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FIELD EVALUATION OF WATER AND NITRATE FLUX THROUGH THE ROOT ZONE OF A DRIP/TRICKLE IRRIGATED VINEYARD

Annual (Final) Progress Report

CDFA CONTRACT NO. 91-0556

Donald W. Grimes
Water Scientist
Land, Air and Water Resources, U.C. Davis

U.C. Kearney Agricultural Center

A. Project Title: Field Evaluation of Water and Nitrate Flux Through the Root Zone of a Drip/Trickle Irrigated Vineyard

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Principal Investigator: Donald W. Grimes, Water Scientist; Land, Air and Water Resources; University of California, Davis; located at the U.C. Kearney Agricultural Center, 9240 S. Riverbend Ave., Parlier, CA 93648.
Phone (209) 891-2500.

Cooperator: Larry E. Williams; Plant Physiologist; Viticulture and Enology; University of California, Davis; located at the U.C. Kearney Agricultural Center.

B. Objective Statement:

The central objective is to determine the extent to which nitrate flux below the root zone occurs for a chemigated, drip/trickle irrigated, Thompson Seedless vineyard when fertilization and added water amounts are at optimum levels. Specific directed objectives include:

1) determination of the temporal nitrate distribution in the lower profile of a sandy loam soil for both surface water release and buried lateral, subsurface water release conditions with chemigation,

2) measurement of possible water and nitrate flux below the root zone of a mature Thompson Seedless vineyard, and

3) evaluation of acceptable methods to prevent root intrusion of underground drip irrigation emitters.

C. Executive Summary:

A field study was conducted in 1992 at the U.C. Kearney Agricultural Center on sandy loam soil to measure the extent to which water and nitrogen moved below the root zone of a Thompson Seedless grape vineyard. The vineyard was drip irrigated with water and nitrogen delivered through the growing season to present nonstressed conditions. There were four basic tasks to be accomplished by the study:

1) by means of a uniformity study, establish normal and usual conditions for a 1.2 ha Thompson Seedless vineyard,

2) install neutron probe access tubes, tensiometers, and solution suction probes and characterize soil water retention-transmission properties,

3) install drip irrigation laterals and impose treatment irrigation and chemigation, and

4) measure water and nitrogen flux below the effective root zone.

Season-long water flux below the root zone was only 23 mm (slightly under one inch). With the measured nitrogen concentration in this quantity of water, only 1.5 kg N per ha (1.3 lbs N per acre) was moved below the effective root zone of the crop. This study clearly shows that nitrogen fertilization and irrigation to fully meet water and nutrient requirements of grape vineyards can be done without contaminating groundwater.

Based on comparisons of measured flow with factory flow specifications of the various drip materials, there was no evidence to indicate root intrusion and plugging for any treatment.

Background

Nitrates and pesticides are frequently detected in wells in the U.S. at levels of concern for human health. Detrimental effects from too much nitrate ingestion include methemoglobinemia (blue baby disease) and possibly stomach cancer in adults (Bauwer, 1990; Follett and Walker, 1989). Numerous wells have been closed in the Fresno metropolitan region within the last two years because of DBCP concentrations above allowable limits. Sites of relatively high nitrate concentrations have been identified throughout the San Joaquin Valley. Once ground water is contaminated, treatment options, while available (for example, anion exchange and denitrification for nitrates), are usually expensive.

Intensive agriculture has a potential for being a nonpoint source of groundwater contamination. Chemigation, i.e., the application of agricultural chemicals using irrigation systems, has gained popularity in recent years (Miller et al., 1976; Rauschkolb et al., 1976; Rolston et al., 1979) especially where drip/trickle water delivery systems are used. Though this technique is effective and efficient considering soil-plant-water relationships, the potential exists for ions like nitrates, that are essentially nonreactive at the soil particle interface, to move below the root zone (Jennings and Martin, 1990; Mansell et al., 1980; Goldberg et al., 1971; Snyder et al., 1984) and possibly reach the underlying groundwater. Several agronomic practices have been evaluated to minimize the potential for nitrate movement below the plant root zone including the careful control of timing and amounts of nitrogen fertilizer applied to meet crop needs using slow release fertilizer materials, and adding nitrification inhibitors (Walters and Malzer, 1990). All of these practices can contribute to minimizing nitrate contamination if properly used. However, in irrigated arid and semiarid regions, such practices need to be coupled with the avoidance of extensive water flux through the root zone except that necessary as a leaching fraction to maintain a desired salt balance. Water delivery systems should have a good distribution uniformity with scheduling accomplished to meet actual crop water needs, but avoid over irrigating.

There are approximately 300,000 hectares of land devoted to vineyard production in California with 86 percent of the total in the San Joaquin and Tulare Basin hydrological regions. Our recent studies have been directed to defining an optimum irrigation strategy for Thompson Seedless grapevines (Grimes and Williams, 1990) and to assessing irrigation strategies for vineyards grown on slowly permeable soils where getting adequate water into the soil profile is difficult at certain times of the year (Grimes et al., 1990; Munk et al., 1989).

For drip/trickle irrigation systems, the water release position is important where soil surface sealing slows water infiltration. Buried systems have an advantage under such conditions (Grimes et al., 1990), however, the greatest number of active roots occurs near the water release position (Araujo, 1987; Grimes et al. 1990) and root intrusion and plugging of water release orifices can become a problem. Adding nitrogen at the site of highest root activity, through chemigation, is advantageous because small frequent additions can be made. At the release site, however, the total soil volume is low and solution concentration in this volume may be high. Also, soil water potential will be greatest (least negative) at and below the water release site. Both of these conditions could lead to downward nitrate movement, especially in sandy soils. The extent to which these conditions contribute to nitrate flux below the root zone is not known at present, but with more than 4 million hectares chemigated annually in the U.S. (Jennings and Martin, 1990), the procedure is being subjected to increased scrutiny.

Procedures

<u>Field plot establishment</u>

The study was conducted at the University of California Kearney Agricultural Center located in eastern Fresno County. The soil is predominately Hanford sandy loam (coarse-loamy, mixed, nonacid, thermic Typic Xerorthents) that is typical of vineyard-utilized soils.

Five treatments were evaluated in a randomized complete block field design with three replications. The treatments were:

1) control: conventional drip irrigation with above ground water release,

2) buried (30 cm below the soil surface) T-tape,

3) same as (2), but phosphoric acid (pH = 2.0) was injected occasionally to prevent root intrusions,

4) buried lateral (30 cm) with in-line turbulent flow emitters (SUB-FLOW), and

5) buried lateral (30 cm) with in-line turbulent flow emitters with slow release Treflan (GEOFLOW) to prohibit root intrusion.

