An Irrigation Scheduling Model for Turnip Greens

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Abstract. An irrigation scheduling model for turnip (*Brassica rapa* L.) was validated using a line-source irrigation system in a 2-year field trial. The model used a water balance, a variable root length, and a crop factor function of plant age (i). Evapotranspiration was computed daily as class A pan evaporation times a crop factor [$CF(i) = 0.365 + 0.0154i - 0.00011i^2$]. Irrigation according to the model maintained soil water tension at <25 kPa at a 30-cm depth. When rainfall amounts were less than water use, leaf yields responded quadratically to irrigation rates, from 0% to 160% of the model rate, and the highest leaf yield with the lowest water applications corresponded to the model rate. Therefore, this model could replace the "feel or see" methods commonly used for scheduling irrigation of leafy vegetables grown in the southeastern United States.

Turnip has a high nutritional value (Salunkhe et al., 1973) and is widely grown under irrigation and high N fertilization in the southeastern United States as a fresh-market and processing-greens crop. The most widely used methods for scheduling irrigation of leafy greens are the "feel" or "see" methods, which consist of applying 19 mm of water when the soil looks dry or when plants wilt. Because water applications are not adjusted to weather condition or crop age, excessive water may leach essential nutrients, or water stress may reduce yields.

Information on the water requirements of leafy vegetables is limited, and few irrigation scheduling methods for greens crops are available. Water use by red cabbages (*Brassica oleracea* L.) (Nieuwhof, 1969) or water applications of 7.5 mm every 10 days to spinach (*Spinacia oleracea* L.) (Breimer, 1983) cannot be used for scheduling irrigation without adjustments for weather conditions. McSay and Moore (1980) developed regression equations based on cumulative evaporation from Bellani plates to predict soil water tension (SWT) and schedule irrigation of lettuce (*Lactuca sativa* L.). Although water applications could be reduced by 66% without affecting yields, this method was not practical, and rainfall amounts less than cumulative water deficit were neglected. Irrigating turnip to field capacity when plants wilted produced 41% higher leaf yields than nonirrigated turnip (del Valle et al., 1965). Mustard (*Brassica juncea* L.) and turnip produced higher leaf yields if irrigated at 25 kPa rather than at 50 or 75 kPa SWT (Smittle et al., 1992b). Water use rates increased quadratically with crop age and were higher with irrigation at 25 kPa than at 50 or 75 kPa SWT.

Class A pan evaporation (E_p) can estimate evapotranspiration (ET) if a crop factor ($CF = ET/E_p$) is used to adjust E_p (Jensen and Middleton, 1970). Irrigation scheduling methods using the water balance technique (Stansell and Smittle, 1980; Stegeman et al., 1980), in which ET was estimated from E_p , and CF was a function of plant age (i), were developed for snap bean (*Phaseolus vulgaris* L.) (Smittle et al., 1990) and summer squash (*Cucurbita pepo* L.) (Smittle et al., 1992a). Smittle et al. (1992b) developed a $CF(i)$ that estimated ET by turnip grown in the spring.

Although turnip leaf yields were responsive to N fertilization

(del Valle et al., 1965; McFerran et al., 1963), N source effects on leaf yields were variable. Leaf yields with $NaNO_3$ and NH_4NO_3 were similar, but both of these N sources produced higher yields than $(NH_4)_2SO_4$ (del Valle and Harmon, 1970). Other studies (Bowers and Vose, 1959; Bowers et al., 1962) reported higher leaf yields with $NaNO_3$ than with NH_4NO_3 . Brantley (1960) found that NH_4NO_3 , $NaNO_3$, and $(NH_4)_2SO_4$ were equally effective in influencing the leaf yields of fall-grown turnip. Although sodium dispersed clays and altered soil structure (Tan, 1982), $NaNO_3$ is the N source recommended for turnip (Adams, 1991).

This paper presents the field validation of an irrigation scheduling model for turnip grown in the spring. Because N form influenced the yields of most vegetables (Barker and Mills, 1980), and because the N source that maximizes turnip leaf yield has not been determined, the model was validated using the most commonly used N fertilizers.

