1.17	0.92	0.13	**0.88**
6	4.01	0.83	3.85	1.42	0.94	0.25	**0.97**
7	4.48	0.73	4.62	1.34	1.02	0.20	**1.05**
8	4.03	0.88	4.41	1.06	1.10	0.19	**1.05**
9	3.77	0.87	3.69	1.28	0.96	0.25	**1.05**
10	2.80	0.59	2.99	0.80	1.06	0.22	**1.05**
11	2.34	0.51	2.45	0.69	1.05	0.26	**1.05**
12	1.75	0.54	1.41	0.60	0.78	0.28	**0.80**
Annual	**3.15**	**1.16**	**2.90**	**1.38**	**0.90**	**0.27**	

SUMMARY AND CONCLUSIONS

Citrus is one of the most important agricultural crops in Florida. It also accounts for 80% of the citrus production in the United States. Irrigation is required to ensure citrus quantity and quality due to low soil water holding capacity on sandy soils commonly found in Florida. Citrus evapotranspiration and crop coefficients are critical parameters for citrus irrigation scheduling and water management. An experiment was conducted in central Florida, at Weirsdale, Marion County from August 1, 2004 to July 31, 2006. Citrus ET_c and K_c values were estimated using the eddy correlation method. The eddy correlation method is an innovative approach to estimate ET by measuring ET above crop canopy. This method is extremely useful for the tall trees and hilly landscape that is characteristic of a ridge citrus grove. The measured citrus ET_c showed a clear annual cycle similar to radiation energy flux, with a decrease in May due to frequent rainfall events. Citrus crop coefficients were estimated from the ratio of citrus ET_c to ET_o calculated from weather data over a grass reference site. The recommended citrus K_c values were 0.70 for dormant conditions from January to March. The recommended citrus K_c peak values were 1.05 from July to November. In December, the K_c value reduction from 1.05 to 0.80 was triggered by a continuous minimum temperature (about a week) below 10^oC for the both years of the study period.

ACKNOWLEDGEMENT

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APPENDIX

Figure A1. Citrus grove at Weirsdale, Florida in January 5, 2006 (from south to north direction).

Figure A2. Grass at the reference ET site near Citra, Florida in February 15, 2005.

Figure A3. Citrus grove at Weirsdale, Florida in March 7, 2006 (from south to north direction).

Figure A4. Citrus grove at Weirsdale, Florida in April 5, 2005 (from north to south direction).

Figure A5. Citrus grove at Weirsdale, Florida in May 10, 2006 (from south to north direction).

Figure A6. Citrus grove during weather station installation at Weirsdale, Florida in June 10, 2004 (from southeast to northwest direction).

Figure A7. Citrus grove from the top of the weather station at Weirsdale, Florida in July 22, 2004 (from north to south direction).

Figure A8. Citrus grove during weather station maintenance at Weirsdale, Florida in August 15, 2005 (from east to west direction).

Figure A9. Citrus grove at Weirsdale, Florida in September 16, 2005 (from south to north direction).

Figure A10. Citrus grove at Weirsdale, Florida in October 27, 2005 (from north to south direction).

Figure A11. Citrus grove at Weirsdale, Florida in November 14, 2005 (from north to south direction).

Figure A12. Citrus grove at Weirsdale, Florida in December 9, 2005 (from south to north direction).

REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL

APPENDIX 6
CROP COEFFICIENTS FOR SOD
(TASKS 28 32 & 35)

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ABSTRACT

Sod is an extremely important agricultural commodity in Florida. According to a turfgrass industry survey, 4.5 million acres of turf existed in Florida in 1991-92. Industry sales and services amounted to approximately $7 billion during that time (Hodges et al., 1994). Irrigation is required to ensure sod quantity and quality due to low soil water holding capacity sandy soils commonly found in Florida. Evapotranspiration and crop coefficients are critical parameters for sod irrigation scheduling and water management. Florida sod is typically grown on sand-based soils (73%), muck (23%), or clay (3%) (Haydu et al. 2003). In this study, an experiment was conducted in northeastern Florida, near Bunnell, Flagler County from January 1, 2006 through July 31, 2007. Sod evapotranspiration (ET_c) and crop coefficient (K_c) values were estimated using the eddy correlation method. The eddy correlation method is an established method for estimating ET in Florida by measuring ET above crop canopy. The measured sod ET_c showed a clear annual cycle similar to radiation energy flux, with a decrease in May due to frequent rainfall events. Sod crop coefficients were estimated from the ratio of sod ET_c to reference evapotranspiration (ET_o) calculated from weather data over a grass reference site. The coefficients were estimated from a dual crop coefficient approach that separates the crop coefficient (K_c) into two coefficients: a basal crop coefficient (K_{cb}) and a soil evaporation coefficient (K_e). The effect of crop transpiration is described by K_{cb} and soil evaporation from a soil surface evaporating at a potential rate by K_e. The sum of K_{cb} + K_e is the sod K_c. Tthe K_{cb} and the K_c values both are reported here for sod. The K_{cb} values range from 0.67 to 0.83 with the lowest values occurring after harvest. The K_c values range between 0.88 and 0.98. For the GWRAPPS model, K_c values are recommended.

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FIGURES

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL
APPENDIX 6 - CROP COEFFICIENTS FOR SOD

1. INTRODUCTION

1.1 Overview

The importance of evapotranspiration (ET) in the hydrologic cycle, irrigation scheduling and water resources management has long been recognized. In agricultural applications, evapotranspiration is a fundamental and important process and is the main loss of water from the vegetation and soil surface. Therefore, accurate estimation of ET is important in agricultural water management. However, accurate ET measurement is difficult to obtain due to numerous factors. The magnitude of ET varies seasonally and diurnally. It is influenced by climate conditions, soil vegetation surfaces, soil moisture status, crop phenology, growth stage, shading, and ground cover.

There are two common ways to determine the evapotranspiration rate, direct and indirect methods. Direct measuring methods include soil water depletion, lysimeter, water balance, energy balance, mass transfer, eddy correlation, and combination of energy and heat (Jensen et al. 1990). Indirect measuring methods relate reference evapotranspiration (ET_o) to a crop coefficient (K_c). The ET_o can be calculated from weather data collected from a well-watered reference crop surface. Many methods have been developed to estimate ET_o and the most current method has been developed by the American Society of Civil Engineers, Environmental and Water Resources Institute (ASCE-EWRI 2005). Crop coefficient (K_c) development requires both crop evapotranspiration (ET_c) and ET_o estimates for a specific crop, location, and agronomic or horticultural practices.

Eddy correlation is a new and innovative method that has been used successfully to directly measure evapotranspiration (Sumner 2001; Sumner and Jacobs 2005). This method overcomes the need to determine each component in the energy balance. It also avoids soilsurface heterogeneity issues by placing the sensors above the crop canopy. The temporal resolution of ET measurement is less than 1 hour.

1.2 Purpose and scope

The University of Florida (UF), in cooperation with the St. Johns River Water Management District, began a study in 2003 to determine major crop coefficients (K_c) in central Florida. Crop coefficients were obtained for three crops, bahiagrass, citrus, and sod. The measured K_c values are used to update and improve the Agricultural Field Scale Irrigation Requirement Simulation (AFSIRS) software, as well as, to provide guidance in evapotranspiration estimates.

This report summarizes the experimental design and results for the sod coefficient experiment. Sod evapotranspiration rates were measured on a nearly continuous basis from January 1, 2006 through July 31, 2007, using an eddy correlation system. Results include daily measurements of sod evapotranspiration, reference crop evapotranspiration rates and monthly crop coefficients as well as their variations due to a shallow water table.

2. DESCRIPTION OF THE STUDY AREA

The experimental station is located at Strickland Sod Farm, a commercial sod farm, east of Bunnell, Flagler County, Florida (latitude 29° 23’ 56” N, longitude 81° 14’ 29” W, and the elevation is about 7 m above sea level) (Figure 1). The sod field, where the weather station is located, has 75 ha of St. Augustine grass, about 500 m wide and 1500 m long (Figure 2). The weather station is set up at about one third of the field from the north side or the third run of the liner move irrigation system from the north side of the field, near an irrigation system riser. This location of the instrumentation was preferred by the farm owner for easy maintenance. The weather station is about 500 m from the north, 1000 m from the south, and 200 m from the west and 300 m from the east edges of the field. The wind prevailing wind blows from the south, which means the air flow travels through the longest footprint (1000 m) to the weather station. The research field is also surrounded by other agricultural fields, mainly sod in this area (Figure 2).

Figure 1. Experimental site (picture from GoogleEarth).

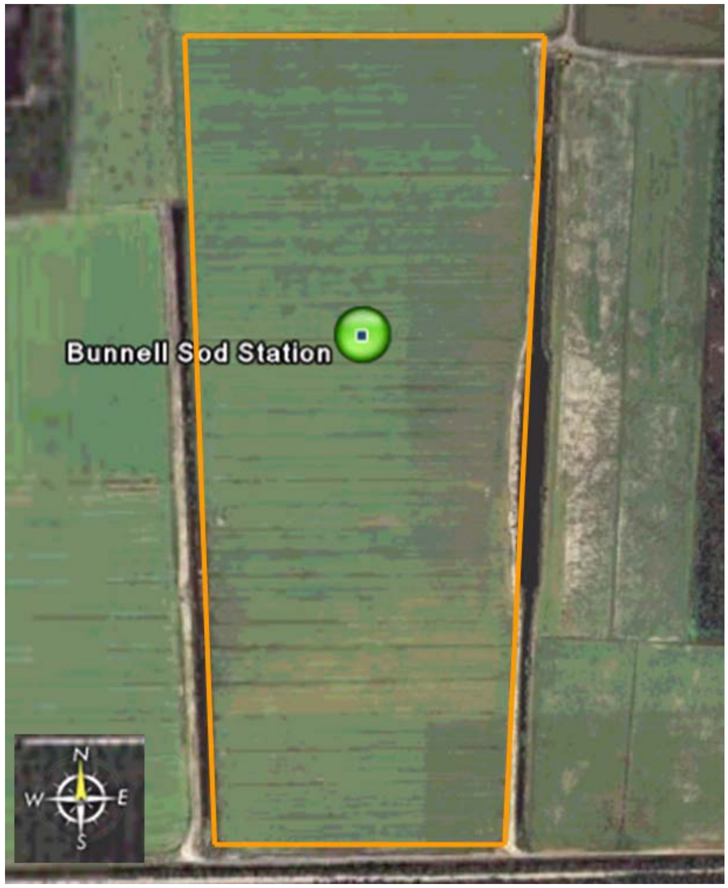


Figure 2. Layout of experimental plot (500 x 1500 m) (modified from GoogleEarth).

A linear move sprinkler irrigation system is used in this field. The total length of the irrigation system is about 105 m, and two high pressure sprinklers are equipped at both ends, covering additional 30 m irrigated width. The total irrigated width for one irrigation run is about 165 m. The height of the sprinkler hoses ranges from 1.1 to 1.4 m, which is lower than the height of the weather station. Since the grass is kept at about 5 cm, the instrumentation height should be at about 1.5 m (Campbell and Norman 1998), which is taller than the sprinkler hoses. To avoid hitting the weather station, three sprinkler hoses directly above the weather station were lifted to 3 m height. In such arrangement, the irrigation system can move freely above the weather station without interfering with the instruments.

The sod is harvested in 30 cm wide strips and stacked on pallets before transport to the market, and the remaining narrow strip is about 10-15 cm wide (Figure 3). The resulting area covers 20-30% of the ground. This remaining grass is allowed to refill in the 70-80% bare soil area. Grass is harvested approximately annually. The grass at the experimental field where the weather station is located was harvested in June – July 2005, approximately 6 months prior to the experiment start and again September 2006.

Figure 3. Sod farm ground cover on July 28, 2005 (from southeast to northwest direction).

Meteorological variables measured at a Jacksonville station indicate the average annual temperature is 20.2^{o}C, with a maximum monthly temperature of 32.6^{o}C in July and an average minimum temperature of 5.7^{o}C in January. The average values for relative humidity is 63.5 and the average solar radiation is 16.5 MJ m^{-1} day^{-1}. The soil type at this site is predominantly a EuGallie fine sand (56.6% of the field). Other portions are the Pineda-Wabasso complex (13.3%) and Hicoria, Riveria, and Gator soils (9.2%). The EuGallie fine sand has available water content of 11% (VWC) to 15 cm and 8% 15-25 cm (Carlisle et al., 1985)

3. MEASUREMENT AND METHODOLOGY

Evapotranspiration is the combined process by which water is transferred from the earth's surface to the atmosphere; evaporation of liquid water from the soil surface and water intercepted by plants, plus transpiration by plants (Jensen et al. 1990). Potential ET refers to evapotranspiration of a disease-free crop, grown in very large fields, not short of water and fertilizer (Doorenbos and Pruitt 1977). Actual ET (i.e. crop ET or ET_c) will depend on many other factors, such as climate, soil water conditions, water table depths, methods of irrigation, and cultural practices.

In this study, the eddy correlation method was used to estimate the ET_c using one and half years of data. Daily ET_c and monthly ET_c values were estimated. Daily and monthly crop coefficients were developed using the reference evapotranspiration calculated by the ASCE-EWRI method (ASCE-EWRI 2005) and the dual crop coefficient method (Allen et al. 1998).

3.1 Instrument installation

A weather station (Figure 3) and the eddy correlation system were set up in December 2005 and data from January 1, 2006 to July 31, 2007 were used in the analysis. Table 1 lists instrumentation used in the study. Other meteorological and environmental variables measured include air temperature, relative humidity, wind speed and wind direction, soil heat flux, soil temperature, rainfall, net radiation and incoming solar radiation.

The eddy correlation system was mounted at one tower. The weather station was located at about 5 m west of the eddy correlation station (Figure 4). The source area of an eddy

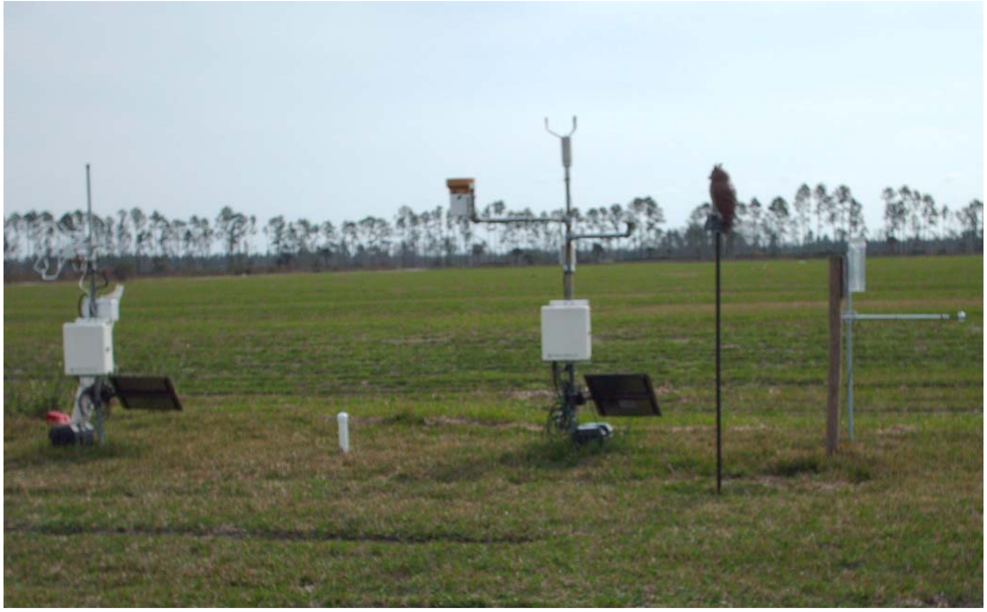


Figure 4. Instrument layout at the weather station (from northwest to southeast direction).

Table 1. Study instrumentation in the experiment

Measurement	Instrument	[3]Height (m)
Evapotranspiration	CSI[1] 3D sonic anemometer	1.65
Evapotranspiration	CSI KH20 krypton hygrometer	1.65
Air temperature/relative humidity	Vaisala HMP45C probe	1.5
Net radiation	REBS[2] Q*7.1 net radiometer	1.0
Incoming solar radiation	Li-Cor LI200X pyranometer	1.8
Wind speed/direction	Vaisala WS425 ultrasonic wind sensor	2.4
Soil heat flux	REBS HFT-3 soil heat flux plates (2)	-0.08
Soil temperature	Soil thermocouple probes (2)	-0.02, -0.06
Soil moisture	CSI CS616 TDRs	-0.05, -0.15
Rainfall	Texas Elec. TE525WS tipping bucket	2.0
	Forestry Suppliers, Inc. rain gauge	1.7
Water table	WL16 Water Level Logger	-0.65
Datalogging	CSI 10X datalogger (2)	

12 volt deep-cycle battery (2)
20 watt solar panel (2)

1. CSI: Campbell Scientific, Inc.

2. REBS: Radiation and Energy Balance Systems, Inc.

2. Negative height is depth below land surface.

correlation measurement is generally extended to an upwind distance of about 100 times the sensor height above the canopy (Campbell and Norman 1998). With this criterion and sensors height of 1.65 meters (average 1.6 m above canopy), the source areas are dominated by sod. A shallow well was located between the two stations and a WL16 water level logger (combine transducer and datalogger) (Global Water, Gold River, CA) was secured inside the tube for continuous water table monitoring.

3.2 Eddy correlation method

3.2.1 Background

Eddy correlation measures actual evapotranspiration using measurements of the turbulent atmosphere. The average vertical movement of water is measured using a high frequency sampling of the atmosphere's water specific humidity and vertical wind speed averaged over 30-minute periods.

The eddy correlation station is used to directly measure actual evapotranspiration using an energy-budget approach (Tanner and Greene 1989; Twine et al. 2000). It is a proven approach for estimating evapotranspiration from various types of vegetation (Sumner 1996 2001; Gholz and Clark 2002; Sumner and Jacobs 2005; Jia et al., 2007). This method overcomes uncertainties due to soil surface conditions and crop growth stages by measuring water vapor fluxes above the crop canopy.

3.2.2 Eddy correlation instruments

An eddy correlation system consists of two major instruments, the CSI CSAT3 3D Sonic Anemometer and KH20 Krypton Hygrometer. As discussed in detail by Jia et al. (2005), the sonic anemometer measures wind speed and the speed of sound using three pairs of nonorthogonal sonic transducers. A high frequency resolution enables the sensor to detect any changes that may be induced by wind fluctuations. By capturing the covariance of vertical wind speed fluctuations, as well as temperature and vapor density changes (using the Krypton hygrometer), the anemometer measurements are used to calculate the sensible and latent heat fluxes, which are components of the energy balance. The measurement of the path length is 10 cm vertically and 5.8 cm horizontally. The transducer path angle is 60 degrees from horizontal. Each transducer has a 0.64 cm diameter. The anemometer was set up facing the prevailing wind (facing to the south at this location) to minimize the negative effect by the anemometer arms and other supporting structures. After the anemometer was installed, the head of the instrument was adjusted so that the apparatus was level and parallel to the grass surface. The anemometer is incapable of measuring wind speed when water droplets are present on the transducers. As soon as the water droplets evaporate or are removed, the sensor automatically makes measurements. The frequency of the CSAT3 is 10 Hz with output averaged every 30 min.

The Krypton hygrometer is normally mounted 10-15 cm from the center of the CSAT3, with the source tube (the longer tube) on the top and the detector tube (the shorter tube) on the bottom. The KH20 tubes were tilted to reduce water accumulation on the lenses. The measurement of vapor density is based on the attenuation of ultraviolet radiation emitted from the source tube to the detector tube, with a path distance of 1 cm. The output voltage of the hygrometer is proportional to the attenuated radiation, which is in turn related to vapor density fluctuations. The KH20 source and detector tube windows become scaled (weakened) with time, especially when exposed to a moist environment. The emitted signal will drop with time; therefore, distilled water is carefully used to clean the lenses every two weeks at the eddy covariance station to restore the strength of the signal. The fluctuations of the signal are used in calculating the vapor density fluctuations. The data is still useful as long as the signals are not near zero or negative. The frequency of the hygrometer is 10 Hz with an average output every 30 min.

The sensible and latent heat fluxes were measured using a CSI CSAT3 3-D Sonic Anemometer and a CSI KH20 Krypton Hygrometer. The anemometer measures the three directional wind speeds and the hygrometer measures the vapor density of the air above the sod canopy. Fluctuations in wind speed, virtual air temperature, and vapor density were sampled at 10 Hz frequency and 30-minute average covariances were calculated to estimate the latent and sensible heat fluxes. Flux and atmospheric measurements were recorded by a CR23X datalogger.

3.2.3 Eddy correlation methods

In addition to being a component of the water balance, evapotranspiration is also a component of the energy budget equation. Evapotranspiration is the only term common to both the water budget and energy budget. The energy budget equation is

$$R_n = LE + H + G \qquad (1)$$

where R_n is the net radiation, in watts per square meter, H is the sensible heat flux into the atmosphere, in watts per square meter, G is the soil heat flux into ground, in watts per square meter, and LE is the latent heat flux, in watts per square meter. L is the latent heat of vaporization (2450 J/g at 20^{o}C) and E is the water evaporated, in grams per square meter per second.

The eddy correlation method measures the turbulent fluxes of vapor and heat above the canopy surface. The eddy correlation fluxes are calculated and recorded in a 30-min temporal resolution. Assuming the net lateral advection of vapor transfer is negligible, the latent heat flux (evapotranspiration) can be calculated from the covariance between the water vapor density (ρ_v) and the vertical wind speed (w) as

$$LE = \lambda \overline{w'\rho_v'} \qquad (2)$$

where LE is the latent heat flux (W/m^2), λ is the latent heat of vaporization (J/kg), ρ_v' is the fluctuation in the water vapor density (kg/m^3), and w' is the fluctuation in the vertical wind speed (m/s). The overbar represents the average of the period and the primes indicate the deviation from the mean values during the averaging period.

Sensible heat flux can be calculated from the covariance of air temperature and the vertical wind speed as

$$H = \rho_a C_p \overline{w'T'} \qquad (3)$$

where H is the sensible heat flux (W/m^2), ρ_a is the air density (kg/m^3), C_p is the specific heat of moist air (J/kg/^{o}C), and T' is the fluctuation in the air temperature (^{o}C).

For this experiment, the latent heat fluxes were corrected for temperature-induced fluctuations in air density (Webb et al. 1980) and for the hygrometer sensitivity to oxygen (Tanner and Greene 1989). Sensible heat fluxes were corrected for differences between the sonic temperature and the actual air temperature (Schotanus et al. 1983). Both the sensible and latent heat fluxes were corrected for misalignment with respect to the natural wind coordinate system (Baldocchi et al. 1988). The Bowen-ratio method was used to close the surface energy balance relationship (Twine et al. 2000). Missing periods were modeled using the atmospheric data in the modified Priestley-Taylor method (Priestley and Taylor 1972) with a monthly averaged alpha value to determine total daily ET. Sumner (1996) stated that the Priestley-Taylor approach performed superior to Penman-Monteith for successional vegetation in central Florida. Details on these corrections are provided below.

The fine wire thermocouples (0.01 mm diameter) were not included in the eddy correlation system. The air temperature fluctuations, measured by the sonic anemometer, are corrected for air temperature fluctuations in estimation of sensible heat fluxes. The correction is for the effect of wind blowing normal to the sonic acoustic path. The simplified formula by Schotanus et al. (1983) is as follows:

$$\overline{w'T'} = \overline{w'T_s'} - 0.51\left(\overline{T + 273.15}\right)\overline{w'q'} \qquad (4)$$

where w'T' is rotated covariance of wind speed and sonic temperature (m ^{o}C/s), T is air temperature (^{o}C), and q is the specific humidity in grams of water vapor per grams of moist air.

Estimation of turbulent fluxes is highly dependent on the accuracy of the vertical wind speed measurements. Measurement of wind speed in three orthogonal directions with sonic anemometer requires a refined orientation with respect to the natural coordinate system through mathematic coordinate rotations (Sumner 2001). The vector of wind has three components (*u*, *v*, *w*) in three coordinate directions (x, y, z). The z-direction is oriented with respect to gravity, and the other two are arbitrary. Tanner and Thurtell (1969) and Baldocchi et al. (1988) provided procedures to transform the initial coordinate system to the natural coordinate system. Described in detail by Sumner (2001), the coordinate system is rotated by an angle η about the z-axis to align *u* into the x-direction on the x-y plane, and then rotated by an angle θ about the y-direction to align w along the z-direction. The results force $\bar{v}$ and $\bar{w}$ equal to zero, and $\bar{u}$ is pointed directly to the airstreams. When θ was greater than 10 degrees, the turbulent flux data should be excluded based on the assumption that spurious turbulence was the cause of the excessive amount of the coordinate rotation.

$$\cos\theta = \sqrt{\frac{\left(u^2 + v^2\right)}{\left(u^2 + v^2 + w^2\right)}} \qquad (5a)$$

$$\sin\theta = \frac{w}{\sqrt{\left(u^2 + v^2 + w^2\right)}} \qquad (5b)$$

$$\cos\eta = \frac{u}{\sqrt{\left(u^2 + v^2\right)}} \qquad (5c)$$

$$\sin\eta = \frac{v}{\sqrt{\left(u^2 + v^2\right)}} \qquad (5d)$$

The latent heat and sensible heat fluxes are computed from the coordinate rotation-transformed covariance as follows:

$$\left(\overline{w'\rho_v{}'}\right)_r = \overline{w'\rho_v{}'}\cos\theta - \overline{u'\rho_v{}'}\sin\theta\cos\eta - \overline{v'\rho_v{}'}\sin\theta\sin\eta \qquad (6)$$

$$\left(\overline{w'T_s{}'}\right)_r = \overline{w'T_s{}'}\cos\theta - \overline{u'T_s{}'}\sin\theta\cos\eta - \overline{v'T_s{}'}\sin\theta\sin\eta \qquad (7)$$

After the coordinate rotation, the final latent heat flux can be estimated from equation (2) with the corrections for air density (Cor_Webb) (Webb et al., 1980) and oxygen (Cor_O_2) (Tanner and Greene 1989) given as

$$Cor\_Webb = \frac{\overline{\rho_v}\,\overline{H}}{\overline{\rho}C_p\left(\overline{T} + 273.15\right)}\lambda \qquad (8)$$

$$Cor\_O_2 = \frac{FK_o\overline{H}}{K_w(T+273.15)}\lambda \qquad (9)$$

where F is the factor used in krypton hygrometer correction that accounts for molecular weights of air and oxygen, and atmospheric abundance of oxygen, equal to 0.229 g ^{o}C/ J, K_o is the extinction coefficient of hygrometer for oxygen, estimated as 0.0045 m^3/g.cm, K_w is the extinction coefficient of hygrometer for water, from the manufacture is 0.149 m^3/g.cm.

The modified Priestley-Taylor (PT) approach (1972) is used to estimate any missing 30-min LE values as follows

$$LE = \alpha\frac{\Delta(R_n - G)}{\Delta+\gamma} \qquad (10)$$

where α is empirical coefficient introduced to the original theoretical equation. Δ is the slope of saturation (kPa/^{o}C) and γ is the psychrometric constant in kPa/^{o}C. In this study, the empirical coefficient α was estimated from the measured LE values, and a monthly average α value was used in the calculations. Among the total 586 days, 380 days (63%) were measured by eddy correlation system and 216 days (37%) were estimated by the PT approach.

3.3 Dual crop coefficient method

In United Nations Food and Agriculture Organization paper number 56 (FAO56) (Allen et al., 1998), the crop coefficient can be estimated from a single crop coefficient (K_c) or a dual crop coefficient approach. Thus, the crop coefficient (K_c) is separated into two coefficients: a basal crop coefficient (K_{cb}) and a soil evaporation coefficient (K_e). The crop coefficient represents an integration of the effects of four primary characteristics that distinguish the actual crop from a grass reference. These characteristics are crop height, albedo of the crop-soil surface, canopy resistance, and evaporation from soil surface. This section describes the dual crop coefficient method used to determine crop coefficients for sod production and quotes or paraphrases FAO56 (Allen et al., 1998) extensively.

For the single crop coefficient approach, the effect of crop transpiration and soil evaporation are combined into a single K_c coefficient. The K_c integrates differences in the soil evaporation and crop transpiration rate between the crop and the grass reference surface. As soil evaporation may fluctuate daily as a result of rainfall or irrigation, the single crop coefficient expresses only the time-averaged (multi-day) effects of crop evapotranspiration. Thus, the K_c in the single crop coefficient approach predicts ET_c under standard conditions and represents the upper limit of crop ET at which no limitations are placed on crop growth or ET due to water shortage, crop density, or disease, weed, insect or salinity pressures.

In the dual crop coefficient approach, the effect of crop transpiration is described by the basal crop coefficient (K_{cb}) and evaporation from the soil surface is described by the soil water evaporation coefficient (K_e). The basal crop coefficient is defined as the ratio of actual crop evapotranspiration (ET_c) to reference crop evapotranspiration (ET_o) when the soil surface layer is dry, but the average soil water content of the root zone is adequate to sustain full plant transpiration. The K_{cb} serves as the baseline potential K_c in the absence of the additional effects of soil wetting by irrigation or precipitation. The soil evaporation coefficient represents the evaporation from soil surface. When the soil surface is wet, the K_e is large, but sum of the K_{cb} + K_e is less than the K_{cmax}, which is the maximum K_c value determined from the available energy for evaporation at the soil surface. When the soil surface is dry, the K_e becomes smaller and approaches zero at the wilting point, a point at which there is no water available for evaporation.