The 1.2 hectare vineyard used in the study had vines spaced 2.4 m within the row and 3.7 m between rows. This configuration allowed three rows, 63 m in length, for individual plots. The vineyard was cane-pruned 'Thompson Seedless' (Vitis vinifera L.); the entire vineyard has been drip/trickle irrigated since 1984 (Grimes and Williams, 1990).

All plots were irrigated uniformly to fully meet crop water needs. Potential evapotranspiration (ET_o) was determined from a nearby CIMIS station (Snyder et al., 1985) with the appropriate crop coefficient (K_c) determined as previously reported (Grimes and Williams, 1990). Crop coefficients were determined from the expression $K_c = -1.52 + 0.0231(DOY) - 0.0000568(DOY)^2$ where DOY is day of the year. Required water amounts to meet 100% of the expected crop evapotranspiration (ET_c) were calculated on a weekly basis with water addition controlled with a time clock - solenoid valve assembly. Calibrated, duplicate, in-line water meters measured water delivery amounts to individual treatments.

Fertilization with required nitrogen (ammonium nitrate) and potassium (murate) was done by chemigation at weekly intervals beginning 14 May and continuing through 6 July. A total of 45 kg N/ha and 150 kg K/ha were added for optimum fertilization. No other required nutrient has been identified as being deficient with this vineyard.

Soil water content was measured, with a neutron probe, at approximately biweekly interval throughout the 1992 growing season. Each plot was monitored with a series of nine neutron probe access tubes. Three tubes were placed in the row; adjacent to the vine trunk, and at 0.6 m and 1.2 m away from the trunk center. Three tubes each were placed parallel to the tubes in the row on the north side of vines at distances of 0.9 m and 1.8 m from the row. The neutron probe was site calibrated and volumetric water content measured at the mid-point of 0.3 m depth increments to a depth of 1.2 m (slightly deeper than the effective rooting depth for this soil). This procedure gave a three dimensional view of the volumetric water content distribution in the profile.

Harvest was done on 24-25 August, 1992 with individual plot yields determined by summing the weights from each row of the three-row plots. Yield component measurements and grape quality parameters were measured on three-vine samples collected during the week before harvest.

Soil water flux

Soil water flux at the bottom of the root zone was measured by the procedure illustrated by LaRue et al. (1968) and Hanks and Ashcroft (1980). Unsaturated hydraulic conductivity and volumetric soil water content - matric suction relations were determined in the field site by the internal drainage method of Hillel et al. (1972). Three 9 m^2 basins, one each in the three replications of the study, were flooded during vine winter dormancy, covered with black plastic to prevent surface evaporation and allowed to drain for up to 36 days.

Soil water flux was computed from field-measured soil-water potential gradients at the bottom of the effective root zone and the site determined soil-water characteristics. Two tensiometers were placed in each of the 15 plots to monitor the soil water hydraulic gradient over a 0.3 m distance between depths that averaged 0.75 m and 1.05 m for all plots. Depths varied slightly because the lower tensiometer was placed immediately above the cemented pan that forms a lower boundary for effective rooting in this soil. Tensiometer readings were made with a pressure transducer unit three times weekly. Water flux density was determined on a weekly basis by averaging the three tensiometer readings and selecting appropriate unsaturated hydraulic conductivity values. Total season water flux densities were determined from the sum of weekly measurements.

Nitrogen flux

Although some procedures allow for the measurement of nitrogen flux directly (Montgomery et al., 1987; Schnable, 1983) such techniques are cumbersome for large scale field observations and frequently require considerable soil excavation for installation. Disturbing large soil volumes is a significant disadvantage for this study; therefore, porous ceramic cup soil-water samplers were used. Some disadvantages do exist (Hansen and Harris, 1975), but with proper precautions any potential error source is minimized.

Two each of ceramic cup samplers were installed in the 15 plots coinciding with tensiometer depths. Since the ceramic cup samplers measure solution concentration at a given point in time, samples were collected at weekly intervals to provide continuous information. Nitrate and ammonia were determined on the samples by the procedures of Carlson (1978, 1986). Nitrogen concentration, as an average of the two lower profile depths, and water flux density were used to calculate nitrogen flux density below the vineyard root zone. Total nitrogen movement for the year was determined as a cumulative of weekly values.

D. Work Description:

TASK 1: Uniformity Study

The purpose of this task is to establish normal and usual conditions for the 1.2 hectare Thompson Seedless vineyard including residual nutrients in the soil profile and to establish a production base for each plot of the experimental area.

Task products will include a uniform vineyard, ready for instrumentation and treatment water delivery system installation.

Subtask 1.1: Irrigate the vineyard to meet 100% of the crop's evapotranspiration (ETc) requirement for 1991.

Subtask 1.2: Measure grape production of each plot of the experimental field (fresh weight) at maturity.

TASK 2: Field Instrumentation and Site Characterization

The purpose of this task is to instrument the study vineyard for treatment imposition and characterize the soil water retention-transmission properties.

The task products are the study field with instrumentation and water delivery systems fully installed along with the fundamental water retention and flow characteristic data base. These products are essential to the future results.

Subtask 2.1: Purchase tensiometer components and assemble, purchase soil water samplers, trenching device, and specific ion electrodes.

Subtask 2.2: Field install tensiometers, soil water samplers, and water delivery system.

Subtask 2.3: Collect samples and determine soil water retention-transmission properties of the study site soils.

TASK 3: Treatment Imposition Through Irrigation and Chemigation

This task purpose is to impose the five differential treatments to evaluate water release position (above ground vs. subsurface) for chemigation and to measure vineyard production in 1992 and 1993.

The product of this task will be the end result in the field of treatment imposition including possible water and nitrogen flux at the bottom of the root zone, and effectiveness of treatment to alleviate root plugging for subsurface water release positions.

Subtask 3.1: Irrigate to fully meet crop water requirements based on California Irrigation Management Information System (CIMIS) potential evapotranspiration (ETo) data and appropriate crop coefficient (Kc) values determined from our previous studies. Irrigation shall start in April and end before harvest in each of 1992 and 1993.

Subtask 3.2: Fertilize by chemigation with required nitrogen (urea) and potassium (murate) at weekly intervals beginning in May and continuing through June for each of 1992 and 1993. Follow described protocol for imposing treatment to prevent root clogging of below surface emitters.

Subtask 3.3: Measure productivity of each plot of the study (fresh grape weight) in early Sept. of 1992 and 1993. Grape quality parameters (^{o}brix, pH and titratable acidity) will also be measured.

TASK 4: Water and Nitrogen Flux Determination

The purpose of this task is to monitor soil water status throughout the soil profile and the potential for water and nitrogen flux at the bottom of the vineyard root zone.

Task products are the data base on soil profile water content, determined potential for water and nitrogen flux at the bottom of the vineyard root zone, and effectiveness of the protocol to preclude water release point root plugging.