Materials and methods

Model development. The irrigation scheduling model used the water balance method (Stegeman et al., 1980) which consisted of computing daily use (d_i , mm) as:

$$d_i = ET_i - R_i - I_i \quad [Eq. 1]$$

where ET was evapotranspiration (mm), R was rainfall (mm), and I was irrigation (mm); cumulative soil water deficit on day i (D_i , mm) as:

$$D_i = D_{i-1} + d_i \quad [Eq. 2]$$

where D_{i-1} was the cumulative soil water deficit on day i-1; and the daily water balance as:

$$A_i = D_{i-1} + (ET_i - R_i - I_i) \quad [Eq. 3]$$

where A_i was the allowable water use (mm).

The proposed model for spring-grown turnips was:

$$12.7 \times (i - 3) \times 0.5 \text{ ASW} = D_{i-1} + (ET_i - R_i - I_i) \quad [Eq. 4]$$

where i was days from planting, and ASW was the available soil

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Abbreviations: A_i , allowable water use; ASW, available soil water; CF, crop factor; d_i , daily water use; D_i , cumulative soil water deficit; DAP, days after planting; E_p , class A pan evaporation; ET, evapotranspiration; i, plant age; I, irrigation; R, rainfall; SWT, soil water tension.

water (mm water/mm soil).

A_i was computed as $12.7 \times (i - 3) \times 0.5$ ASW and depended on effective rooting depth, soil water retention characteristics, crop sensitivity to water stress, and plant age. The model assumed a 6.7-mm seeding depth, 3 days for radicle emergence, and a $12.7\text{-mm}\cdot\text{day}^{-1}$ root elongation (Hansen et al., 1980). A maximum rooting depth of 300 mm was used because hard pans or low soil pH restrict root depth of most vegetable crops in the southeastern United States. The maximum rooting depth may be greater in areas where soil conditions are not restrictive. The ASW for a Tifton loamy sand soil (plinthitic Paleudult of a fine loamy, siliceous, thermic family) was 0.1 mm of water/mm of soil depth. A 50% depletion of ASW was allowed.

ET was computed as class A pan evaporation (E_p , mm) $\times$ CF(i), where $CF(i) = 0.365 + 0.0154i - 0.0001 i^2$ (Smittle et al., 1992b).

Replacing 12.7×0.5 by 6.35 in the calculation of A_i would be numerically correct; however, it is easier to adapt the model to different growing conditions when each term appears individually. Also, solving Eqs. 3 or 4 for the unknown I would result in negative irrigations on the dates no irrigation was scheduled.

For record keeping, a tabular format (Smittle and Dickens, 1992) with column headings of age, rooting depth, date, pan evaporation, crop factor, daily water use, cumulative water use, allowable water use, rainfall, and irrigation was used to compute soil water status (Table 1). Rooting depth, crop factor, allowable water use, and cumulative water use were computed by days after planting (DAP). To operate the model, the date and daily pan evaporation were entered. Daily water use and cumulative water use were computed (Eq. 1 and 2), and the decision whether to irrigate was made daily.

When cumulative water use (D_i) approximated the allowable water use (A_i), an irrigation amount (I) equal to the cumulative water use was applied. The cumulative water use became 0 following irrigation or when rainfall was equal to or greater than the value for allowable water use. Only water amounts equal to or less than cumulated water deficit could be stored in the soil. Rain amounts in excess of soil water deficit at the time of the rain were considered lost, and upward water movements from the water table were considered negligible.

Model validation. Model validation consisted of scheduling irrigation according to the model and applying increasing water

amounts across the field (Smittle et al.; 1990; 1992a). The model was acceptable if SWT remained ≤ 25 kPa, and leaf yields were highest in areas receiving the water amounts predicted by the model.

Rye (*Secale cereale* L.) cover crop was incorporated 15 cm deep with a disc harrow before moldboard plowing to 30-cm depth in 1990 and 1991. We incorporated 1121 kg preplant fertilizer/ha (5N-4.4P-12.4K) 15 cm deep with a rotary tiller. 'Shogoin' turnip was direct-seeded in four rows spaced 30.5 cm apart on 1.5-m-wide beds on 5 Mar. 1990 and 11 Mar. 1991. Each planter sowed twin rows 38 mm apart with seeds 20 mm apart. Plant population was ≈ 1 million plants/ha. Ammoniated polyphosphate fertilizer (10N-15P) was banded at $204\text{ kg}\cdot\text{ha}^{-1}$, and dimethyl-tetrachloroterephthalate herbicide (Dacthal) was broadcast at $9\text{ kg}\cdot\text{ha}^{-1}$ after seeding. An irrigation of 19 mm on 9 Mar. 1990 and 13 mm on 12 Mar. 1991 over the entire field incorporated herbicide and fertilizers and ensured uniform germination. Pest control measures were those recommended for turnip production in Georgia (Brown, 1989).

