IRRIGATOR PRO: PROGRESSION OF A PEANUT IRRIGATION SCHEDULING DECISION SUPPORT SYSTEM

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HIGHLIGHTS

- The logic used in developing a decision support system for irrigating peanut based on max/min soil temperature is described
- Logic to transform decision support system from peanut to irrigate corn and cotton with and without soil sensors.
- Progression of a decision support system from a desktop program to a web/mobile application

ABSTRACT. *Irrigator Pro is a decision support tool for scheduling irrigation events in peanut. It was deployed in 1995 as a rule-based system using crop history, yield potential, soil type, in-season irrigation/rainfall and maximum/minimum soil temperature. As computing platforms have progressed from desktop personal computers to mobile web-based platforms, Irrigator Pro has been updated and is now deployed as a web-based program and an application for mobile devices. Irrigator Pro not only works for peanuts but has been modified to irrigate both corn and cotton. The irrigation decisions are now based on in-field soil water potential measurements in addition to the traditional checkbook with max/min soil temperatures. Users are individual growers, extension agents, and agronomic consultants. The objective of this manuscript is to document the initial development of Irrigator Pro as an expert system combining data and experiential knowledge and the progression from a checkbook-based decision support system to a hybrid system using observed weather data and soil moisture measurement. The background knowledge, equations, and thresholds for triggering irrigation recommendations are included.*

Keywords. *Decision support system, Irrigation scheduling, Irrigator Pro, Mobile app, Peanut, Soil water potential.*

Since the discovery of peanut's many uses by Dr. George Washington Carver and the boll weevil's devastation of cotton in the 1920's, peanut has been an economically important crop in the southern United States from southeastern Virginia along the coastal plain through the Carolinas, Georgia, Florida, Alabama, Texas, Oklahoma, and New Mexico. When a change in the 2000 Farm Bill eliminated the peanut quota system, peanut production expanded into Mississippi and Arkansas (NASS, USDA, 2018). Production has also shifted into non-traditional areas within peanut producing states. For instance, some peanut production moved from the Wiregrass region of southeastern Alabama to southwestern Alabama as a result of the legislative change. The availability of water for irrigation has also played a significant role in the redistribution of peanut production over the years.

Of course, irrigating peanuts is not a new concept. The methods of scheduling irrigation have been quite variable over the years, many times relying on a grower's intuition and experience in producing a peanut crop. A recent survey indicated that growers in the South Atlantic-Gulf region of the United States use multiple criteria to determine when to irrigate their crops (NASS, USDA, 2019). Most growers in the region (86%) irrigated based on crop condition and approximately 34% based an irrigation decision on the feel of the soil. Approximately 2% of respondents stated that some of the time, they irrigated when the neighbors irrigated. These data imply that non-technical methods of triggering an irrigation event are the most prevalent and that there may be potential for improved water use efficiency.

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Methods promoted by irrigation professionals fall into one of three primary categories: seasonal water balance (checkbook), soil moisture measurements, or computer models and decision support systems (Harrison, 2012). One decision support tool for scheduling irrigation in peanut is Irrigator Pro, a tool developed by engineers at the USDA-ARS National Peanut Research Laboratory in Dawson, Georgia.

The objective of this article is to document the initial development of Irrigator Pro as an expert system combining data and experiential knowledge and the progression from a checkbook-based decision support system to a hybrid system using observed weather data and soil moisture measurement.

EXNUT: Development of an Expert System

The 10-year average peanut yield in the U.S. between 1975 and 1985, was 2840 kg ha^{-1}. In 1980, Georgia planted 208,008 ha of peanuts (NASS, USDA, 1981) with 109,800 ha (53%) being irrigated (Harrison, 2008). There were unofficial reports that some growers were experiencing substantially lower yields in their irrigated peanuts than in their non-irrigated or rainfed peanuts, especially in the wetter than average seasons. In these instances, field observations indicated that excessive water was applied and increased some of the fungal pathogens such as leafspot (*Cercospora*), white mold (*Sclerotium rolfsii*) (Backman et al., 1978), and possibly limb or pod rot (*Rhizoctonia solani*). Therefore, an effort to develop an expert system incorporating research, peanut physiology and phenology, production history, field data, and experience of "expert" growers to improve irrigation scheduling was undertaken by Mr. James I. Davidson, Jr., Mechanical Engineer at the USDA-ARS National Peanut Research Laboratory.

Boote et al. (1982) thoroughly discussed the state of the art of peanut irrigation summarizing research on root growth and water uptake, the timing of water deficit and its effect on vegetative and reproductive growth, yield response to water use, and irrigation strategies. Mantell and Goldin (1964) showed that as irrigation interval (days between irrigation) increased, the relative amount of water extracted from the surface (0-30 cm) decreased while the amount of water extracted from the lower depths increased (table 1). Allen et al. (1976) showed that during periods of drought stress, roots continued to grow downward to moist soil zones even though above-ground vegetative growth appeared to stop. This characteristic lead to greater rooting depth for water-stressed peanuts than in irrigated fields (Lin et al., 1963; Lenka and Misra, 1973; Narasimham et al., 1977).

Table 1. Effect of irrigation interval on water extraction from various soil layers by Virginia Bunch peanut in Israel during July-August, 1960.[a]

Soil Depth (cm)	Irrigation Interval 40 d	30 d	21 d	14 d	10 d
0-30	28[b]	32	34	37	48
30-60	21	25	29	28	23
60-90	20	20	18	17	15
90-120	16	13	11	10	9
120-150	15	10	8	8	5

[a] Adapted from Mantell and Goldin (1964).
[b] Expressed as a % of total water extracted from all depths.