Subtask 4.1: Measure soil water content at approximately two-week intervals with a neutron probe, April through August of 1992, less frequently at other times.

Subtask 4.2: Measure water flux at the bottom of the root zone with tensiometer date; measurement frequency about every second day during the water delivery season, less frequent during winter dormancy.

Subtask 4.3: Measure nutrient status at tensiometer depths with solution samplers; calculate potential nitrogen flux below the root zone.

Subtask 4.4: Perform statistical evaluation using accepted analysis of variance and regression techniques. Write the final report. Additional informational dissemination will be accomplished during field days at appropriate times.

E. Results and Discussion

Uniformity study

A uniformity study of the 1.2 hectare Thompson Seedless Grape vineyard (Task 1) was done in 1991. Figure 1 presents cumulative reference evapotranspiration (ET_o) from a California Irrigation Management Information System (CIMIS) station located near the study site. Cumulative ET_c was determined from available crop coefficients (K_c) and ET_o. Applied water essentially fully met 100 percent of the crop water requirements for the irrigation season.

Average grape production for the 1991 growing season was 27.5 t ha^{-1}; standard deviation bars are illustrated (Fig. 2). Reps. I and II had similar productivities, but Rep. III was about 2 t ha^{-1} lower than either of Reps. I or II. Replicate production trends illustrate normal field variability, but the completely randomized block field design demonstrates the potential for removing variability not associated with treatments.

Soil water characteristics

Soil water retention and conductivity characteristics of the location (Task 2) one given in Figures 3 and 4. The average matric potential from tensiometers in individual plots was used to define an appropriate conductivity from the functional relationships illustrated.

Crop evapotranspiration and applied water

Applied water and cumulative ET_c (Task 3) are given in Figure 5; total season applied water of 542 mm before harvest was slightly lower than that required in the 1991 uniformity study because of the general early maturity of the 1992 crop. Irrigation was initiated 26 April and terminated 23 August three days before harvest. Cumulative applied water of Figure 5 represents an average of the five treatments. Standard deviation (SD) bars were included in the graph but were so small they were mashed by weekly cumulative data points.

Observations on ET_c began 1 April 1992 to generally coincide with vineyard budbreak. Since the profile was essentially wet to field capacity by winter rainfall and irrigation water delivered following the 1991 harvest, about 30 mm of water were allowed to deplete from the profile before irrigation was initiated. This appears a desirable practice to minimize the potential for water and nutrient flux early in the season. Once initiated, required water was metered to plots daily. By early July, ET_c was approaching peak weekly use amounts of 38 mm (1.5 inches) that were sustained until near mid-August.

Production and quality

Production and yield component parameters for the five treatments are given in Table 1. An analysis of variance revealed no statistical separation of treatments (at a 0.05 probability level) for any of these parameters, however some general trends are noteworthy. During this initial study year, root disruption from burying the laterals resulted in an average yield reduction of two tons (metric) per hectare (1 ton/acre) that is consistent with our previous finding (Grimes et al., 1990). All buried systems had slightly reduced bunch numbers per vine, but bunch weight averages were slightly larger for the buried systems.

There was no statistically significant or visible trend of treatment effect on soluble solids, pH, or titratable acidity (Table 2).

Soil water content distribution

The equilibrium (6 August) soil water content and distribution for the five contrasting treatments (Task 4) is presented in Table 3. The contrast between surface water (control) and subsurface release positions was similar to an earlier (Grimes et al., 1990) result. Generally, the soil water content of the upper profile of a surface release treatment was higher than for subsurface release treatments. With a water release directly within the row for the surface release treatment, soil water content was linearly depleted with time to a point mid-way between vineyard rows. Positioning the buried laterals on the north side of vineyard rows resulted in a uniform water content at measured positions within the row and the 0.9 m distance between rows. Soils did progressively dry at mid-row distance (1.8 m) sites for buried lateral treatments. Overall, buried lateral treatments had a more uniform distribution of soil water than the surface release (control) treatment.

Profile water content and distribution for the SUB-FLOW treatment shows a lower water content than for other treatments. Early in the irrigation period a problem with this material allowed high water delivery in a few places in the field where improper alignment of inline emitters and holes in the lateral were observed. Metered water delivery was in agreement with calculated required amounts and the problem was not detected until profile drying was observed with the neutron probe and excessively wet sites appeared were problem conditions existed. The problem was correct with removal/replacement of sections of laterals. Since water was delivered only to fully meet ET_c, the average soil water content of the profile at access tube sites remained below that of other treatments for the remainder of the growing season.

Water and nitrogen flux

Weekly and season-long cumulative water flux at the bottom of the soil profile are illustrated in Fig. 6. As indicated by SD bars on weekly values, considerable variability existed among the 15 plot total of the study. This degree of variability was not unexpected and is within an anticipated level. Total season flux was subjected to an analysis of variance with the result that no treatment difference was in evidence.

There was little or no flux below the root zone before early June when weekly irrigation delivery amounts were small. By late-June through mid-August, measurable water flux was still quite small amounting to about 2 to 3 mm per week. This gave a total season cumulative water flux of about 23 mm or slightly under one inch of water for the entire growing season.

As with total season water flux, total nitrogen flux below the root zone for the growing season was quite variable with no treatment effect evident by an analysis of variance procedure. Weekly and season-long cumulative nitrogen fluxes below the root zone are illustrated in Fig. 7. A maximum total nitrogen flux below the crop root zone amounted to only 1.5 kg N per hectare (1.3 lbs N per acre).

Root intrusion

Metered water delivery amounts throughout the entire growing season provided an indirect measure of root intrusion and plugging of buried systems when metered amounts were compared with factory specifications on water delivery for the various systems. There was no significant departure of measured vs. specification amounts during the season. This would indicate that root intrusion was not a problem during the first year of the study.

Conclusions

Perennial crops that are grown with relatively wide row spacing logically would appear to represent situations that might lead to water and nutrient flux below the crop root zone. This is especially true on sandy soils where drip irrigation concentrates a water and nutrient release in a relatively limited part of the root zone that is expected to fully meet ET_c and crop nutrient needs.

This study clearly demonstrates that nitrogen fertilization and irrigation to fully meet water and nutrient requirements of grape vineyards can be done without a potential for contamination of groundwater supplies. Either surface of subsurface drip laterals can be used with equal effectiveness.

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Table 1. Thompson grape yield and yield components of contrasting drip irrigation systems each irrigated to fully supply crop evapotranspiration demand.