The model was tested with several rates of N applied as a sidedressing. In 1990, 50, 62, and 73 kg N/ha, corresponding respectively to 80%, 100%, and 120% of the median recommended range for Georgia (Plank, 1989), were applied as NaNO_3 (16% N). In 1991, 62 kg N/ha was applied as NaNO_3 (16% N), NH_4NO_3 (34% N), or $\text{Ca}(\text{NO}_3)_2$ (15.5% N). Sidedressed fertilizers were applied 3 weeks after seeding and again after harvesting the first crops.

A line-source irrigation system (Hanks et al., 1976) consisting of a single line of sprinklers spaced 6.1 m apart provided uniform water distribution parallel to the irrigation line and a water gradient perpendicular to the irrigation line. Preliminary tests showed that in the absence of wind, the gradient was uniform. The irrigation line was placed on a central guard bed and depths of water application to each bed on both sides of the irrigation line were measured at each irrigation. The line source created seven irrigation rates, decreasing from rate 1 to 7. The amounts and dates of application of irrigation rate 3 were determined by the irrigation scheduling model (model rate). Rates 2 and 1 represented progressively greater water applications, and rates 4, 5, 6, and 7 represented progressively smaller ones than the model rate. The water regime of irrigation rate 7 corresponded to a nonirrigated crop.

Table 1. Irrigation scheduling model for turnip²: $12.7 \times (i - 3) \times 0.5$ ASW = $D_{i-1} + [E_p(0.365 + 0.0154i - 0.0001i^2) - R - I]_i$ ³

Age (DAP) ^a	Rooting depth (mm)	Date (1990)	Class A pan evaporation (mm)	Crop factor	Daily use (mm)	Rain (mm)	Cumulative water use (mm)	Allowable water use (mm)	Irrigation (mm)
21	216	26 Mar.	4.6	0.64	3.0		3.0	10.9	
22	229	27 Mar.	6.4	0.65	4.2		7.2	11.4	
23	241	28 Mar.	4.8	0.66	3.2		10.4	12.2	
24	254	29 Mar.	2.5	0.67	1.7		12.0	12.7	12.0
25	267	30 Mar.	3.6	0.68	2.5	1.0	1.5	13.5	
26	279	31 Mar.	6.9	0.69	4.7	22.8	0.0	14.0	
27	292	1 Apr.	3.1	0.70	2.2	1.0	1.2	14.7	
28	305	2 Apr.	4.1	0.71	2.9	0.3	2.8	15.3	
29	305	3 Apr.	3.6	0.72	2.6	0.7	4.7	15.3	

²Turnip grown in the spring as a greens crop on a Tifton loamy sand soil.

³ASW is available soil water (0.1 mm water per mm soil), D_{i-1} is cumulative soil water deficit (mm), E_p is class A pan evaporation (mm), R is rainfall (mm), and I is irrigation (mm). To operate the model, values for rooting depth [$12.7 \times (i - 3)$], crop factor ($0.365 + 0.0154i - 0.0001 i^2$), and allowable water use (rooting depth $\times$ 0.5 ASW) are calculated as a function of plant age (i). Date and E_p are recorded. E_p is multiplied by the crop factor to estimate daily water use (d_i), and d_i is added to D_{i-1} . R is subtracted from D_i . Irrigation, in the amount of cumulative water use, is applied when cumulative water use approximates allowable water use.

^aDAP is days after planting.

Table 2. Irrigation rates, water applications, irrigation gradient, and total rainfall of four crops of 'Shogoin' turnip during Spring 1990 (crops 1 and 2) and 1991 (crops 3 and 4).

