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# A comparative study of young 'Thompson Seedless' grapevines under drip and furrow irrigation. I. Root and soil water distributions

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**Abstract**

Soilwater distribution, soilwater extraction, and root distributions were determined for young grapevines (*Vitis vinifera* L. cultivar 'Thompson Seedless') grown under drip and furrow irrigation near Fresno, CA, USA. Soilwater content and extraction was determined to a depth of 0.9 m by neutron scattering from an array of nine access tubes installed throughout one-quarter of the soil volume available to each vine. Root distribution was determined from root intersections with vertical planes established parallel and perpendicular to the vine row. Drip irrigation was applied daily according to estimated evapotranspiration, and furrow irrigation was managed according to 50% depletion of the plant available soil water. Drip and furrow irrigated vines showed similar water status and shoot growth patterns. There was a confined soil wetted zone beneath the emitter discharge that largely coincided with a confined and shallow root system of drip irrigated vines. In contrast, furrow irrigated vines had a deeper and more widespread root system. Differences between water applied and soilwater content 3 days after irrigation suggested large water losses by evaporation during that period for furrow irrigated vines. Consumptive use of furrow irrigated vines was 12.5% greater than drip irrigated vines, but similar irrigation efficiencies were obtained for both irrigation systems when soilwater status was carefully monitored. Water applications for both irrigation systems were less than 50% of the long-term mean for irrigation deliveries to farms in the area. Thus, the results indicate that a significant potential for water savings exists in the San Joaquin Valley by means of irriga-

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tion management. It is concluded that relatively high and similar irrigation efficiency can be obtained with both drip and furrow irrigation of young grapevines in arid and semi-arid regions when careful management is used.

*Keywords:* Efficiency; Evapotranspiration; Irrigation; Root growth

## 1. Introduction

The cultivation of grapes in arid or semi-arid regions of high evaporative demand, the increasing requirement for efficient use of irrigation water, and the seasonal sensitivity of reproductive development of grapevines to water deficits (Matthews and Anderson, 1988, 1989; Williams and Matthews, 1990) create a high priority for a more complete understanding of the role of irrigation strategy in successful grapevine production. In the San Joaquin Valley of California, for example, where evaporative demand is six times greater than the annual precipitation (Department of Water Resources, 1986), irrigation is essential to maintain adequate crop yields of perennial grapevines. Inexpensive water has led to excessive use by substituting water for labor, energy, or capital investment (Robie, 1980).

Ideally, only the water transpired by crop plants would be supplied in irrigation. The average unit of water applied for grapevines in Fresno County is estimated to be 30% greater than the evapotranspiration during the growing season (Department of Water Resources, 1986). A similar analysis for grapevines grown in Arizona showed that evapotranspiration accounted for only 50% of applied water (Erie et al., 1982). Thus, irrigation applications in grape production often significantly exceed the crop requirement.

One potential technological improvement has been the introduction of drip irrigation. In theory, one can apply only the water that the plant needs to its root system on a daily basis with a minimum of losses. Several studies with mature grapevines in the US and Australia (Smart et al., 1974; Freeman et al., 1976; Peacock et al., 1977) have reported greater irrigation efficiencies with drip than with furrow irrigation. However, studies with other crops (e.g. Sammis, 1980) have suggested that similar irrigation efficiencies can be obtained with careful use of furrow irrigation. It is not clear whether the previous studies with grapevine exploited the maximum potential for irrigation efficiency with furrow. Timing of furrow irrigation was based on tensiometers or on estimated potential evapotranspiration without considering the actual soilwater content in the root zone and its relationship to soilwater potential and vine water status.

However, mature grapevines have a widespread and deep root system (Richards, 1983) that may contribute to higher furrow irrigation efficiency than typically occurs with annual crops. With conventional furrow irrigation, high efficiency may be difficult to attain during the first few years of vine growth. The potential for large water losses during the first few seasons is great because vine rows are widely spaced, root systems are limited, and water is usually applied to furrows between vine rows.

Because the problem of irrigation efficiency is inextricably linked to root distribution, a comparative study was conducted to determine (1) crop water needs of young vines under drip and furrow irrigation, and (2) root and soilwater distribution under drip and furrow water delivery methods.