Boote et al. (1982) also presented research from several sources that indicated excessive early season irrigation/rainfall led to increased vegetative growth with no corresponding increase in pod yield. They also presented research that indicated that moderate drought during the early vegetative growth and prior to fruiting (initial flowering) had no detrimental effect on peanut yield. Researchers showed that water partitioning to vegetative or reproductive growth was dependent upon the timing of water deficit relative to the fruit initiation and pod set. Water deficit during pod formation, 50-80 d after planting (DAP), reduced flowering, pod formation, and yield more than any other time in the crop phenology. Boote and Hammond (1981) showed that drought between 40 and 80 DAP delayed rapid fruit addition and pod maturation. Drought stress from 36 to 105 DAP of Florunner (Norden et al., 1969) reduced the percent sound mature kernels to 34% (Stansell and Pallus, 1979).

Boote et al. (1982) discussed the interaction of soil characteristics, water availability, and irrigation practices. They stated that the soil is a reservoir for water storage for use by the crop whose storage capacity is a function of the soil texture and structure. The ability of the plant to utilize the stored water is related to the ability of the roots to proliferate throughout the soil profile. A restrictive layer, or hard pan, may lead to a shallow system requiring smaller, more frequent irrigation events. Stansell et al. (1976) and Hammond et al. (1978) showed that soils with unrestricted root growth will have a water storage reservoir 100 to 200 cm deep.

In the early 1980's, methods for scheduling irrigation were basically the same as reported in the survey for NASS-USDA (2019) and included the checkbook based on potential evapotranspiration (ET_p) and water applied, sensors, observed crop condition, or some combination thereof. The checkbook or water balance models would have been based on pan evaporation or ET_p calculated from parameters observed at a weather station. The grower would have to multiply the ET_p by a crop coefficient based on the peanut growth stage or DAP. Functions for the crop coefficients were not readily available to growers. Similarly, agricultural weather station networks were not widely distributed throughout the peanut production regions nor were low-cost weather stations available for in-field installation.

Sensors used by growers to monitor soil water potential included tensiometers and electrical resistance blocks. Each field would have required tensiometers installed at multiple depths to monitor soil water potential to represent the water use over the rooting depth. Proper installation and maintenance are very time consuming for a grower with multiple fields requiring irrigation. Electrical resistance blocks consist of porous blocks, usually gypsum, with electrodes attached and wires extending above the soil surface. The electrical current transmitted through the porous block when an AC voltage was applied was proportional to water absorbed by the material and could be calibrated to the soil water potential. Electrical resistance blocks required installation like tensiometers. The resistance blocks were relatively insensitive to soil water potential between 0 and

-20 kPa. The electrical leads are subject to corrosion and mechanical or rodent damage. In addition to the installation and maintenance, both of these soil sensors required that the grower or irrigation manager physically visit each sensor to obtain a reading and then have the knowledge to interpret the data in conjunction with other field observations relative to crop health. Other technologies such as neutron probes were expensive and required specialized training. Time domain reflectometry was in its infancy and not yet fully developed for commercial use.

Research by Stansell et al. (1976) utilized rainout shelters to determine daily water use by three different peanut cultivars: Florigiant (Carver, 1961); Florunner, and Tifspan (Hammons, 1970). In a well-watered scenario, the peak water use ranged from approximately 0.45 cm day^{-1} for Florunner to 0.6 cm day^{-1} for Tifspan. The maximum water use for Tifspan occurred approximately 65 DAP, while the peak water use for Florunner peanut occurred 80 DAP, and the peak water use for the Florigiant variety occurred approximately 90 DAP. Tifspan is a Spanish type peanut which was more determinate in its reproductive cycle with a growing season of approximately 120 d. Florunner, a runner market type, and Florigiant, a Virginia market type, were more indeterminate than the Spanish type and had a growing season of approximately 140 d.

Blankenship et al. (1983) developed and utilized rainout shelters with heating cables buried approximately 10 cm below the soil surface to manipulate the soil temperature in the geocarposphere. The geocarposphere is defined as the top 5 cm below the soil surface where the peanut pods are formed and develop. Research was conducted in these environmental control plots to determine soil conditions under which peanuts became contaminated with aflatoxin (Cole et al., 1985). They found that in irrigated peanuts, 43% of the edible grade kernels were colonized by *Aspergillus flavus*. However, aflatoxin was below detectable limits. They stated the following conclusions regarding *A. flavus* and preharvest aflatoxin contamination: 1) Sound kernels from peanut plants grown under adequate moisture are not likely to become contaminated with aflatoxin; 2) the mean geocarposphere temperature during the latter 4-6 weeks of the growing season for peanuts grown with adequate moisture is independent of the ambient temperature; 3) the upper temperature limit for aflatoxin formation in the undamaged peanut kernels grown under drought stress is between 29.6°C and 31.3°C, while the lower limit is between 25.7°C and 26.3°C. As a result, prolonged drought stress with elevated geocarposhere temperatures must occur during the latter part, pod fill and maturation, of the peanut growing cycle in order to have aflatoxin contamination.

As a result of this research, Davidson et al. (1991) conceived the idea of using maximum and minimum geocarposphere (GCS) temperature as a tool to manage irrigated peanut production. Between 1981 and 1987, they conducted research to monitor maximum and minimum GCS temperatures measured at a depth of 5 cm in the crop row in irrigated and rainfed grower fields. Data were recorded for a total of 33 fields over this 7-yr period. Each season was broken down into five growth stages relative to the fruit initiation date (table 2). They developed regression equations correlating the degree-days that the maximum GCS temperature was below 26.7°C and the incidence of white mold, rhizoctonia, and pod rot. They also developed regression equations correlating the degree-days that the maximum GCS temperature was above 29.4°C to the incidence of crown rot.