Irrigation rate ^z	Crop				Crop			
	1	2	3	4	1	2	3	4
	<i>Water applied (mm)</i>				<i>Water gradient (% Model)^y</i>			
1	982	1483	512	316	166	163	147	136
2	779	1179	469	289	131	130	132	125
3	591	910	348	232	100	100	100	100
4	460	708	279	191	79	78	80	82
5	368	538	211	151	62	59	61	65
6	206	347	105	100	35	38	30	43
7	6	12	0	0	1	1	0	0
Rainfall (mm)	88	10	107	133				

^zAll plots received an additional irrigation of 19 mm in 1990 and 12.7 mm in 1991 after seeding. Irrigation rate 3 was determined by the irrigation scheduling model. The irrigation gradient was created by a line-source irrigation system.

^yIrrigation gradient calculated as percent of the model rate.

Gypsum resistance blocks were installed at 15cm and 30-cm depths in the center of inside rows after seedling emergence for SWT measurements. SWT was determined before each irrigation with an ammeter (KS-2; Delmhorst Instruments Co., Boonton, N.J.). Class A pan evaporation and rainfall were recorded at a #2 U.S. National Weather Service station 300 m from the field.

Turnip leaf yields were recorded by harvesting the leaves from 1.5 m² in the center of each subplot. The leaves were cut 4 to 5 cm above the soil twice each season as done in commercial production. In 1990, the first harvest (crop 1) occurred 36 DAP, and the second harvest (crop 2) 56 DAP. In 1991, the first harvest (crop 3) was made 37 DAP, and the second harvest (crop 4) 63 DAP.

Treatments were arranged in a split-plot design with two replications on each side of the irrigation line. Main plots (15 × 10.5 m) were N rates in 1990 and N sources in 1991. Subplots (1.5 × 15 m) were irrigation rates. Analysis of variance determined significance of main effects and interactions. Regression analysis by N fertilization determined mean yield response to irrigation (SAS, 1987).

Results and Discussion

Responses of the two crops in 1990 and the two crops in 1991 are discussed as four separate crops, because all the foliage above 5-cm height was removed at harvest, irrigation scheduling was based on plant age, and weather conditions were different. In addition, the year effect was not significant ($P = 0.10$) for SWT but was significant ($P < 0.01$) for leaf yield, while the crop effect was significant ($P < 0.01$) for SWT and leaf yield.

Rainfall during the four crops differed by amount and distribution. Total rainfall was 88 mm during the 36-days growth of turnip for crop 1, 10 mm during the 20-days regrowth for crop 2, 107 mm during the 37-day growth for crop 3, and 133 mm during the 26-day regrowth for crop 4. The 4, 2, 6, and 5 rainfalls during crops 1, 2, 3, and 4, respectively, and exceeded the respective cumulative soil water deficit by 67, 0, 65, and 80 mm. Excessive rainfall results in lateral movement, runoff, or deep percolation of the water in excess of field-capacity. Lateral water movement in the profile reduces the accuracy of water balance models in small plots, but is of little practical concern, because irrigation is not applied when rainfall meets crop needs and because irrigation amounts do not exceed soil water deficits. However, deep percolation from excessive rainfall can leach mobile nutrients in small or large fields.

In 1990, total irrigation for plots receiving the model rate was 591 mm applied on six dates for crop 1, and 910 mm applied on five

dates for crop 2. In 1991, total irrigation was 348 mm applied on five dates for crop 3 and, 232 mm applied on two dates for crop 4. The irrigation gradient created by the line source ranged from 0% to 166% of the model rate (Table 2).

The SWT differences at 15-cm and 30-cm depths before irrigation were not significant ($P = 0.90$); thus, data for both depths were pooled. This suggested that the model allowed the control of soil water status in the top 30 cm of soil.