Daily water balance computations are required for the K_e calculation of the soil water content remaining in the upper topsoil. The drying of the soil surface is classified into two stages, 1st stage and 2nd stage. While a single "time-averaged" K_c curve incorporates averaged wetting effects into the K_c factor, the dual K_c approach calculates the actual increases in K_c for each day as a function of both the plant development and the wetness of the soil surface. Again, the K_{cb} describes only the plant transpiration, at a point below the K_c curve. The largest differences between K_c and K_{cb} are normally found in the initial growth stage, when there is significant bare soil. During the initial growth stage, ET_c is dominated by soil evaporation and crop transpiration is relatively small. For this experiment, after the sod was harvested, only about 20% of the field was left in sod. The remaining 80% was bare soil. Thus, a large difference between K_c and K_{cb} would be expected immediately after the sod was harvested. In the late growing season, the K_{cb} and K_c would be expected to be nearly the same due to a complete canopy cover.

K_{cb} is the ratio of ET_c to ET_o, when the soil surface is dry, but transpiration is occurring at a potential rate. For the sandy soil at this station, the infiltration rate is high. Precipitation infiltrates quickly and the soil surface rapidly dries after precipitation events. Thus, dual K_c approach is appropriate for sod at this location. In Table 17 of the FAO56, the basal crop coefficient for turf grass is 0.8 during the mid-season. As shown later in this document, these values correspond well with measured ET_c/ET_o values at this location. This implies that using this measured K_{cb}, additional consideration regarding the soil evaporation is necessary.

Soil evaporation coefficient, K_e, describes the evaporation component of ET_c. Following precipitation or irrigation, the K_e is at its maximum. When the soil surface is dry, $K_e = 0$, indicating no water remains near the soil surface for evaporation.

The $K_{c\ max}$ is determined by the energy available for ET at the soil surface, ($K_{cb} + K_e \leq K_{cmax}$), or $K_e \leq K_{cmax} - K_{cb}$.

When the topsoil dries out, less water is available for evaporation and a reduction in evaporation begins to occur, therefore,

$$K_e = K_r\,(K_{cmax} - K_{cb}) \leq f_{ew}\,K_{cmax} \qquad (11)$$

where

K_e soil evaporation coefficient,

K_{cb} basal crop coefficient,

K_{cmax} maximum value of K_c following precipitation or irrigation,

K_r dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted from the topsoil, and

f_{ew} fraction of the soil that is both exposed and wetted, i.e., the fraction of soil surface from which most evaporation occurs.

Following precipitation or irrigation, the evaporation reduction coefficient $K_r = 1$, indicates evaporation is only determined by the energy available for evaporation; while $K_r = 0$ for soils at wilting point.

The K_{cmax} represents an upper limit on the evaporation and transpiration from any cropped surface and is imposed to reflect the natural constrains placed on available energy. The K_{cmax} ranges from 1.05 to 1.3 when using a grass reference (ET_o). The K_{cmax} can be estimated as

$$K_{cmax} = \max(\{1.2 + [0.04(U_2-2)-0.004(RH_{min}-45)(h/3)^{0.3}\}, \{K_{cb}+0.05\}) \quad (12)$$

where

U_2 is wind speed at 2 m height (m/s),

RH_{min} is the minimum relative humidity, and

h is mean maximum plant height during the period of calculation (m)

The K_{cmax} is always greater than or equal to the sum of K_{cb}+0.05. The wet soil surface increases the value for K_{cb} by 0.05, following a complete wetting of the soil surface, even during periods of full ground cover. A value of 1.2 instead of 1 is used for K_{cmax} in equation 12 due to the effect of increased aerodynamic roughness of surrounding crops, which can increase the turbulent transfer of vapour from the exposed soil surface. The "1.2" coefficient also reflects the impact of the reduced albedo of a wet soil and the contribution of heat stored in dry soil prior to the wetting event. The "1.2" represents effects of wetting intervals that are greater than 3 to 4 days. If the rainfall or irrigation events are more frequent, such as 1-2 days, the "1.2" may be changed to "1.1" because the soil has less opportunity to absorb heat between wettings. For this site, the 1.11 value was appropriate.

The soil evaporation reduction coefficient, K_r, is the soil evaporation from the exposed soil. Here the evaporation is assumed to have two stages: an energy limiting stage and a falling rate stage. During the first stage, the soil surface is wet and the K_r is 1. During the second stage, the soil water is limited for evaporation and the K_r is reduced below 1 becoming close to zero when there is no water is available for evaporation, or near the wilting point.

Following rainfall or irrigation, there is a maximum amount of water that can be evaporated from the soil. When the soil becomes dry, the available water for evaporation can be estimated as the difference between the water content at field capacity and the halfway between oven dry and wilting point:

$$TEW = 1000\ (\theta_{fc} - 0.5\ \theta_{wp})\ Z_e \qquad (13)$$

where

TEW total evaporable water or maximum depth of water that can be evaporated from the soil when the topsoil has been initially completely wetted (mm),

θ_{fc} soil water content at field capacity (m^3/m^3),

θ_{wp} soil water content at wilting point (m^3/m^3), and

Z_e depth of the surface soil layer that is subjected to drying by way of evaporation (0.1-0.15 m).

The field capacity of the sandy soil is 0.15, and the wilting point is 0.05. At this location, the depth of the surface soil layer is chosen to be 0.1 m because of the properties of the sandy soil. For a sandy soil, the TEW is estimated to be between 6 and 12 mm.

During the stage 1 evaporation process, following a heavy rain or irrigation event, the soil water content in the topsoil is at the field capacity and the amount of water depleted by evaporation, D_e is zero. The K_r is assumed to be 1 when the soil water content is above the field capacity. At the stage 2 (falling rate stage), the evaporation rate from the exposed soil decreases in proportion to the amount of water remaining in the surface soil layer given by

$$K_r = (TEW - D_{e,\ i-1})\ /\ (TEW - REW) \qquad \text{for } D_{e,\ i-1} > REW \qquad (14)$$

where

$D_{e, i-1}$ cumulative depth of evaporation (depletion) from the soil surface layer at the end of day i-1 (mm),

TEW maximum cumulative depth of evaporation from the soil surface layer when K_r =0, and

REW cumulative depth of evaporation at the end of stage 1.

The exposed and wetted soil fraction (f_{ew}):

$$f_{ew} = \min (1-f_c, f_w) \qquad (15)$$

where

$1-f_c$ the average exposed soil fraction not covered by vegetation (0.01- 1) and

f_w the average fraction of soil surface wetted by irrigation or precipitation (0.01-1).

The f_c ranges from 0.2 after sod harvest to 0.85 at full cover and the f_w is 1 for sprinkler irrigation at this location. Because the f_c estimated changes everyday due to K_{cb}, the measured f_c values are preferred in the calculation. However, if the f_c is not measured, it can be estimated as

$$f_c = ((K_{cb} - K_{cmin})/(K_{cmax} - K_{cmin}))^{(1+0.5h)} \qquad (16)$$

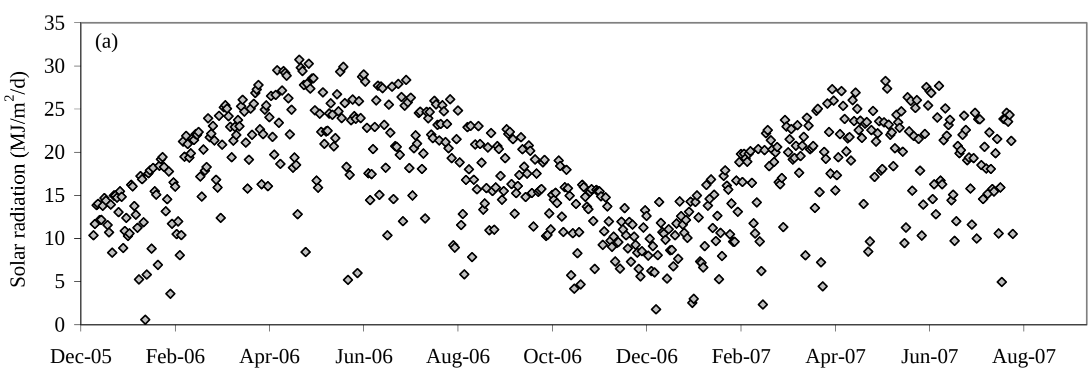
The K_{cmin} is the minimum K_c values in the range of 0.15- 0.2, corresponding with the initial growing stage K_c value. At this location, a K_{cmin} 0.15 is chosen.

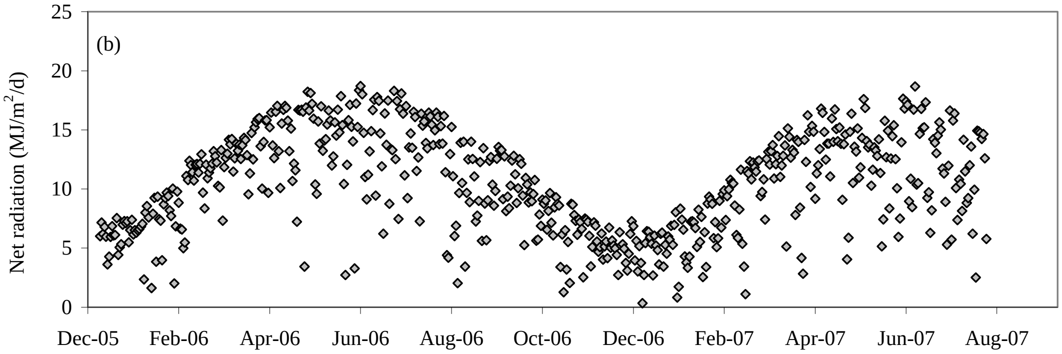
The daily D_e values representing the cumulative depth of evaporation following complete wetting from the exposed and wetted fraction of the topsoil may be estimated using a daily soil water balance equation provided in FAO56. For this experiment, near surface soil moisture was measured daily. These values provide a direct means to determine daily D_e values. Following heavy rain or irrigation, the minimum value for the depletion D_e is zero. As the soil dries out, D_e increases and in absence of any wetting event, it will reach its maximum value TEW, at a point where there is no water is left for evaporation in the upper soil layer, K_r becomes zero, and the D_e stays at TEW until the next wetting event. Therefore, the limit on D_e is defined as $0 \leq D_e \leq TEW$.

4. RESULTS

4.1 Meteorological conditions

Figure 5 shows the daily average solar radiation (R_s, MJ/m^2/d), the net radiation (R_n, MJ/m^2/d), temperature (T, ^{o}C), relative humidity (RH, %), vapor pressure deficit (VPD, kPa), and wind speed at 2 m displacement height (U_2, m/s) below.





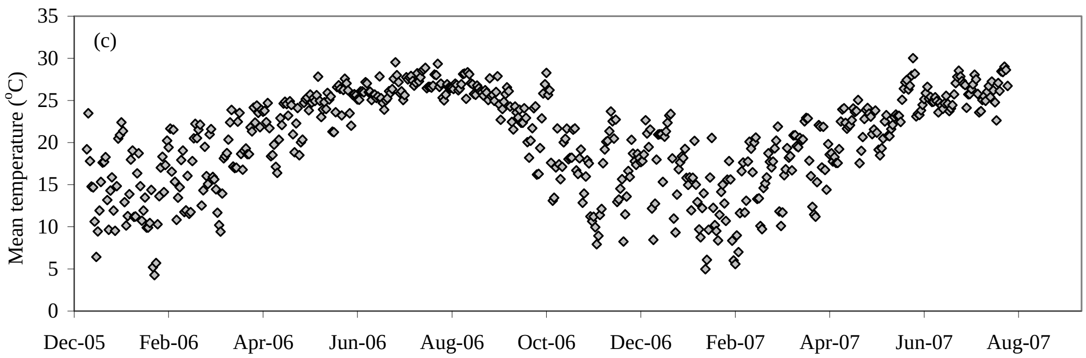
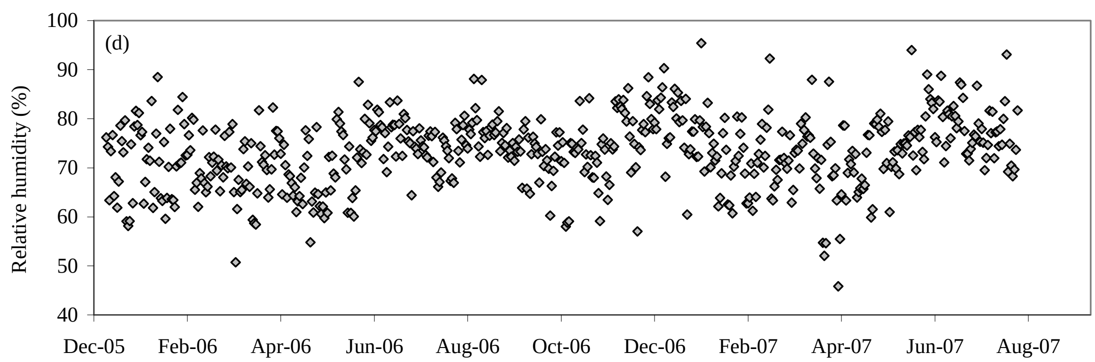
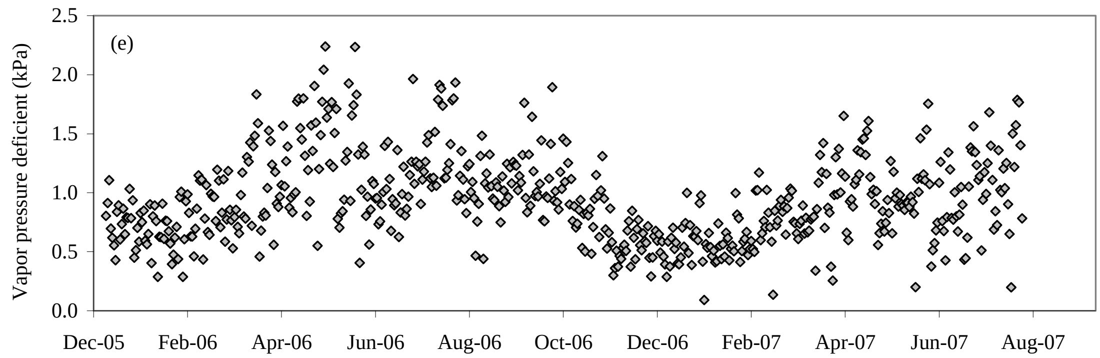


Figure 5. Daily average climate variables, (a) solar radiation, (b) net radiation and (c) temperature from January 2006 to June 2007 at Bunnell, Florida.





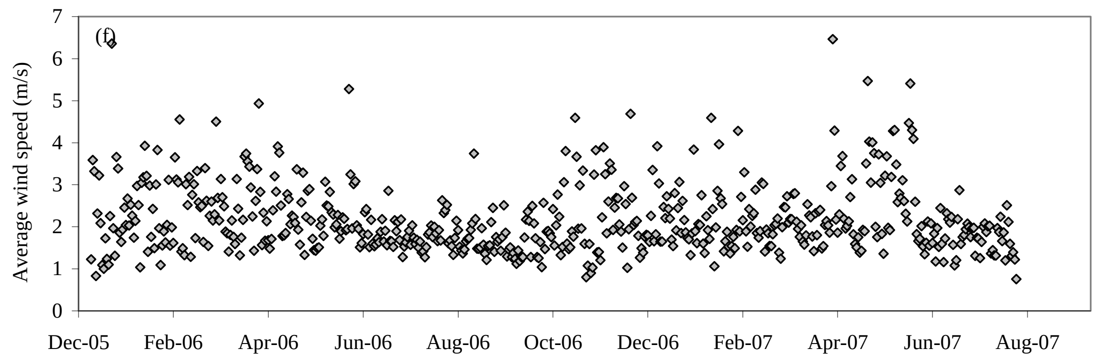


Figure 5 (cont.). Daily average climate variables, (d) relative humidity, (e) vapor pressure deficit, and (f) wind speed at 2 m displacement height from January 2006 to June 2007 at Bunnell, Florida.

The solar radiation and net radiation were high in the summer and low in the winter, with peak radiation values occurring in May. Starting in June, the incoming and net energy decreased due to increased cloud cover. The lowest radiation energy values occurred in December. A strong relationship existed between the measured R_s and R_n.

The mean temperature at the experimental site followed an annual trend similar to the radiation energy, higher in the summer and lower in the winter. However, there was not a strong relationship between the temperature and the radiation. The highest temperature was in August and the lowest temperature was in February. The highest temperature variability occurred during the winter.

The vapor pressure deficit (VPD), calculated from temperature and relative humidity, showed an annual cycle, higher in the spring and summer and lower in the winter months. The highest VPD occurred in May, when the temperature was high and the relative humidity was low.

The relative humidity and wind speed did not show a clear pattern during the study period. Wind was normally from the southwest or southeast directions, where the Atlantic Ocean is located 15 km to the east of the weather station. The anemometer was located at 2.42 m high.

4.2 Reference crop evapotranspiration

Reference crop evapotranspiration (ET_o) is defined as " the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (ASCE-EWRI 2005). The most recent standard method was established by the American Society of Civil Engineers, Environmental and Water Resources Institute and was used in this study. This method required solar radiation, temperature, relative humidity, and wind speed as the input data collected from a weather station. The detailed equations were also documented in the previous report (Jia et al. 2005). Before calculating the ET_o, all climate data were processed through the standard data quality check (ASCE-EWRI 2005). The daily ET_o rates during the study period are shown in Figure 5.

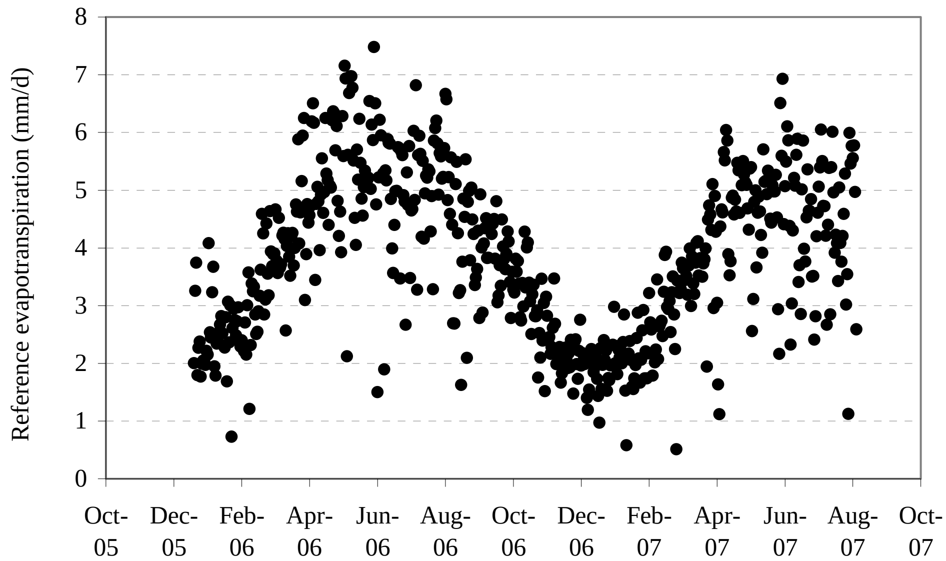


Figure 6. Daily average climate variables, (a) solar radiation, (b) net radiation and (c) temperature from January 2006 to June 2007 at Bunnell, Florida.

In the ASCE-EWRI (2005), the weather data required for the calculation of reference evapotranspiration should be collected from the environment within the area which an estimate of ET is required. In the American Society of Agricultural and Biological Engineers (ASABE) standard for automatic weather station setup (ASABE 2005), an agricultural weather station should be sited in level, open terrain representative of the local agricultural environment. The station should be free from any influence of obstacles such as buildings, trees, small hills as well as away from paved or graveled areas (highways) and large open water surfaces. The fetch distance requirement for a weather station is traditionally recommended to be 100 times the height of the measurement above ground surface (for a short grass). Considering all the requirements, the reference ET station was located 5 m away from the eddy correlation system and was the best arrangement.

4.3 Eddy correlation evapotranspiration measurements

4.3.1 Energy fluxes

Figure 6 shows the daily average daytime energy fluxes at the experimental site. The total available energy (Net radiation (R_n) – soil heat flux (G)) were calculated for daytime only, corresponding to the daytime values when the latent heat flux (LE) and the sensible heat flux (H) were measured. The LE and H measurements were not consistently available during the nighttime.

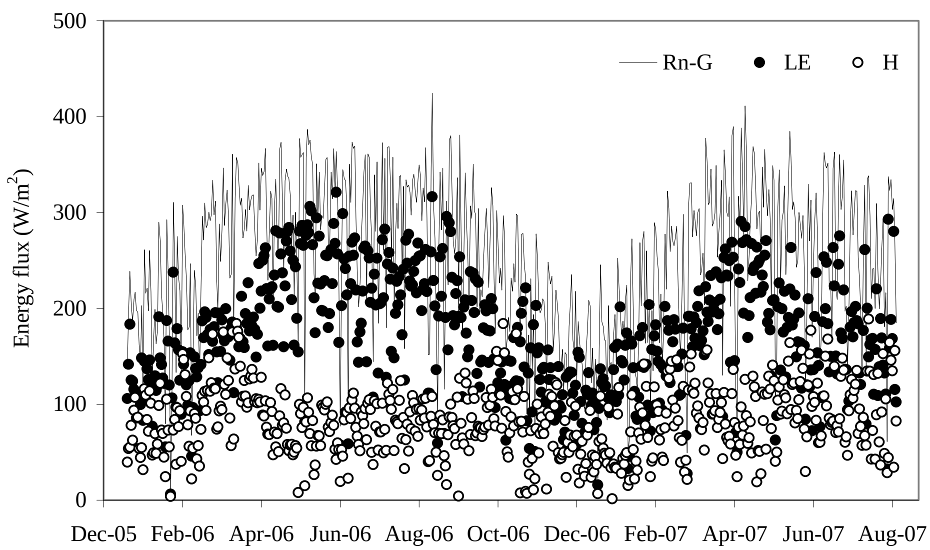


Figure 7. Daily average daytime energy fluxes at Bunnell, Florida from January 2006 to July 2007.

The LE showed an annual cycle similar to the R_n – G, higher in the summer and lower in the winter, which implied that the evapotranspiration process depended on the available energy and changed simultaneously with the energy at the land surface. In the spring (April and May), the difference between the R_n-G values and the LE values was larger than in the fall (September and October), which indicated that more available energy was used for ET in the fall than in the spring. The highest R_n-G values occurred in April, and starting from May, the R_n-G magnitudes were gradually reduced, corresponding to the start of the rainy season.

The H values had a different pattern than either the LE, or the R_n-G values. The H values were higher in the beginning of the year, from January to May, and lower in the summer months. As expected, both LE and H were below the R_n-G during the entire study period. The LE values were greater than the H during the growing season, indicating a large fraction of energy being used for sod evapotranspiration – energy used for changing the phase of water from liquid to vapor under isobaric-isothermal condition (ASCE 1996). During the rest of the months in the fall or spring, the LE and the H values were about the same.

The evaporative ratio, LE/R_n, and the Bowen ratio, H/LE, are plotted in Figures 7 and 8, respectively. These ratios were relatively consistent on a day-to-day basis, but varied seasonally. The fraction of net radiation used for evapotranspiration, LE/R_n, ranged from 69% in March to 88% in September. The Bowen ratio, H/LE, was smaller in the summer months, indicating the sod had adequate soil moisture supply and was actively transpiring. In the winter months, January to March, the Bowen ratio was close to or greater than 1, indicating a reduction in the relative use of available energy for crop evapotranspiration.

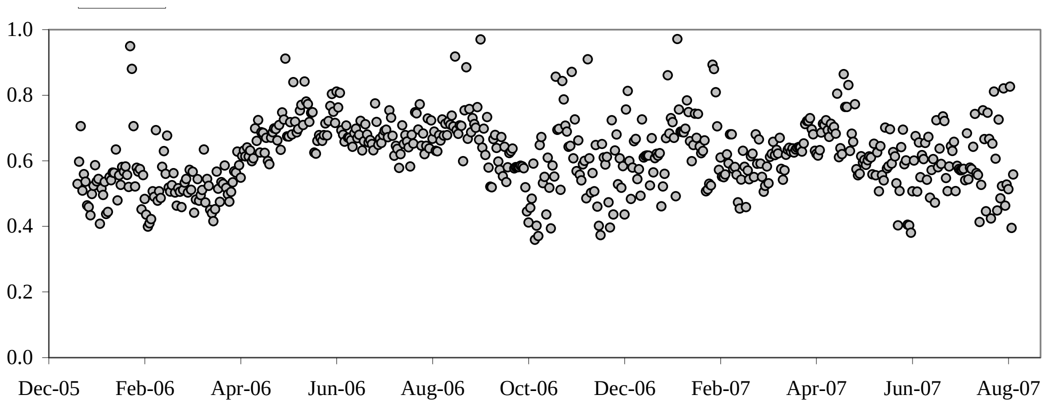


Figure 8. Ratio of daytime latent heat flux (LE) to daytime net radiation (R_n) over sod surface at Bunnell , Florida from January 2006 to July 2007.

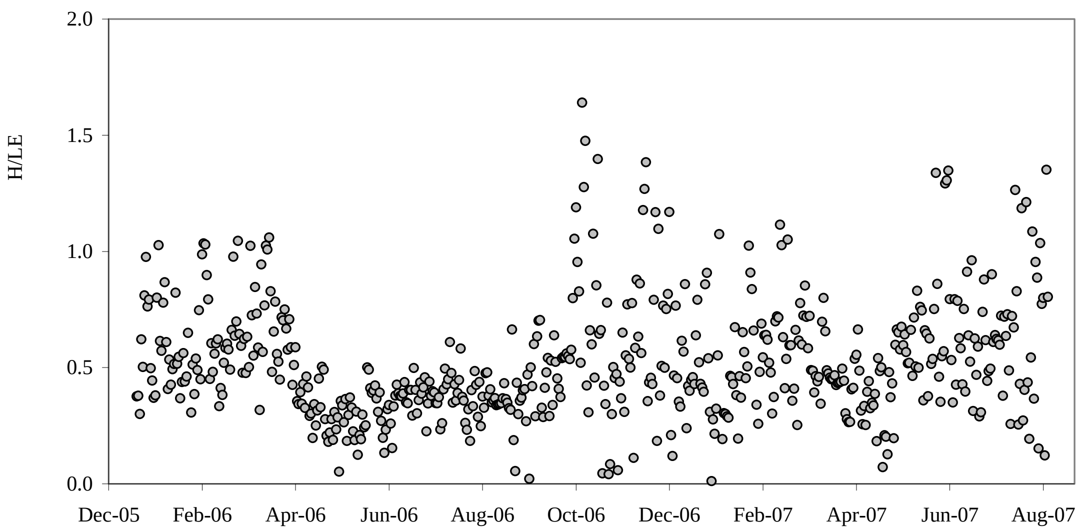


Figure 9. The Bowen ratio (ratio of daytime sensible heat flux (H) to daytime latent heat flux (LE)) over sod surface at Bunnell, Florida from January 2006 to July 2007.

Table 2 summarizes the monthly average values for daytime energy fluxes. The R_n values were highest in April and lowest in December, and the LE values were highest in August and lowest in December. For the whole study period, the net radiation partitioned 65% into latent heat flux, 27% into sensible heat flux and 9% into soil heat flux.

Table 2. Monthly values of daytime energy fluxes (R_n = net radiation, LE= latent heat flux, H=sensible heat flux, and G=soil heat flux) and ratios of LE/R_n, H/R_n, G/R_n, and H/LE over sod surface at Bunnell, Florida from January 2006 to July 2007.

Month	Rn	LE	H	G	LE/Rn	H/Rn	G/Rn	H/LE
1	213.4	125.0	64.7	23.7	0.60	0.30	0.11	0.53
2	246.2	138.0	78.2	30.0	0.58	0.31	0.10	0.57
3	318.9	176.2	107.9	35.1	0.56	0.34	0.11	0.62
4	334.6	216.4	84.9	33.4	0.65	0.26	0.10	0.41
5	321.9	210.9	86.8	24.5	0.66	0.27	0.07	0.45
6	303.1	195.3	88.0	19.8	0.64	0.30	0.06	0.50
7	288.7	182.6	87.1	19.0	0.63	0.30	0.06	0.51
8	304.1	203.3	81.0	19.8	0.67	0.28	0.05	0.45
9	300.9	198.9	79.2	22.8	0.66	0.26	0.07	0.42
10	267.5	147.5	96.4	23.6	0.55	0.36	0.09	0.72
11	196.9	116.0	64.9	16.0	0.60	0.32	0.08	0.60
12	173.1	104.9	53.4	14.8	0.60	0.30	0.09	0.53
Annual	**280.8**	**184.4**	**72.1**	**24.9**	**0.65**	**0.27**	**0.09**	**0.40**

All energy fluxes are in W/m^2 and ratios have no units.

4.3.2 Evapotranspiration rates

The daily average evapotranspiration rates by eddy correlation method are plotted in Figure 9. The evapotranspiration rates showed a clear annual pattern that decreased in May, corresponding to the radiation energy flux changes. The highest daily ET_c (7.48 mm) occurred on May 4, 2006 and the lowest (0.03 mm) on February 3, 2006.