## 2. Materials and methods

### 2.1. Experimental material

Cuttings of *Vitis vinifera* L. (cultivar 'Thompson Seedless') were planted on 1.2 ha at the University of California, Kearney Agricultural Center on 15 April 1984. Two soil types, a Hanford fine sandy loam and a Hanford sandy loam (coarse–loamy, mixed, non-acid, thermic, Typic Xerorthents), occurred with similar areas within the vineyard with a hardpan at 0.6–1.0 m. Vine and row spacings were 2.4 m and 3.6 m, respectively, with east to west row direction. The vines were trained up stakes in 1985 and pruned to two 12-bud canes in February, 1986. The trellis system consisted of a 0.45 m cross-arm at a height of 1.8 m with a wire at each end of the cross-arm. No fertilizer was applied.

### 2.2. Irrigation

The vines were maintained at high water status by furrow irrigation from gated pipe during the first growing season (1984). For the subsequent growing seasons, one-half of the vineyard was changed to drip irrigation with one emitter (3.8 l $h^{-1}$ at 0.14 MPa) per vine located approximately 0.2 m from the trunk. Drip irrigation was applied daily from late April until mid-August in the second and third seasons according to:

$$WA = K_c \times ET_o \times 0.7 \tag{1}$$

where $WA$ is applied water, $K_c$ is the crop coefficient for 'Thompson Seedless' (Grimes and Williams, 1990), $ET_o$ is potential evapotranspiration, and 0.7 is an arbitrary coefficient used in adjusting the water application to the smaller canopy of the young vines in this experiment as compared with mature vines. $ET_o$ was calculated by the California Irrigation Management System using meteorological data collected 0.5 km from the study site. The amount of water applied daily was controlled by a time clock–solenoid valve assembly and directly measured with two in-line meters downstream from the pump. Each row had an in-line pressure regulator that was adjusted weekly to maintain constant pressure throughout the experiment.

Furrow irrigation, initiated in 1986 on 7 May (day of year (DOY) 128), was scheduled according to 50% depletion of plant available soil water (i.e. the soil water between soil matric potentials of −0.033 and −1.5 MPa). The volume of water to be applied in each furrow irrigation was calculated from:

$$WA = \Delta SWC/100 \times SV \tag{2}$$

where $\Delta$SWC (% v/v) is the difference between soilwater content at field capacity (22% v/v) and the minimum soilwater content just prior to irrigation, and $SV$ is the soil volume irrigated. The latter was estimated as 4720 $m^3$ (5242 $m^2$ in the furrow vineyard $\times$ 0.9 m mean soil depth). The water flow was measured at each gate during each irrigation to ensure accurate delivery.

### 2.3. Soilwater content

The relationship of soilwater content to soil matric potential (Fig. 1) was determined from the volume of water expressed at various applied pressures in a pressure plate apparatus. Soil samples were taken for both soil types at 0–30, 30–60, and 60–90 cm depths with the Veihmeyer samples, air dried, and pulverized using a mortar. Two 25 g subsamples from each depth and soil type were tested at each pressure. For the 0.01, 0.033, 0.1 and 0.5 MPa pressures, ceramic plates were used, while for the 1.5 MPa pressure, a cellulose acetate membrane was used.

Soilwater content was monitored throughout the experiment in each irrigation system using neutron scattering techniques (Holmes, 1956; Van Bavel, 1963) by means of a neutron moisture probe (Troxler model 3332 depth moisture gauge,

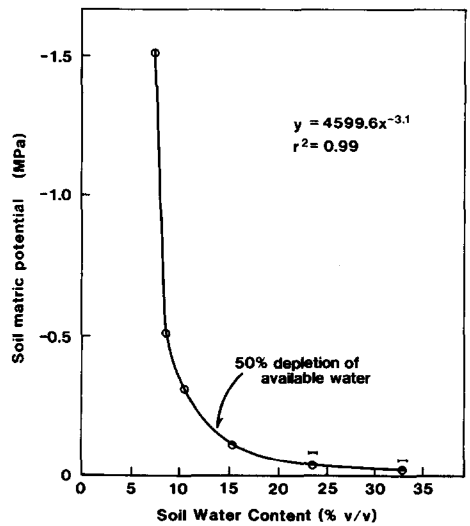


Fig. 1. Soil moisture curve obtained for the experimental vineyard. The soil moisture curves for the Hesperia and Exeter soil series were combined in order to facilitate the irrigation management of the entire plot. Soilwater content (SWC) at 50% depletion of plant available water was 14% (v/v). Average bulk density was 1.63 g $cm^{-3}$. Standard error was smaller than the symbol where no error bar is shown. Equation for curve is $y = -218.72 \times -2.704$; $R^2 = 0.96$.