Treatment	Yield (t per ha)	Bunch (no. per line)	Bunch wt. (kilograms)	Berry size (grams per berry)
Surface emitter	27.201a*	52.8a	0.513a	1.72a
Bury; T-tape	26.931a	51.8a	0.530a	1.76a
Bury; T-tape+acid	25.370a	44.2a	0.640a	1.64a
Bury; SUB-FLO	23.843a	46.9a	0.523a	1.63a
Bury; GEOFLOW	24.711a	52.3a	0.560a	1.86a

* Averages in the same columns not followed by the same letter differ at a 0.05 probability level by Duncan's multiple range test.

Table 2. Thompson grape juice quality of contrasting drip irrigation systems each irrigated to fully supply crop evapotranspiration demand.

Treatment	Soluble solids (°brix, %)	pH	Titratable acidity (g tartaric acid per 100 ml juice)
Surface emitter	21.2a*	3.7a	0.45a
Bury; T-tape	21.5a	3.7a	0.44a
Bury; T-tape+acid	21.6a	3.6a	0.45a
Bury; SUB-FLO	21.5a	3.6a	0.44a
Bury; GEOFLOW	21.9a	3.6a	0.45a

* Averages in the same columns not followed by the same letter differ at a 0.05 probability level by Duncan's multiple range test.

Table 3. Soil water content distribution in the soil profile for contrasting drip irrigation materials and water release positions on August 6, 1992. Nin neutron probe access tubes were positioned to measure volumetric soil water content at four depths (23, 46, 76, and 107 cm) below the surfac Tubes were positioned near the base of vines and within the vine row [vine (r)ow], at 0.6 m [vine (r) 1/4] and 1.2 m [vine (r) 1/2] from the vin base. Tubes were spaced between rows [vine (m)iddle], at 0.9 m [vine (m) 1/4], and 1.8 [vine (m) 1/2] from rows and aligned perpendicular with within row tubes.

	Depth (cm)	vine (m)iddle	Vine (m) 1/4	Vine (m) 1/2	Ave.	Vine (m)iddle	Vine (m) 1/4	Vine (m) 1/2	Ave.	Vine (m)iddle	Vine (m) 1/4	Vine (m) 1/2	Ave.	Vine (m)iddle	Vine (m) 1/4	Vine (m) 1/2	Ave.	Vine (m)iddle	Vine (m) 1/4	Vine (m) 1/2	Ave
		Surface drip[†] (control)				T-tape[‡] (bury)				T-tape (bury) + acid				Sub-flow[§] (bury)				GEOFLOW[¶] (bury)			
		volume (%)																			
Vine (r)ow	23	24.1	16.4	13.4	18.0	15.4	16.3	7.6	13.1	18.9	18.4	10.1	15.8	12.6	14.8	9.5	12.3	19.5	17.5	9.6	15.
	46	20.2	15.8	15.0	17.0	18.1	15.2	8.8	14.0	15.4	15.3	11.9	14.2	9.0	9.6	6.9	8.5	17.0	14.5	10.3	13.
	76	18.6	17.7	17.5	17.9	17.1	18.9	12.8	16.3	16.1	19.5	15.1	16.9	9.0	10.6	7.1	8.9	15.3	16.0	12.7	14.
	107	23.0	23.0	21.3	22.4	20.4	19.9	16.3	18.9	18.5	20.2	15.6	18.1	10.8	14.9	11.8	12.5	19.7	21.2	16.8	19.
	Ave	21.5	18.2	16.8	18.8	17.8	17.6	11.4	15.6	17.2	18.4	13.2	16.3	10.4	12.5	8.8	10.6	17.9	17.3	12.4	15.
Vine (r) 1/4	23	23.1	13.8	10.5	15.8	15.2	15.8	7.0	12.7	16.6	18.2	15.4	16.7	12.8	15.8	13.6	14.1	18.6	18.2	12.3	16.
	46	19.8	14.9	13.7	16.1	17.6	15.7	10.3	14.5	15.3	16.5	12.0	14.6	9.3	10.3	7.7	9.1	20.4	14.9	11.0	15.
	76	18.6	16.1	16.8	17.2	17.6	18.4	14.4	16.8	15.5	22.1	15.7	17.8	10.0	12.5	6.7	9.7	16.7	15.4	11.9	14.
	107	21.9	20.0	22.8	21.6	20.6	19.0	18.1	19.2	18.1	22.0	18.2	19.4	11.5	16.3	11.2	13.0	18.5	18.9	15.8	17.
	Ave	20.8	16.2	16.0	17.7	17.8	17.2	12.4	15.8	16.4	19.7	15.3	17.1	10.9	13.7	9.8	11.5	18.6	16.8	12.8	16.
Vine (r)1/2	23	24.4	15.4	8.9	16.2	17.5	15.8	7.6	13.6	20.0	18.9	15.1	18.0	18.6	14.3	10.4	14.4	20.6	17.0	13.9	17.
	46	21.6	14.3	12.8	16.2	19.0	15.9	11.8	15.6	16.7	15.9	12.1	14.9	12.0	10.8	6.9	9.9	15.5	15.1	12.3	14.
	76	18.0	17.0	17.4	17.5	19.0	19.4	14.7	17.7	15.9	21.9	15.7	17.8	11.6	12.7	7.1	10.5	14.4	17.5	13.5	15.
	107	21.7	20.5	20.6	20.9	22.0	22.9	19.0	21.3	20.8	23.7	19.5	21.3	12.4	16.7	13.4	14.2	18.1	20.9	15.6	18.
	Ave	21.4	16.8	14.9	17.7	19.4	18.5	13.3	17.1	18.4	20.1	15.6	18.0	13.6	13.6	9.4	12.2	17.2	17.6	13.8	16.

[†] BOWSMITH Irrigation Products, Inc. (Exeter, CA); two S-10 emitters spaced 30 cm on both sides of vine trunks.
[‡] T-Tape (T-SYSTEMS CORPORATION, San Diego, CA); buried 30 cm deep. With and without phosphoric acid injection to prohibit root intrusion.
[§] SUB-FLO (AGRIFIM, Fresno, CA); buried 30 cm deep.
[¶] GEOFLOW (GEOFLOW, Inc., San Francisco, CA); slow release Treflan in emitters to prohibit root intrusion); buried 30 cm deep.