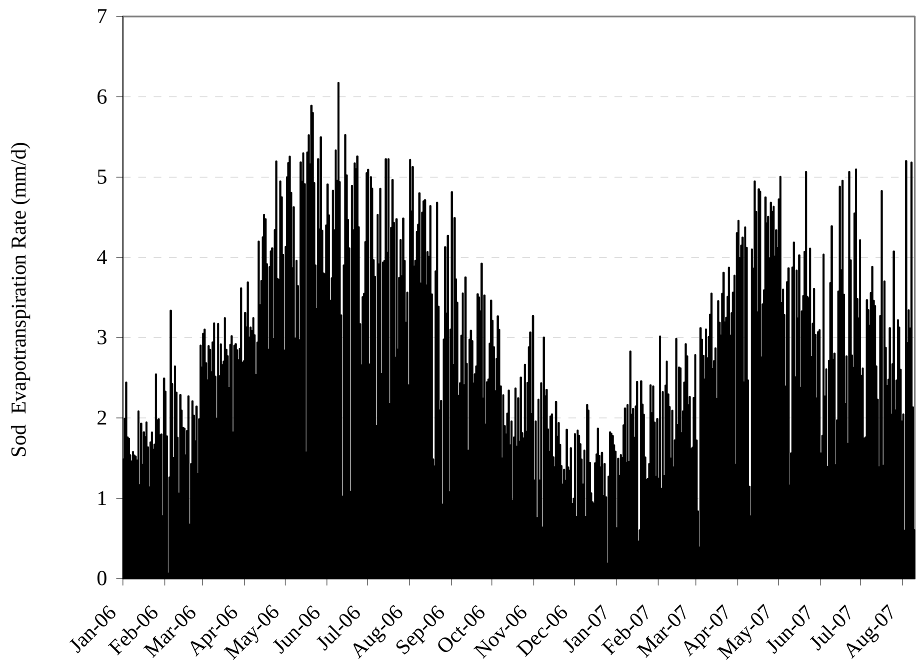


Figure 10. Daily sod evapotranspiration rates estimated by eddy correlation method at Bunnell, Florida from January 2006 to July 2007.

Figure 10 shows the monthly ET_c and precipitation values at the weather station. The ET_c exceeded precipitation rates during most of the months. The 2006 growing season was very dry, except the month of June.

Figure 11 shows the sod ET_c rates by the eddy correlation method versus the ET_o rates. The two values showed a similar annual cycle, higher in the summer and lower in the winter. The ET_c values were typically lower than the ET_o values and the relationship was described as $ET_c = 0.7806\ ET_o - 0.0944$ with a $R^2 = 0.8006$.

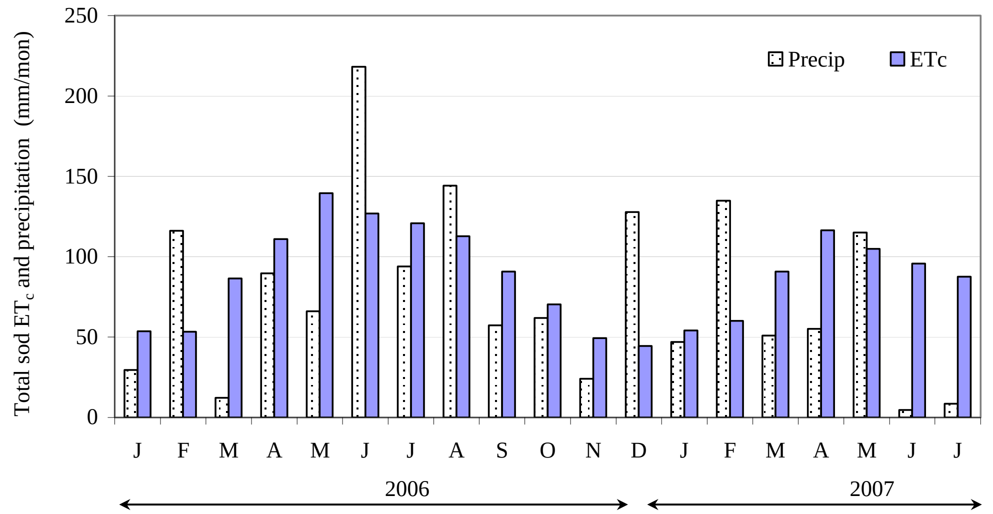


Figure 11. Total monthly sod evapotranspiration rates and precipitation at Bunnell, Florida from January 2006 to July 2007.

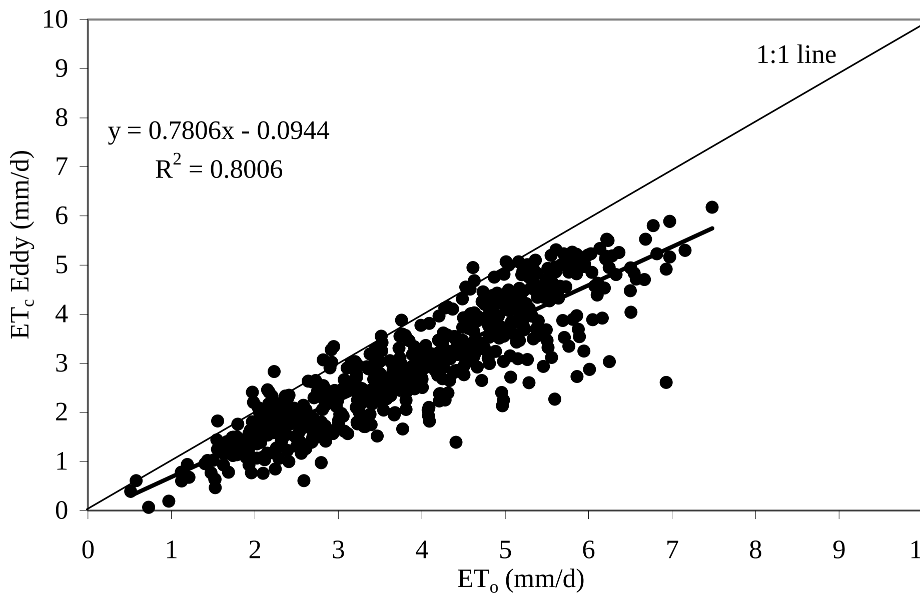


Figure 12. Daily sod ET_c by eddy correlation vs. calculated ET_o values from January 2006 to July 2007 at Bunnell, Florida.

4.4 Sod crop coefficients

As discussed in section 3.3, the dual crop coefficient approach includes both the effect of crop transpiration as described by the basal crop coefficient (K_{cb}) and soil evaporation from the soil surface by soil water evaporation coefficient (K_e). The total crop coefficient is the sum of the K_{cb} + K_e. Here we first present the basal crop coefficient results, followed by the total $K_c = K_{cb} + K_e$.

4.4.1 Basal crop coefficients

The basal crop coefficient (K_{cb}) is defined as the ratio of actual crop evapotranspiration (ET_c) to reference crop evapotranspiration (ET_o) when the soil surface layer is dry, but the average soil water content of the root zone is adequate to sustain full plant transpiration. The K_{cb} serves as the baseline potential K_c in the absence of the additional effects of soil wetting by irrigation or precipitation.

K_{cb} values for sod were calculated as the ratio of the actual measured sod ET_c to grass ET_o. Figure 12 shows the monthly K_{cb} values from January 2006 to July 2007. For August and December 2006, the K_{cb} values relied on values estimated using the PT approach because less than 50% of the days had measured values due to data logger problems. K_{cb} values were in generally close to 0.8, but decreased after the grass was harvested in September 15, 2006 to approximately 0.65. These values agree well with FAO56's basal crop coefficient values for warm season turf grass of 0.75 during the initial growth and 0.8 during the mid-season and end-season.

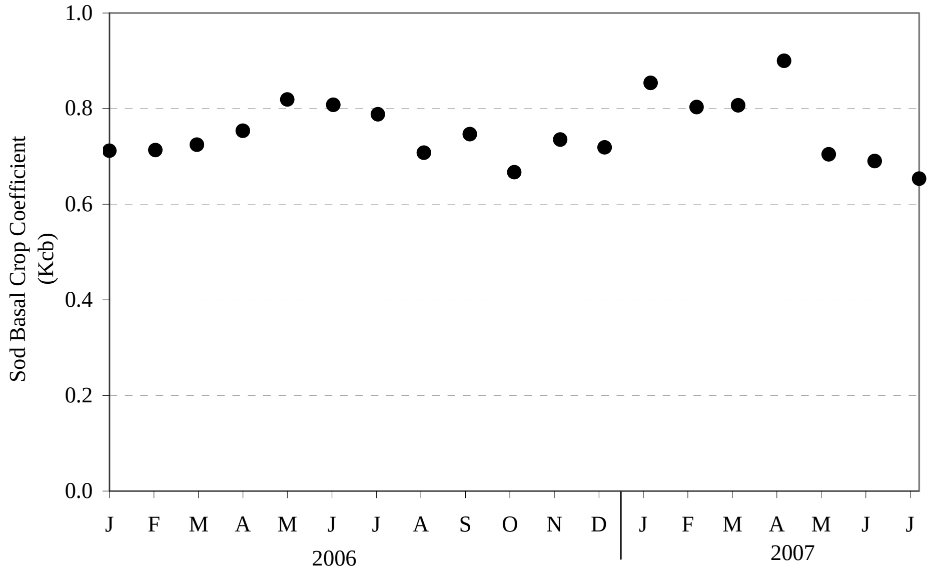


Figure 13. Monthly sod basal crop coefficient (K_{cb}) by eddy correlation from January 2006 to July 2007.

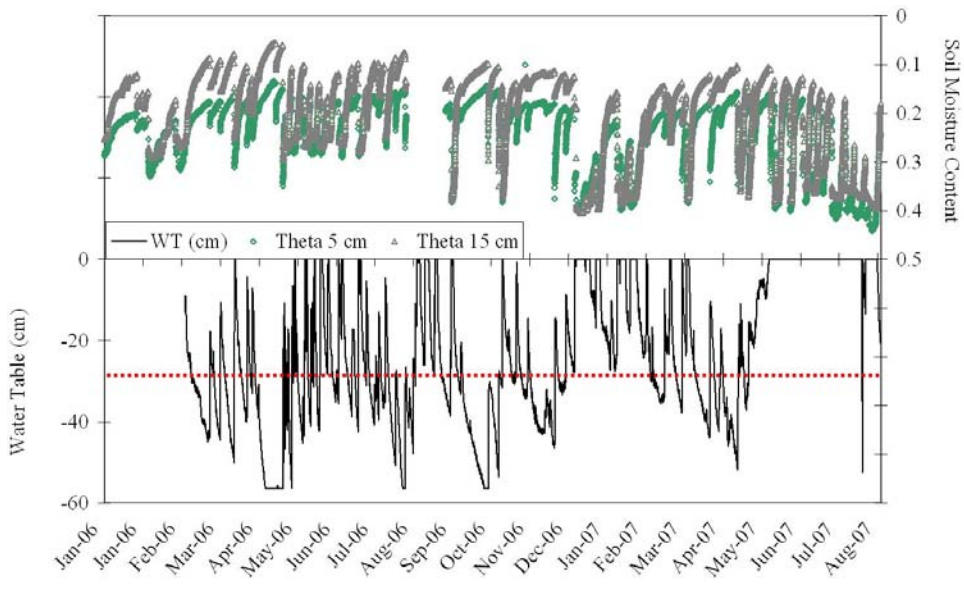


Figure 14. 30-min water table and soil moisture content (cm^3/cm^3) at 5 cm and 15 cm below surface from March 2 2006 to July 31, 2007. The dashed line is at 30 cm below the surface.

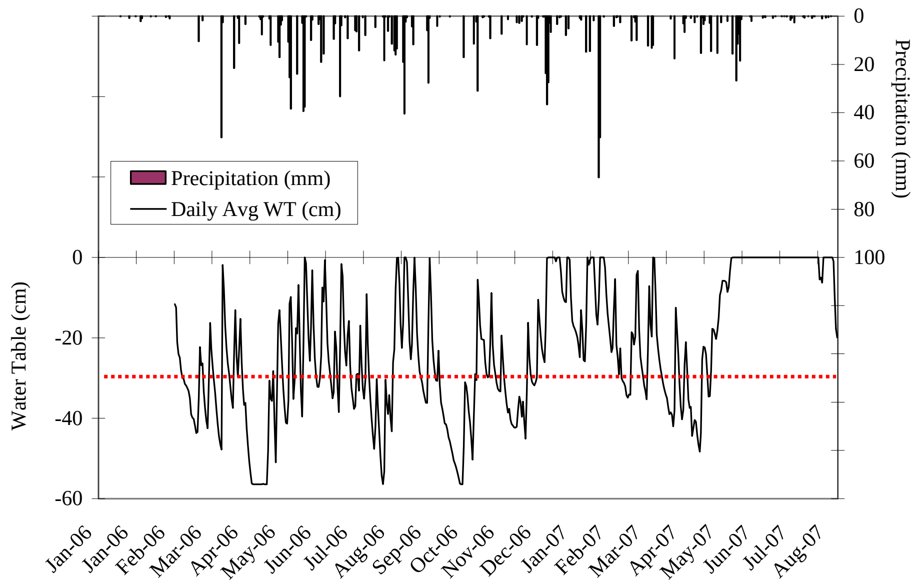


Figure 15. Daily average water table and the daily total precipitation at the experimental site from March 2 2006 to July 31, 2007. The dashed line is at 30 cm below the surface.

4.4.2 Dual crop coefficients

The total crop coefficient requires knowledge of the basal crop coefficient results as well as the soil evaporation coefficient, K_e. K_e has a relatively high value when the soil surface is moist and a minimum value when the soil surface is dry. Here, daily K_e values were estimated using the FAO56 method described in section 3.3 and monthly values are shown in Figure 15. These results show that the typical K_e values range from 0.08 to 0.20. There are periods during the experiment when K_e values exceeded 0.2. These periods coincided with months having very high soil moisture (on average greater than 0.20). High soil moisture values are problematic for two reasons. First, the soil moisture sensor used in the water balance reflects local conditions. Field records indicate prolonged periods with having a leaky irrigation pump and flooded conditions near the stations. These local conditions do not represent field conditions. Second, during periods with high soil moisture and wet surface conditions, the assumptions used to determine K_{cb} are not valid. Specifically, under these conditions, the eddy correlation system measures both soil evaporation and evapotranspiration.

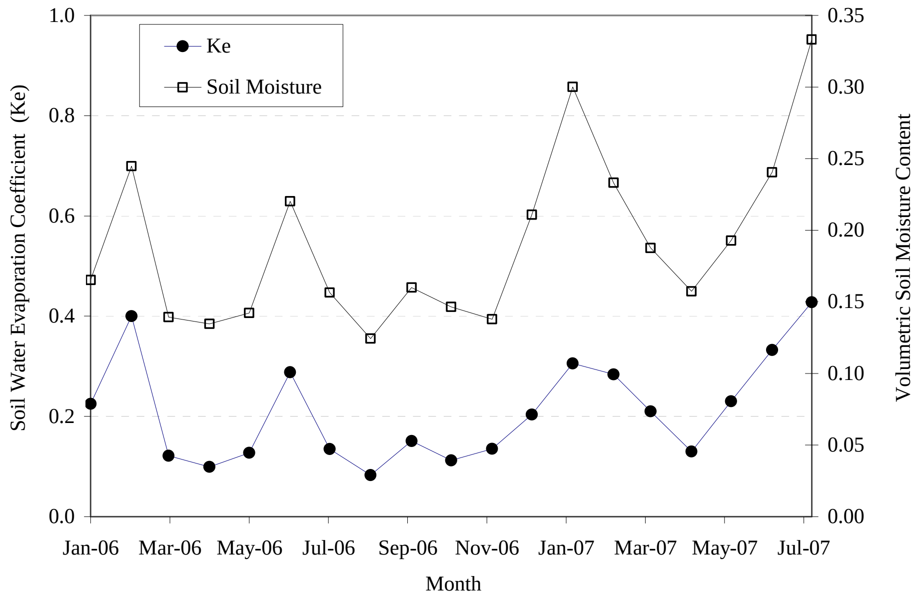


Figure 16 . Monthly values of the soil water evaporation coefficient (Ke) and the average monthly soil moisture content for sod grass from January 2006 to July 2007.

Based on these findings, the K_e values for months when the average soil moisture exceeded 0.20 were removed from the analysis. The remaining values K_e ranged 0.08 to 0.23 with an average value of 0.15 and no consistent seasonal trend. Based on this result, we recommend a single K_e value of 0.15 be used for all months.

The difference between the FAO56 single coefficient crop coefficients for warm season turf (FAO56, Table 12) and the FAO56 dual coefficient crop coefficients for warm season turf (FAO56, Table 17) is 0.05. This indicates that FAO56 uses a single annual K_e value of 0.05. This result supports our recommendation of a single annual K_e value. However, the FAO56 value of 0.05 would underestimate the K_e values determined experimentally for our site conditions.

Monthly K_c values were calculated by summing the monthly K_{cb} values and K_e = 0.15. The individual values are shown by month in Figure 16. These results show that the K_c values are slightly lower for approximately four months following the harvest (mid August to mid September). The recommended values will vary slightly monthly.

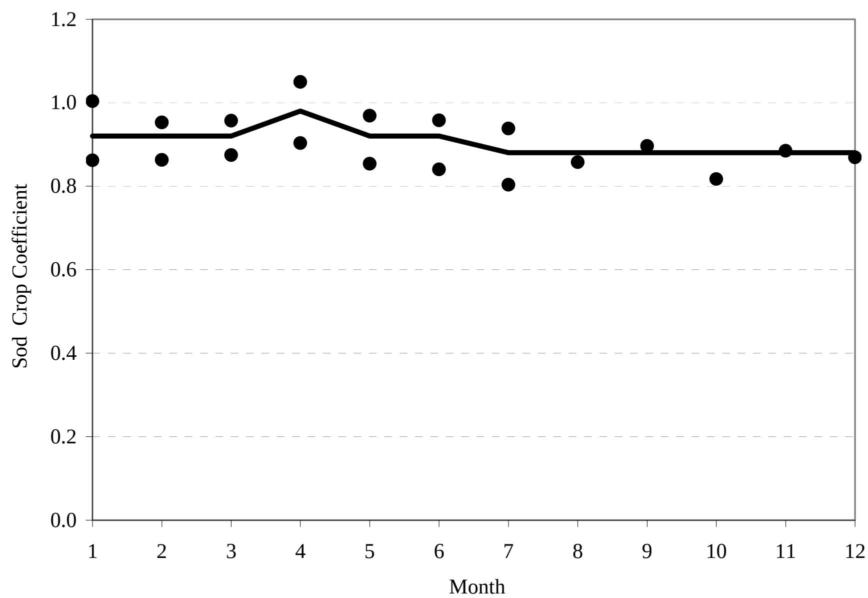


Figure 17. Monthly sod crop coefficients (dots) and recommended Kc values for sod grass from January 2006 to July 2007.

Table 3 summarizes the ET_o, ET_c, K_{cb}, and K_c values by month. The K_c values are fairly consistent throughout the experiment. Somewhat lower values in late summer/early fall reflect the annual harvest.

Table 3. Monthly sod evapotranspiration (ET_c) and crop coefficient (K_c) by eddy correlation measurements and the dual K_c method. Recommended crop coefficient values have a bold type in the last column.

Month	**ET_o (mm/day)**	**ET_c eddy (mm/day)**	**K_{cb}**	**K_c**
1	2.25	1.74	0.78	**0.92**
2	2.65	2.03	0.76	**0.92**
3	3.66	2.79	0.77	**0.92**
4	4.89	4.01	0.83	**0.98**
5	5.13	3.94	0.76	**0.92**
6	4.91	3.71	0.75	**0.92**
7	4.61	3.36	0.72	**0.88**
8	3.99	2.94	0.71	**0.88**
9	4.03	3.03	0.75	**0.88**
10	3.43	2.27	0.67	**0.88**
11	2.36	1.73	0.73	**0.88**
12	2.11	1.51	0.72	**0.88**
Annual	3.67	2.76	0.74	0.91

5. SUMMARY AND CONCLUSIONS

Sod is an important agricultural crop in Florida with respect to production and water demand. Irrigation is required to ensure sod growth and quality due to low soil water holding capacity on sandy soils commonly found in Florida and the shalow root zone. Sod evapotranspiration and crop coefficients are critical parameters for sod irrigation scheduling and water management. An experiment was conducted in northeastern Florida, near Bunnell, Flagler County from January 1, 2006 through July 31, 2007. Sod evapotranspiration (ET_c) and crop coefficient (K_c) values were estimated using the eddy correlation method. The eddy correlation method is an established method for estimating ET in Florida by measuring ET above crop canopy. This method is extremely useful for frequently harvested landscape that is characteristic of a sod farm. The measured sod ET_c showed a clear annual cycle similar to radiation energy flux. The second year (2007) of the experiment had somewhat lower evapotranspiration rates than the first year (2006). This is consistent with evapotranspiration measured at another location in North Central Florida.

Sod crop coefficients were estimated from the ratio of sod ET_c to reference evapotranspiration (ET_o) calculated from weather data over a grass reference site. The crop coefficients were estimated from a dual crop coefficient approach that separates the crop coefficient (K_c) into two coefficients: a basal crop coefficient (K_{cb}) and a soil evaporation coefficient (K_e). The K_{cb} values determined directly from the site specific measurements range from 0.67 to 0.83 with the lowest values occurring after harvest. These values provide the actual evapotranspiration for the experimental site under the site specific management conditions. These values likely somewhat underestimate a site’s potential evapotranspiration. Thus, a single soil evaporation coefficient of 0.15 was found to reasonably describe the soil evaporation from a wet soil surface and was used to adjust the monthly crop coefficients. This site’s coefficient exceeded the FAO56’s single soil evaporation coefficient of 0.05. It is recommended that the soil evaporation coefficient be further investigated. The recommended sod K_c values range between 0.88 and 0.98. The lower values reflect the reduced plant transpiration following harvest and the peak values reflect the active growing periods.

ACKNOWLEDGEMENT

The authors gratefully wish to acknowledge Mr. John Fitzgerald and the St. Johns River Water Management District for support of the project; Mr. Fred W. Williams, Mr. Larry Miller, and Mr. Steve Feagle for assistance with the research activities.

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APPENDIX

Figure A1. Sod at Bunnell, Florida, December 21, 2005 (from west to east).

Figure A2. Sod at Bunnell, Florida, January 25, 2006 (from west to east).

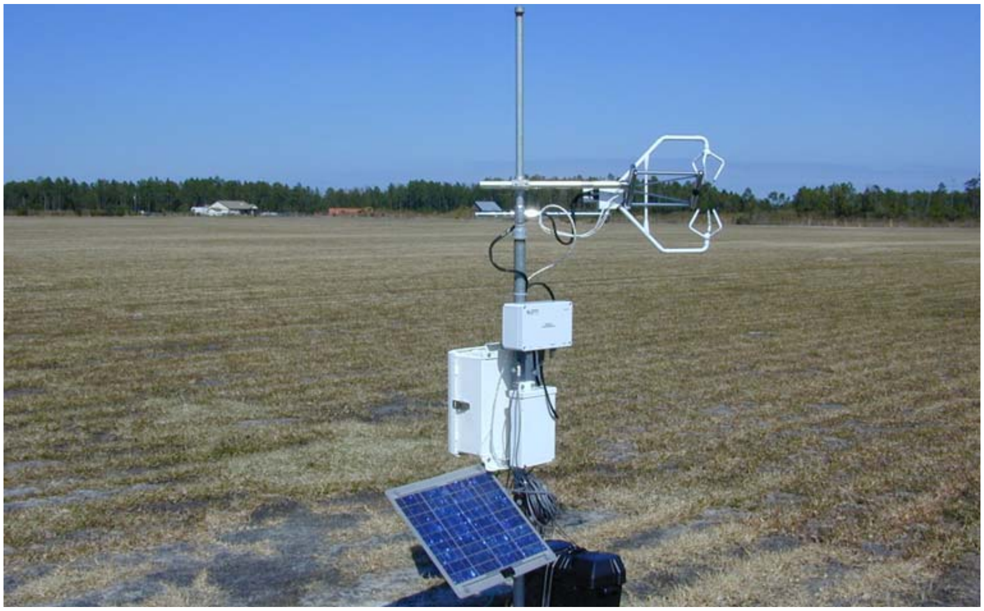

Figure A3. Sod at Bunnell, Florida, February 14, 2006 (from southwest to northeast).

Figure A4. Sod at Bunnell, Florida, April 26, 2006 (from southwest to northeast).

Figure A5. Sod at Bunnell, Florida, May 10, 2006 (from southeast to northwest).

Figure A6. Sod at Bunnell, Florida, June 8, 2006 (from northwest to southeast)

Figure A7. Sod at Bunnell, Florida, July 19, 2006 (from southeast to northwest).

Figure A8. Sod at Bunnell, Florida, August 16, 2006 (from north to south).

Figure A9. Sod at Bunnell, Florida, September 15, 2006 (from southwest to northeast).

Figure A10. Sod at Bunnell, Florida, October 3, 2006 (from south to north).

Figure A11. Sod at Bunnell, Florida, November 8, 2006 (from northwest to southeast).

Figure A12. Sod at Bunnell, Florida, December 6, 2006 (from southeast to northwest).

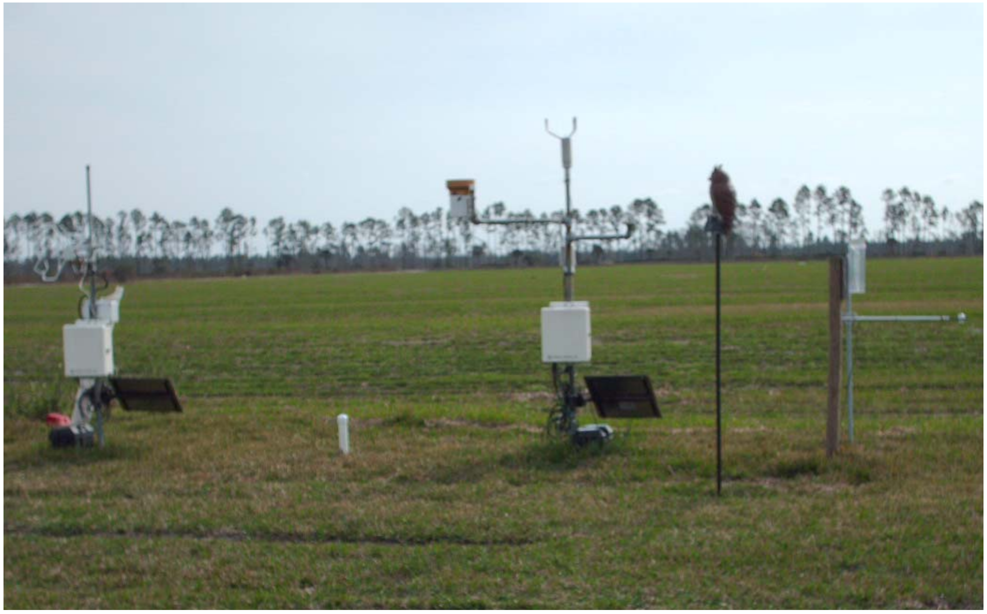

Figure A13. Sod at Bunnell, Florida, December 20, 2006 (from north to south).

Figure A14. Sod at Bunnell, Florida, January 17, 2007 (from northeast to southwest).

Figure A15. Sod at Bunnell, Florida, February 14, 2007 (from southwest to northeast).

Figure A16. Sod at Bunnell, Florida, March 6, 2007 (from east to west).

Figure A17. Sod at Bunnell, Florida, March 21, 2007 (from east to west).

Figure A18. Sod at Bunnell, Florida, April 5, 2007 (from east to west).

Figure A19. Sod at Bunnell, Florida, April 19, 2007 (from east to west).

Figure A20. Sod at Bunnell, Florida, May 1, 2007 (from east to west).

Figure A21. Sod at Bunnell, Florida, May 15, 2007 (from east to west).

Figure A22. Sod at Bunnell, Florida, May 30, 2007 (from east to west).

Figure A23. Sod at Bunnell, Florida, June 21, 2007 (from east to west).

Figure A24. Sod at Bunnell, Florida, July 05, 2007 (from east to west).

REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL

APPENDIX 7
SENSITIVITY ANALYSIS OF MODEL PARAMETERS
(TASK 22)

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April 2005

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL
APPENDIX 7 - SENSITIVITY ANALYSIS OF MODEL PARAMETERS

SENSITIVITY ANALYSIS BACKGROUND

The goal of Task 22 was to conduct a sensitivity analysis using the GIS-based Water Resources and Agricultural Permitting and Planning System (GWRAPPS) to compare the relative influence of climate, soil, and crop factors on regional and farm scale crop-water requirements. The GWRAPPS model was used to quantify irrigation water at a regional scale on a farm-by-farm basis using spatially distributed soils, land-use, and long-term daily climate data. The study's objectives were: 1) to examine the effects of crop coefficients, ET methods, crop-root zone depth, and soil-water holding capacity on irrigation requirements; and 2) to determine the most sensitive factors in the regional irrigation requirement with respect to the regional average and the farm-to-farm variability. The sensitivity analysis was conducted for farms in Florida, with focus on a perennial and an annual crop—ferns and potatoes, respectively.

In this document, we first introduce the GWRAPPS and then cover the GWRAPPS' system design and implementation. The AFSIRS model is explained briefly to provide an overview of the model and the context in which the GWRAPPS sensitivity analysis was conducted. The sensitivity analysis was performed on four critical parameters of the AFSIRS model. This analysis was performed using GWRAPPS for estimating crop-water requirements on a regional scale. The four critical parameters used were reference ET method, crop coefficient, crop-root zone depths, and soil-water holding capacity (WHC). The four methods used for estimating ET_o were the Hargreaves method (Hargreaves and Samani, 1985), the Institute of Food and Agricultural Sciences (IFAS) modified Penman method (Jones et al., 1984), the American Society of Civil Engineers (ASCE) Penman-Monteith method (Jensen et al., 1990), and the United Nations Food and Agriculture Organization (FAO) Penman-Monteith method (Allen et al., 1998). Each ET estimation method is described in detail. The crop-coefficient sensitivity analysis simulated the crop-water requirements for the coefficient given in the AFSIRS database and that coefficient's value +/- 10 and 20%. The soil WHC sensitivity analysis simulated the crop-water requirements for three WHC scenarios. The scenarios included minimum WHC, average WHC, and maximum WHC. The simulations' results for both ET and WHC are presented and discussed.