In a similar fashion, Davidson utilized prior research describing peanut response to drought stress at various phases of growth and the water use curves developed by Stansell et al. (1976). From these reports, Davidson developed optimum and minimum cumulative water use curves to use as thresholds and targets for managing irrigation and rainfall input (fig. 1). Based on the research stating that a deeper root system is promoted by early season stress (Allen et al., 1976), EXNUT did not recommend irrigation during the first 30 DAP except to promote uniform emergence. The optimum cumulative water use curve assumes a daily water use of 1.78 mm day^{-1} (0.07 in. day^{-1}) from planting until the fruit initiation date. During canopy development, the daily water

Table 2. Definition of growth stages and thresholds for managing the geocarposphere temperature used in EXNUT, an expert system for irrigated peanut production adapted from Davidson et al. (1991).

Growth stage	Definition	Geocarposphere Temperature Threshold[a]
Emergence	Planting to crop emergence	20 C ≤ TGCS ≤ 35 C
Vegetative	Emergence to fruit initiation	20 C ≤ TGCS ≤ 31 C
Fruit initiation date	FID[b] = Date of first flush of blooms, i.e. > 10 blooms/plant $FID = Date_{obs} - \left[8 + \frac{(P-10)}{2}\right]$ $Date_{obs}$ = Date of field observation P = Average number of healthy underground fruit components/plant Fruit components = pegs, pins, pods	
Fruiting Stage 1	FID to FID + 20d	If canopy coverage < 90% 21 C ≤ TGCS ≤ 31 C If canopy coverage ≥ 90% 21 C ≤ TGCS ≤ 28 C
Fruiting Stage 2	FID + 21d to FID + 40d	
Fruiting Stage 3	FID + 41d to FID + 50d	22 C ≤ TGCS ≤ 29 C
Fruiting Stage 4	FID + 51d to harvest	21 C ≤ TGCS ≤ 29 C

[a] T_{GCS} = Soil temperature measured 5.1 cm (2 in) below the soil surface in the row under the peanut canopy where peanut pods are formed and grow
$T_{GCS,max}$ = Maximum T_{GCS} greater than 28 C to avoid wet weather pests (white mold, rhizoctonia, pod rot).

[b] FID = fruit initiation date.

use is 5.33 mm day^{-1} (0.21 in. day^{-1}) provided canopy coverage is less than 90%. After 90% canopy coverage, the daily water use is 7.37 mm day^{-1} (0.29 in. day^{-1}). Approximately, 50-55 d after fruit initiation, a 7-d drying out period is imposed where no irrigation is applied to terminate pod addition and entice the plant to partition its energy into maturing the existing fruit load. Following the drying out period, the daily water use is set at 3.56 mm day^{-1} (0.14 in. day^{-1}) for 14 d, then decreased to 2.79 mm day^{-1} (0.11 in. day^{-1}) for another 14 d, then decreased to 1.78 mm day^{-1} (0.07 in. day^{-1}) until harvest.

A computer program was built around these general rules using EXSYS®, an expert system development platform. Decision trees were developed that incorporated information such as soil type, adequate/inadequate irrigation capacity, yield potential being less than or greater than 5600 kg ha^{-1} (5000 lb $acre^{-1}$), and crop rotation, specifically the crop planted the previous year.

In 1991, EXNUT was released in Beta testing to several growers and county extension agents in southwest Georgia, North Carolina, and Texas. One of the features of the expert system platform, was that the rules for a decision would be displayed. This feature was very useful to the growers as an educational tool and helped users gain confidence in the irrigation decision. It was also useful when users disagreed with the recommendation and provided feedback to improve the decision process. Displaying the reasons for the irrigation decision made it difficult to conduct on-farm field tests when trying to compare irrigation schedules using EXNUT with grower's scheduling method. The displayed EXNUT decisions influenced the grower's decision to irrigate making the comparison with EXNUT invalid.

A 3-yr study (1994-1996) was conducted by (Davidson et al., 1998a) comparing the performance of EXNUT and MOISTNUT, a spreadsheet-based checkbook method (Tyson and Curtis, 1989, 1990) on a sandy and medium/heavy type soil. On average, irrigation increased net revenue \$490 ha^{-1} over non-irrigated production. Similarly, a version of EXNUT modified for production practices in North Carolina was evaluated on approximately 20-25 peanut fields each year from 1993-1997 (Davidson et al., 1998b). It was reported that fields irrigated using EXNUT increased yields about 500 kg ha^{-1} compared with farmers' historical yields. They also reported that growers who complied with the EXNUT recommendations at least 71% of the time achieved yields of 4480 kg ha^{-1}. They also estimated that every percentage point increase in compliance with EXNUT recommendations resulted in increased yields of 50 kg ha^{-1} in wet years and 110 kg ha^{-1} in dry years.

Irrigator Pro: Standalone Desktop Program

The expert system platform required users to purchase a runtime license in order to run the executable program. The expert system platform had a very limited library of subroutines for user interface development. After several years of on-farm testing of the prototype, the programming language was changed from the EXSYS® rule-based platform, to Visual C++ and a more graphical user interface. The program was released for desktop application in 1998 operating under the Microsoft Windows® operating system.

During the prototype testing, the number of users increased, and provided feedback for improving the program. Some growers were unable to follow the irrigation recommendations completely because of the water source supplying the irrigation system lacked the capacity. As result, Davidson developed a definition of an adequate irrigation capacity. An irrigation system was described as adequate if the system could supply 38 to 51 mm (1.5 to 2.0 in.) of water per week and 254, 203, and 152 mm (10, 8, and 6 in.) over 40 d with sandy, medium-heavy, and heavy soil categories, respectively. If the irrigation capacity was inadequate, then the recommendations irrigation strategy would target the minimum water curve instead of the optimum water curve (fig. 1).