The SWT of plots receiving irrigation rate 3 was >25 kPa only on 53 DAP in 1990 and on 24 and 34 DAP in 1991. In 1990, the cumulative deficit on 52 DAP was 12.7 mm. Because the allowable use was 15.3 mm, irrigation was delayed until the next day. Water

Fig. 1. Rainfalls (solid bars) and irrigations (open bars) during turnip grown in Spring 1990 and 1991. Positive and negative amounts of water represent water amounts considered as stored or lost, respectively. Rainfall amounts exceeding soil water deficit at the time of the occurrence are considered lost by runoff or deep percolation. E is emergence, and H represent harvests.

use of 6.6 mm on 53 DAP resulted in a cumulative deficit of 19.3 mm, which exceeded the 15.5-mm allowable water deficit and produced a SWT of 35 kPa. In 1991, winds on 23 and 24 DAP delayed the irrigation scheduled for 23 DAP. At irrigation, the 21.4-mm cumulative deficit exceeded the 13.5-mm allowed use and SWT reached 46 kPa. Similarly, wind delayed irrigation from 34 to 35 DAP in 1991. Cumulative water use (19.2 mm) exceeded allowable water use (15.3 mm) by 3.9 mm, and the SWT in the top 30-cm soil profile averaged 59 kPa. These data suggest that cumulative water deficit should not exceed allowable water use by more than 3 mm when allowable water use reaches its maximum. The data also show that the model is accurate, since SWT were <23 kPa at irrigation, and a 1-day delay resulted in SWT >25 kPa. Irrigation rates 4, 5, 6, and 7 resulted in SWT >25 kPa, whereas irrigation rates 1 and 2 resulted in slightly lower SWT. Therefore, the model effectively scheduled irrigation for turnip to meet maximum yield conditions established by Smittle et al. (1992b).

Leaf yield responses to irrigation varied among the four crops and were related to rainfall (Table 2). Although six irrigations were

Table 3. Leaf yields and soil water tension^z preceding irrigations of 'Shogoin' turnip in Spring 1990 and 1991.

		Irrigation rates ^y						
DAP ^x	Crop ^x	7	6	5	4	3	2	1
1990								
Soil water tension (kPa)								
7	1	20	15	15	20	23	18	19
9	1	22	17	18	22	23	18	24
11	1	17	13	13	19	19	14	16
20	1	34	22	17	20	20	18	21
31	1	28	23	25	23	24	23	23
Leaf yield (t·ha ⁻¹)								
36	L(*) ^w	9.8	10.3	10.0	9.9	11.1	10.6	11.1
Soil water tension (kPa)								
39	2	140	53	49	25	19	19	19
42	2	210	118	104	19	17	15	16
45	2	210	210	100	22	9	19	13
49	2	210	210	134	49	19	17	20
53	2	210	210	178	119	35	30	19
Leaf yield (t·ha ⁻¹)								
56	Q(**) ^w	3.3	10.0	12.5	14.2	14.3	13.8	14.3
1991								
Soil water tension (kPa)								
10	1	18	20	21	21	20	21	21
13	1	19	22	26	26	25	26	25
15	1	14	14	18	19	18	18	15
25	1	21	35	68	48	46	46	39
35	1	185	190	140	57	59	23	49
Leaf yield (t·ha ⁻¹)								
37	Q(**) ^w	8.4	10.3	11.3	11.0	11.7	10.8	10.9
Soil water tension (kPa)								
42	2	48	24	18	18	16	20	18
50	2	17	35	24	20	16	16	16
Leaf yield (t·ha ⁻¹)								
63	Q(**) ^w	6.2	7.4	7.8	7.7	7.9	6.9	6.6

^zAverages of soil water tensions at 15 and 30 cm.

^yIrrigation rate 3 was determined by the irrigation scheduling model. Rates 2 and 1 represent progressively greater water applications, and rates 4, 5, 6, and 7 represent progressively lower water applications by a line-source system (see Table 2 for exact rate for each crop).

^xDays after planting. Planting dates were 5 Mar. 1990 and 11 Mar. 1991.

^wYield responses to irrigation Linear (L), or Quadratic (Q) at $P < 0.1$ (*) or $P < 0.01$ (**).