MODEL DESCRIPTION

GWRAPPS Model

GWRAPPS is an integrated system designed as a distributed, regional scale, crop-drought-water requirement model that captures most regional crops, heterogeneous soils, and spatially variable climate (Satti, 2002; Satti and Jacobs, 2004). GWRAPPS operates in a Windows environment and tightly couples a geographic information system, ArcGIS (ESRI), with a crop model, the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model (Smajstrla, 1990). GWRAPPS provides tools for estimating irrigation requirements at a farm scale (permitting tool) and at a multi-farm or regional scale (planning tool). It also provides a climate interpolation utility to generate distributed climate data over a given region. The irrigation requirements for a crop are based on soil, irrigation system, growing season, climate, and irrigation management practice. The AFSIRS model uses the long-term daily irrigation estimates to determine irrigation for average demand and for drought irrigation within a probabilistic framework.

AFSIRS Water Budget

The AFSIRS model uses a water-balance approach with a two-layer soil column to simulate soil-water infiltration, redistribution, and extraction by evapotranspiration as steady state processes on a daily basis. The AFSIRS model simulates the net and/or gross irrigation requirements for a crop, based on plant physiology, soil, irrigation system, growing season, climate, and irrigation management practice (Smajstrla, 1990). The water balance equation for the soil column defined by the crop-root zone is

$$\Delta S = P + I_{net} - Q_{GW} - Q_{SR} - ET_c \quad (1)$$

where ΔS is the change in soil water storage, P is the rainfall, I_{net} is the net irrigation requirement, Q_{GW} is the ground water drainage, Q_{SR} is the surface runoff, and ET_c is the crop evapotranspiration (Figure 1). For Florida's flat, sandy soils, surface runoff and lateral flow are assumed negligible or combined with drainage.

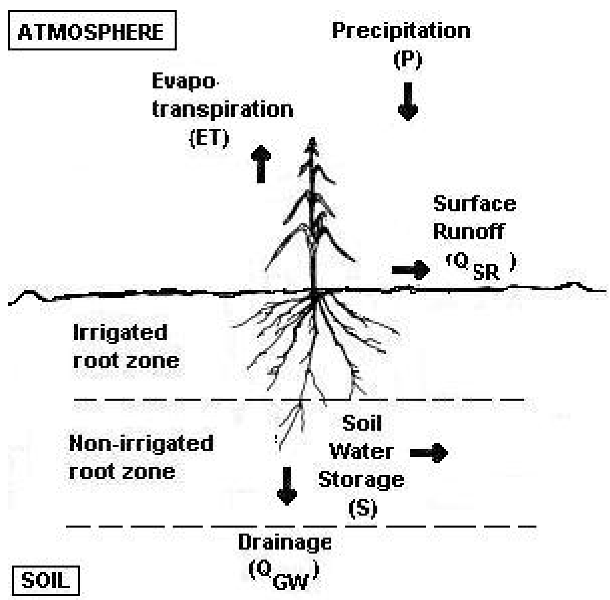

Figure 1. Components of AFSIRS soil-water balance

The water storage capacity (S) in the crop-root zone is expressed as the product of the soil-water holding capacity (WHC) and the crop-root zone depth (z). The available WHC represents the amount of water that the plant can withdraw from the soil without experiencing stress. The AFSIRS soil database consists of 766 soil types obtained from the soil series database mapped by the Natural Resources Conservation Service. The soils are characterized by the WHC for up to five soil layers. Maximum, minimum, and average WHC values that account for the naturally occurring range in soil-water holding capacities within a soil series are defined.

The modeled soil profile depth is equal to the crop-root zone depth. The two soil layers are the irrigated and non-irrigated crop-root zones. The irrigated root zone is the upper 50% of the maximum expected root depth and the non-irrigated root zone is the lower 50%. Crop ET extracted from these zones is 70 % and 30%, respectively, when water is available. Water becomes less available as the non-irrigated root zone dries during drought periods, and a greater proportion is extracted from the irrigated zone in order to meet the total crop ET. The AFSIRS crop database provides root zone information for 16 perennial and 44 annual crops. The crop-root zone for perennial crops is assumed to be constant. The crop-root zone development for annual crops has four growth stages. The average growth-stage lengths differ by crop and are given as fractions of the crop-growing season. The root zone is held constant at the minimum depth throughout crop-growth stage 1 (establishment of the crop). The root zone increases linearly to a maximum depth throughout crop-growth stage 2 (vegetative growth and development). The maximum root zone is attained at the beginning of crop-growth stage 3 (peak growth) and is maintained throughout crop-growth stages 3 and 4 (maturity to harvest).

The crop evapotranspiration (ET_c) is the amount of ET occurring from a specific crop. AFSIRS calculates ET_c by the reference crop ET (ET_o) and the crop coefficient (K_c) as

$$ET_c = K_c * ET_o \tag{2}$$

ET_o is "the rate at which water, if available, would be removed from the soil and plant surface of a specific crop, arbitrarily called a reference crop" (Jensen et al., 1990). The reference crop is typically grass or alfalfa under well-watered conditions. The standard reference crop in Florida is grass, with a height of at least 8 cm and no more than 15 cm (Doorenbos and Pruitt, 1977). The reference crop ET provides a standard response of a plant to the given atmospheric conditions. Monthly K_c values are used for perennial crops; K_c values are based on four crop-growth stages for annual crops. K_c values for growth stage 1 are calculated as the ratio of P to ET_o, with a minimum value based on the soil WHC. K_c values for growth stage 2 are linearly interpolated between stages 1 and 3 values to calculate the daily K_c. Crop specific K_c values are provided for the growth stages 3 and 4. When daily rainfall exceeds ET_o, K_c is set to 1.0.

Drainage (Q_{GW}) is that portion of rainfall in excess of rain stored in the soil profile to field capacity (maximum soil-water storage capacity) or extracted by ET_c as the water is redistributed in the soil. Drainage is determined based on the water content in the crop-root zone by

$$\begin{aligned} Q_{GW} &= 0 && \text{if } P - \left[(\theta_{\max} - \theta)z + ET_c\right] \le 0 \\ Q_{GW} &= P - \left[(\theta_{\max} - \theta)z + ET_c\right] && \text{if } P - \left[(\theta_{\max} - \theta)z + ET_c\right] > 0 \end{aligned} \tag{3}$$

where θ and θ_{max} are the current and maximum soil-water contents, respectively.

The net irrigation requirement (I_{net}) is calculated as the depth of water required to restore the soil water to field capacity in the irrigated crop-root zone. Irrigation water is added to the water balance when the available soil-water storage decreases to a minimum allowable level. The minimum allowable level is the product of the AWHC in the crop-root zone and the maximum allowable soil-water depletion percentage (AWD), where AWD is a fraction of the crop-root zone's AWHC. AWD values for perennial crops are provided on a monthly basis. AWD values for annual crops are given for the four crop-growth stages.

The model results include the monthly and the annual irrigation requirements under normal, 1-in-5-year drought and 1-in-10-year drought conditions. The probabilities of occurrence of drought are calculated from a conditional probability model that uses the type I extreme value distribution for positive non-zero irrigation values (Haan, 1977; Stedinger et al., 1993).

Sensitivity Analysis

The sensitivity analysis was performed on a regional scale using GWRAPPS. This analysis was performed on two crops, ferns and potatoes, in Volusia and St. Johns Counties, respectively (Figure 2). For each crop, the sensitivity analysis involved four ET methods, five crop coefficient values, three water holding capacities, and five crop-root zone depths. This resulted in a total of 28 simulation runs of the GWRAPPS planning tool.

Data

In the ferns case study, the net irrigation requirements for all the farms growing ferns in Volusia County, Florida, were estimated. There are 161 farms growing ferns, comprising about 4068 ha. The study area, Volusia County, is located on the east coast of Central Florida (Figure 2). The study area lies between $80^{o}40'$W and $81^{o}41'$W longitude and between $28^{o}37'$ and $29^{o}26'$ latitude. Volusia County has an average summer temperature of approximately 27^{o}C, average winter temperature of approximately 16.4^{o}C, and a mean annual rainfall of about 122 cm. The study area is comprised of 79 different soil types. Approximately 5% of the total study area is agricultural land.

St. Johns County, Florida, was the study area for the GWRAPPS model runs on potatoes. St. Johns County is located on the east coast of Florida. The study area lies between $81^{o}10'$W and $81^{o}42'$W longitude and between $29^{o}36$ and $30^{o}16'$ latitude. The study area comprises 66 different soil types. About 37% of the study area is comprised of either agricultural land or golf courses. St. Johns County, along with Flagler and Putnam Counties, comprises about 85% of the total potato production in Florida (Hochmuth and Cordasco, 2000). St. Johns County has 109 farms that grow potatoes. The total acreage of these farms is 18,173 ha. Potatoes are planted in December–January in St. Johns County and are harvested in May–June, in what is considered the spring planting. The planting and harvesting dates in the present scenario are January 1 and May 15, respectively.

All the GIS layers, excluding the climate layers, were obtained from the SJRWMD GIS data repository. The climate layers were generated using the climate interpolation tool.

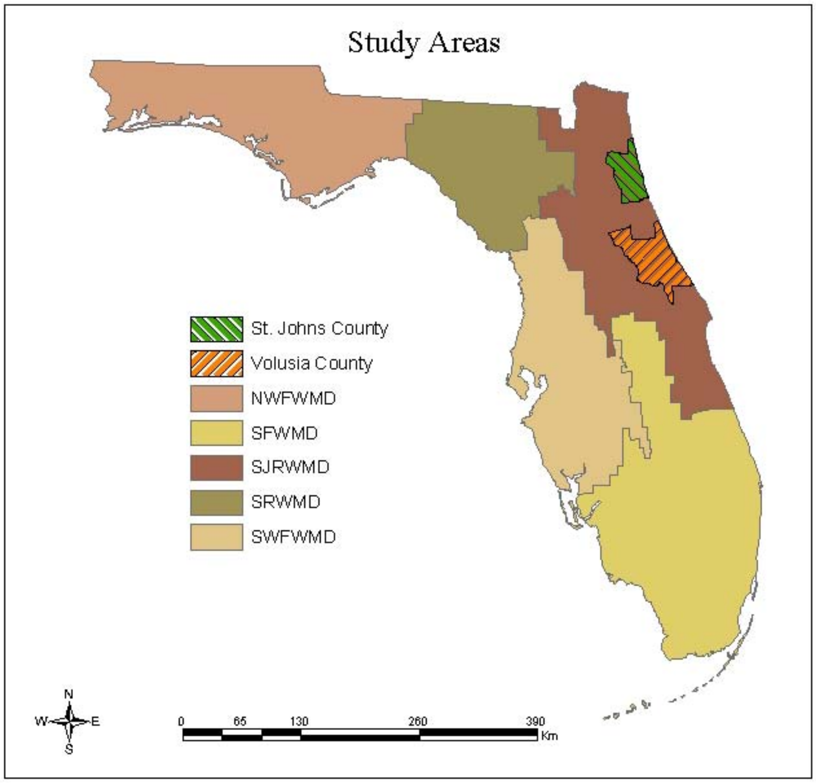

Figure 2. Study areas in Florida
The potato study is in St. Johns County and the fern study is in Volusia County and Florida's ater management districts.

Evapotranspiration

The evapotranspiration (ET) from vegetated surfaces is a critical component in the computation of water balances to estimate soil water availability and irrigation requirements. ET is a combination of two processes: evaporation and transpiration. Evaporation is the direct vaporization of water from a free water surface, such as a lake or any wet or moist surface. Transpiration is the flow of water vapor from the interior of the plant to the atmosphere. Because direct measurement of ET is difficult, numerous methods for estimating ET have been developed. These methods are based on the physics of evaporation, conservation of mass and energy, and other basic principles. The choice of the method depends on: 1) the purpose of the analysis (i.e., determination of the amount of ET that has actually occurred in a given situation, incorporation in a hydrologic model, reservoir design, etc.), 2) the available data, and 3) the period of interest (i.e., hourly, daily, monthly). The Penman-Monteith method is the most widely accepted method for estimating ET when sufficient data are available. No method, however, is considered the most appropriate when data are limited (Itier, 1996).

Jacobs and Satti (2001) conducted a detailed literature review on the existing methods to estimate reference crop ET. The methods for estimating ET can be divided into three general approaches: temperature methods, radiation methods, and combination methods. The temperature methods are empirical equations that rely on air temperatures as a surrogate for the amount of energy available to the reference crop for ET. The generalization of the temperature methods is limited, owing to the absence of a direct, unique relationship between temperature and energy. Radiation methods use a measure of solar radiation and air temperature to estimate ET. Solar radiation can be used directly to estimate ET or indirectly to provide a measure of the net available radiation. The combination methods are based on the original Penman (1948) combination equation, consisting of two terms: the radiation term and the aerodynamic term. The combination methods require more data than other methods, including net radiation, air temperature, wind speed, and relative humidity. The combination methods give the best results for a variety of vegetated surfaces and climates.

Four methods of estimating ET were considered for performing the sensitivity analysis of ET in the AFSIRS model, based on the analysis performed by Jacobs and Satti (2001) on 14 different ET methods, and Itenfisu et al. (2000). They are the Hargreaves method, the Institute of Food and Agricultural Sciences (IFAS) modified Penman method, the American Society of Civil Engineers (ASCE) 1990 Penman-Monteith Method, and the FAO Penman-Monteith method.

Hargreaves Method

The Hargreaves method (Hargreaves and Samani, 1985) of computing daily grass reference ET is an empirical approach, used where the availability of weather data is limited. The original Hargreaves equation is:

$$ET_o = 0.0135\frac{R_s}{\lambda}(T + 17.8) \tag{4}$$

where ET_o is the reference ET (mm day^{-1}), λ is the latent heat of vaporization (MJ kg^{-1}) = 2.45 MJ kg^{-1}, R_s is the solar radiation (MJ m^2 d^{-1}), and T is the mean air temperature (^{o}C).

Often, solar radiation data are not available. Therefore, an alternate approach is available that combines measurements of maximum and minimum temperature with extraterrestrial radiation (R_a). R_a is dependant on the latitude and the day of the year. The relationship between R_s and R_a is given by

$$R_s = k_{rs} R_a (T_{max} - T_{min})^{0.5} \tag{5}$$

where k_{rs} is the adjustment coefficient based on mean monthly relative humidity. k_{rs} is 0.16 for interior regions not influenced by a large water body and is 0.19 for coastal locations. T_{max} is the mean monthly maximum temperature (^{o}C), and T_{min} is the mean monthly minimum temperature (^{o}C).

With this estimate, the method becomes temperature-based. The working Hargreaves equation is given by

$$ET_o = 0.0023(T + 17.8)(T_{max} - T_{min})^{0.5} R_a \tag{6}$$

where R_a is in mm day^{-1}.

IFAS Modified Penman Method

The IFAS modified Penman method (Jones et. al, 1984) is based on four major climatic factors: net radiation, air temperature, wind speed, and vapor pressure deficit. The potential ET, after taking into account all the above factors, can be expressed as

$$ET_o = \frac{\Delta}{\Delta + \gamma} \frac{R_n}{\lambda} + \frac{\gamma}{\Delta + \gamma} E_a \tag{7}$$

where R_n is the net radiation (cal cm^{-2} day^{-1}), Δ is the slope of saturated vapor pressure curve of air (mb ^{o}C^{-1}), γ is the psychrometric constant (0.66 mb ^{o}C^{-1}), and λ is the latent heat of vaporization of water (cal cm^{-2} mm^{-1}).

From Bosen (1960), saturated air vapor pressure (as a function of temperature), e(T), and the slope of the saturated vapor pressure-temperature function, Δ, can be computed as follows:

$$e(T) = 33.8639\left\lfloor (0.00738T + 0.8072)^8 - 0.000019(1.8T + 48) + 0.001316 \right\rfloor \tag{8}$$

$$\Delta = 33.8639\left\lfloor 0.05904(0.00738T + 0.8072)^7 - 0.0000342 \right\rfloor \tag{9}$$

Penman proposed couple of relationships for calculating the net radiation. They are

$$R_n = (1 - \alpha)R_s - R_b \tag{10}$$

$$R_b = \sigma T^4 \left(0.56 - 0.08\sqrt{e_d}\right)\left(1.42 \frac{R_s}{R_{so}} - 0.42\right) \tag{11}$$

where R_n is the net radiation (cal cm^{-2} day^{-1}), R_s is the total incoming solar radiation (cal cm^{-2} day^{-1}), R_b is the net outgoing thermal or long-wave radiation (cal cm^{-2} day^{-1}), α is the albedo or reflectivity of surface for R_s. α is 0.23 for green vegetated surfaces, σ is the Stefan-Boltzmann constant (11.71 x 10^{-8} cal cm^{-2} day^{-1} ^{o}K^{-1}), T is the average air temperature (^{o}K), R_{so} is the total daily cloudless sky radiation, R_s is the total incoming solar radiation. Rs = (0.35 + 0.61 S) R_{so}, and S is the percentage shine hours.

The empirical equation to calculate E_a is given by

$$E_a = 0.263(e_a - e_d)(0.5 + 0.006u_2) \tag{12}$$

where e_a = vapor pressure of air and is given by $(e_{max} + e_{min})/2$ (mb), e_{max} is the maximum vapor pressure of air during a day (mb), e_{min} is the minimum vapor pressure of air during a day (mb), e_d is the vapor pressure at dew point temperature (mb), and u_2 is the wind speed at a height of 2 m (km day^{-1}).

Wind speed can be measured at many different heights above the ground surface. The Penman equation requires wind speed at a height of 2 m. Wind speed can be adjusted to a height of 2 m using

$$u_2 = u_z \left(\frac{2}{z}\right)^{0.2} \tag{13}$$

where u_z is the wind speed at height z (km day^{-1}), and z is the height of wind measurement (m).

The latent heat of vaporization of water is given by

$$\lambda = \left(59.59 - 0.055 T_{avg}\right) \tag{14}$$

where T_{avg} is the average daily temperature ^oC. $T_{avg} = (T_{max} + T_{min})/2$, where T_{max} is the maximum daily temperature (^oC), and T_{min} is the minimum daily temperature (^oC).

Combining all the above equations into a single equation, the working Penman equation is given by

$$ET_o = \frac{\frac{\Delta}{\Delta+\gamma}\left[(1-\alpha)R_s - \sigma T^4\left(0.56 - 0.08\sqrt{e_d}\right)\left(1.42\frac{R_s}{R_{so}} - 0.42\right)\right]}{\lambda} + \frac{\gamma}{\Delta+\gamma}\left[0.263(0.5 + 0.0062 u_2)(e_a - e_d)\right] \tag{15}$$

ASCE 1990 Penman-Monteith Method

The original Penman-Monteith method has been modified by many researchers and extended to crop surfaces by introducing resistance factors. The "full" version of the Penman-Monteith (PM) equation is described in ASCE Manual 70 (Jensen et al., 1990). The ASCE 1990 Penman-Monteith (ASCE PM-90) method is valid for neutral atmospheric stability. This equation can be applied to either a grass or alfalfa reference surface, with the aerodynamic and surface resistances treated as functions of vegetation height. ASCE PM-90 reference ET values are often used as the measure against which to evaluate the proposed equations.

The ASCE PM-90 form of the combination equation is

$$ET = \frac{1}{c}\frac{\Delta(R_n - G) + k_1 \frac{0.622\lambda\rho}{P}\frac{1}{r_a}(e_s - e_a)}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \tag{16}$$

where ET is the reference evapotranspiration (mm day $^{-1}$), c is the conversion factor used for conversion of MJ m^{-2} day^{-1} to mm day^{-1}, R_n is the net radiation (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), (e_s-e_a) is the vapor pressure deficit of the air (KPa), ρ is the mean air density at constant pressure (Kg m^{-3}), c_p is the specific heat of air (MJ kg^{-1} $^oC^{-1}$), Δ is the slope of the saturation vapor pressure/temperature relationship (KPa $^oC^{-1}$), γ is the psychrometric constant (KPa $^oC^{-1}$), λ is the latent heat of vaporization (0.0583 KPa $^oC^{-1}$), and r_s, r_a are the bulk surface and aerodynamic resistances (s m^{-1}).

When using mean daily wind speed in ms^{-1}

$$k_1 \frac{0.622\,\lambda\rho}{P} = (1710 - 6.85T) \tag{17}$$

The aerodynamic resistance (r_a) determines the transfer of heat and water vapor from the evaporating surface into the air above the canopy.

$$r_a = \frac{\ln\left[\frac{z_m - d}{z_{om}}\right]\ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_z} \tag{18}$$

where z_m is the height of wind measurements (m), z_h is the height of humidity measurements (m), d is the zero plane displacement height (m), z_{om} is the roughness length governing momentum transfer (m), z_{oh} is the roughness length governing transfer of heat and vapor (m), k is the von Karman's constant (0.41), and u_z is the wind speed at height z_m (ms^{-1}).

For a wide range of crops the zero plane displacement height, d, and the roughness length governing momentum transfer, z_{om}, can be estimated from the crop height, h, by the following equations

$$d = (2/3)h \tag{19}$$

$$z_{om} = 0.123h \tag{20}$$

The roughness governing transfer of heat and vapor, z_{oh}, can be approximated by

$$z_{oh} = 0.1z_{om} \tag{21}$$

The bulk surface resistance describes the resistance of vapor flow through the transpiring crop and evaporating soil surface. An acceptable approximation to the complex relation of the surface resistance for dense full cover vegetation is

$$r_s = \frac{r_1}{LAI_{active}} \tag{22}$$

where r_1 is the bulk stomatal resistance of the well-illuminated leaf (s m^{-1}), and LAI_{active} is the active leaf area index, (m^2 (leaf area) m^{-2} (soil surface)).

Only the upper half of the canopy is considered to actively control the transfer of water vapor and sensible heat. Thus, a general equation for LAI_{active} is given as

$$LAI_{active} = 0.5 LAI \tag{23}$$

where LAI is the leaf area index. The LAI is given by LAI = $0.24(h)$ where h is the crop height (cm).

From the original ASCE 90 equation and the equations of aerodynamic and surface resistances discussed above, the ASCE PM-90 method to estimate ET_o is given by

$$c \cdot ET_o = \frac{\Delta(R_n - G) + \gamma(1710 - 6.85T)\frac{1}{r_a}(e_s - e_a)}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \tag{24}$$

FAO Penman-Monteith Method

The FAO 56-PM method (Allen et al., 1998) is an hourly or daily grass reference ET equation derived from the ASCE PM-90 by assigning certain parameter values, based on a specific reference surface. This surface assumes a height of 0.12 m, a fixed r_s of 70 s m^{-1}, and an albedo of 0.23. The zero plane displacement height and roughness lengths are estimated as a function of the assumed crop height, so that r_a becomes a function of only the measured wind speed. The height for the temperature, humidity, and wind measurements is assumed to be 2 m. The latent heat of vaporization (λ) is assigned a constant value of 2.45 MJ kg^{-1}.

The Penman-Monteith form of the combination equation is

$$ET_o = \frac{1}{\lambda} \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \tag{25}$$

where R_n is the net radiation (MJ m $^{-2}$ day $^{-1}$), G is the soil heat flux (MJ m $^{-2}$ day $^{-1}$), ρ_a is the mean air density at constant pressure (Kg m $^{-3}$), c_p is the specific heat of air (MJ kg $^{-1}$ $^oC^{-1}$), e_s is the saturation vapor pressure (*KPa*), e_a is the actual vapor pressure (KPa), e_s-e_a is the saturation vapor pressure deficit (KPa), Δ is the slope of the saturation vapor pressure temperature relationship (KPa $^oC^{-1}$), γ is the psychrometric constant (KPa $^oC^{-1}$), and r_s, r_a are the bulk surface and aerodynamic resistances (s m $^{-1}$).

The FAO 56-PM aerodynamic resistance equation is identical to the ASCE PM-90 formulation. The FAO 56-PM aerodynamic resistance equation for a grass reference surface is calculated for reference conditions. Assuming a constant crop height of 0.12 m and a standardized height for wind speed, temperature, and humidity at 2 m, the aerodynamic resistance for the grass reference surface is only a function of wind speed at 2 m. The bulk surface resistance that describes the resistance of vapor flow through the transpiring crop and evaporating soil surface also follows the ASCE PM-90 formulation.

The aerodynamic resistance is given as

$$r_a = \frac{\ln\left[\frac{2-2/3\left(0.12\right)}{0.123\,(0.12)}\right]\ln\left[\frac{2-2/3\,(0.12)}{(0.1)\,0.123\,(0.12)}\right]}{(0.41)^2\ u_2} = \frac{208}{u_2} \tag{26}$$

where u_2 is the wind speed at 2 m.

The bulk vapor resistance, which describes the resistance of vapor flow through the transpiring crop and evaporating soil surface, also follows the ASCE PM-90 formulation. Again, an acceptable approximation to a much more complex relation of the surface resistance of dense full-cover vegetation is:

$$r_s = \frac{r_1}{LAI_{active}} \tag{27}$$

where r_1 is the bulk stomatal resistance of the well-illuminated leaf, s m $^{-1}$, and LAI_{active} the active leaf area index, m ^{2} (leaf area) m $^{-2}$ (soil surface).

A general equation for LAI_{active} is:

$$LAI_{active} = 0.5\ LAI \tag{28}$$

Moreover, for clipped grass a general equation for LAI is:

$$LAI = 24\ h \tag{29}$$

where h is the crop height, m.

The derivation of the surface resistance for the 0.12 m grass reference surface is as follows: The stomatal resistance of a single leaf has a value of about 100 s m^{-1} under well-watered conditions. By assuming a crop height of 0.12 m, the surface resistance for the grass reference surface becomes

$$r_s = \frac{100}{0.5\,(24)\,(0.12)} \approx 70\,\mathrm{sm}^{-1} \qquad (30)$$

The working FAO56 PM method to estimate ET_o is given by eqns. (25) – (30) as

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \dfrac{900}{T + 273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \qquad (31)$$

Soil-Water Holding Capacity

The amount of water that can be used by a crop depends on the water holding characteristics of the soil and the rooting depth of the crop. The soil's water holding capacity (WHC) governs the amount of rainfall or irrigation that can be retained in the soil. Soil characteristics are traditionally identified as one of the major bottlenecks in estimating irrigation. The total available WHC is the amount of water held in the root zone between field capacity and permanent wilting point. Field capacity (FC) is the amount of water held in soil after excess water has drained away. Permanent wilting point (PWP) is the soil-water content at which the plants have extracted all the water that can be extracted from a soil. Theoretically, crops can use all the water available between FC and PWP. But some water is strongly adhered to the soil particles (hygroscopic water) and is difficult for the plants to extract. The available WHC represents the amount of water that the plant can withdraw from the soil without undergoing stress.

Soil WHC is controlled primarily by the soil texture. Soil texture is a reflection of the particle size distribution of a soil. In general, the higher the percentage of silt and clay-sized particles contained within the soil, the higher the water holding capacity. The small particles (clay and silt) have a much larger surface area than the larger sand particles. This large surface area allows the soil to hold a greater quantity of water. Soils with higher WHC can provide water to plants longer than soils with low WHC, such as fine sands.

Crop-Root Zone Depth

The crop-root zone depth is very important for the process of water transfer from soil to the plant. The crop-root zone depth defines the depth of the soil profile from which the plant can extract soil water. The crop-root zone also determines the extent (depth) to which the water budget simulation for the crop can be simulated. The extent and depth of a root system determines how much water can be extracted by the vegetation from the soil and recycled back into the atmosphere. With deeper roots, the soil volume is expanded and more soil water is accessible for evapotranspiration during dry periods. The crop-rooting depth varies with crop species, type, and stage of growth.

RESULTS AND DISCUSSION

The GWRAPPS simulations were conducted to estimate the irrigation requirements for each of the 109 potato farms and 161 ferneries, using a total of 28 different scenarios having a range of ET methods, soil WHCs, crop coefficients, and crop-root zone depths. Table 1 summarizes the regional annual average net irrigation requirement for each scenario, by crop and by normal and drought conditions. The baseline study uses the ASCE PM-90 reference ET method, an average soil WHC, the default crop coefficients, and the default crop-root zone depth. For each farm, the percentage difference between the baseline scenario and 14 sensitivity studies was calculated. Summary statistics for the farm-based percentage differences were determined to characterize the range of variability among the farms (Table 2). The statistics include the minimum and maximum percentage differences, the average percentage difference, the standard deviation of the percentage difference, and the coefficient of variation of the percentage differences. The following sections discuss the modeled results for each of the critical variables.