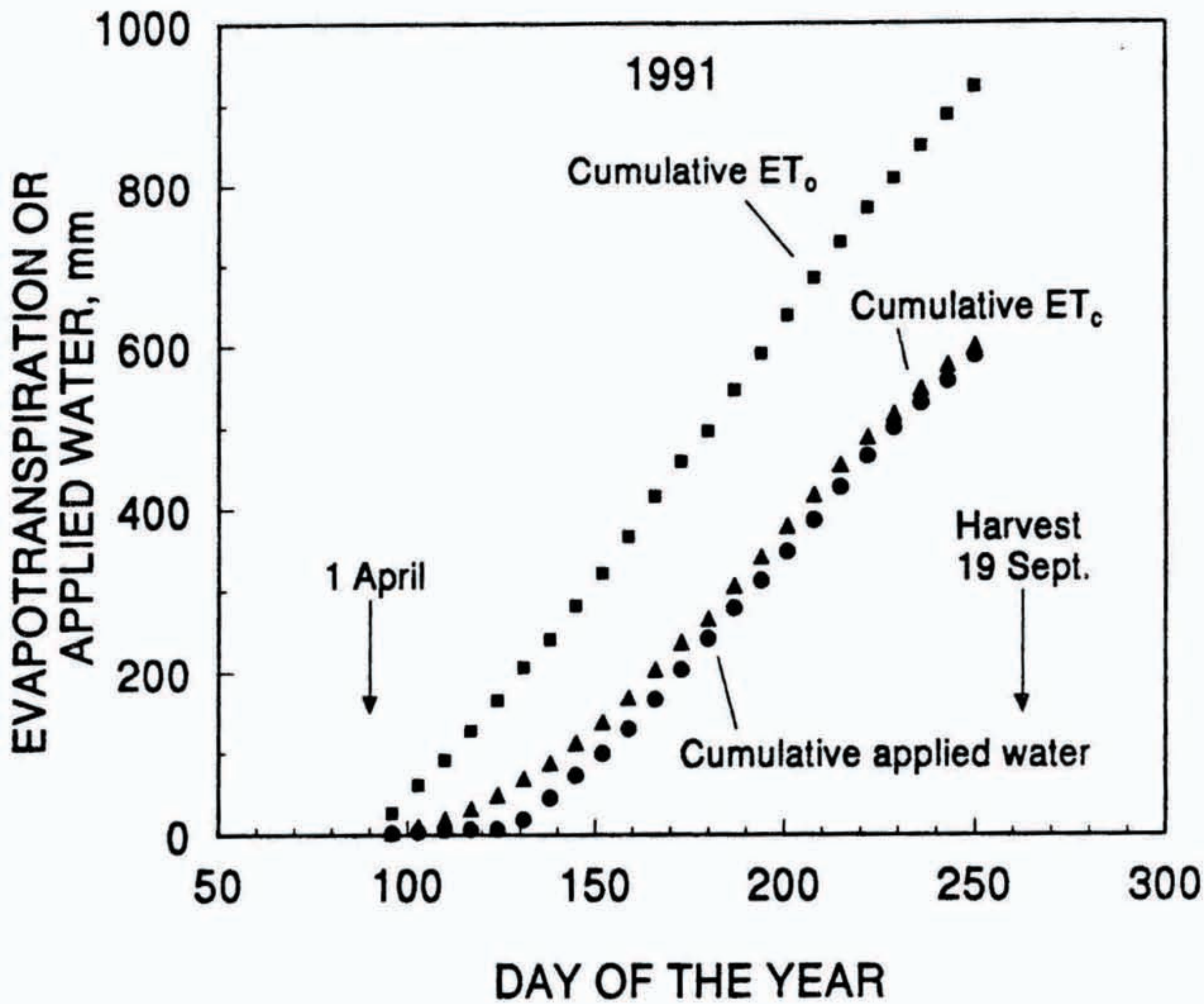

Fig. 1. Reference evapotranspiration (ET_o) from a climatic station located near the study site, crop evapotranspiration (ET_c) and applied water for the 1991 uniform crop year.

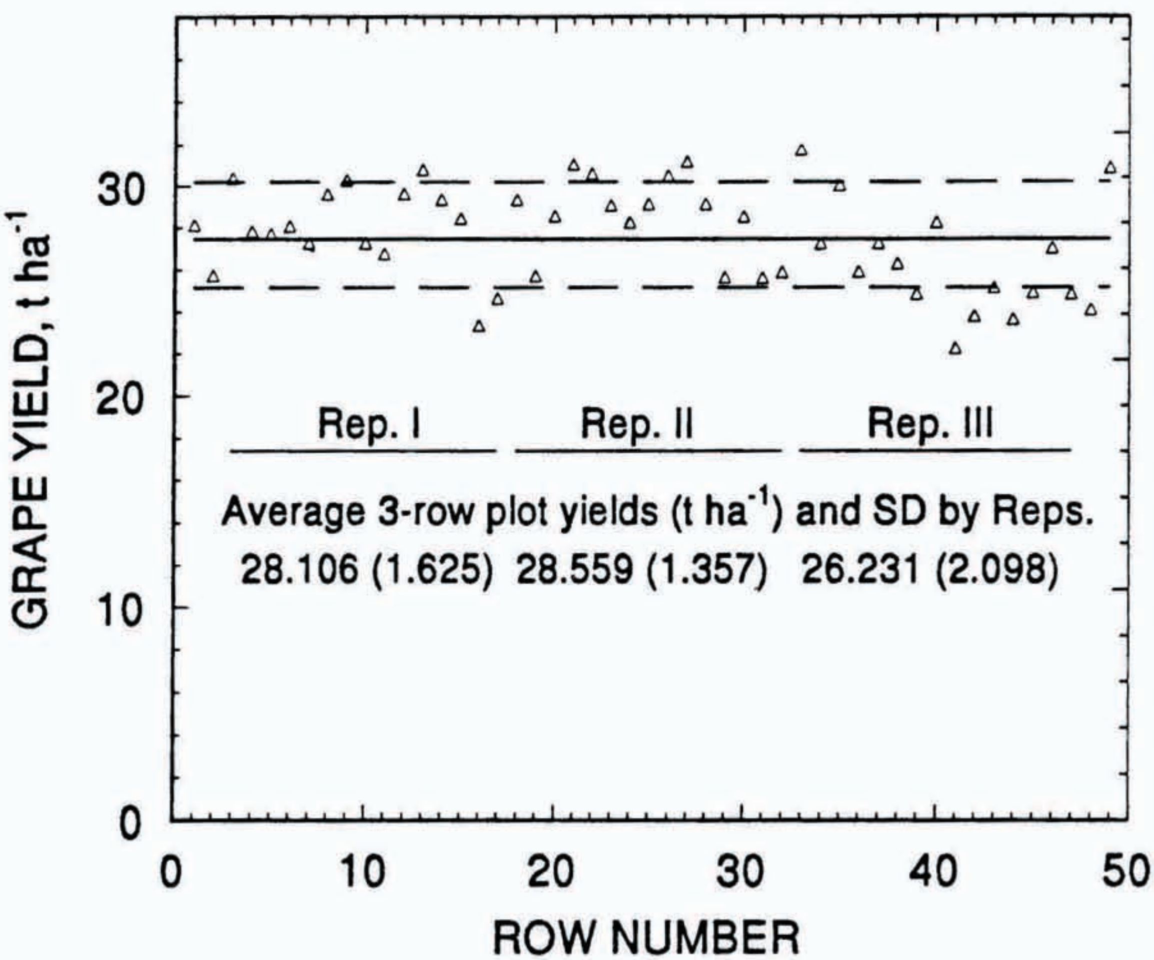

Fig. 2. Average production (solid line extending across rows 1 through 4a) and standard deviations (broken line above and below the mean yield solid line) for 49 individually harvested rows of the study. Individual replicates are 15 rows that comprise five treatment plots that are each three rows wide. Replicate averages are means of the five-three row plots.