Troxler, Research Triangle Park, NC, USA). An array of nine access tubes that allowed analysis of one-quarter of the vine's soil volume were installed near each of four single-vine replicates in each vineyard (Fig. 2). Soilwater content was measured at depths of 23, 46, and 76 cm before and 3 and 8 days after each water application in the furrow irrigated vines. For drip irrigated vines, neutron probe readings were taken after the daily irrigation at various times throughout the season. The neutron probe was calibrated according to Dickey and Schwankl (1980), and each measurement utilized readings of 30 s duration. Eighteen access tubes located in both soils of each irrigation plot were used for calibrating the probe. Undisturbed volumetric soil samples (60 $cm^3$) were taken with a 'Madera' sampler at depths of 23, 46, and 76 cm from at least two of the four cardinal sides of the tubes and within 15 cm of the tubes. The calibration curve was established for SWC between 7 and 23% (v/v) with $r^2=0.93$ (Fig. 3).

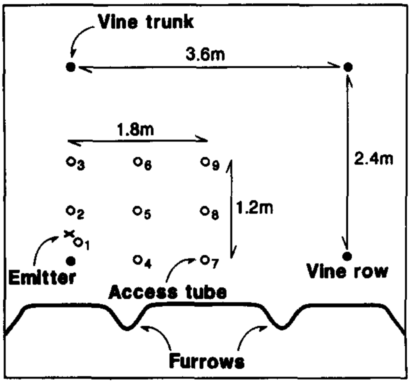


Fig. 2. Schematic diagram of vine and neutron probe access tube placement. Also shown are the positions of the emitter for drip irrigated vines and the furrows for surface irrigated vines.

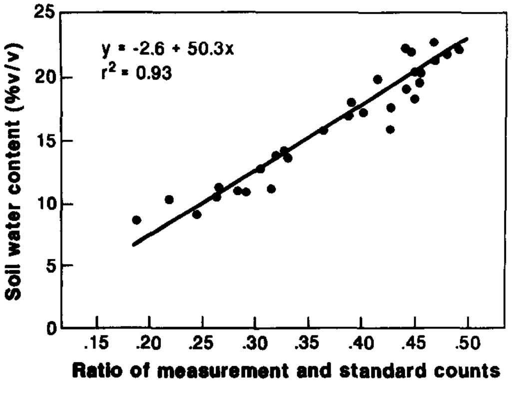


Fig. 3. Neutron probe calibration curve for the experimental vineyard. The line represents the linear regression fit between the ratio of measurement and standard counts and soilwater content (% v/v). SWC was determined gravimetrically and converted to v/v with the known sample volume.

### 2.4. Root distribution

Root distribution was quantified using the trench profile method (Bohm, 1979) in August of 1985 and 1986. Trenches were opened parallel and perpendicular to the row and about 30 cm from the vine trunk using a backhoe. Subsequently, an additional layer of soil of approximately 15 cm was removed from the vertical profile wall using a sharpened, flat-faced shovel, being careful to make the final working face vertical. The roots were exposed by removing a soil layer of approximately 10–15 mm with a knife and water stream using a hand sprayer. A wooden frame, $1\times1$ m$^2$ with $10\times10$ cm$^2$ grids made with nylon thread was fastened with nails to the profile wall. The exposed roots were then mapped in their natural position.

## 3. Results

Under drip and furrow irrigation, the soilwater profile was dynamic during the season. For both irrigation systems, mean SWC for the total profile was initially high and decreased during the season to approximately 15% (Figs. 4A (Total Volume) and 4B). However, the distribution of soil water through the soil profile was not similar under drip and furrow irrigation. Under drip, soilwater distribution was initially stratified vertically (Fig. 5A), but quickly became laterally stratified after irrigation was initiated (Figs. 5B–5D). Before drip irrigation began, SWC was laterally uniform at a given soil depth and increased with depth (Fig. 5A). At 60–90 cm depth, wet soil (SWC > 20%) occurred across the profile early in the season (Fig. 5A).