					Ferns			Potatoes		
Sensitivity	**ET Method**	**WHC**	**Kc Var. (%)**	**Root Zone Var. (%)**	**Normal Irrigation (cm)**	**1-in-5 Irrigation (cm)**	**1-in-10 Irrigation (cm)**	**Normal Irrigation (cm)**	**1-in-5 Irrigation (cm)**	**1-in-10 Irrigation (cm)**
Baseline	ASCE 90 PM	Ave.	0%	0%	61.03	68.38	71.48	14.79	18.80	20.84
Climate	Hargreaves	Ave.	0%	0%	64.75	71.65	74.49	13.94	17.70	19.60
	IFAS Penman	Ave.	0%	0%	58.33	67.23	71.12	12.66	16.66	19.60
	FAO 24 Penman	Ave.	0%	0%	61.07	68.27	71.28	14.62	18.63	20.69
	FAO 56 PM	Ave.	0%	0%	59.07	66.55	69.72	14.08	18.59	21.02
Soil	ASCE 90 PM	Minimum	0%	0%	63.73	70.70	73.59	16.43	20.65	22.75
	ASCE 90 PM	Maximum	0%	0%	58.80	66.73	70.13	13.46	17.58	19.77
Crop Coefficient	ASCE 90 PM	Ave.	-20%	0%	44.19	80.33	52.99	10.35	13.55	15.28
	ASCE 90 PM	Ave.	-10%	0%	52.53	59.27	62.13	12.51	16.16	18.08
	ASCE 90 PM	Ave.	+10%	0%	70.03	78.13	81.50	17.27	21.89	24.24
	ASCE 90 PM	Ave.	+20%	0%	79.48	88.29	91.94	19.55	24.66	27.21
Root Zone	ASCE 90 PM	Ave.	0%	-20%	60.62	67.87	70.91	15.33	19.51	21.64
	ASCE 90 PM	Ave.	0%	-10%	60.72	68.12	71.23	14.97	18.96	20.99
	ASCE 90 PM	Ave.	0%	+10%	61.24	68.74	71.91	14.59	18.68	20.79
	ASCE 90 PM	Ave.	0%	+20%	56.44	64.18	67.49	14.27	18.33	20.45

Table 1. Summary of the irrigation requirements estimated using GWRAPPS for two crops, five ET methods, three WHCs, five crop coefficients, and five crop-root zone depths

					Ferns					Potatoes				
Sensitivity	**ET Method**	**WHC**	**Kc (%)**	**Root Zone (%)**	**Ave.**	**St. Dev.**	**CV**	**Min**	**Max**	**Ave.**	**St. Dev.**	**CV**	**Min**	**Max**
Climate	Hargreaves	Ave.	0%	0%	6.1	0.64	0.10	4.4	8.6	-5.8	1.82	-0.31	-9.4	-2.8
	IFAS Penman	Ave.	0%	0%	-4.5	0.92	-0.21	-6.2	0.2	-14.5	2.07	-0.14	-18.0	-10.9
	FAO 24 Penman	Ave.	0%	0%	0.1	0.92	9.96	-3.4	1.4	-1.2	1.23	-1.01	-5.2	1.8
	FAO 56 PM	Ave.	0%	0%	-3.2	0.43	-0.13	-5.1	-2.3	-4.9	0.83	-0.17	-6.8	-2.8
Soil	ASCE 90 PM	Min.	0%	0%	4.5	2.75	0.61	-3.7	11.9	11.0	3.49	0.32	4.5	22.7
	ASCE 90 PM	Max.	0%	0%	-3.7	2.36	-0.63	-9.1	3.8	-9.0	2.16	-0.24	-13.2	-2.8
Crop Coefficient	ASCE 90 PM	Ave.	-20%	0%	-27.8	2.37	-0.09	-42.5	-24.9	-30.1	2.12	-0.07	-33.4	-24.2
	ASCE 90 PM	Ave.	-10%	0%	-14.0	1.09	-0.08	-19.0	-12.3	-15.5	2.38	-0.15	-20.2	-12.2
	ASCE 90 PM	Ave.	+10%	0%	14.8	1.40	0.09	13.2	22.7	16.8	1.77	0.11	11.3	21.6
	ASCE 90 PM	Ave.	+20%	0%	30.5	3.07	0.10	26.4	46.5	32.3	3.19	0.10	23.7	40.0
Root Zone	ASCE 90 PM	Ave.	0%	-20%	-0.6	0.53	-0.82	-1.3	1.9	1.4	1.01	0.73	-1.8	3.0
	ASCE 90 PM	Ave.	0%	-10%	-0.5	0.61	-1.26	-1.8	0.9	0.6	0.52	0.81	-1.2	2.0
	ASCE 90 PM	Ave.	0%	+10%	0.3	0.37	1.10	-1.7	1.2	-0.4	0.30	-0.68	-1.8	0.6
	ASCE 90 PM	Ave.	0%	+20%	-7.5	1.39	-0.19	-10.1	-3.9	-0.8	0.56	-0.71	-2.2	0.2

Table 2. Statistics of the percentage differences on an individual farm basis between the baseline irrigation requirements and the estimated requirements for five ET methods, three WHCs, five crop coefficients, and five crop-root zone depths by crop

Evapotranspiration

The sensitivity of irrigation water requirements to reference ET methods was conducted by performing GWRAPPS simulation runs, using the Hargreaves method, the FAO 24 Penman method, the IFAS Penman method, the Food and Agriculture Organization FAO 56 Penman-Monteith method, and comparing the results to the baseline case conducted using the ASCE 1990 Penman-Monteith method. Here, the FAO 56-PM method will be used for the revised climate database. Only the reference ET data were varied during these simulations.

The annual normal irrigation requirements ranged from 58.3 cm to 64.8 cm for ferns, and 12.7 cm to 14.8 cm for potatoes (Table 1). The annual 1-in-10-year irrigation requirements ranged from 69.7 cm to 74.5 cm for ferns, and 19.6 cm to 21.0 cm for potatoes. Most methods performed reasonably well on an annual basis. FAO 24 Penman method provided the best estimates, with annual average differences of approximately 1% (Table 2). This result, however, is somewhat misleading, as revealed by a relatively high coefficient of variation and the tendency of the FAO 24 Penman method to both overestimate and underestimate on a farm basis. The FAO 56-PM method also performed well, underestimating the irrigation requirements throughout the entire season by approximately 3% for ferns and 5% for potatoes, as compared to the baseline, and having a relatively consistent but small negative bias. Both the Hargreaves and the IFAS Penman methods had much larger bias on an annual basis. The IFAS Penman method consistently underestimated the water demand for potatoes for all farms by at least 10% and as much as 18%.

Figures 3(a) and 4(a) show the average monthly normal irrigation requirements estimated for ferns and potatoes, respectively, using the five ET methods. The magnitude of the variation in irrigation requirements among different ET methods was very high and was not constant throughout the growing season. While the FAO 24 Penman method performed well on an annual basis, it exhibited large seasonal variation—underestimation during summer and overestimation during winter. The Hargreaves and IFAS Penman methods also exhibited seasonal variation in the estimated irrigation requirements. Hargreaves overestimated the irrigation requirements during summer. The overestimation for ferns ranged from approximately 5% to 21%. The overestimation for potatoes was approximately 6%. The IFAS Penman method overestimated the irrigation requirements for ferns by approximately 2% to 15% during the same period. Both these methods underestimated the irrigation requirements during winter. The monthly differences ranged from 15% for ferns, using IFAS Penman, to 35% for potatoes, using the Hargreaves method.

The primary source of the observed variations in the irrigation requirements is due to the ability of the methodologies to calculate ET consistent with the ASCE PM-90 standard reference ET, using the available meteorological data. Hargreaves is an empirical method that is highly dependent on temperature, but in a humid climate with strong convective systems, temperature alone cannot provide an adequate estimate of the available energy for ET. Stomatal resistance describes the resistance of vapor flow through the transpiring crop and evaporating soil surface and is a critical component in calculating crop ET (McCabe and Wolock, 1992; Singh et al., 1993). The IFAS Penman and the FAO 24 Penman methods do not consider stomatal resistance in estimating ET.

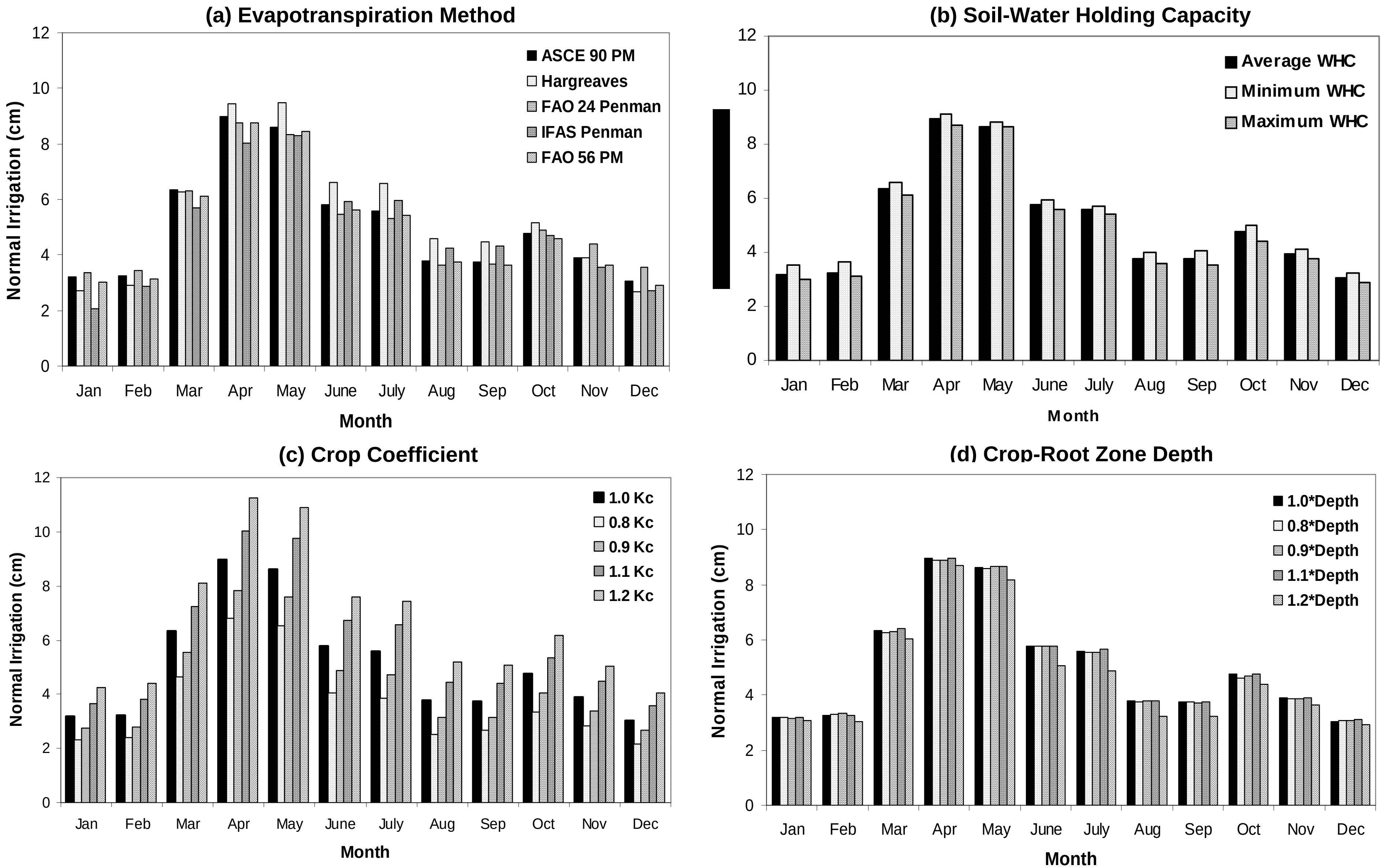

Figure 3. Annual normal irrigation requirements for farms growing ferns in Volusia County

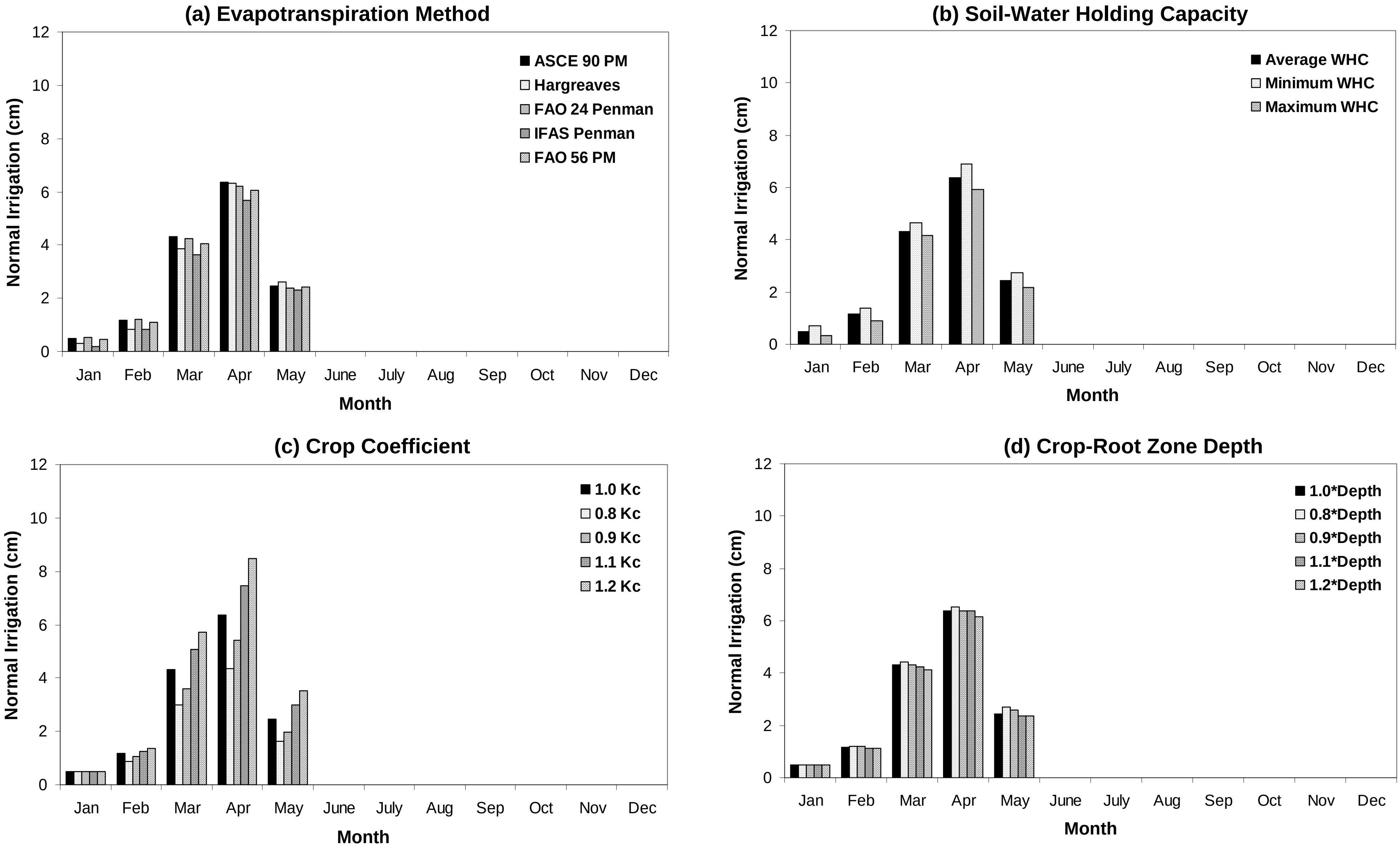

Figure 4. Annual normal irrigation requirements for farms growing potatoes in St. Johns County

Soil-Water Holding Capacity

The net irrigation requirements for ferns and potatoes were estimated for three different WHC scenarios—the minimum, average (baseline), and maximum WHC—while the other variables were held constant. Table 1 provides the annual normal, 1-in-5 drought and 1-in-10 drought irrigation requirements. The differences in annual irrigation requirements were approximately 2.7 cm for ferns and 1.64 cm for potatoes. The annual irrigation requirements for ferns were overestimated by about 4%, using minimum WHC, and underestimated by 4%, using maximum WHC. The annual average irrigation requirements for potatoes were more sensitive to the WHC than ferns. The annual normal potato irrigation requirements were overestimated by approximately 11%, using minimum WHC, and underestimated by about 9%, using maximum WHC. The mean absolute differences ranged from 0.52 cm for maximum WHC to 0.64 cm for minimum WHC. While the sensitivity of the annual average differences to soil-water holding capacity was greater for potatoes than ferns, the ferneries' soil property differences resulted in a greater range of variability. Both overestimates and underestimates of the water demand were observed, as compared to the baseline conditions.

The variation in the differences in the 1-in-10 drought irrigation requirements is similar to that of normal irrigation requirements. The 1-in-10 irrigation requirements were overestimated by approximately 4% for ferns and 9% for potatoes, when using minimum WHC. The 1-in-10 irrigation requirements were underestimated by approximately 2% for ferns and 5% for potatoes, when using maximum WHC.

Figures 3(b) and 4(b) show the normal irrigation requirements estimated for ferns and potatoes, respectively. The irrigation requirements were negatively correlated to the soil WHC. Soils with a higher WHC can provide water to plants longer than can soils with lower WHC. Correspondingly, it is observed from Figures 3(b) and 4(b) that higher WHC resulted in lower irrigation needs, and lower WHC resulted in higher irrigation needs. The differences in the monthly normal irrigation requirements ranged from 0.00 to 0.39 cm for ferns and from 0.15 to 0.56 cm for potatoes.

The differences in the irrigation requirements for ferns are relatively low during the period May through July, as compared to the remainder of the year (Figure 3(b)). This may be explained by the climate during these months. The evapotranspiration during May is higher than the amount of rainfall. Frequent, small rainfall events occur during June and July, due to local convective storms. These storms typically are not large enough to restore the soil-water content in the crop-root zone to field capacity. Therefore, most of the rainfall during these months is effective rainfall. Any additional water supplied by irrigation restores the soil-water content to field capacity without generating drainage. Under these conditions of minimal drainage and no overland flow, eqn (1) dictates that the irrigation requirement is a function of only the difference between ET and P. The net irrigation during periods of minimal drainage is independent of WHC, as both ET and P are the same for all the WHCs.

Crop Coefficients

Four GWRAPPS simulations were run for each crop, in which the model crop coefficients were increased and decreased by 10% and 20%, while the other model parameters were held constant. The baseline AFSIRS crop coefficient is 1.00 for ferns throughout the growing season. The potatoes' K_c values used definitions for standard growth for stages 1 and 2, and values of 1.05 and 0.70 for stages 3 and 4, respectively. Daily K_c values throughout the growing season were determined by linear interpolation.

A large variability in the annual normal irrigation requirements resulted from modest changes in crop coefficients—from 44.2 cm to 79.5 cm for ferns and from 10.4 cm to 19.6 cm for potatoes (Table 1). A 20% increase in the crop coefficient overestimated the baseline irrigation requirement by 30.5% for ferns and by 32% for potatoes. Differences of up to 46.5% and 40.0% for ferns and potatoes, respectively, were observed at individual sites. There was considerable site-to-site variability in the magnitude of the differences (Table 2). The consistently low coefficients of variation, however, indicate that this variability is relatively low, considering the average magnitude of the differences. The 1-in-10-year drought irrigation requirements showed similar results.

Figures 3(c) and 4(c) show the regional monthly average normal irrigation requirements for ferns and potatoes, respectively, using the five crop coefficients. The average monthly normal irrigation requirements also varied, with a magnitude of 24% to 33% for ferns and 0% to 43% for potatoes. K_c is essentially a scaling factor applied to the reference ET throughout the growing season in a crop coefficient approach to estimate crop ET. Therefore, the variations in crop coefficients exhibit strong positive correlation with the variations in the irrigation requirements. The simulation results showed that for every 1% variation in K_c, there is approximately 1.5% variation in the irrigation requirement estimation for both ferns and potatoes.

Crop-Root Zone Depth

The crop water requirements for each crop were estimated, with five different crop-root zone depths obtained by scaling the AFSIRS model's crop-root zone depths by -20%, -10%, 0% (baseline), +10%, and +20%. The actual root zone depth of ferns in the AFSIRS crop database is 25.4 cm (Soil Conservation Service (SCS), 1982), and the minimum and maximum root zone depths of potatoes are 30.5 and 45.7 cm (SCS, 1982). All the simulations were run using the same climate information, average WHC, and the GWRAPPS multiple soil scenario.

AFSIRS uses a constant root zone depth for the entire irrigation period for ferns, a perennial crop. The overall irrigation requirements for ferns are underestimated by approximately 0.6% when using shallow root zone depths. Depths greater than the typical 25.4 cm resulted in overestimation by approximately 0.3%. The 1-in-10 drought irrigation requirements also followed a similar trend, and overestimated by 0.8% when using shallow depths and underestimated by 0.6% when using depths greater than 25.4 cm. The worst-case scenario of using a root zone depth of 30.5 cm resulted in underestimation of normal irrigation requirements by 7.5%. This was due to an extended root zone and a modified soil profile with a higher WHC.

Figure 3(d) shows the normal irrigation requirements for ferns using five different root zone depths. The irrigation requirements are negatively correlated with the crop-root zone depth. There are no large variations in the monthly normal irrigation requirements among the different root zone depths, except for 30.5 cm. The normal irrigation requirements in ferns, except for the crop-root zone depth of 30.5 cm, ranged from 60.6 to 61.2 cm. Both the monthly and annual irrigation requirements for the 30.5 cm root zone depth were different from those using other depths. The crop roots enter a new soil profile at a depth of 30.5 cm, with distinct soil properties that result in the larger differences in the irrigation requirements.

Figure 5 shows the crop-root zone development of potatoes of the five maximum root zone depths considered in the sensitivity analysis. The minimum root zone depth was kept constant as 30.5 cm, and the maximum crop-root zone depth was varied during the GWRAPPS simulation runs. The average lengths of the potato-growth stages, as fractions of the crop-growing season, are 0.23, 0.29, 0.29 and 0.19. The root zone depths are the same during growth stage 1 and increase linearly to the maximum root zone depth during growth stage 2, as can be observed from Figure 5. The maximum root zone depth is attained by the end of growth stage 2 and is maintained throughout growth stages 3 and 4.

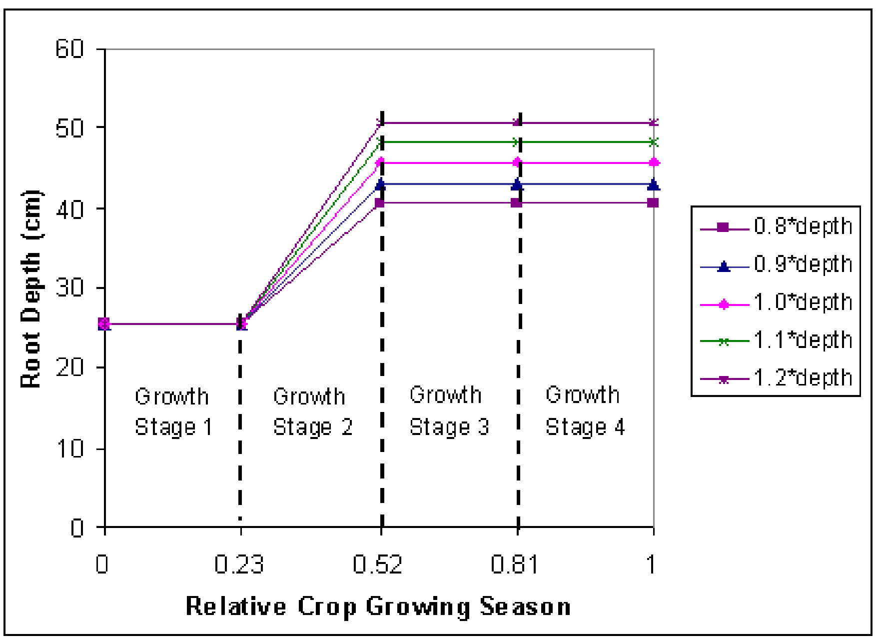

Figure 5. Potatoes crop-root zone development for five root zone depths considered in St. Johns County

The overall irrigation requirements are overestimated by approximately 4% when using shallow maximum root zone depths and underestimated by approximately 4% when using deeper maximum root zone depths. The 4% difference represents approximately 0.59 million cubic meters of water. Similarly, the 1-in-10 drought irrigation requirements were overestimated by 4% when using depths less than the actual root zone depth and underestimated by 2% when using depths greater than the actual crop-root zone depth. The irrigation requirements also followed a similar pattern as the root zone depths on a monthly basis, as shown in Figure 4(d). The irrigation requirements estimated were the same during growth stage 1 for all scenarios, but patterns of differences emerged during the later growth stages as the root zones depths' differences became larger. The normal irrigation requirements during growth stage 4 for potatoes were overestimated by up to 10%, while the 1-in-10 irrigation requirements were overestimated by 24% when using shallower depths.

Crop Water Demand Sensitivity

The sensitivity analyses showed a range of responses to the variables under consideration. When comparing the results from all 28 simulations, crop coefficient simulations had the greatest irrigation response. This observation was consistent for both the fern and potato simulations. The net result is that every 1% difference in K_c values results in approximately 1.5% change in the irrigation requirements on a regional scale, and between a 1% and 2% change for individual sites. Clearly, the appropriate selection and application of crop coefficients is critical to determining irrigation requirements.

The magnitude of differences in annual normal irrigation requirements was not significantly large among the simulated ET methods, as compared to the variation in the monthly normal irrigation requirements. The Hargreaves and the IFAS Penman methods underestimated during colder months and overestimated during hotter months, whereas FAO 24 Penman method overestimated during colder months and underestimated during hotter months. The underestimation and overestimation of the irrigation requirements by the same ET method mitigated the magnitude of the differences in the annual irrigation requirements. The Hargreaves method, for example, overestimated the irrigation requirements of ferns by 21% in August and underestimated by 15% in January. The annual requirements, however, were overestimated by only 6%. These results indicate that caution should be used in the selection of an appropriate reference ET method if the monthly irrigation requirements are desired. Irrigation requirements that used the FAO 56-PM method provided the best agreement among the four reference ET methods, as compared with the ASCE PM-90 method. This agreement is consistent for both ferns and potatoes.

Regional irrigation requirements differences may occur approximately 5% for ferns and 10% for potatoes, within a reasonable range of water holding capacities defined for specific soil series. Individual sites may have significantly larger differences. The GWRAPPS model defines and uses up to 766 soil types within a single region. Aggregation of soils to more general classifications or lumping of soil layers would likely result in much more significant errors. The irrigation requirements from different WHCs exhibited limited seasonal variation. The monthly irrigation requirements throughout the growing season were overestimated when using minimum WHC, and underestimated when using maximum WHC. The magnitude of the variation is less during periods with relatively high effective rainfall. During the worst-case scenario, the minimum WHC overestimated by approximately 12% for ferns and by 48% for potatoes during drier months, while the maximum WHC underestimated by approximately 7% for ferns and by 31% for potatoes during wetter months. A relatively high magnitude of variation for potatoes was observed during the early growth stages of the crop.

The crop-root zone depth did not affect the variation of the irrigation requirements significantly, unless the soil profile had distinctly different soil properties with depth. This variation is clearly observed in Figure 3(d), where the irrigation requirements using a crop-root zone depth of 30.5 cm for ferns were significantly lower than the irrigation requirements from different crop-root zone depths. The variation for ferns ranged between 1% and 3% for depths below 30.5 cm. The magnitude of variation ranged from approximately 3% to 17% when using a depth of 30.5 cm for ferns. The magnitude of variation also is dependent on whether the crop is perennial or annual. Perennial crops exhibited relatively less sensitivity to the change in crop-root zone depth than annual crops. Annual crops were more sensitive to the crop-root zone depths during the later growth stages, due to differences in the crop-root zone development estimations by the AFSIRS model for perennial and annual crops.

CONCLUSION

GWRAPPS was used to study the average regional sensitivity of irrigation water requirements to critical variables and variability among sites within a region. The sensitivity was examined, based on the changes in the annual and monthly irrigation demands. The analysis studied the possible effects on irrigation requirements when the critical variables involved in the model are altered. Crop water requirements responded in different ways to changes in each of the climate, soil, and crop variables studied.

The irrigation requirements were most sensitive to crop coefficients, followed by ET_o methods, soil WHC, and crop-root zone depth, in that order. Thus, accurate determination of crop coefficients for different crops is vital for efficient irrigation practices. Most ET_o methods performed relatively well on an annual basis, but much larger differences were observed among methods when compared on a monthly basis, with different ET_o methods exhibiting seasonal variability. This seasonal variability makes the choice of ET_o method critical when the irrigation requirements are estimated at a daily or monthly scale for irrigation scheduling purposes. The irrigation requirements were sensitive to soil WHC, with the sensitivity decreasing under drier conditions. The crop-root zone depth was the least sensitive variable of the four, if the soil profile was reasonably homogeneous.

Crop coefficients, the most sensitive variable for irrigation requirements, exhibited limited site-to-site variability of irrigation requirements, as compared to the overall average magnitude of the differences. The study results, however, indicate that there is often considerable variability among the results for individual sites for the remaining variables. This is particularly the case for soil properties, as considerable average regional differences and variability among sites both were found. Thus, the extrapolation of site-specific sensitivity studies may not be appropriate for determination of regional characteristics.

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APPENDIX A

Benchmark Farms Data

The benchmark farms database, which contains data from 1989 to 1997, was obtained from SJRWMD. The following pages contain comparison plots of the monthly irrigation requirements that were modeled and those measured at each coincident farm.