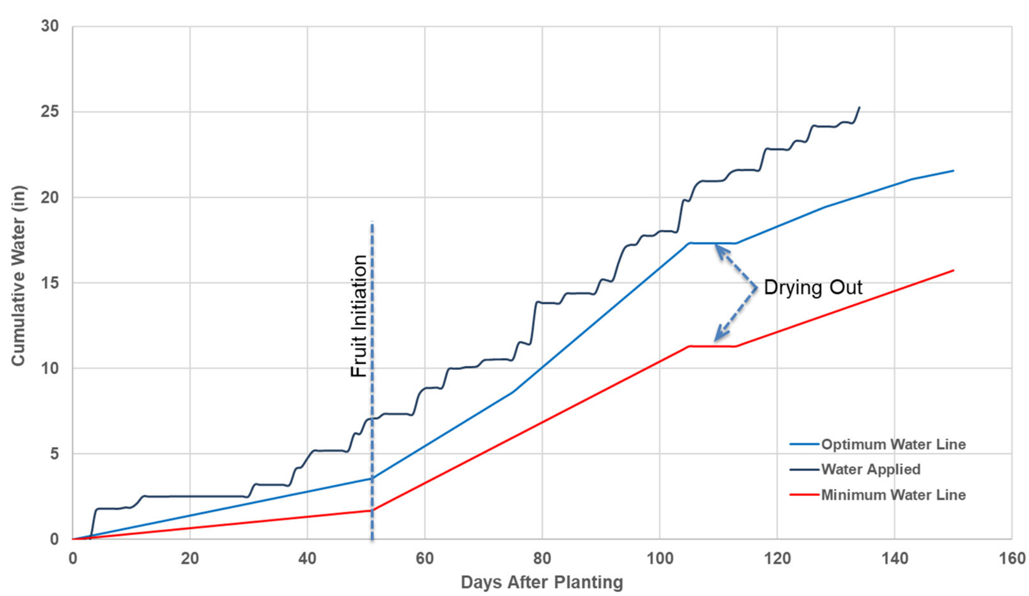

Figure 1. Minimum and optimum cumulative water use curves used in EXNUT.

Growers had also noted that their fields had varying yield potential due to soil type, soil fertility, weed, and disease pressure. Mr. Frank McGill, retired University of Georgia Peanut Extension Specialist, provided expertise related to the agronomic response of peanut to irrigation under various scenarios. Mr. McGill and Mr. Davidson developed slightly different irrigation strategies depending on whether the yield potential of the field was greater than or less than 5600 kg ha^{-1}. If the maximum historical yield in that field was greater than or equal to 5600 kg ha^{-1}, then the irrigation strategy would aggressively maintain the optimum cumulative water schedule.

Sometimes growers had difficulty determining whether their soil should be classified as sandy, medium/heavy, or heavy. However, most growers know the soil series and the relative proportions of soils in their fields. Mr. Jerry Pilkinton, USDA-NRCS Soil Scientist (retired), assisted in categorizing various soil series as sandy (I), medium/heavy (II), heavy (III), or not typically used for peanut production (IV) (table 3). The soil category was a generalization of the soil water holding capacity and forecasting when to scout the field again.

Peanut cultivars dictated the timing of inflection points in the cumulative water use curve, timing of the drying out period to terminate fruit addition, and maturation of the crop. The list of available cultivars included runner, Spanish, and Virginia market types (table 4). Mr. Davidson determined the inflection points of the many peanut cultivars used with assistance from geneticists developing and releasing these cultivars and field observations.

Growers also chose the previous crop planted in the field. The list of available prior crops included corn, cotton, grass, peanut, and soybean. These were primarily used when making recommendations regarding warnings of possible diseases. Peanut crops planted following a legume (peanut or soybean) were at higher risk for yield reductions due to diseases.

Growers had the choice of including recommendations for fungicide applications, primarily for leafspot control. The fungicide recommendations could follow a calendar schedule recommended by university extension specialists or the weather-based AU-Pnuts decision support system (Jacobi et al., 1995; Jacobi and Backman, 1995). AU-Pnuts is a rule-based system for applying fungicides to control leafspot using the number of rain events since the last spray and the 3-day average probability of precipitation (Jacobi et al., 1995). Figure 2 is an image of the primary screen used to input data and execute the program to receive an irrigation recommendation. Figure 3 is an image of the primary output screen. Table 5 is a typical log sheet used to record data for each field.

Table 3. Categorization of various soil series as Type I (Sandy), Type II (Medium/Heavy), Type III (Heavy), or Type IV (not well-suited for peanut production) for use in Irrigator Pro (version 1.0) by domain expert, Mr. Jerry Pilkinton retired USDA, NRCS Soil Scientist.

Soil Series Name	EXNUT Soil Category	Soil Series Name (cont'd)	EXNUT Soil Category (cont'd)
Ailey	I	Irvingon	II
Alaga	I	Izagora	II
Albany	I	Johns	II
Altavista	II	Johnston	I
Americus	I	Kalmia	II
Angie	IV	Kinston	II
Ardilla (Robertsdale)	II	Kenansville	I
Augusta	II	Kolomoki	II
Bibb	II	Lakeland	I
Bigbee	I	Leefield	II
Blanton	I	Leon	I
Bonifay	I	Lucy	I
Bonneau	I	Lynchburg	II
Cahaba	II	Marlboro	III
Carnegie	IV	Maxton	II
Chipley	I	Muckalee	IV
Chipola	I	Nankin	IV
Chisolm	I	Norfolk	II
Clarendon (Irvington)	II	Ocilla	I
Cowarts	II	Orangeburg	II
Craven	IV		
Doque	IV	Pelham	I
Dothan	II	Rains	II
Dulpin	IV	Red Bay	II
Esto	IV	Rutlege	I
Eulona	II	Riverview	II
Eulonia	IV	Shubuta	IV
Eustis	I	Stilson	II
Faceville	III	Suffolk	II
Foxworth	I	Sunsweet	IV
Freemanville	III	Tifton	II
Fuquay	I	Troup	I
Gilead	II	Varnia	III
Goldsboro	II	Vaucluse	II
Grady	IV	Wagram	I
Greenville	III	Wickham	II
Gritney	IV	Wicksburg	I
Hornsville	IV		
Henderson	IV	Other sandy soil	I
Herod	IV	Other med/heavy soil	II
Iuka	II	Other heavy soil	III