After the initiation of drip irrigation (and canopy development, see Fig. 2 in Araujo et al., 1994), SWC increased in the upper soil near the vine (and emitter) and decreased laterally away from the vine (Figs. 5B–5D). High SWC developed throughout the vertical profile near the vine under the emitter (Figs. 5–5D). Isolines for 14, 16, and 18% SWC migrated downward and toward the vine as distal soil dried (Figs. 5A–5D). Accordingly, the volume of wet soil decreased from initial values of approximately 33% of the soil profile to less than 15% of the profile on 8 August (DOY 220) (Table 1). A corresponding increase in the volume of dry soil (SWC < 16%) occurred. Initially, the SWC of the entire profile was approximately 16%, but by 8 August approximately 47% of the profile had SWC of less than 16% (Table 1).

The lateral stratification of soil water when drip irrigated was also apparent from the mean SWC for selected access tubes. Access Tubes 1 and 2 were 0.3 m and 0.6 m away from the vine trunk, respectively (see Fig. 2 for placement). The mean SWC for all depths of Access Tubes 1 and 2 indicates that a wetted zone was established and maintained near the vine (Fig. 4A). For this wetted zone, SWC averaged 20.5% ($s=1.4\%$) throughout the experiment. These data indicate that there was at least a column of soil (radius 0.3 m) that was continually at very high water status. Away from the vine, the mean SWC for Access Tubes 7, 8, and

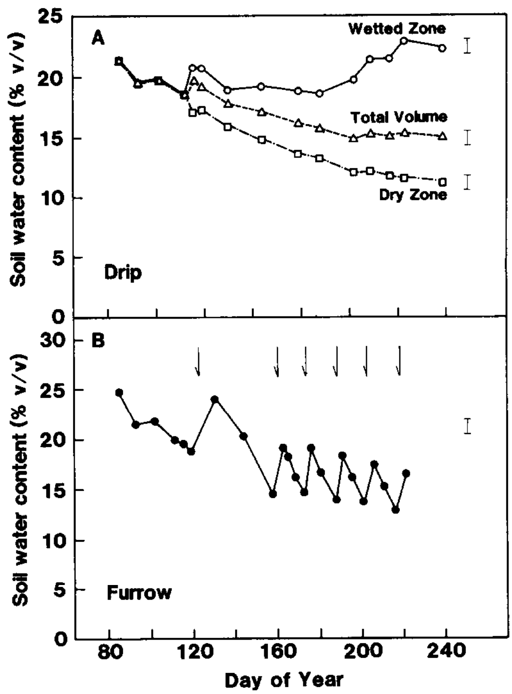


Fig. 4. Average percent volumetric soilwater content at various times during the growing season for drip (A) and furrow (B) irrigated soils. For drip (A), each point represents the mean SWC measured in Access Tubes 1-9, 1 and 2, and 7-9, for the total volume, wetted zone, and dry zone, respectively (see methods). For furrow (B), each point represents the mean water content of the total soil volume (measured in Access Tubes 1-9). Arrows indicate time of each furrow irrigation. Bars represent the average standard error through the experiment.

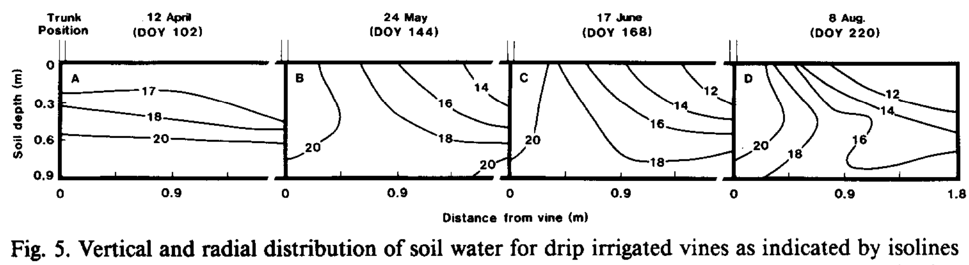


Fig. 5. Vertical and radial distribution of soil water for drip irrigated vines as indicated by isolines calculated from neutron probe measurements on four different dates during the season. Each isoline is the mean generated from soilwater content measurements from all access tubes (Fig. 2).

9, all greater than 1.8 m away from the emitter, indicated that a dry zone developed in which the water status decreased more rapidly during the season than the mean SWC for the entire profile (Fig. 4A). From the soilwater isolines (Figs. 5B–5D), it is clear that the dry zone (Fig. 4A) was expanding during the season in that it was initially established near the soil surface (Fig. 5B) and progressed to almost 0.9 m deep by 8 August (Fig. 5D).