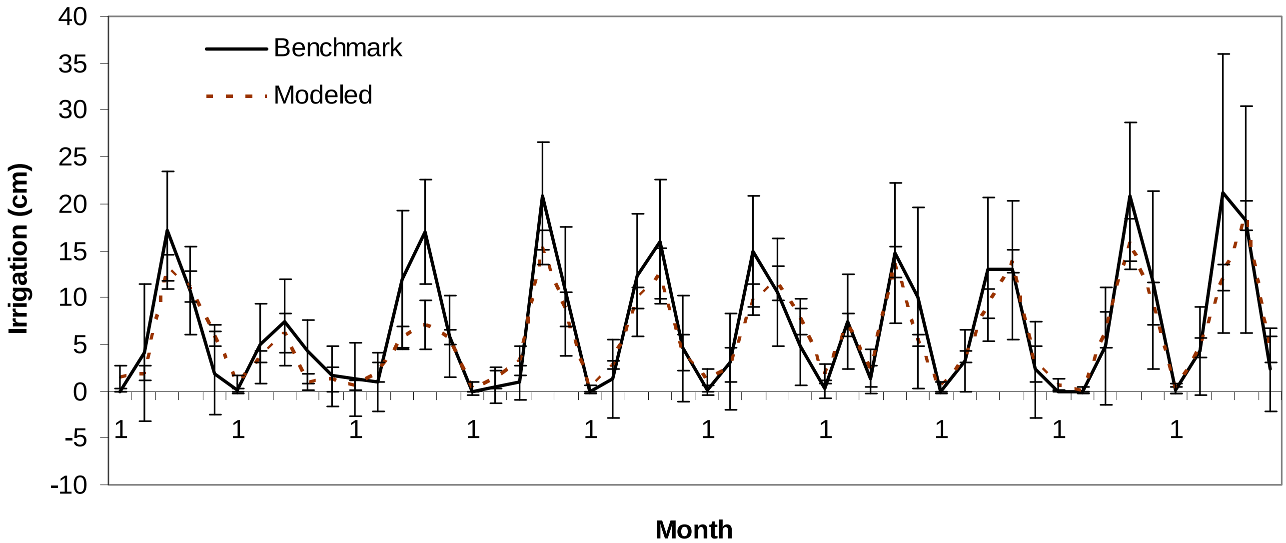

Figure A.1. Monthly average gross irrigation of all potato sites by year (+/- one standard deviation)

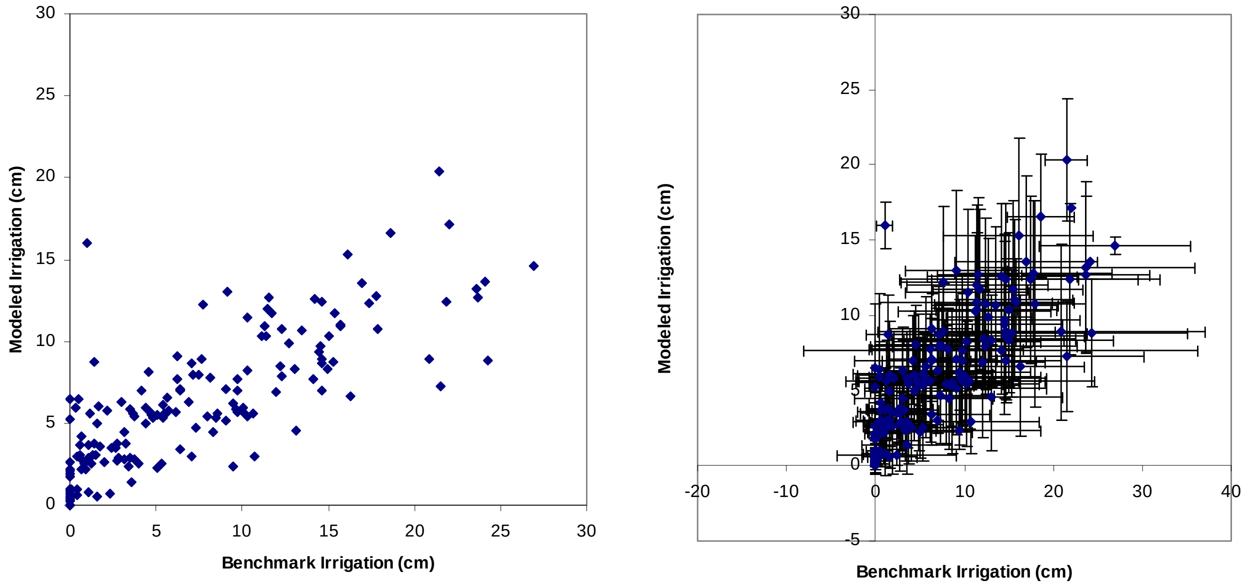

Figure A.2. Average gross irrigation presented on a monthly basis for 34 individual potato sites modeled and benchmark farm values. These plots are based on average modeled and BM irrigation data only for those years for which data from both the model and the benchmark farms were available

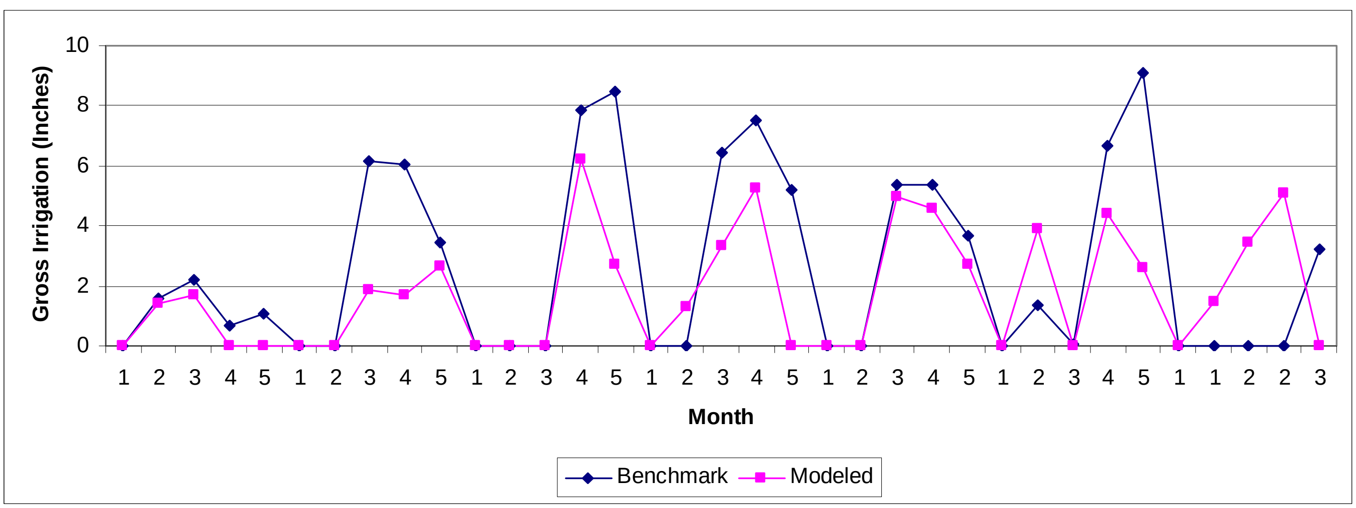

Figure A.3. Monthly gross irrigation at Site No. 43 (GRS #2728) Potatoes (1991-1997)

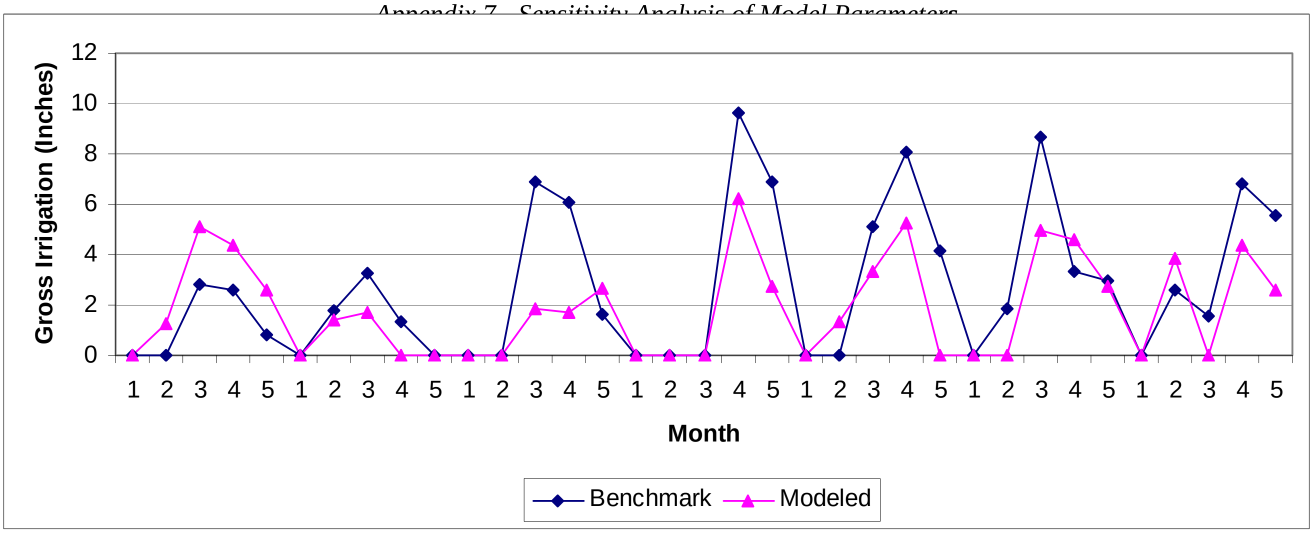

Figure A.4. Monthly gross irrigation at Site No. 44
Potatoes (1990-1996)

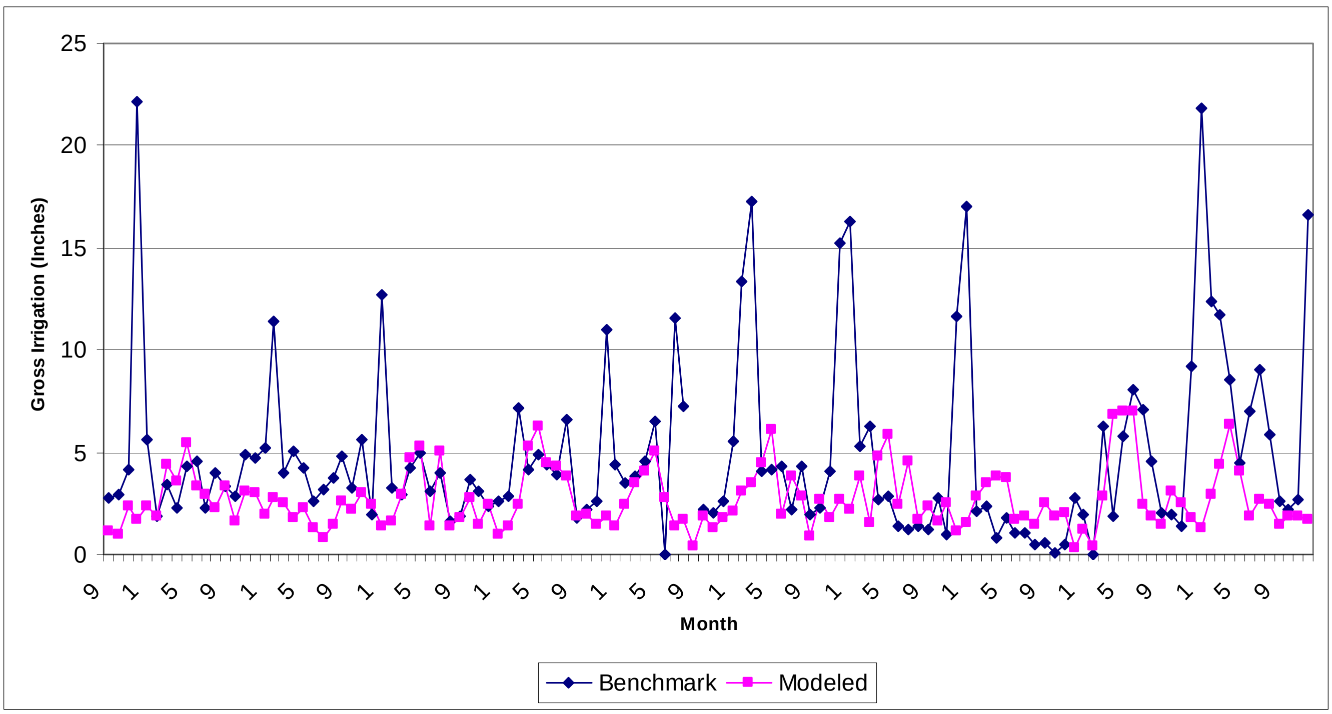

Figure A.5. Monthly gross irrigation at Site No. 79 (GRS #1621)
Leatherleaf ferns 1989–1999
Volusia County, sprinkler irrigation

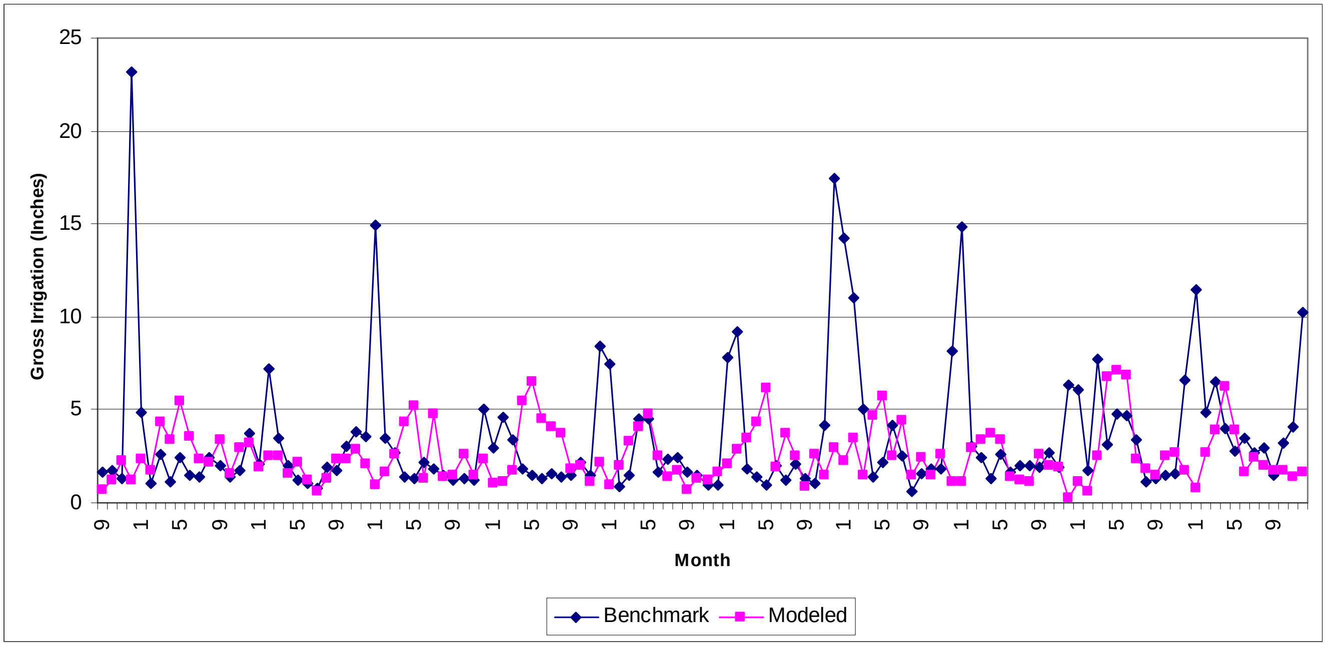

Figure A.6. Monthly gross irrigation at Site No. 82 (GRS #9042)
Leatherleaf ferns 1989–1999
Volusia County, sprinkler irrigation

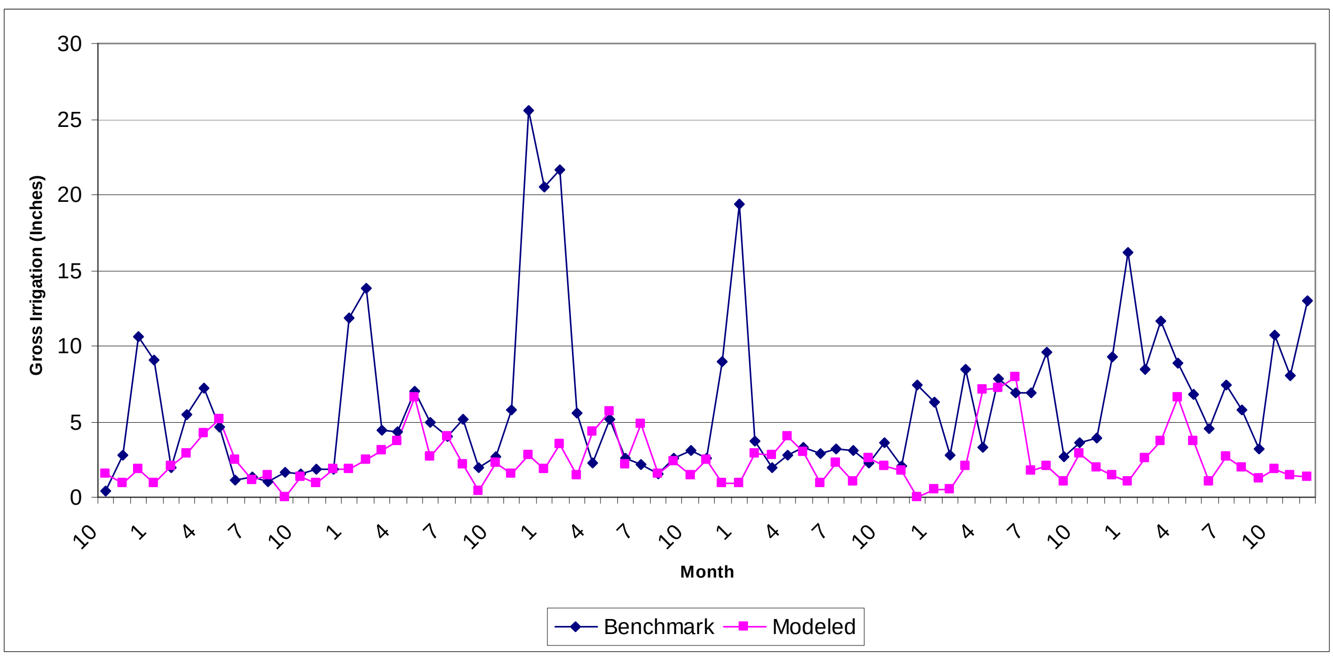

Figure A.7. Monthly gross irrigation at Site No. 174 (GRS #3997)
Leatherleaf ferns 1993–1999
Volusia County, sprinkler irrigation

REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL

APPENDIX 8
TYPES AND EFFICIENCIES OF FLORIDA IRRIGATION SYSTEMS (TASK 6)

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INTRODUCTION

The purpose of this document is to describe the concept of irrigation system efficiency, describe irrigation systems typically found in Florida, and present efficiency values derived from relevant research data and or the literature. Pictures of systems are referenced and in the body of the document.

In general, efficiency can be defined as,

$$E = \frac{O}{I} \tag{1}$$

where E is efficiency, O is system output, and I is system input. Efficiency may be expressed as a decimal or percentage. In the context of irrigation, input is the water taken from the water source while output is the water used for beneficial purposes. Beneficial purposes include consumptive use, leaching of salts, freeze protection, seedbed preparation, and maintenance to name a few. Water that is used by plants to satisfy evapotranspiration (ET) demands is a consumptive use and in general is the largest beneficial use of water by Florida irrigation systems. Sometimes, consumptive use is the only beneficial use considered . Non-beneficial uses include evaporation during application, runoff, and drainage below the effective crop root zone.

IRRIGATION SYSTEM EFFICIENCY DEFINITIONS

Reservoir storage efficiency is defined as,

$$E_s = \frac{V_r}{V_{dr}} \tag{2}$$

where E_s is reservoir storage efficiency, V_r is water taken from the reservoir, and V_{dr} is water delivered to the reservoir. A reservoir may be a pond, lake, tank, or other storage mechanism. The most common type of reservoir is a pond, which can be natural, or man made. Losses occur due to seepage through the bottom, evaporation from the water surface, and transpiration from vegetation growing in the reservoir. Typically reservoirs are assumed to be 50% efficient in Florida, while groundwater reservoirs (aquifers) are assumed to be 100% efficient (Smajstrla et al. 1991).

Water conveyance efficiency is defined as,

$$E_c = \frac{V_f}{V_t} \tag{3}$$

where E_c is water conveyance efficiency, V_f is water delivered to the field, and V_t is water taken from the source. For pressurized irrigation systems E_c is normally close to 1.0 because water is delivered in pipelines; however, for seepage irrigation (subirrigation) systems or surface irrigation systems where water is delivered via unlined canals, losses can be significant.

Water application efficiency is defined as,

$$E_a = \frac{V_s}{V_{df}} \tag{4}$$

where E_a is the water application efficiency, V_s is water stored in the root zone as a result of irrigation, and V_{df} is water delivered to the field. Application efficiency can be a source of significant losses. Many types of irrigation systems such as sprinkler and seepage are designed to irrigate a field as uniformly as possible (i.e. even application). If part of a field is under irrigated then other parts of the field will have to be over irrigated to compensate.

Overall irrigation system efficiency can be defined as,

$$E_o = E_s * E_c * E_a \tag{5}$$

where E_o is the overall irrigation system efficiency and other terms are as previously defined.

Effective irrigation efficiency can be defined as follows,

$$E_e = E_o + FR * (1 - E_o) \tag{6}$$

where E_e is the effective irrigation system efficiency, FR is the fraction recycled, and the other terms were defined previously. The fraction recycled would be any water that is captured leaving the irrigated area and returned to the source without degradation in quality. Tailwater return systems in seepage irrigation would be an example of a method to increase the effective efficiency of an irrigation system.

EFFICIENCY COMPONENTS

Irrigation system efficiency depends primarily on three components: 1) design, 2) installation and maintenance, and 3) management. A properly designed and maintained system can be highly inefficient due to mismanagement. Proper management is difficult if a system is not designed properly. The previously defined efficiency components only deal with design and maintenance.

Burt et al. (1997) discuss various irrigation system efficiency definitions and distribution uniformity definitions. Irrigation system efficiency is difficult to measure because it depends on management and design. It can be measured with continuous soil moisture measurements and or with crop lysimeters. Often to gauge the performance of an irrigation system, the low quarter distribution uniformity is used in sprinkler and microirrigation as follows (Burt et al. 1997; ASAE, 1996).

$$DU_{lq} = \frac{V_{lq}}{V} \tag{7}$$

where DU_{lq} is the low quarter distribution uniformity, V_{lq} is the average volume caught in the lowest 25% of volumes collected, and V is the overall average of volumes collected. Distribution uniformity gives an indication of possible efficiency if the system is managed properly. That is to say that it is unlikely efficiency would exceed distribution uniformity.

FLORIDA IRRIGATION SYSTEMS

The categories of irrigation systems found in Florida include: sprinkler, micro, surface, and seepage, which is also known as subirrigation.

Sprinkler

Sprinkler irrigation is a broad category consisting of several types of sprinkler systems that in total comprise approximately 18% of agricultural irrigation in Florida (USDA 1998). Generally, these systems are designed to use overlapping patterns in an attempt to provide uniform coverage over an irrigated area. Sprinklers are normally spaced 50-60% of their diameter of coverage to provide uniform application in low wind conditions. In high wind conditions, spacing can be decreased to help compensate for horizontal redistribution. Sprinkler irrigation systems are supplied by pressurized pipelines that result in E_c approaching 100%. In hot arid areas, efficiency is reduced due to evaporation losses. Studies have shown that 1.5 to 7.6% of irrigated water can be lost due to wind drift and evaporation during application (Frost and Schwalen 1960; Kohl et al. 1987).

Solid set irrigation systems consist of a lateral with sprinklers along that lateral. These systems can be portable (Figure 1) moved by hand, moved by tractor, or self propelled (Figure 2). When moved by tractor, these systems are called “end tow” sprinkler systems. The self propelled systems are also called “periodic move laterals” or “wheel lines” and are not common in Florida. These self propelled systems are limited to low and medium height crops. In solid set

Figure 1. Portable solid set system with sprinklers attached to aluminum pipe laterals

Figure 2. Wheel line self propelled sprinkler system

systems, sprinklers may be attached directly to the pipeline (Figure 1) for low growing crops or may be attached to risers in the case of medium size crops such as vegetables, or tall crops such as citrus and container nurseries. Permanent systems typically have sprinklers on risers that are attached to buried laterals (Figure 3).

Residential irrigation systems with sprinklers are classified as permanent solid set irrigation systems (Figures 4-6). Efficiency of agricultural solid set systems ranges between 15 and 80% with the lowest being containerized nursery irrigation due to the large area that is irrigated but is not used for crop production. Efficiencies of residential and landscape solid set systems are usually much lower than agricultural systems due to poor design and management. Solid set systems irrigating a uniformly planted crop can have efficiencies of 65-80% (Table 1).

Figure 3. Permanent solid set sprinkler system showing sprinklers on risers

Figure 4. Residential impact sprinkler nozzle

Figure 5. Residential fixed pattern spray head sprinkler nozzle

Figure 6. Gear driven pop-up rotary sprinklers irrigating a turf area

Table 1. Florida irrigation systems attainable efficiencies[1] (Adapted from Smajstrla et al. 1991; Burt et al. 2000; Baum et al. 2001)

Method	Range	Average
Sprinkler		
Solid set	70-80	75
Solid set, container nursery	15-50	20
Portable guns	60-70	65
Traveling guns	65-75	70
Center pivot and lateral move	70-85	75
Periodic move lateral	65-75	70
Residential solid set	10-85	45
Micro		
Surface drip	70-90	85
Subsurface drip	70-90	85
Spray or jet	70-85	80
Bubbler	70-85	80
Surface		
Crown flood	25-75	
Flood	25-75	
Seepage		
Open ditch		
Flow through	20-70	
Tailwater recycle	30-80	
Semi-closed		
Flow through	30-70	
Tailwater recycle	40-80	
Subsurface conduit system	40-80	

[1] Attainable efficiencies do not consider management, only efficiency through design and installation.
[2] Average efficiency not given for surface or seepage systems since this varies with soil hydraulic properties and will be site specific.

Center pivot and lateral move irrigation machines account for 48% of sprinkler systems in Florida (USDA 1998). These machines have a pipeline that is supported by A-frame towers with drive wheels at the bottom. Older models use high pressure impact sprinklers attached to the top of the pipeline (Figure 7). Newer machines use low pressure sprinklers on drop tubes and require less energy to operate (Figure 8). Center pivot machines are fixed at one end and rotate to irrigate a circular area (Figure 9), while linear move machines are similar except that they are not fixed at one end and move along a square or rectangular field. Linear move machines are supplied by buried pressurized irrigation pipe or by open ditches (Figure 10), whereas center pivot systems are typically supplied by buried pipelines. The open ditches are lined with concrete to prevent seepage if necessary. Center pivot and lateral move machines can be used on a variety of crops ranging from sod to corn and potatoes. Smajstrla (1983) found that high pressure center pivot irrigation machines had higher uniformity (90% compared to 83%) but that low

Figure 7. Center pivot irrigation machine with high pressure impact sprinklers

Figure 8. Low pressure sprinklers on drop tubes attached to a center pivot irrigation machine

Figure 9. Circular field irrigated by a center pivot irrigation machine

Figure 10. Linear move irrigation system supplied by a ditch

pressure systems had higher efficiency under the tested conditions (77% compared to 72%). New center pivot and linear move technology such as low energy precision agriculture (LEPA) result in application efficiencies in excess of 95% (Schneider 2000). In general, maximum efficiency for center pivot and linear move irrigation machines is 70-85% (Table 1).

Large sprinklers called "big guns" are also used for irrigation. These large diameter nozzles (Figure 11) have flow rates ranging from several hundred gallons per minute (gpm) up to 1,000 gpm. These big guns can be manually portable (Figure 12), fixed to a cart and reeled back toward a fixed point by an automated mechanism (cable tow big gun, Figure 13), or attached to a hard hose and reeled back to the machine by an automated mechanism (hose drag machine, Figure 14). The rate that the sprinkler cart travels along the field determines the application rate (expressed as inches/hour, in/hr) of water over the field. The cable tow and hose reel devices can

Figure 11. Large diameter “big gun” sprinkler

Figure 12. Portable big gun sprinkler

Figure 13. Cable tow big gun sprinkler

Figure 14. Big gun hose reel sprinkler

irrigate a square or rectangular field, while the portable big gun must be moved manually and can irrigate fields of various dimensions. These sprinklers are often fixed to the end of center pivot irrigation machines to help irrigate corners of square fields (Figure 15). Maximum attainable efficiency for these sprinklers ranges from 60 to 75 % and they are subject to wind drift and evaporation losses in particular (Table 1). These guns are used on a variety of crops ranging from pasture to vegetable crops.

Figure 15. Center pivot irrigation machine with end gun operating

Microirrigation

Microirrigation has become popular in recent years because of the high efficiency of these devices compared to other types of irrigation systems. Microirrigation has many common names such as “drip,” “trickle,” “low volume,” and “micro.” These systems comprise 44% of all agricultural irrigation in Florida (USDA 1998). There are essentially three types of devices according to ASAE (2001): drip emitters, sprays, and bubblers. Drip emitters may be a single emitter that is connected to a polyethylene supply lateral. Recently, drip “tape” or “tubing” has been developed and has become very popular because emitters are molded into the tubing at the factory (Figure 16). Drip tape is generally thinner than tubing and is supplied in rolls where the tape is flat on the roll and expands when connected to a water supply. Drip tubing is a rigid tube either oval or round in cross section. Drip tape is often installed on the soil surface below plastic mulch in Florida vegetable production (Figure 17). This virtually eliminates evaporation losses that occur when the drip tape is placed on bare soil. Individual emitters connected to small tubing are popular in nursery production (Figure 18). Subsurface drip irrigation (SDI) is a relatively new practice where the drip tape is buried at a shallow depth in each crop row or every

Figure 16. Drip tape on bare soil

Figure 17. Drip tape installed under plastic mulched vegetable beds

Figure 18. Microirrigation emitter in nursery production

other crop row. This type of system can remain in place for several years in contrast to the conventional plastic mulch system that must be replaced each year. Drip tape has also been buried at large spacings (30-60 ft) to create a perched water table for seepage irrigation (see seepage irrigation below). Microspray emitters also called "microjet" emitters are used extensively in citrus production (Figures 19 and 20) and are becoming popular in landscape applications (Figure 21). The third category of microirrigation, bubbler, is used extensively in landscaping and nursery applications (Figure 22). These systems are not designed to irrigate the entire crop root zone. Maximum efficiencies of microirrigation systems can be much higher than other types of systems and range between 70 and 90%. Average efficiency for these systems is typically in the mid 80% range (Table 1). New systems typically have distribution uniformities of 0.88-0.94 while older systems typically have lower uniformities in the 0.70-0.85 range (Jensen 1980).

Figure 19. Microjet irrigation on young citrus

Figure 20. Wetted perimeter of microjet irrigation on mature citrus

Figure 21. Microjet emitter in a landscape bed

Figure 22. Bubbler microirrigation device

Solomon and Keller (1978) found that microirrigation inefficiency was a result of improper emitter spacing, clogging, and pressure differentials within the system.

Surface

There are two main types of surface irrigation techniques practiced in Florida, crown flood and flood. Surface irrigation comprises approximately 19% of the total irrigated area in the state (USDA 1998).