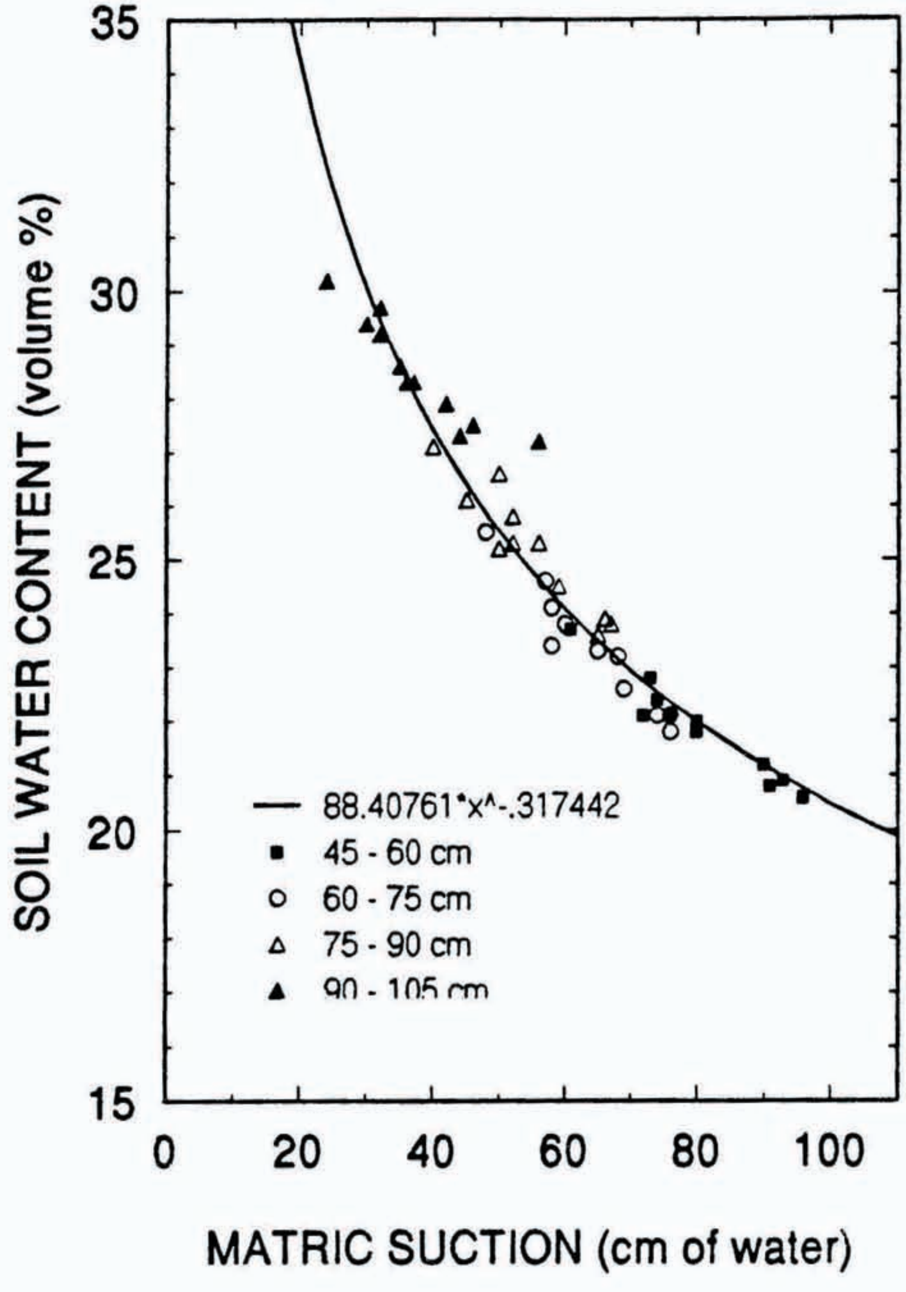

Fig. 3. A relationship between volumetric soil water content and matric suction determined from drainage basins at the study site. Depths above 45 cm did not represent the same continuous relationship as the 45-105 cm depths illustrated.