applied to crop 1, the combination of rainfall and lateral movement into lower rate plots provided enough water for all plots. Differences in SWT due to irrigation rates were not significant ($P = 0.57$), and leaf yield response to irrigation was linear ($R^2 = 0.88$, $P = 0.07$). When irrigation supplied most of the water needs for the turnip, as during crop 2, SWT values were affected significantly by irrigation rates ($P < 0.01$), leaf yield responses to irrigation were quadratic ($R^2 = 0.99$, $P < 0.01$), and highest yield occurred at the model rate. Water applications rates higher than irrigation rate 3 did not increase yields whereas water rates lower than irrigation rate 3 restricted yields. Rainfall also supplied a substantial portion of the water requirements during crop 3; however, the rainfall pattern for crop 3 (Fig. 1) resulted in 1) less potential for lateral water movement than occurred for crop 1, 2) visible water stress and significantly higher SWT ($P < 0.01$) in plots receiving water rates lower than the model rate, and 3) a quadratic leaf yield response ($R^2 = 0.98$, $P < 0.01$) (Table 3). During crop 4, SWT was little affected by irrigation rates ($P = 0.11$). Leaf yields responded quadratically to irrigation rates ($R^2 = 0.95$, $P < 0.01$), but N deficiency symptoms were evident in all plots about 2 weeks before harvest. The lower leaf yields and N deficiency symptoms of crop 4 were attributed to N leaching due to excessive rainfall soon after N application and foliage disease due to frequent foliage wetting (15 times in 26 days).

Leaf yields for crops 1 and 2 increased as N rates increased ($P < 0.01$). Yield responses to N applications at 80%, 100%, and 120% of the median recommended rate, respectively, were 9.5, 10.7, and, 11.0 t·ha⁻¹ for crop 1, and 10.7, 11.4, and 13.1 t·ha⁻¹ for crop 2, respectively. Yield responses to N rates were similar at all irrigation rates for crop 1, but a significant ($P = 0.02$) interaction

Fig. 2. Turnip leaf yield responses to irrigation and NaNO_3 rates at 80% (50 kg N/ha), 100% (62), and 120% (73) of the median recommended range for Georgia, for crops 1 and 2. Points and half intervals are means and variance of four observations, respectively.

between irrigation rate and N rate for leaf yields occurred for crop 2 (Fig. 2). A combination of high N rate and adequate moisture resulted in a synergistically increased leaf yield, but did not affect the conclusions of the validation.

In 1991, NaNO_3 gave significantly ($P < 0.01$) higher yields than the average yield for $\text{Ca}(\text{NO}_3)_2$ and NH_4NO_3 for crops 3 and 4. Ammonium nitrate gave higher yields than $\text{Ca}(\text{NO}_3)_2$ ($P = 0.06$ and $P < 0.01$ for crop 3 and crop 4, respectively). Yield responses to NaNO_3 , $\text{Ca}(\text{NO}_3)_2$, and NH_4NO_3 were, respectively, 12.3, 10.1, and 10.6 $\text{t}\cdot\text{ha}^{-1}$ for crop 3, and 8.2, 6.0, and 7.1 $\text{t}\cdot\text{ha}^{-1}$ for crop 4. These results support the current recommendation for NaNO_3 as the N source for turnips in Georgia (Adams, 1991). Whether the beneficial effect of NaNO_3 was due to its solubility or to interactions between sodium and potassium or ammonium has not been established.

For crop 3, leaf yields for all N sources increased with increased irrigation, but turnips with NaNO_3 produced higher leaf yield with increased irrigation than those with $\text{Ca}(\text{NO}_3)_2$ or NH_4NO_3 (Fig. 3).

Under the rainfall conditions of crop 4 that caused soil water deficit to be exceeded repeatedly, leaf yields with NaNO_3 or $\text{Ca}(\text{NO}_3)_2$ decreased at irrigation rates higher than irrigation rate 4, but leaf yields with NH_4NO_3 continued to increase with higher water application rates (Fig. 3). We attribute the higher leaf yields with NH_4NO_3 to the ammonium ion being adsorbed by soil colloids, thereby reducing its leaching rate compared to nitrate.

We have shown that irrigation of turnip grown in the spring could be scheduled with the water balance method, class A pan evaporation, and a crop factor of $0.365 + 0.0154i - 0.00011i^2$, where i was plant age. Because this model is simple to operate and requires only class A pan evaporation data, it could replace the "feel" or "see" methods to determine the time and amount of irrigation water. The model could be used under most N fertiliza-

tion conditions commonly used in commercial leafy greens production in the southeastern United States.

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Fig. 3. Turnip leaf yield responses to irrigation and NaNO_3 , $\text{Ca}(\text{NO}_3)_2$, and NH_4NO_3 applied at 100% of the median recommended N rate (62 kg N/ha) for crops 3 and 4. Points and intervals are means and variance of four observations, respectively.