Crown flood is used primarily to irrigate citrus in Florida (Figure 23). This method originally evolved to enable both drainage and irrigation on high water table (flatwoods) soils. Soil is removed from furrows and used to form berms 2-4 ft high. Citrus trees are planted on the

Figure 23. Crown flood irrigation of citrus

berms. Thus, the furrows allow drainage from the field and when flooded they provide irrigation by allowing water to penetrate the berms in the vertical and horizontal direction. Irrigation events typically occur 1-2 times each week. Maximum efficiency of this type of system ranges from 25 to 75% (Table 1). Smajstrla et al. (1982) studied a crown flood system and found that the system had an efficiency of 87% because unused water was recycled to the reservoir; however, they calculated that the efficiency would have been 24% if recycling had not occurred.

Flood irrigation is a practice that ponds water in the entire field rather than just down furrows such as in crown flood irrigation. This type of irrigation is common for rice production and is not widely practiced in Florida. Efficiency is similar to crown flood and ranges between 25 and 75% (Table 1).

Seepage

Seepage irrigation is sometimes called “subirrigation” or “water table control” and accounts for 19% of irrigated agricultural land in Florida (USDA 1998). This method utilizes either open ditches or buried perforated tubing (drain tile) to maintain the water table at a desired level near the bottom or just below the crop root zone. Seepage irrigation requires a shallow restrictive layer of soil that allows a perched water table. Seepage irrigation is common on organic or “muck” soils found in Florida because the water table must be kept as high as possible to prevent oxidation of the soil. Figure 24 shows a picture of seepage irrigated row crops and Figure 25 shows seepage irrigation on organic soils. In the past seepage irrigation systems consisted of open ditch conveyance systems and open ditches in the fields to maintain a given

Figure 24. Seepage irrigated row crops

Figure 25. Seepage irrigation ditch on an organic soil

water table. In an effort to improve efficiency of the system, the open ditch conveyance system can be changed to a semi-closed system where the water is supplied at the head of the field ditches by underground main lines. Also, the tailwater at the end of the field ditches can be collected and recycled to the water supply to increase efficiency. Factors affecting the efficiency of these systems include: 1) depth to the impermeable layer, 2) continuity of the impermeable layer, 3) water table on fields surrounding the site of interest, 4) water table level at the beginning of rain events. Efficiencies for these systems range between 20 and 80% (Table 1).

IRRIGATION SYSTEM EFFICIENCY IN AFSIRS

There are eight defined irrigation system types in the AFSIRS model and one category that allows the user to customize the irrigation system parameters. The irrigation system types are presented below with efficiency values specified by AFSIRS (Smajstrla et al. 1990).

Irrigation system	AFSIRS efficiency
Micro, drip	85%
Micro, spray	80%
Multiple sprinkler	75%
Sprinkler, container nursery	20%
Sprinkler, large guns	70%
Seepage	50%
Crown flood	50%
Flood	50%

The program allows the user to calculate net irrigation requirement that does not consider irrigation system efficiency and gross irrigation requirement. The two terms are related as follows,

$$IRR_{gross} = \frac{IRR_{net}}{E_0} \tag{8}$$

where IRR_{gross} is the gross irrigation requirement and IRR_{net} is the net irrigation requirement.

The irrigation system efficiency is essentially application efficiency for sprinkler and microirrigation and the overall system efficiency for surface and seepage irrigation. As such, the values do not account for management factors and assume that management does not result in loss of water. These values were compiled from irrigation texts. They were not developed from research data in the region. These values present efficiencies that are ideally maximized and efficiencies in actual production are likely much lower. It is recommended that actual efficiency of common types of irrigation systems in Florida such as sprinkler, microspray, and seepage be studied under management practices ranging from typical producer practice to practices designed to maximize efficiency such as deficit irrigation and automatic irrigation based on soil moisture status.

Other factors in the model that will impact the estimate of crop consumptive use include crop rooting depth as a function of growth stage and crop type as well as crop coefficient values under typical management practices in the humid region. According to the AFSIRS Technical Manual (Smajstrla, 1990) values for crop root depth and crop coefficients were taken from the literature and very little of the data was developed in Florida. It is recommended that in combination with irrigation efficiency studies, crop root length experiments, and crop coefficient experiments be conducted.

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL

APPENDIX 9
CLIMATE DATABASE UPDATE
(TASK 9a)

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CLIMATE DATABASE UPDATE

Update AFSIRS Climate Database

The original AFSIRS climate database provides daily evapotranspiration (ET) and rainfall (P) data from eight locations in and near Florida: Mobile, Tallahassee, Jacksonville, Daytona Beach, Orlando, Tampa, West Palm Beach, and Miami. The length of time for recording the data at these locations ranged from 18 to 24 years. The updated AFSIRS climate database includes daily data from 1970 to 1999 for the eight previously mentioned stations, as well as for Gainesville (Table 1). The updated reference ET database was generated using the FAO Penman-Monteith method (Allen et al., 1998).

Location	Latitude	Longitude	Elevation Above Mean Sea Level (m)
Daytona Beach, Fla.	29° 11′	W 83° 03′	2.0
Gainesville, Fla.	29° 38′	W 82° 22′	29.3
Jacksonville, Fla.	30° 30′	W 81° 42′	9.0
Key West, Fla.	24° 33′	W 81° 45′	1.0
Miami, Fla.	25° 48′	W 80° 16′	2.0
Mobile, Ala.	30° 41′	W 88° 15′	7.0
Tallahassee, Fla.	30° 23′	W 84° 22′	11.0
Tampa, Fla.	27° 58′	W 82° 32′	3.0
West Palm Beach, Fla.	26° 41′	W 80° 06′	6.0

Table 1. NOAA weather stations included in the updated AFSIRS climate database

Data Compilation

The FAO method requires daily measurements of incoming solar radiation, wind speed, minimum and maximum temperature, and relative humidity. These data are compiled from NOAA weather stations at the nine locations. A quality assurance procedure was applied to measured data and a threshold analysis was applied to limit the maximum relative humidity to 100 percent. The solar radiation accuracy was evaluated by comparing the daily average measured values against computed maximum solar radiation value that can reach the earth in clear-sky conditions. Temperature, solar radiation, or wind speed was assessed using graphical tools. The erroneous or missing values on a given day were replaced with average recorded values, using the remaining years' observations on that day. Table 2 shows the variables used to estimate ET and their units.

Climate Variable	Units
Incoming solar radiation	MJ m^2
Minimum temperature	°C
Maximum temperature	°C
Relative humidity	%
Height of relative humidity measurement	m
Wind speed	m s^{-1}
Height of wind speed measurement	m
Rainfall	mm
Evapotranspiration	mm day^{-1}

Table 2. Measured and calculated climate variables and their units

NOAA weather stations discontinued measuring incoming solar radiation in 1990. As this variable is critical in estimating ET, a solar radiation product was used from 1990 to 1999. The solar radiation data were obtained from the long-term hydrologic dataset developed for the Variable Infiltration Capacity model (Maurer et al., 2002) (http://www.ce.washington.edu/pub/HYDRO/edm/VIC_retrospective/index.html). No statistically significant difference was found between the estimated ET that used the solar radiation product and the measured solar radiation for a two-year period. The compiled data for the nine locations were provided to SJRWMD digitally.

ET Estimation

A Fortran program was used to calculate reference ET, given the climate dataset. The source code and sample input and output files were provided to SJRWMD digitally. The data format in the output file is identical to that of the input file, except for an additional column with ET data. The ET units are mm day^{-1}.

Climate Database

The estimated ET and rainfall data for each location are stored in a Microsoft Access database table. ET and rainfall units are in inches. This Access database was provided to SJRWMD digitally with the GWRAPPS software. Figure 1 shows a sample climate table.

Daytona : Table

YEAR	DAY	ET	PREP
1970	1	0.056	0.09
1970	2	0.044	0.39
1970	3	0.038	1.509
1970	4	0.051	0
1970	5	0.072	0
1970	6	0.077	0.959
1970	7	0.071	0
1970	8	0.058	0
1970	9	0.047	0
1970	10	0.045	0
1970	11	0.069	0
1970	12	0.116	0.029
1970	13	0.062	0
1970	14	0.052	0

Record: 1 of 10950

Figure 1. Access climate-data table for Daytona Beach, Florida

GWRAPPS Climate Database

The updated AFSIRS climate data were used to generate 30 years of daily climate data at 368 locations across the state of Florida. These locations are spaced at a 20-kilometer resolution. The database was generated using the GWRAPPS climate interpolation utility. This utility employs the spline interpolation technique and stores the interpolated data for each location in a separate Microsoft Access database. These databases have been provided to the District digitally.

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REVISION OF AFSIRS CROP WATER SIMULATION MODEL

APPENDIX 10
REVIEW OF METHODS TO ENHANCE SPATIAL INTERPOLATION OF CLIMATE DATABASE
(TASK 9b)

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APPENDIX 10 - REVIEW METHODS TO ENHANCE SPATIAL INTERPOLATION OF CLIMATE DATABASE

INTRODUCTION

The Water Management Districts use crop water use models to determine water needs for agricultural consumptive water use permits. These models estimate the crop water requirements under varying climate, soil and irrigation management conditions. Understanding climate variability is crucial for superior model predictions and thus, effective agricultural water management. The most common source of climate data is from meteorological stations. Individual stations provide data for local conditions only. A critical examination of approaches is imperative to model regional climate spatial variation from the point location data. This study examines different methods for interpolating climate data over a region. This report begins with a brief introduction to the interpolation techniques. Data sources identification and study description follow. Interpolation techniques' performance is reported in terms of mean absolute differences and relative percent differences. In addition, as the spatial distribution of the current AFSIRS climate database is quite sparse some potential sources for expanding the AFSIRS climate database are identified and their merits and demerits are discussed.

INTERPOLATION

Spatial interpolation estimates property values at unsampled sites within an area covered by sampled points, using the data from those points. The choice of the interpolation approach is dictated by the available input data. Most interpolation techniques perform well and yield similar results when data are abundant. When data are sparse, as is the case with the AFSIRS climate database, the underlying assumptions about the variation among sampled points may differ and the choice of interpolation method becomes critical. Understanding the interpolation methods is the first step towards determining the best choice for the given data set. The four interpolation techniques employed in this study are a) Inverse Distance Weighting (IDW), b) Spline, c) Kriging, and d) Trend. These methods were chosen based upon ArcGIS functionality and available data. The remaining portion of this section describes these methods in more detail. More complete description of the methods can be found elsewhere (Isaaks and Srivastava, 1989; Goovaerts, 1997).

The interpolation methods can be classified using three approaches. The first approach categorizes the methods into 'deterministic' or 'stochastic' methods based on the criteria for choosing weights. Deterministic methods weigh points based on distance while stochastic methods use statistical criteria. The second approach categorizes the methods into 'exact' or 'inexact.' A method is exact if it assigns a value identical to the measured value at a sampled point. All other interpolation methods are described as inexact. The third approach describes a method as 'global' or 'local.' Global techniques fit a model through the prediction variable over all the points in the study area and typically do not accommodate local features well. Local techniques estimate values for an unsampled point from a specific number of neighboring points. Table 1 provides the classification of the four methods used in this study.

Table 1. Categorization of the four interpolation methods studied

Interpolation Method	Deterministic/ STOCHASTIC	Exact/Inexact	Global/ Local
Inverse Distance Weighting	Deterministic	Exact	Global
Spline	Deterministic	Exact	Local
Kriging	Stochastic	Exact	Local with global variograms
Trend Surface	Stochastic	Inexact	Global

Inverse Distance Weighting

IDW is a deterministic estimation method whereby values at unsampled points are determined by a linear combination of values at known sampled points. The weights are strictly a function of distance. The assumption is that values closer to the unsampled location are more representative of the values to be estimated than values from samples further away. In general, the estimated value at an unsampled point is expressed as

$$v = \frac{\sum_{i=1}^{n} \frac{1}{d_i^p} v_i}{\sum_{i=1}^{n} \frac{1}{d_i^p}}$$

where d_i is the distance from the unsampled point to the sampled point i, v_i is the value at the sampled point i, n is the number of sampled points, and p is the power. The choice of power significantly affects the interpolation results. As p decreases, the weights given to the samples become more similar, and the interpolated value approaches the average values of all sampled points. As p increases, the IDW approaches the nearest neighbor interpolation method, in which the interpolated value simply takes on the value of the closest sampled point. This study uses a power of 2, the most common power used.

Spline

The spline method is a deterministic technique and estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes exactly through the sampled points. Conceptually, it is similar to bending a sheet of rubber to pass through the points while minimizing the total curvature of the surface. The spline method fits a mathematical function to a specified number of nearest input points while passing through the sample points. When using higher weight, a regularized spline generates smoother surfaces while tension spline generates coarser surfaces. For this study, a regularized spline is used.

Kriging

Kriging is a stochastic technique similar to IDW, in that it uses a linear combination of weights at sampled points to estimate the value at unsampled point. The main difference is in the process employed for determining weights. While in IDW weights are strictly based on distance, kriging weights change according to the spatial arrangement of the samples. This interpolation method assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. It fits a mathematical function to a specified number of points, or all points, to determine the output value for each location.

The most commonly used mathematical function is a ‘semi-variogram.’ Semi-variogram gives a measure of spatial correlation between pairs of points describing the variance over a distance or lag h and is given by

$$\gamma(h) = \frac{1}{2} E\left(y(x) - y(x+h)\right)^2$$

where $\gamma(h)$ is the semi-variogram, dependant on lag or distance h, (x,x+h) is a pair of points with distance vector h, y(x) is the regionalized variable y at point x, y(x)-y(x+h) is the difference of the variable at two points separated by h, and E denotes mathematical expectation. A variogram model is then fit through the semi-variogram values for various distance and lag classes. The most common variogram models are the linear model, the spherical model, the exponential model, and the Gaussian model.

As the available climate database was sparse, a spatially dense ET dataset developed using the variable infiltration capacity (VIC) model by the University of Washington (UW), was used (Maurer et al. 2002). This dataset provided 50 years of monthly values of ET at a $1/8^{o}$ resolution for the entire U.S. From this dataset, 991 points covering the entire state of Florida are selected and average monthly ET values were computed. Variogram analysis was performed on a monthly basis. For every month, the exponential model and the spherical models fitted the data best. Thus, exponential model was used for Kriging interpolations.

Trend Surface

The trend surface method fits a global polynomial function to all points. It uses a least-squares regression fit, which results in a surface that minimizes the variance of the surface relative to the input values. The resulting surface is very smooth and rarely passes through the input points. The surface is constructed so that for every input point, the total of differences between the actual values and the estimated values will be the smallest possible. This method is very sensitive to large and small values.

DATA

12 National Oceanographic and Atmospheric Administration (NOAA) weather stations and 7 Florida Automated Weather Network (FAWN) stations were used in this study. Data from

the NOAA stations were used in interpolation while the data from FAWN stations was used for validating the method (Figure 1). Table 2 provides the list of stations.

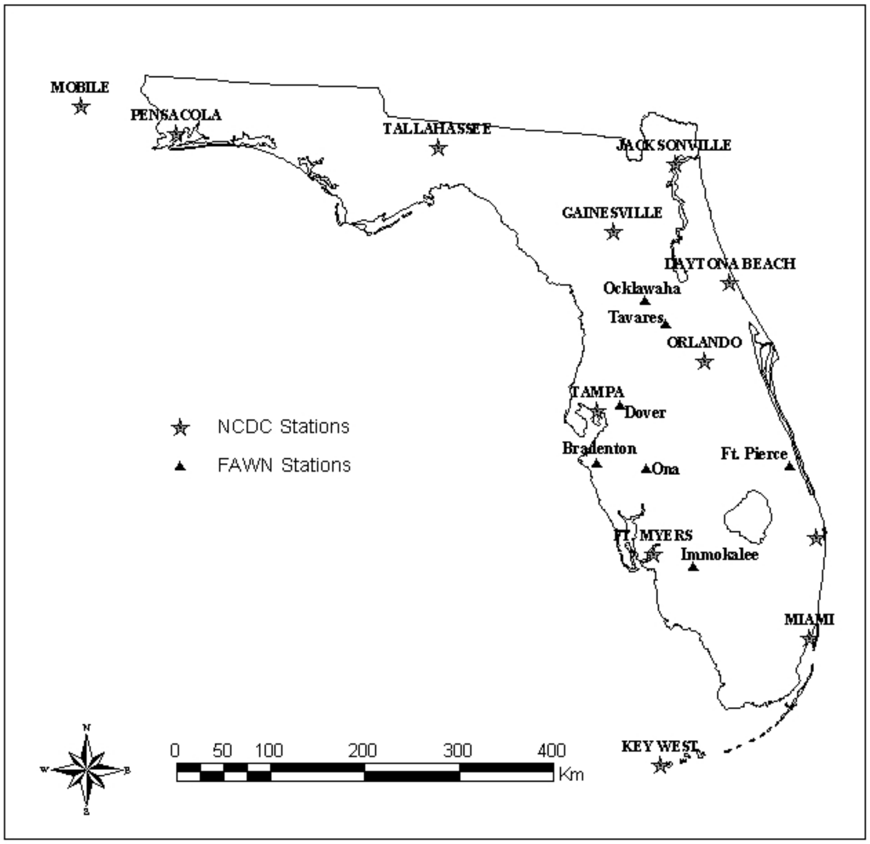

Figure 1. Stations used in the interpolation study

Table 2. National Oceanographic and Atmospheric Administration (NOAA) weather stations and Florida Automated Weather Network (FAWN) stations used in this study

NOAA/NCDC Stations	FAWN Stations
Daytona Beach	Bradenton
Fort Myers*	Dover
Gainesville	Fort Pierce
Jacksonville	Immokalee
Keywest	Ocklawaha
Miami	Ona
Mobile	Tavares
Orlando*	
Pensacola*	
Tallahassee	
Tampa	
West Palm Beach	

*Stations not available in the updated AFSIRS climate database

Three NOAA stations, Fort Myers, Orlando, Pensacola were added in addition to the 9 stations available in the updated AFSIRS climate database. These were added to overcome a limitation of kriging method, the requirement that at least 10 data points are necessary to estimate a variogram. The stations were selected based on the availability of long-term climate data (1960-1999) necessary to estimate ET. One year of daily ET and rainfall data are used in this study. Calendar year 1999 was chosen based on the availability of solar radiation data from the UW dataset, the 3 newly added NOAA stations, and the number of fully functional FAWN stations.

STUDY RESULTS

The four interpolation methods described above were applied to daily ET and rainfall data for the calendar year 1999. QA/QC was conducted on the data from the FAWN stations. Data were missing for some days. Days with erroneous data were excluded from the study. Table 3 shows the number of days data were available at the FAWN stations after QA/QC.

Table 3. Number of days incorporated into the interpolation study for each FAWN station

FAWN Station	Number of Days used in the Study
Bradenton	363
Dover	362
Fort Pierce	356
Immokalee	340
Ocklawaha	283
Ona	360
Tavares	257

Evapotranspiration

Table 4 provides 7 FAWN stations' validation statistics for the 4 interpolation methods. All methods performed relatively well with <14% relative differences between the estimated and measured ET values. IDW provided the best agreement and spline the worst agreement with the estimated ET values. One station (Dover) had a relative difference of >10% using all interpolation methods. Spline had relative differences larger than 10% at 3 stations. From these observations, it is recommended to use IDW interpolation technique for ET.

Table 4. Validation statistics for evapotranspiration at seven stations. The interpolation methods considered are inverse distance weighting (IDW), spline, kriging, and trend surface

Station	Mean Absolute Difference (mm/day)				Relative Difference (%)			
	IDW	Spline	Kriging	Trend	IDW	Spline	Kriging	Trend
Bradenton	0.5	0.5	0.5	0.5	7	7	6	9
Dover	0.6	0.6	0.6	0.6	11	13	14	16
Ft. Pierce	0.6	0.7	0.6	0.6	8	14	8	9
Immokalee	0.5	0.5	0.5	0.5	0	1	-2	-3
Ocklawaha	0.5	0.5	0.5	0.5	6	3	6	8
Ona	0.5	0.6	0.5	0.5	8	13	8	8
Tavares	0.5	0.5	0.5	0.5	7	4	5	7

Rainfall

Satisfactory results were not obtained for precipitation from any interpolation technique considered using 12 stations. Negative precipitation was estimated at the validation stations frequently by all methods except IDW. Kriging was not feasible for this study as variograms cannot be determined from the few non-zero values. Table 5 shows the mean absolute differences observed at the 7 stations. From this study, it was observed that the 12 NCDC stations are not sufficient to represent the spatial distribution of precipitation over the entire state. In Florida, precipitation exhibits a particularly highly variable spatial distribution due to the local convective storms. A denser precipitation network is necessary to both conduct a study to determine the appropriate interpolation technique and provide meaningful spatial interpolation. Towards this end, a network of 80 NCDC stations having a long-term (1960-current) precipitation record was compiled. Figure 2 shows the spatial distribution of the new precipitation network. The interpolation techniques were reanalyzed and the prediction accuracy increased by approximately 50%. IDW performed best using both the networks. IDW also had no or a very small bias with a maximum negative bias of <1 mm.

Table 5. Validation statistics for daily rainfall at seven stations. The interpolation methods considered are inverse distance weighting (IDW), spline, and trend surface

Station	Mean Absolute Difference (mm)					
	Using 12 NCDC Stations			Using 80 NCDC Stations		
	IDW	Spline	Trend	IDW	Spline	Trend
Bradenton	5	5	9	3	5	3
Dover	3	4	8	3	3	3
Ft. Pierce	8	11	9	6	7	7
Immokalee	9	13	7	4	5	4
Ocklawaha	7	8	7	4	5	4
Ona	7	12	8	4	5	4
Tavares	10	12	8	5	6	5

POTENTIAL DATA SOURCES

The limiting factor to estimating ET is the availability of climate measurements. NCDC discontinued solar radiation measurement from 1990 onwards. Other parameters (e.g. relative humidity and wind speed) are only measured at a few stations. To bridge the gap in ET data from 1990 to 2000, other sources of solar radiation have to be used. This section identifies some potential data sources.

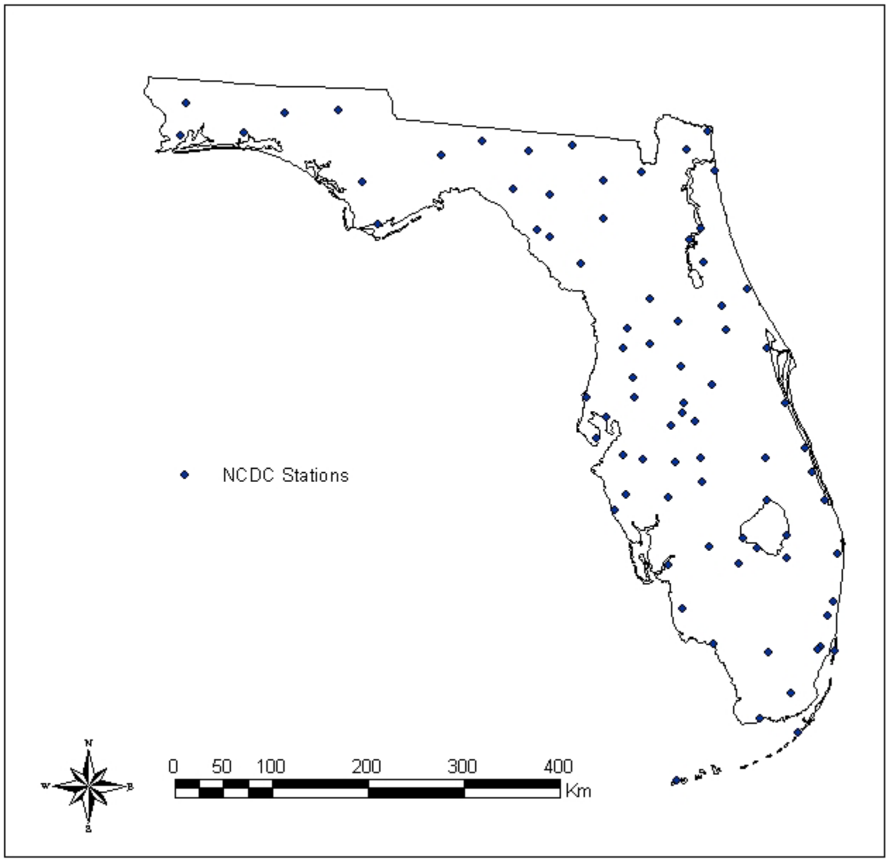

Figure 2. Precipitation network used in the interpolation study

GOES Solar Radiation Product

University of Wisconsin developed an algorithm to estimate solar radiation from GOES satellite data. Using this algorithm, daily solar radiation maps were generated for the entire United States. A study using 52 stations in Florida and southern Georgia was conducted for establishing the validity of the solar radiation data in the southeastern United States. Daily solar radiation data for the complete year of 2001 were collected from 21 FAWN stations, 21 SFWMD stations (www.sjwmd.gov), and 10 Georgia Automated Environmental Monitoring Network (GAEMN) stations (www.griffin.peachnet.edu/bae/). GOES solar radiation had a good agreement with most of the stations. A bias in the GOES solar radiation data was observed that could be addressed either by fitting a regression line for GOES data or by adjusting the algorithm, if feasible, to account for these differences. Currently, the algorithm is not applied during winter due to complications from snowfall in much of the United States. However, it is feasible to develop the full year product for Florida.

University of Washington Data

University of Washington developed a long-term hydrological dataset (1950-2000) for the conterminous United States. The dataset comprises all the climate variables necessary to estimate ET. A comparison study was conducted to validate the use of the modeled solar radiation data with other measured climate variables to estimate ET. The study involved three years (1988-1990) of modeled and measured solar radiation data at the 9 NCDC stations available in the AFSIRS climate database. ET values estimated using the modeled solar radiation dataset were not statistically significant from those obtained using the measured solar radiation. Table 6 shows the observed mean absolute differences. Stations closer to the coast had relatively high mean absolute differences when compared with the inland stations.

Table 6. Comparison between evapotranspiration estimated using modeled and measured solar radiation data

NCDC Stations	Mean Absolute Difference (mm/day)
Daytona Beach	0.4
Gainesville	0.3
Jacksonville	0.3
Keywest	0.7
Miami	0.6
Mobile	0.3
Tallahassee	0.3
Tampa	0.4
West Palm Beach	0.6

Additional Information: http.//www.ce.washington.edu/pub/HYDRO/edm/VIC_retrospective/index.html

FAWN

FAWN was established in 1997 by Institute of Food and Agricultural Services (IFAS). Though FAWN stations measure all climate variables necessary to estimate ET, they are relatively new and cannot provide long-term historical data. Also, the FAWN datasets need to be validated. FAWN currently has a network of 32 stations and can provide measured solar radiation data for future datasets. (Additional information: http://fawn.ifas.ufl.edu).

CONCLUSIONS AND RECOMMENDATIONS

Four interpolation methods, IDW, spline, kriging, and trend surface were used to estimate ET and precipitation at ungaged sites. The IDW method performed best for ET interpolation. No method gave reasonable results using the 12 station precipitation data. However, the prediction accuracy increased by approximately 50% by using a denser network of 80 stations. IDW performed best for the denser precipitation dataset. To make efficient use of the available data, separate datasets should be used to develop the regional ET and precipitation databases. IDW is recommended for both ET and precipitation interpolations. The identified climate data from sources other than NCDC provide reasonable alternative and additions to complement the sparse network of full NCDC climate stations. The inclusion of one or more of these stations is recommended to compile future long-term datasets and to potentially improve the interpolation techniques' prediction accuracy.

REFERENCES

Goovaerts, P. 1997. Geostatistics for Natural Resources Evaluation. Oxford University Press. 483 pp.

Isaaks, E.H., and R.M. Srivastava. 1989. Applied Geostatistics. Oxford University Press. 561 pp.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States, J. Climate 15, 3237-3251.

DATA SOURCES

Florida Automated Weather Network – fawn.ifas.ufl.edu

Georgia Automated Environmental Monitoring Network – www.griffin.peachnet.edu/bae/

National Climatic Data Center – www.ncdc.noaa.gov

VIC Retrospective Land Surface Dataset – http://www.ce.washington.edu/pub/HYDRO/edm/VIC_retrospective/index.html

REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL

APPENDIX 11
CLIMATE DATABASE IMPLEMENTATION
(TASK 13)

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REVISION OF AFSIRS CROP WATER USE SIMULATION MODEL
APPENDIX 11 - CLIMATE DATABASE IMPLEMENTATION

AFSIRS CLIMATE DATABASE BACKGROUND

The original AFSIRS climate database provides daily evapotranspiration (ET) and rainfall (P) data from eight locations in and near Florida. The locations are Mobile, Tallahassee, Jacksonville, Daytona Beach, Orlando, Tampa, West Palm Beach, and Miami. The record lengths at these locations range from 18-24 years. Task 9a extended the record for these stations and an additional station at Gainesville to include data from 1970 to 1990. The updated AFSIRS climate data were used to generate 30 years of daily climate data at 368 locations covering the state of Florida. These locations are spaced at a 20-km resolution. The database was generated using the GWRAPPS climate interpolation utility. Task 9a employed the spline interpolation technique and, for each location, stored the interpolated data in a separate Microsoft Access database.

Task 9b compared four interpolation methods, Inverse Distance Weighting (IDW), spline, kriging, and trend surface to estimate ET and precipitation at ungaged sites. The results show that the IDW method performed best for ET interpolation. No method gave reasonable results using the 12 station precipitation data. However, the prediction accuracy was significantly improved by using a denser network of 80 stations. IDW performed best for the denser precipitation dataset. The final recommendation was to make efficient use of the available data by using separate datasets to develop the regional ET and precipitation databases. IDW is recommended for both ET and precipitation interpolations.

UPDATE AFSIRS CLIMATE DATABASE

The final AFSIRS 1970-1999 climate database includes daily ET data generated from the nine stations used in Task 9a (Table 1) and the 80 daily precipitation stations used in Task 9b (totaling 80 stations) as shown in Figure 1. The locations and station details are provided in the clim_all_pt ArcGIS point feature class and provided in Appendix A. The updated reference ET database was generated using the FAO Penman-Monteith method as described in United Nations Food and Agriculture Organization paper number 56 (FAO56) (Allen et al., 1998). A complete overview of the steps used to develop the updated climate database is provided in this paper.