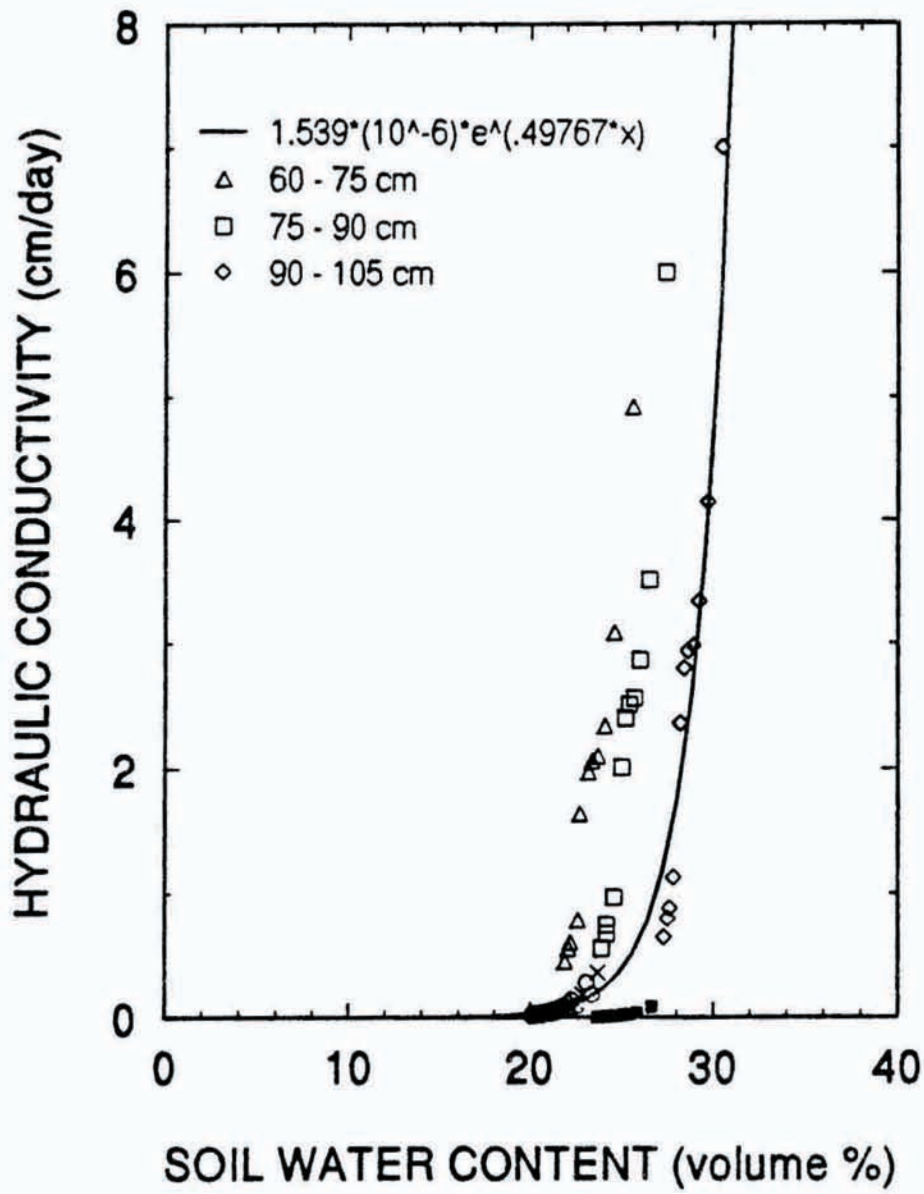

Fig. 4. Hydraulic conductivity as a function of soil water content at the study location.

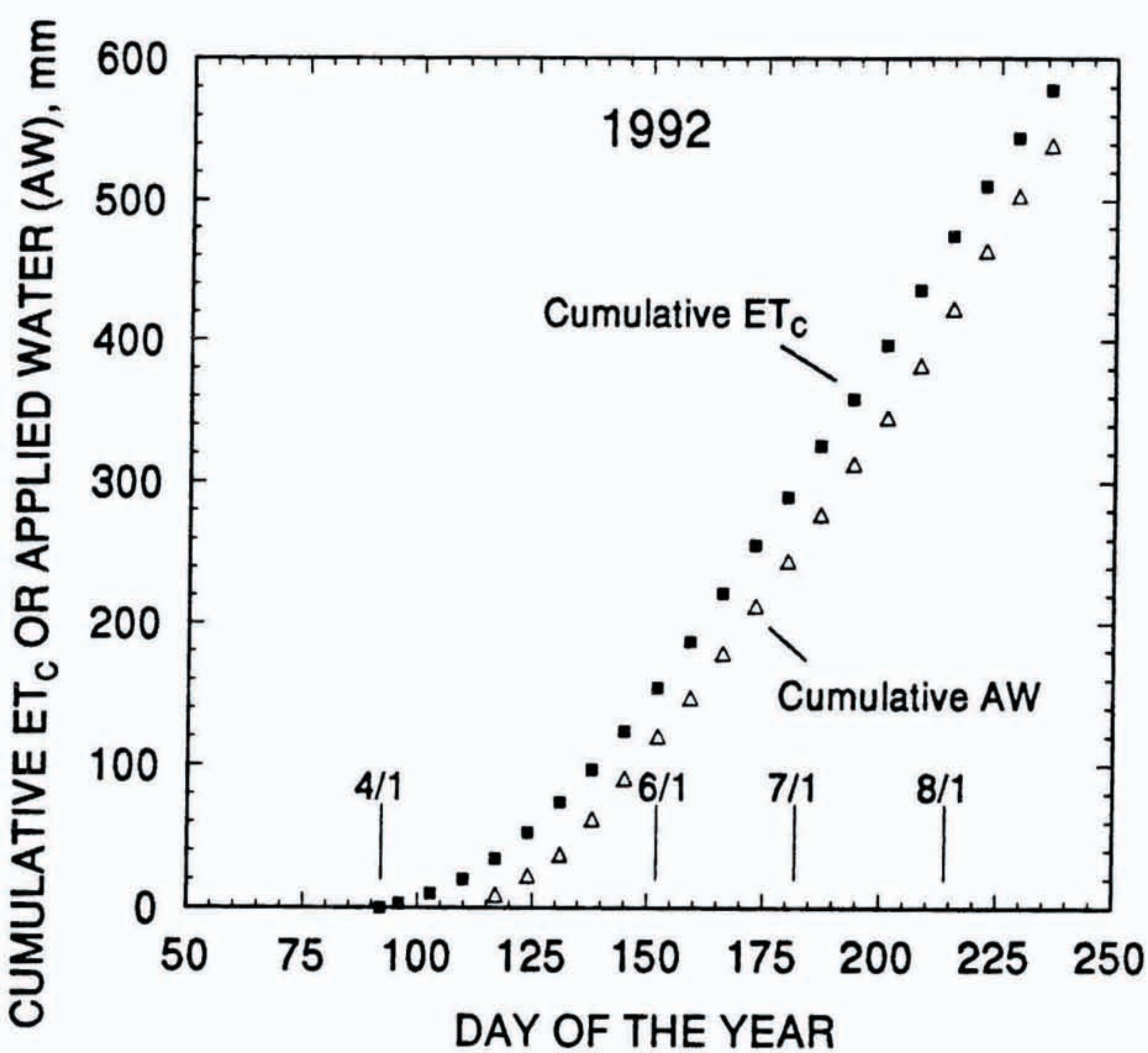

Fig. 5. Cumulative crop water use (ET_C) and applied water (AW) during 1992.