Practicality of Using and Maintaining Irrigator Pro

Each season the user must set up a new field and enter the initial data required including the soil type, irrigation capacity, yield potential, prior crop, cultivar, growing region, and planting date. The program saved each field as a separate file. As the season progressed, the user recorded the field data including rainfall, irrigation, and the maximum and minimum soil temperature. All these data were collected as part of the normal field scouting process. When recording and entering the rainfall data, the user would have to make a judgement on the effective amount of a rainfall event. For instance, if the rain gauge in the field indicated that a 25 mm rain event had occurred, the user would have to make an estimate of the portion of the rain that infiltrated into the soil. To make that determination, the user needed some knowledge of the time over which that rain occurred. If the rain event was less than 3 mm, then it was assumed that the event had little effect on the water status and was ignored.

The max/min recording thermometers generally weren't installed until about 30 DAP so that the selected installation site would be representative of the field. Max/min soil thermometers were installed in the peanut row so that the temperature at 5 cm deep under the canopy was monitored and recorded. If soil conditions varied considerably in the field, it was recommended that at least two thermometers be in-

Table 4. Peanut cultivars used in EXNUT.

Runner Peanut Varieties	Spanish Peanut Varieties	Virginia Peanut Varieties
Andru-93	Pronto	Florigiant
AgraTech 101	Spanco	Gregory
AgraTech 108	Starr	NC-2
AgraTech 120	Tamnut	NC-4
AgraTech 201	Tamspan	NC-6
AgraTech VC-1		NC-7
AgraTech VC-2		NC-8
Andru II		NC-9
ANorden		NC-10C
AP-3		NC-12C
C99-R		NC-15
Carver		NC-V11
DP-1		Perry
Flavor Runner-458		VA-81B
Florida MDR-98		VA-C 92R
Florunner		VA 93B
Georgia-01R		VA 98R
Georgia-02C		
Georgia Bold		
Georgia Browne		
Georgia Green		
Georgia Runner		
GK-3		
GK-7		
GK-7 Hi Oleic		
Hull		
Marc I		
Okrun		
Southern Runner		
Sun Runner		
Sunoleic 95R		
Sunoleic 97R		
Tamrun 88		
Tamrun 96		
Tamrun 98		
ViruGard		

stalled. It was also imperative that the maximum and minimum be reset within 24 h of a rainfall or irrigation event exceeding 3 mm.

When users had multiple fields, the file for each field was opened, data entered, run, and the recommendation printed. In the case of a crop consultant, this process could be very time consuming because of the number of fields scouted each day. The recommendation to irrigate or spray had to be relayed to the grower by phone, fax, or other medium on a timely basis.

From a software maintenance and operations standpoint, Irrigator Pro ran only on the Microsoft Windows operating system. It was not compatible with the Apple® platform. The Windows operating system has transitioned through many iterations requiring updates to the software libraries used to make the graphical user interface. When an update occurred, the availability of the update had to be communicated to all users and mailed on a CD-ROM. ARS software specialists were able to make the software available for download, but communicating its availability and the need for an update remained challenging. Maintaining backward compatibility for older operating systems was also a challenge, as many growers did not upgrade computers or operating systems on a routine basis.

Irrigator Pro: Web and Mobile Application

Davidson et al. (2002) presented data showing that Irrigator Pro could reduce water and pesticide use by 10-20% while increasing net returns over variable costs by 20-30%. As a result, of these and similar unpublished data, USDA-NRCS qualified the use of Irrigator Pro for reimbursement under the Environmental Quality Incentives Program (EQIP). In 2015, a partnership between the National Peanut Research Laboratory and the Flint River Soil and Water Conservation District was formed, and with funding from the USDA-NRCS, began the process of migrating Irrigator Pro from a desktop Windows based platform to a web-based