Table 1. NOAA weather stations included in the updated AFSIRS climate database

Location	Latitude	Longitude	Elevation Above Mean Sea Level (m)
Daytona Beach, FL	29° 11′	W 83° 03′	2.0
Gainesville, FL	29° 38′	W 82° 22′	29.3
Jacksonville, FL	30° 30′	W 81° 42′	9.0
Key West, FL	24° 33′	W 81° 45′	1.0
Miami, FL	25° 48′	W 80° 16′	2.0
Mobile, AL	30° 41′	W 88° 15′	7.0
Tallahassee, FL	30° 23′	W 84° 22′	11.0
Tampa, FL	27° 58′	W 82° 32′	3.0
West Palm Beach, FL	26° 41′	W 80° 06′	6.0

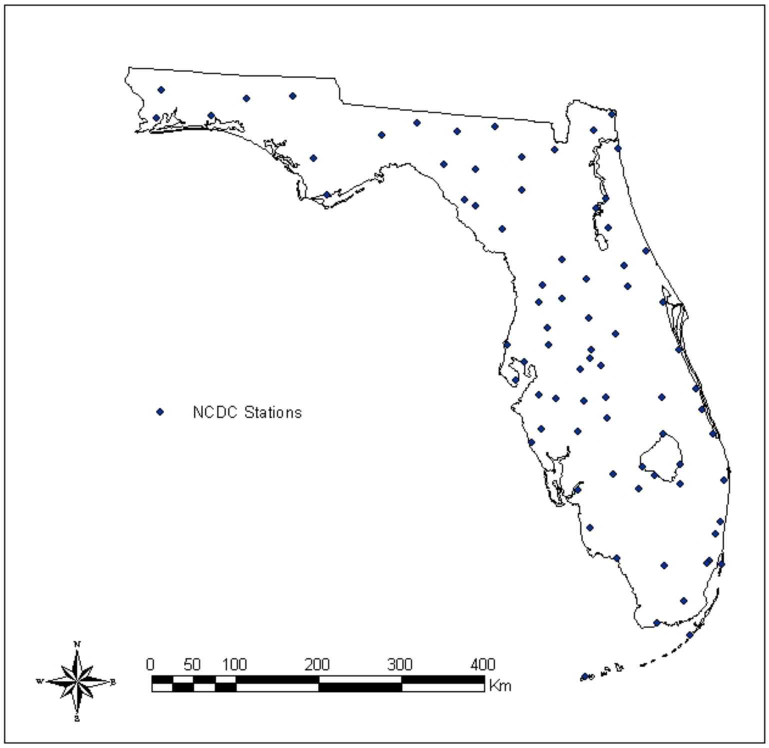

Figure 1. Precipitation network used in the interpolation study

Data Compilation

The FAO method requires daily measurements of incoming solar radiation, wind speed, minimum and maximum temperature, and relative humidity. These data are compiled from NOAA weather stations at the nine locations. A quality assurance procedure was applied to measured data. A threshold analysis was applied to limit the maximum relative humidity to 100%. The solar radiation accuracy was evaluated by comparing the daily average measured values against computed maximum solar radiation values that can reach the Earth under clear sky conditions. Temperature, solar radiation, or wind speed were assessed using graphical tools. The erroneous or missing values on a given day were replaced with average recorded values using the remaining years' observations on that day. Table 2 shows the variables used to estimate ET and their units of measure.

Table 2. Measured and calculated climate variables and their units

Climate Variable	Units
Incoming solar radiation	MJ m^2
Minimum temperature	°C
Maximum temperature	°C
Relative humidity	%
Height of relative humidity measurement	m
Wind speed	m s^{-1}
Height of wind speed measurement	m
Rainfall	mm
Evapotranspiration	mm day^{-1}

NOAA weather stations discontinued measuring incoming solar radiation from 1990 to present. As this variable is critical in estimating ET, a solar radiation product was used for the period 1990 to 1999. The solar radiation data were obtained from the long-term hydrologic dataset developed for the Variable Infiltration Capacity model (Maurer et al., 2002) (http://www.ce.washington.edu/pub/HYDRO/edm/VIC_retrospective/index.html). No statistically significant difference was found between the ET estimated using the solar radiation product and measured solar radiation for a 2-year period. The compiled data for the nine locations are provided on the CD in the **NOAA_Climate_Data** folder as a deliverable under Task 9.

ET Estimation

A FORTRAN program was used to calculate reference ET based on the climate dataset. The source code and sample input and output files are provided on the CD in the **ET_Estimation** folder. Except for an additional column with ET data, the data format in the output file is identical to that of the input file. The ET units are mm day^{-1}.

Precipitation

The 12 National Climatic Data Center (NCDC) stations are not sufficient to represent the spatial distribution of precipitation over the entire state. In Florida, precipitation exhibits a particularly highly variable spatial distribution due to the local convective systems. A denser precipitation network was developed to provide meaningful spatial interpolation. The network of 80 NCDC stations having a long-term (1960-current) precipitation record was compiled as part of Task 9b (Figure 1). A quality assurance procedure was applied to identify outliers in rainfall data.

Climate Database

For each of the 80 locations, the estimated ET and rainfall data are stored in a Microsoft Access database (climateDB.mdb). Each location has a separate table in climateDB.mdb. The table name for each station is maintained in the clim_all_pt ArcGIS point feature class and a complete list of station name, county, database name, and location are provided in Appendix A. ET and rainfall units are inches. For those locations having not ET values, the ET values were set to –9999. Missing values of precipitation were set to

–99999. This Access database is provided both with the GWRAPPS software and on the CD in the **Updated_AFSIRS_Climate** folder. Figure 2 shows a snapshot of a sample climate table.

Daytona : Table

YEAR	DAY	ET	PREP
1970	1	0.056	0.09
1970	2	0.044	0.39
1970	3	0.038	1.509
1970	4	0.051	0
1970	5	0.072	0
1970	6	0.077	0.959
1970	7	0.071	0
1970	8	0.058	0
1970	9	0.047	0
1970	10	0.045	0
1970	11	0.069	0
1970	12	0.116	0.029
1970	13	0.062	0
1970	14	0.052	0

Record: 1 of 10950

Figure 2. Access climate data table for Daytona Beach, Florida

Generate GWRAPPS Climate Database

The updated AFSIRS climate data were used to generate 30 years of daily climate data at 368 locations covering the state of Florida. These locations are spaced at a 20-km resolution. The database was generated using the GWRAPPS climate interpolation utility. This utility employs the inverse distance weighting technique and, for each location, stores the interpolated data in a separate Microsoft Access database. These databases are provided in the **GWRAPPS_Climate_Data** folder on the CD. The *Climate* ArcGIS shape feature class contains the location and database name corresponding to each location (provided in the **GIS_Data** folder on the CD).

References

Allen, R.G., L.S. Periera, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop requirements. *Irrigation and Drainage Paper No. 56*, FAO, Rome, Italy, 300 pp.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen. 2002. A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. *J. Climate*, 15, 3237-3251.

APPENDIX A – CLIMATE STATIONS

Location	County	DB Table	Latitude	Longitude
Apalachicola Ap Fbo	Franklin	211	29.726	-85.021
Arcadia	Desoto	228	27.218	-81.874
Avon Park 2 W	Highlands	369	27.594	-81.525
Bartow	Polk	478	27.899	-81.843
Belle Glade Exp Stn	Palm Beach	611	26.657	-80.63
Brooksville Chin Hill	Hernando	1046	28.616	-82.366
Bushnell 2 E	Sumter	1163	28.662	-82.083
Canal Point Usda	Palm Beach	1276	26.864	-80.626
Chipley 3 E	Washington	1544	30.783	-85.483
Clermont 7 S	Lake	1641	28.45	-81.748
Clewiston	Hendry	1654	26.742	-80.94
Clewiston	Hendry	1654	26.742	-80.94
Crescent City	Putnam	1978	29.428	-81.508
Cross City 2 Wnw	Dixie	2008	29.65	-83.167
Daytona Beach	Volusia	Daytona	29.192	-81.053
Daytona Beach Intl Ap	Volusia	2158	29.183	-81.048
De Funiak Springs	Walton	2220	30.733	-86.067
Deland 1 Sse	Volusia	2229	29.018	-81.311
Desoto City 8 Sw	Highlands	2288	27.37	-81.514
Devils Garden	Hendry	2298	26.603	-81.129
Everglades	Collier	2850	25.846	-81.387
Federal Point	Putnam	2915	29.755	-81.539
Fernandina Beach	Nassau	2944	30.659	-81.464
Flamingo Ranger Stn	Monroe	3020	25.142	-80.914
Fort Drum 5 Nw	Okeechobee	3137	27.588	-80.843
Fort Green 12 Wsw	Manatee	3153	27.571	-82.138
Fort Lauderdale	Broward	3163	26.102	-80.201
Fort Myers Faa/Ap	Lee	3186	26.586	-81.864
Fort Pierce	St. Lucie	3207	27.462	-80.354
Ft. Myers	Lee	Ftmyers	26.583	-81.862
Gainesville	Alachua	Gainesville	29.674	-82.336
Glen St Mary 1 W	Baker	3470	30.272	-82.186
Hialeah	Dade	3909	25.817	-80.286
High Springs	Alachua	3956	29.829	-82.597
Hillsborough Rvr St Pk	Hillsborough	3986	28.15	-82.233
Inverness 3 Se	Citrus	4289	28.803	-82.313
Jacksonville	Duval	Jacksonville	30.335	-81.658

Location	County	DB Table	Latitude	Longitude
Jacksonville Beach	Duval	4366	30.29	-81.392
Jacksonville Intl Ap	Duval	4358	30.495	-81.694
Jasper	Hamilton	4394	30.523	-82.945
Key West	Monroe	Keywest	24.563	-81.775
Key West Intl Ap	Monroe	4570	24.552	-81.758
Kissimmee 2	Osceola	4625	28.28	-81.418
La Belle	Hendry	4662	26.752	-81.439
Lake Alfred Exp Stn	Polk	4707	28.104	-81.714
Lake City 2 E	Columbia	4731	30.184	-82.593
Lisbon	Lake	5076	28.873	-81.786
Madison	Madison	5275	30.45	-83.417
Mayo	Lafayette	5539	30.05	-83.167
Melbourne Wfo	Brevard	5612	28.103	-80.646
Miami	Dade	Miami	25.776	-80.211
Miami Beach	Dade	5658	25.78	-80.13
Miami Intl Ap	Dade	5663	25.791	-80.316
Milton Experiment Stn	Santa Rosa	5793	30.779	-87.141
Mobile	Mobile	Mobile	30.683	-88.25
Monticello 3 W	Jefferson	5879	30.533	-83.917
Moore Haven Lock 1	Glades	5895	26.84	-81.087
Mountain Lake	Polk	5973	27.935	-81.593
Myakka River St Pk	Sarasota	6065	27.242	-82.316
Naples	Collier	6078	26.169	-81.716
Niceville	Okaloosa	6240	30.531	-86.492
Ocala	Marion	6414	29.08	-82.078
Okeechobee	Okeechobee	6485	27.197	-80.832
Orlando	Orange	Orlando	28.433	-81.333
Palatka	Putnam	6753	29.644	-81.661
Parrish	Manatee	6880	27.609	-82.348
Pensacola	Escambia	Pensacola	30.483	-87.183
Pensacola Regional Ap	Escambia	6997	30.478	-87.187
Perry	Taylor	7025	30.1	-83.567
Pompano Beach	Broward	7254	26.233	-80.141
Royal Palm Ranger Stn	Dade	7760	25.387	-80.594
Saint Leo	Pasco	7851	28.338	-82.26
Sanford	Seminole	7982	28.802	-81.269
St Petersburg	Pinellas	7886	27.763	-82.627
Steinhatchee 6 Ene	Dixie	8565	29.717	-83.3

Location	County	DB Table	Latitude	Longitude
Stuart 1 S	Martin	8620	27.189	-80.226
Tallahassee	Leon	Tallahassee	30.457	-84.281
Tallahassee Wso Ap	Leon	8758	30.393	-84.353
Tamiami Trail 40 Mi Ben	Dade	8780	25.761	-80.824
Tampa	Hillsborough	Tampa	27.959	-82.482
Tampa Wscmo Ap	Hillsborough	8788	27.961	-82.54
Tarpon Springs Swg Plnt	Pinellas	8824	28.15	-82.75
Tavernier	Monroe	8841	25.007	-80.521
Titusville	Brevard	8942	28.63	-80.833
Usher Tower	Levy	9120	29.408	-82.819
Venice	Sarasota	9176	27.101	-82.436
Vero Beach 4 W	Indian River	9219	27.686	-80.435
Wauchula	Hardee	9401	27.55	-81.8
West Palm Beach	Palm Beach	Westpalm	26.748	-80.126
West Palm Beach Int Ap	Palm Beach	9525	26.685	-80.099
Wewahitchka	Gulf	9566	30.117	-85.2
Winter Haven	Polk	9707	28.015	-81.733

REVISION OF AFSIRS CROP WATER SIMULATION MODEL

APPENDIX 12
CROP COEFFICIENT UPDATE
(Task 37)

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TABLES

Revision Of AFSIRS Crop Water Use Simulation Model
Appendix 12 - Crop Coefficient Update

BACKGROUND

A literature review was conducted to obtain updated crop coefficients (Kc) for those crops relevant to the St. Johns River Water Management District. The focus was on studies conducted since 2002 in the Southeastern United States. (including the US Geological Survey work being conducted in Florida) and national databases developed by the American Society of Civil Engineers (ASCE) Evapotranspiration Committee. The final recommendations from this review were used to update the Kc file for the GWRAPPS software.

The original Kc values used in the AFSIRS model were transferred directly to the GWRAPPS model. These values are documented in the AFSIRS model technical documentation completed in 1990. Since that time, additional studies have been conducted to develop new coefficients and to standardize existing coefficients.

In 2002, the ASCE Evapotranspiration in Irrigation and Hydrology committee (ET committee) proposed a Task Committee on the Transferability of Crop Coefficients (Kc committee). This committee has met annually since 2003. The Kc committee is collating peer reviewed journal articles that document experimentally determined crop Kc values and supporting methods and practices. Upon completion of this review, a peer reviewed document will be produced that provides recommendations for crop coefficients. Once this document is complete, it is recommended that the SJRWMD compare the ASCE crop coefficient values to their existing dataset and update coefficients as appropriate. While locally determined crop coefficients are preferred to support irrigation requirement estimation, in many cases this is may not be feasible or efficient. In these cases, the ASCE recommendations can provide a peer-reviewed set of coefficients to estimate irrigation water requirements.

METHODS

A crop coefficient is calculated as follows:

$$Kc = \frac{ET_0}{ET_c}$$

where Kc is the crop coefficient typically across time periods such as a month or crop growth stage, ETo is the reference evapotranspiration (depth units), and ETc is the crop evapotranspiration. The crop coefficient integrates a number of variables such as agronomic or horticultural practice (e.g. row spacing, plant density, etc.). Small differences in either ETo or ETc can impact Kc values significantly. Thus, understanding the methods used to determine ETo and ETc are critical to interpreting the documented Kc values.

The most up to date and a de facto "standardized" ETo methodology in the United States is the ASCE-Environmental and Water Resources Institute (EWRI) Standardized Evapotranspiration methodology (ASCE-EWRI, 2005). This method is quite similar to the international standard methodology documented in the United Nations Food and Agriculture Organization Irrigation and Drainage Paper No. 56 (FAO-56) (Allen et al., 1998). For the daily ETo calculations, the ASCE-EWRI method is identical to the method presented in FAO-56.

A challenge to conducting a literature review is that the methodology used to determine ETo is frequently not well documented. Without this documentation, it is not possible to reconstruct the calculations of ETo, nor to interpret the Kc values. Thus, it is recommended to use only Kc values from the peer reviewed literature that use the current standardized procedures or that contain sufficient information so that the reported Kc values can be adjusted to the standardized form.

The focus on Kc values determined for the Southeastern U.S. is motivated by difficulties in transferring Kc values from one climate to another (e.g. Midwest to the Southeast). One potential outcome from the Kc task committee is a standardized method to transfer Kc values across regions. Until such a method is available, it is recommended to update GWRAPPS Kc values only with values developed in the Southeastern U.S. or for a similar climate that can reasonably be adapted to Florida conditions.

SJRWMD CROPS

The literature search focused on crops important within SJRWMD. Table 1 lists the 9 crops which constitute a total of 88.2 % of the acreage under cultivation in the SJRWMD. Of these, no relevant information was available for cabbage. Because cabbage constitutes only 2.1% of the area under cultivation the current AFSIRS values should not be modified. The remaining 11.9% of unassigned acreage is divided among numerous crops, each representing a very small proportion of the total acreage.

Table 1 Crops grown in the SJRWMD region in 88.2% of the total cropped area

Crop	Acres	Percentage of Total
Citrus	113,978	37.4
Pasture	63,629	20.9
Sod	24,415	8.0
Potatoes	20,623	6.8
Sorghum	19,323	6.3
Field Corn	9,085	3.0
Nursery, Container	6,360	2.1
Cabbage	6,314	2.1
Nursery, Field	4,892	1.6

EXISTING GWRAPPS CROP COEFFICIENTS

As previously stated, the crop coefficient database in the GWRAPPS model was taken directly from the AFSIRS model. The AFSIRS crop coefficient values for crops listed in Table 1 appear in Table 2. Values for annual crops consist of a Kc value used during crop development and a peak Kc during crop growth. Values for perennial crops are monthly Jan – Dec.

Table 2 Crop coefficients used in the AFSIRS model.

Crop	Kc	
Annual	Crop Development	Crop Growth
Sorghum	0.50	1.00
Potato	0.70	1.05
Field Corn	0.55	1.05

Perennial	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Citrus	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sod	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pasture	0.65	0.70	0.75	0.90	0.90	0.95	0.95	0.95	0.90	0.80	0.70	0.65
Nursery	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

LITERATURE CROP COEFFICIENTS

Crop coefficient values identified by the scientific literature are summarized in Tables 3 through 8 for significant crops in SJRWMD identified in Table 1.

Citrus

Literature Kc values for citrus are shown in Table 3. The values used in the AFSIRS model, shown in Table 2, for citrus are from Rogers et al. (1983). The study shows that Kc values were near 1.0 for most of the year for the Penman potential ET equation. The other studies presented in Table 2 show lower Kc values from Spain (Castel et al., 1987), Arizona (Hoffman et al., 1980) and Florida (Morgan et al., 2006; Jia et al., 2007b). Higher values were obtained in California (Snyder and O'Connell, 2007).

Based on these consistent results, it is reasonable to recommend a reduction of the Kc values for citrus in GWRAPPS to those values as measured in Florida. The source of differences among Jia et al.'s two sites and Morgan et al.'s results may be a function of landscape position, crop type, location, and/or management type. A conservative recommendation is to modify the Kc based on Jia et al.'s finding for ridge citrus, but future update may support further reductions for the active growing season.

Sod

The AFSIRS model uses a sod crop Kc of 1.0 (Table 2). This value was selected due to the lack of Kc data available for sod and as a conservative level for agricultural production. Lower Kc values were reported by Brown et al. (2001) as shown in Table 4. However these values are for desert conditions dissimilar to Florida. The Tasks 7, 14, 18, and 25, Crop Coefficients for Sod, report will allow revision of the AFSIRS values to be used in GWRAPPS.

Pasture

Jia et al. (2007a) observed lower Kc values for pasture relative to the AFSIRS Kc values. Sumner and Jacobs (2005) also show slightly lower Kc values for pastures especially in the early and late part of the year. However, their site was not irrigated. Thus, lower values in the spring likely reflect the drier conditions. It is recommended to that Kc values for pasture should be adjusted but caution must be taken when using the Kc values developed by Jia et al. (2007a) since they were measured in North Florida. The seasonality of Kc values may differ in regions with longer growing seasons (i.e. for Central and South Florida).

Potato

The AFSIRS Kc values for potato (Table 2) show a similar trend in one of the studies reported (Table 6). The lower values in the initial stages increase to the AFSIRS value in later growth stage. End of season values are also comparable. Adjusting the potato Kc values in GWRAPPS is not recommended until site specific data become available.

Sorghum

The AFSIRS model uses a Kc of 0.5 for sorghum during crop development and 1.0 for the growing season (Table 2). The different studies in the literature show a slightly lower crop coefficient during the early growth stage and reaching values around 1.00 during later stages of growth (Table 7). End season values are in close agreement with the values used in the AFSIRS model. Accordingly, adjusting the potato Kc values in GWRAPPS is not recommended for sorghum, especially since this is typically a dryland crop.

Field corn (Maize)

The AFSIRS database for field corn specifies a Kc of 0.55 during crop development and 1.00 at full development. Literature values are slightly higher in the peak and slightly lower at the end of the season (Table 8). Thus, without Florida specific data (i.e. similar climate), adjusting these values is not recommended at this time.

Nursery plants

The Kc values for nursery container plants found in the literature show wide variations (Table 9). Values range from 0.3 to 4.3. This is mainly due to the differing methodology used to measure ETc and thus develop Kc values. Most of this variation is due to the different species of plants and container sizes used to grow them. Due to the wide variability in Kc values attributed primarily to study methodology, it is not recommended to adjust the Kc values for nursery production since that adjustment would surely lead to higher allocations. Development of Kc values for nursery production should be a high priority for SJRWMD in the immediate future.

SUMMARY

The crop Kc values in the literature were reviewed to update the values in the GWRAPPS model if appropriate. It is clear that much work has been done on Kc determination since the AFSIRS (i.e. GWRAPPS) database was developed; however, much of this work has been on crops not critical to water use in SJRWMD or developed in other climate regions, making transferability difficult. It is recommended to update selected Kc values in the GWRAPPS database with those developed as part of this work including those for citrus, pasture, and sod.

Table 3 Crop coefficients of Citrus

Study	Location	Kc												Method		Irrigation
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ETc	ETo	
Rogers et al.	Florida	0.90	0.85	0.77	0.72	0.95	1.11	1.02	1.00	1.08	1.00	0.96	1.05	Water Balance	Penman–Monteith	Pop-up sprinkler
Castel et al.	Spain	0.66	0.65	0.66	0.62	0.55	0.62	0.68	0.79	0.74	0.84	0.73	0.63	Water Balance	Penman–Monteith	Strip border
Hoffman et al.	Arizona	0.75	0.75	0.80	0.80	0.80	0.85	0.85	0.85	0.85	0.85	0.80	0.80	Water Balance	Modified Penman	Drip Irrigation
Snyder & O'Connell	California	1.9	1.61	1.37	1.22	1.1	1.03	0.96	1.02	1.02	1.07	1.70	1.79	Surface Renewal	Penman–Monteith	Micro-sprinkler
Morgan et al.	Florida	0.78	0.68	0.75	0.83	0.85	0.83	0.83	0.86	0.79	0.75	0.80	0.76	Water Balance	Penman–Monteith	Micro-sprinkler
Jia et al. (2007b)	Florida (flatwood citrus)	0.65	0.65	0.65	0.65	0.65	0.85	0.85	0.85	0.85	0.85	0.65	0.65	Eddy Flux	ASCE-EWRI	Micro-sprinkler
Jia et al. (2007b)	Florida (ridge citrus)	0.70	0.70	0.70	0.80	0.88	0.97	1.05	1.05	1.05	1.05	1.05	0.80	Eddy Flux	ASCE-EWRI	Micro-sprinkler
Boman	Florida	0.60	0.60	0.70	0.85	1.00	1.10	1.10	1.00	0.85	0.80	0.70	0.60	Lysimeter	Penman–Monteith	Micro-sprinkler

Table 4 Crop coefficients of Sod

Study	Location	Kc												Method		Irrigation
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Etc	Eto	
Brown et al.	Arizona	0.80	0.78	0.82	0.88	0.82	0.76	0.76	0.81	0.84		0.85	0.82	Lysimeter	Penman–Monteith	NI*

* Not indicated in study.

Table 5 Crop coefficients of Pasture

Study	Location	Kc												Method		Irrigation
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Etc	Eto	
Jia et al. (2007a)	Florida	0.35	0.37	0.57	0.83	0.90	0.77	0.72	0.70	0.68	0.65	0.62	0.46	Eddy Flux	ASCE-EWRI	Spray irrigation
Wight and Hanson	S Dakota	0.82												Lysimeter	JHET	NI*
	Wyoming	0.79												Lysimeter	JHET	No irrigation
	Idaho	0.85												Lysimeter	JHET	No irrigation
Irmak et al.	Florida	0.84												Atmometer	FAO56-PM	Spray irrigation
Sumner & Jacobs	Florida	0.46	0.51	0.59	0.61	0.54	0.85	0.92	0.91	0.81	0.72	0.62	0.50	Eddy Flux	FAO98-PM	NI

* Not indicated in study.

Table 6 Crop coefficients of Potato

Study	Approx. Planting/ Harvesting date	K_c				Location	Method		Irrigation
		Initial	Crop Development	Mid-season	End season		ETo	ETc	
Kashyap and Panda	Dec / March	0.42	0.85	1.27	0.57	India	Lysimeter	Various	NI*
Sahin et al.	May /Oct	0.60				Turkey	Penman–Monteith	Water Balance	NI

* Not indicated in study.

Table 7 Crop coefficients of Sorghum

Study	Approx. Planting/ Harvesting date	K_c				Location	Method		Irrigation
		Initial	Crop Development	Mid-season	End season		ETo	ETc	
Kato and Kamichika		10 (K_{cb})		0.98 (K_{cb})	0.53 (K_{cb})	Japan	S-W model	Bown ratio energy budget	NI*
Kuo et al.	March / June	0.44 (15)**	0.71 (28)	0.87 (42)	0.62 (21)	Taiwan	Penman–Monteith	Lysimeter	NI
Tyagi et al. (2000)	June / Oct	0.53 (20)	0.82 (35)	1.24 (40)	0.85 (30)	India	Penman–Monteith	Lysimeter	NI
Bashir et al.	July / Nov	0.62	0.85	1.15	0.48	Sudan	Penman–Monteith	SEBAL	NI

* Not indicated in study.
** Indicates number of days in each growth stage.

Table 8 Crop coefficients of Field Corn (Maize)

Study	Approx. Planting/ Harvesting date	K_c				Location	Method		Irrigation
		Initial	Crop Development	Mid-season	End season		ETo	Etc	
Kang et al	NI	1.04				China	Penman–Monteith	Lysimeter	NI*
Tyagi et al. (2003)	June/Sep	0.55 (24)**	1.00 (35)	1.23 (21)	0.64 (14)	India	Penman-Monteith	Lysimeter	NI

* Not indicated in study.
** Indicates number of days in each growth stage.

Table 9 Crop coefficients for Nursery Plants

Study	Species	K_c		Location	Method		Irrigation
		Summer	Fall		ETo	Etc	
Irmak	Ker-Gawl	0.93	0.95	Florida	Penman–Monteith	Water Balance	Drip irrigation
Niu et al.	Abelia	0.84		Texas	NI	Lysimeter	NI*
	Euonymus	1.20		Texas	NI	Lysimeter	NI
	Butterfly bush	4.37		Texas	NI	Lysimeter	NI
	Holly	1.78		Texas	NI	Lysimeter	NI
	Oleander	4.30		Texas	NI	Lysimeter	NI
Schuch and Burger	*Arctostaphylos*	2.5		Davis, CA	Penman–Monteith	Weight loss	NI
	Juniperous	2.4		Davis, CA	Penman–Monteith	Weight loss	NI
	Cercis	2.2		Davis, CA	Penman–Monteith	Weight loss	NI
	Pittosporum	2.3		Davis, CA	Penman–Monteith	Weight loss	NI
	Photinia	2.1		Davis, CA	Penman–Monteith	Weight loss	NI
	Heteromeles	1.9		Davis, CA	Penman–Monteith	Weight loss	NI
	Raphiolepis	1.7		Davis, CA	Penman–Monteith	Weight loss	NI
	Buxus	1.6		Davis, CA	Penman–Monteith	Weight loss	NI
	Ceanotuus	1.9		Davis, CA	Penman–Monteith	Weight loss	NI
	Cercocarpus	1.4		Davis, CA	Penman–Monteith	Weight loss	NI
	Rhammus	1.7		Davis, CA	Penman–Monteith	Weight loss	NI

Table 9 Crop coefficients for Nursery Plants (Continued)

Schuch and Burger	*Prunus*	1.2	Riverside, CA	Penman–Monteith	Weight loss	NI
	Raphiolepis	2.1	Riverside, CA	Penman–Monteith	Weight loss	NI
	Pittosporum	2.1	Riverside, CA	Penman–Monteith	Weight loss	NI
	Juniperous	1.7	Riverside, CA	Penman–Monteith	Weight loss	NI
	Photinia	1.8	Riverside, CA	Penman–Monteith	Weight loss	NI
	Arctostaphylos	1.5	Riverside, CA	Penman–Monteith	Weight loss	NI
	Heteromeles	1.5	Riverside, CA	Penman–Monteith	Weight loss	NI
	Buxus	1.2	Riverside, CA	Penman–Monteith	Weight loss	NI
	Ceanotuus	1.5	Riverside, CA	Penman–Monteith	Weight loss	NI
	Rhammus	1.4	Riverside, CA	Penman–Monteith	Weight loss	NI
	Cercis	1.2	Riverside, CA	Penman–Monteith	Weight loss	NI
	Prunus	1.1	Riverside, CA	Penman–Monteith	Weight loss	NI
	Cercocarpus	1.0	Riverside, CA	Penman–Monteith	Weight loss	NI
Beeson	Ligustrum	0.3	Florida	Penman–Monteith	Water Balance	Drip irrigation

* Not indicated in study.

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