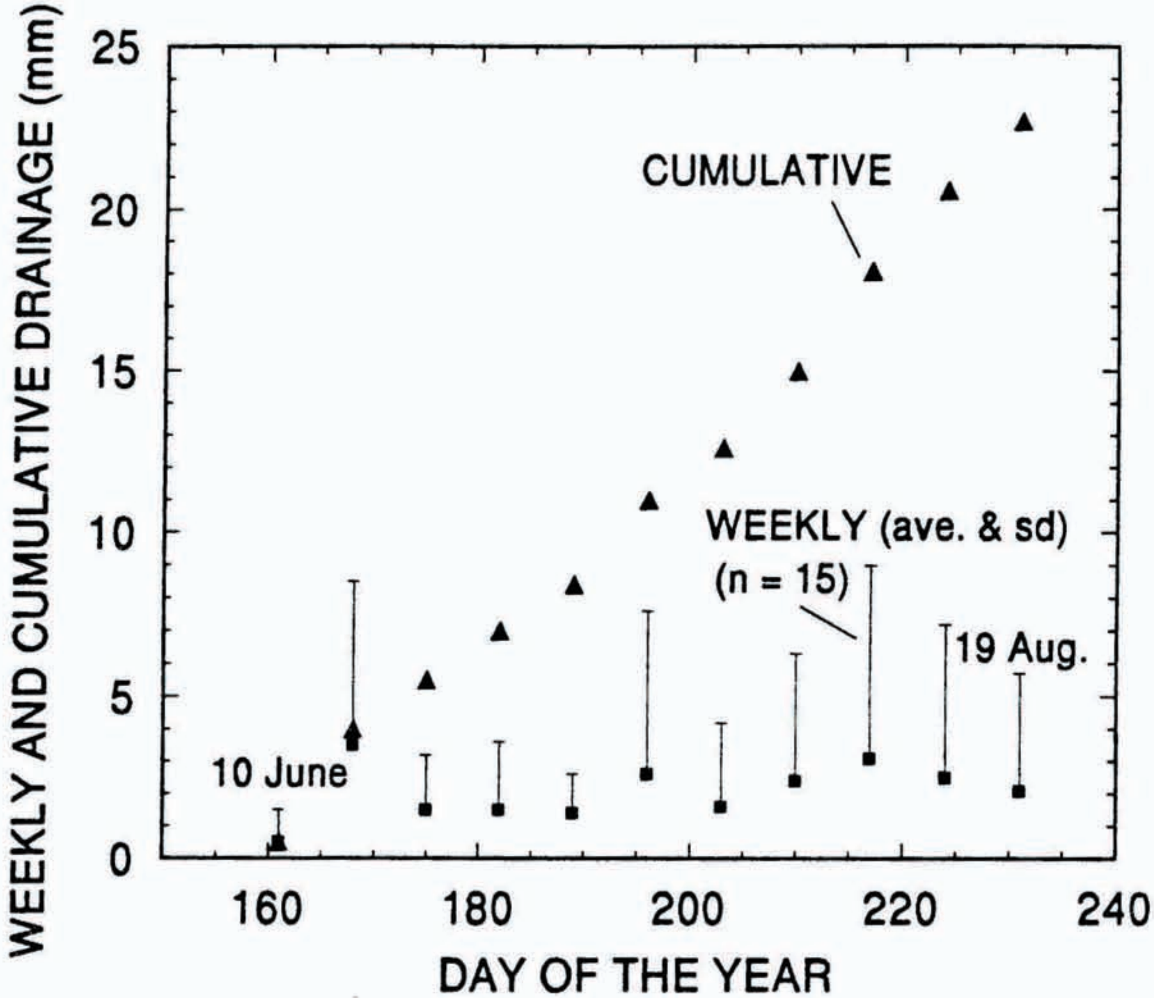

Fig. 6. Weekly and cumulative drainage amounts in a Thompson Seedless grape vineyard during a 1992 study.

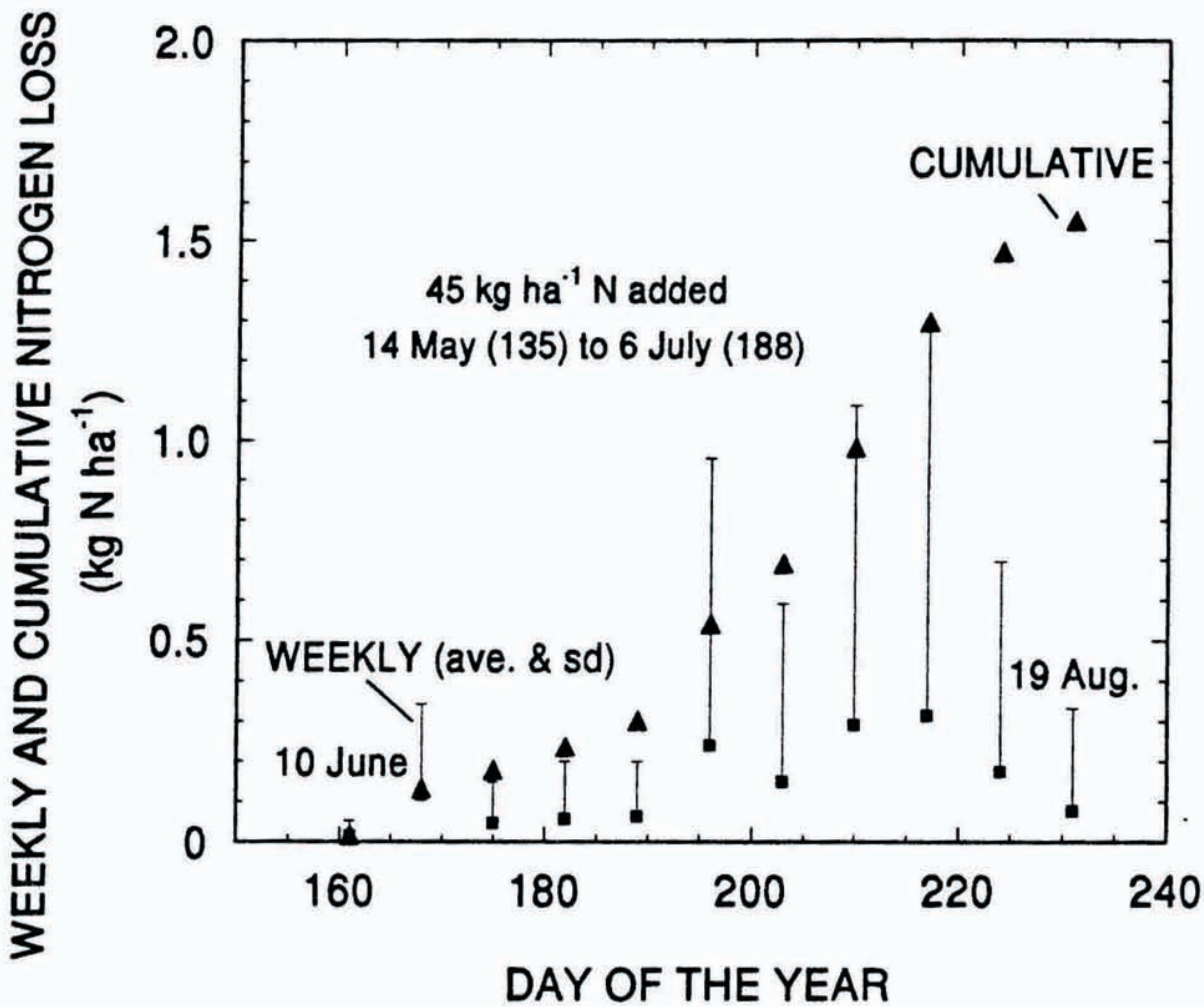

Fig. 7. Weekly and cumulative nitrogen flux below a Thompson Seedless vineyard root zone in 1992.