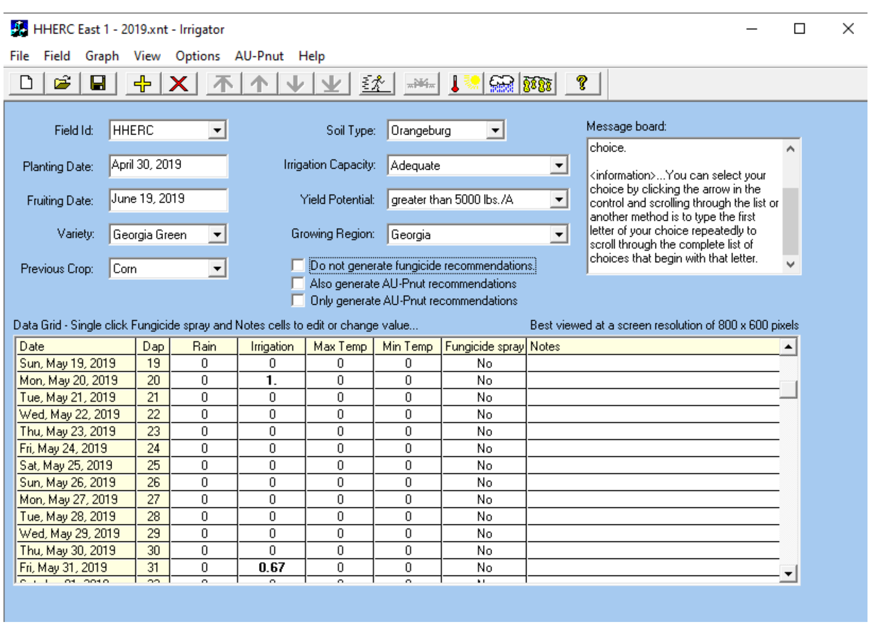

Figure 2. Image of the input and data screen for Irrigator Pro version 1.0.

```
--- Irrigator Pro: Release 3.0.0 ---

File name: C:\Data\Irrigator Pro\Desktop\Peanuts\HHERC East 1 - 2019.xnt
Field id: HHERC
Date: July 5, 2019

--- Irrigator Pro irrigation recommendations ---
DO NOT IRRIGATE

Irrigator Pro should be rerun in no more than 7 days. Reset thermometer(s) 24-48 hours after any rainfall and/or irrigation that exceeds
0.5 inches.

Excessive rainfall and/or irrigation could result in losses estimated at 24 lbs/A per day.

The probability that the decision is correct is 99 %.

Because of the delay in fruit initiation and to make sure Irrigator Pro recommends irrigation for at least 40 days after fruiting occurs, the
actual days after planting (dap) have been adjusted from 66 to 61.

Assuming no rainfall and a maximum temperature increase of 1 degree every two days, Irrigator will recommend an irrigation of 1.5
inches on Wed, Jul 17, 2019.

--- Irrigator Pro fungicide recommendations ---
Apply an approved fungicide for leafspot control.

Fungicide Advisory #1: The first and second fungicide sprays for leafspot control are very important. Banding is an option but make sure
to provide adequate plant coverage.

--- Irrigator Pro pest recommendations ---
Problems with high and low temperature pests should be minimal at this time.  These pests include leafspot, rust, white mold, pythium,
crown rot, foliage feeders, spider mites, lesser cornstalk borer, CBR, rhizoctonia, and Southern corn rootworm.


Field information:
    Planting Date     :      April 30, 2019
    Fruiting Date     :      June 19, 2019
    Yield potential   :      greater than 5000 lbs./A
    Irrigation capacity:     Adequate
    Soil type       : Orangeburg
    Variety         : Georgia Green
    Previous crop     :      Corn
    Growing Region    :      Georgia
    Canopy coverage   :      greater than 90%
    Days after planting:     66

Run Date Information:
    Max temp   :   84.0
    Min temp   :   78.0
    Water 03   :   1.24
    Water 05   :   1.25
    Water 07   :   2.79
    Water 10   :   3.88
    Water 14   :   4.07
    Water 21   :   5.56
    Water 28   :   7.11
    Total water:   11.27
```

Figure 3. Typical recommendation output generated by Irrigator Pro.

software tool. The primary reasons for this were that expertise for maintaining software at the National Peanut Research Laboratory was no longer available and the ability to provide software updates immediately without requiring the user to actively install the update. The web-based application would then be available to all internet users regardless of operating system and could be programmed for use on mobile devices.

The criteria for operation required that the software operate using rainfall, irrigation, and maximum and minimum geocarposphere temperature data for making irrigation recommendations. An additional requirement was that Irrigator Pro be able to utilize soil water potential data in the irrigation decisions, if available.

Other versions of Irrigator Pro had been developed for cotton and corn utilizing soil water potential measurements at 20, 41-cm for corn, and an additional measurement at 61-cm soil depth for cotton. In the cotton and corn versions, the volumetric water content (WC) of soil was estimated using observed soil water tension (kPa) at each depth (i) by:

$$WC_i = a_i + b_i ln\left(kPa_i\right) \tag{1}$$

A lower threshold of 40 kPa was set to trigger an irrigation event. Therefore, the minimum volumetric water content was calculated at 40 kPa:

$$WC\left(40\right)_i = a_i + b_i ln\left(40\right) \tag{2}$$

The available water (AWC_i) for each sensor depth was calculated by taking the difference between WC_i and $WC(40)_I$ then multiplying by the 61-cm (24-in) depth of soil. The average available water was determined by averaging the values of AWC_i:

$$AWC = \frac{\sum_{8,16,24}\left[\left(WC_i - WC\left(40\right)_i\right)*24\right]}{3} \tag{3}$$

The coefficients a and b (table 6) are general representations for the soil categories specified earlier in table 3 and they vary with depth. Each soil category has a maximum available water content AWC_{max} so that if the calculated AWC exceeds the maximum, the AWC is set equal to AWC_{max} (table 6).

A single program has been developed and deployed as a mobile application and a web-application that may be used for peanut, cotton, and corn. Users must register and set up

Table 5. Field information log sheet used to record daily field data from planting until harvest (1-160 days after planting). Information required at least every 7 days or as recommended by the expert system.

Farmer/Field ID: Scout:

Date	DAP	Rainfall/ Irrigation (in.)	Field Activity[a]	2" Soil Temperature (F) Minimum	Maximum	Canopy Cover (%)[b]	Fruit Check[c] No. Plants	No. Pins	No. Pegs	No.Pods	Pesticide/ Application Rate
	0										
	1										
	2										
	3										
	4										
	5										
	6										
	7										
	8										
	9										
	10										
	11										
	12										
	13										
	14										
	15										
	16										
	17										
	18										
	19										
	20										

[a] List any field activity and attach all scouting information.
[b] Divide width of canopy by row width (spacing) and multiply by 100 (ex. 24/36 × 100 = 66%).
[c] Use this information to calculate fruit initiation date (FID).

a user id and password to access their information. Users enter farm and field information such as location, soil category, crop, and planting date. The program will develop a crop phenology calendar based on default intervals between events for each critical phenological event for each crop. Field data is stored in a database table by farm and field name so that the field can be used in multiple seasons without having to re-enter the field characteristics. As an example, Field 1 on Farm A may have been defined when initializing the 2016 crop year when it was planted in peanut. In subsequent seasons, the field can be selected from a menu for the 2017 cotton crop, and then again for the 2020 peanut crop.

A user may grant access to data for individual fields to other registered users. This allows managers to have employees scout fields, enter data, and follow the recommendations, while maintaining oversight over all irrigation operations.

Table 6. Values of coefficients a and b in the general equation WC = a +b ln(kPa) used to estimate the volumetric water content of the soil and the maximum available water for the soil categories in Irrigator Pro.

Soil Category	Description	Depth (in.)	a	b	Maximum Available Water (in.)
I	Sandy	8	0.0638	-0.0173	1.75
		16	0.099	-0.0253	
		24	0.099	-0.0253	
II	Medium/ Heavy	8	0.0885	-0.021	2.00
		16	0.099	-0.0253	
		24	0.099	-0.0253	
III	Heavy	8	0.1179	-0.032	2.50
		16	0.099	-0.0253	
		24	0.099	-0.0253	

All data for each farm and field are stored in an SQL database and may be retrieved and downloaded by the user for review and analysis. The user may also download summary data to generate reports.

Irrigator Pro displays data for the current season and may be shown for a single farm or all farms associated with the user (fig. 4). The main screen summarizes the current status of the fields by displaying planting date, commodity, field size, current growth stage, irrigation recommendation, the AWC and the current daily water use (DWU). The user can obtain additional more detailed data by selecting "View."

Irrigator Pro is available on the web at IrrigatorPro.org and can be accessed and used on desktops, laptops, and mobile devices such as tablets and phones. An Irrigator Pro mobile app has been developed for both Android and Apple devices and are available for download at Google Play and the iStore. The mobile apps use the same database and logic for decisions as the web application.

AUTOMATED DATA RETRIEVAL

Vellidis et al. (2008) described a relatively low-cost wireless telemetry system where multiple soil sensors could be placed in a field and data remotely transmitted back to a central server. The sensor node consisted of three Watermark® soil moisture sensors stacked in a single probe with up to four thermocouples. This smart sensor array (UGA-SSA) has the capability of deploying a dense population of sensors in a field and then transmitting data to a server. The original intent of the UGA-SSA was to provide a network of sensor data within a field on which to base a map for variable rate irrigation. The UGA-SSA database is updated hourly.

When soil water potential data are available the AWC is calculated. If no soil water potential data are available, then

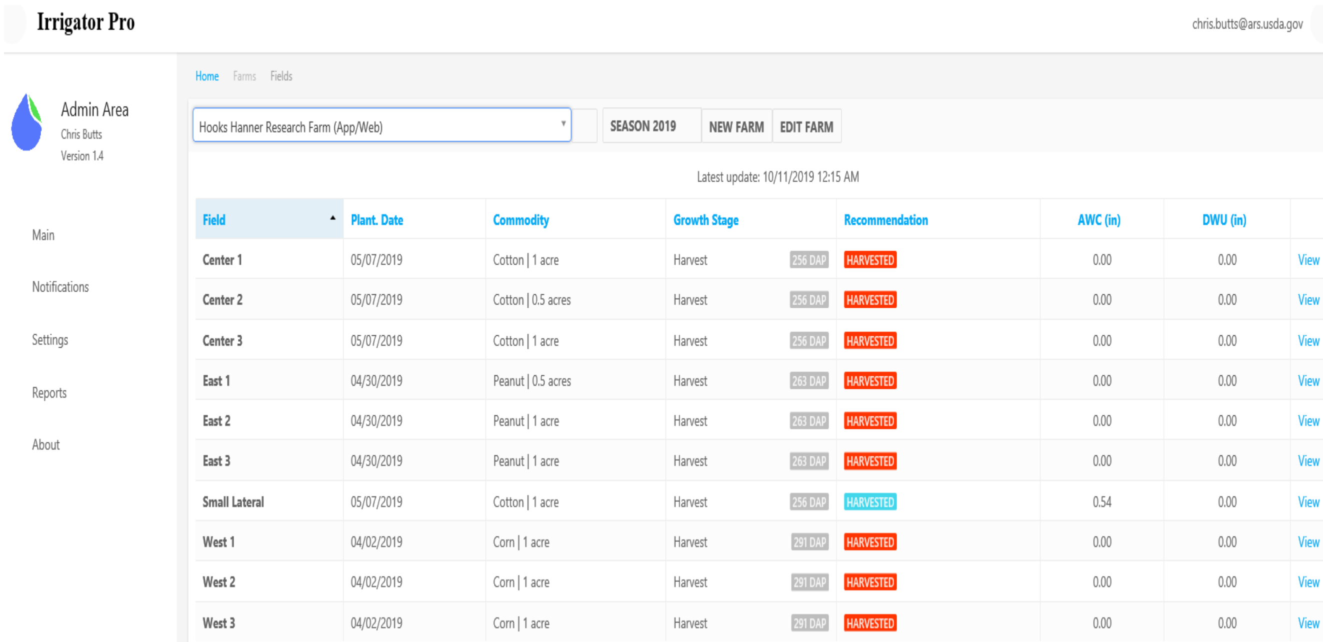

Figure 4. Typical main screen display for the web version of Irrigator Pro.

AWC is calculated by adding irrigation and rainfall and subtracting the estimated daily water use (DWU) from the AWC for the previous day. Irrigation is recommended when the AWC reaches zero, or in the case of peanut, the geocarposphere temperature is exceeded. This allows users who choose not to install soil water potential sensors to continue using the maximum/minimum soil thermometers and rainfall/irrigation records as they have done in the past. It also allows the user to continue using the decision support system if the soil water potential sensors fail during the season and are not replaced.

During the development of the web version of Irrigator Pro, coding was included to access the UGA-SSA database and retrieve soil water potential data from the field, thereby, reducing the need for on-site field visits to collect data. The Irrigator Pro server interrogates the UGA-SSA server on an hourly basis, updates fields with new soil water potential data, makes calculations, and displays an irrigation recommendation based on the most recent data. If no new data are available, Irrigator Pro reverts to the water balance calculations. The current server deployment of Irrigator Pro does not include recommendations for fungicide applications nor scouting alerts for various pests.

Since the UGA-SSA has limited distribution, an application programming interface (API) has been written to import data from commercial vendors, such as Trellis (mytrellis.com). When setting up the field in Irrigator Pro, the user selects the source of the water potential data; manual, UGA-SSA, or Trellis. If the source is not manual entry, then the user provides the account information for the UGA-SSA or Trellis account along with the unique sensor ID. When the sensor is active, Irrigator Pro will automatically begin updating data from the vendor source.

Irrigator Pro Usage

Usage data for the desktop version of Irrigator Pro for Peanut was very difficult to obtain. Program disks were provided to growers, directors of county young farmer organizations, and county extension agents with instructions to install the program on their computers. Users were encouraged to distribute the program to other farmers, so tracking the distribution and use was non-existent. Several hundred disks were distributed at county meetings and training sessions. Several known users were crop consultants who used Irrigator Pro as part of their advisory services. There is no estimate of the crop area on which it was used. Users were in Georgia, Florida, Alabama, North Carolina, South Carolina, and Texas.

The cloud-based version of Irrigator Pro was publicly released in the spring of 2018 and stores grower, farm, field, and crop information in a database that can be accessed by software administrators for analysis. Between April 2018 and November 2019, there were more than 600 downloads of the Irrigator Pro mobile app. At the end of November 2019, there were 570 registered users. During the 2018 crop season, Irrigator Pro was used on 237 fields representing approximately 4,600 ha. During the 2019 crop season, there were 445 fields registered on approximately 12,500 ha (table 7).

Irrigator Pro was accessed by users more than 13,000 times during the 2019 crop season. Irrigator Pro was used primarily for peanut, cotton, and corn. However, some users listed other crops such as vegetables, blueberries, blackberries and hemp. Locations represented outside the United States included Brazil, Argentina, Venezuela, Guatemala, Malawi, South Africa, and Vietnam.

Table 7. Locations, number of fields, and crop area registered for Irrigator Pro during crop year 2019.

Field Location	Fields Number	Fields %	Crop Area Hectares	Crop Area %
Alabama	6	1.3	196	1.6
California	1	0.2	10	0.1
Colorado	1	0.2	10	0.1
Florida	5	1.1	171	1.4
Georgia	381	85.6	10120	80.9
Indiana	1	0.2	6	>0.1
Kansas	1	0.2	53	0.4
Kentucky	2	0.4	202	1.6
Louisiana	1	0.2	16	0.1
Maryland	2	0.4	20	0.2
Missouri	1	0.2	15	0.1
Nebraska	1	0.2	32	0.3
North Carolina	18	4.0	901	7.2
South Carolina	6	1.3	291	2.3
Texas	8	1.8	134	1.1
Wisconsin	1	0.2	24	0.2
Outside United States	8	2.0	302	2.4
Total	445		12,505	

Future Plans

During the adaptation of Irrigator Pro for Peanuts from the desktop to the web, some of the robustness of the original software was lost. For instance, in the desktop version, users were able to select the soil series and the software assigned the soil category. The data in table 3 has been incorporated as a data table in the 2020 update of Irrigator Pro, reinstating the user's ability to choose their soils by soil series. Many of the peanut cultivars listed in table 4 have been replaced by new higher performing cultivars. This will require new cultivar tables to be developed along with their phenology on timing of changes in water requirements per growth stage, particularly the onset of the "drying out" period to terminate the new fruit addition.

Other commodities such as cotton have very well-defined and accurate heat unit or growing degree-day models to predict crop phenology. Peanut has been difficult because of its indeterminate fruiting pattern. Rowland et al. (2006) had some success in using growing degree-days to estimate peanut maturity. They indicated that heat units may be useful in predicting intermediate events such fruit initiation date and possible delays in plant phenology when plants are water stressed.

As additional vendors allow access, API's will be written to import grower's data from those vendors. There are plans to develop algorithms for interpreting and using data from capacitance probes that provide estimates of volumetric soil water content.

Summary

Irrigator Pro was initially developed as an expert system for management decisions related to irrigated peanut production. It began as a heuristic knowledge base that maintained the cumulative amount of water applied to peanuts between the minimum and optimum curves. Irrigation events were recommended when the maximum soil temperature measured at 5 cm below the soil surface in the crop row exceeded thresholds determined by the observed crop growth stage. It progressed from the heuristic expert system, to a custom desk top application program operating only in the Windows operating environment. Versions of Irrigator Pro were developed for cotton and corn that used generalized equations relating soil water potential to available water. Due to difficulty in maintaining, distributing, and supporting the software as a three separate programs, a single cloud-based mobile and web App was developed providing irrigation decision support for peanut, cotton, and corn. The Irrigator Pro Mobile App is available for Apple and Android devices in their prospective App stores. The web-based version accesses the same user information and field database and can be accessed at IrrigatorPro.org.

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