Table 1
Percent of total soil volume in the rooting zone of drip irrigated vines with soilwater content (SWC) at or above 16, 18, and 20% (v/v) on four selected dates during the season. Data were derived from Fig. 5

| SWC (% v/v) | % of total soil volume | | | |
|---|---|---|---|---|
| | 12 April | 24 May | 17 June | 8 August |
| ≥16 | 100.0 | 82.5 | 69.6 | 53.3 |
| ≥18 | 51.2 | 63.9 | 45.4 | 28.1 |
| ≥20 | 33.2 | 16.9 | 9.6 | 13.4 |

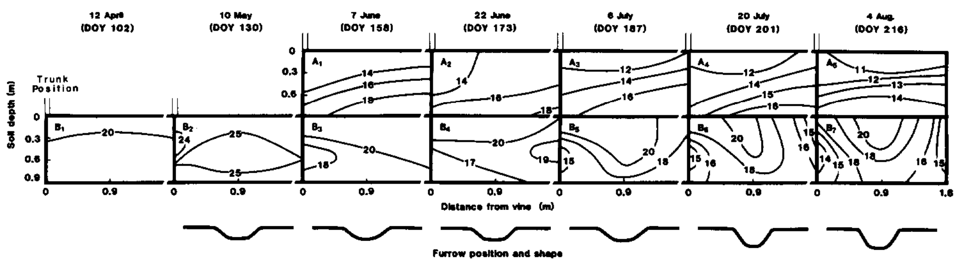


Fig. 6. Vertical and radial distribution of soil water for surface irrigated vines as indicated by isolines calculated from neutron probe measurements on seven different dates during the season. Upper row of figures ($A_{1-5}$) indicates SWC just prior to irrigation; lower row ($B_{1-7}$) indicates SWC 3 days after each irrigation. Each isoline is the mean generated from SWC measurements from all access tubes (Fig. 2). Furrow position and shape are indicated below the figures. Note that furrow shape was changed for the last two irrigations.

Under furrow irrigation, the soilwater profile at the beginning of the season was uniform (Figs. 4B and 6$B_1$). Following the first furrow irrigation, the entire profile was at very high SWC (Fig. 6$B_2$ and Table 2). As soil water was depleted, the profile became stratified vertically with SWC increasing with depth (Fig. 6$A_1$). However, 3 days after surface irrigating, the stratification was inverted, i.e. SWC decreased with depth (e.g. compare Figs. 6$A_2$ and 6$B_4$). This pattern of inverting the soilwater stratification during an irrigation cycle was repeated throughout the remainder of the season (Fig. 6).

As the canopy developed and evaporative demand increased during the season, applied water was more rapidly evapotranspired. The proportion of the soil profile that remained at high water status 3 days after irrigating diminished, and the proportion that was at low water status prior to irrigation increased. Thus, 3 days after irrigating on 7 June, 52% of the profile was wet (SWC > 20%), whereas only 12% of the profile was wet after the irrigation on 4 August (Table 2). The fraction of the soil volume that was above 16% SWC just prior to irrigation decreased from about 42% on 7 June to about 0% on 4 August (Table 2). Following each irrigation, the persisting wet soil, near the surface directly above the furrow, decreased in volume (Fig. 6$B_{4-7}$). From this wet region, SWC decreased laterally

Table 2
Percent of total soil volume in the rooting zone of surface (furrow) irrigated vines with soilwater content (SWC) at or above 16, 18, and 20% (v/v) on several dates during the season. Data were derived from Fig. 6

| SWC (% v/v) | % of total soil volume pre-irrigation | | | | |
|---|---|---|---|---|---|
| | 7 June | 22 June | 6 July | 20 July | 4 August |
| ≥16 | 42.4 | 29.4 | 26.4 | 11.4 | 0.0 |
| ≥18 | 18.8 | 23.5 | 0.0 | 0.0 | 0.0 |
| ≥20 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

| SWC (% v/v) | % of total soil volume post-irrigation | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 April | 10 May | 7 June | 22 June | 6 July | 20 July | 4 August |
| ≥16 | 100.0 | 100.0 | 100.0 | 100.0 | 88.5 | 80.7 | 63.2 |
| ≥18 | 100.0 | 100.0 | 91.9 | 60.9 | 66.7 | 39.8 | 29.9 |
| ≥20 | 71.4 | 100.0 | 52.3 | 33.3 | 37.9 | 11.4 | 11.5 |

Table 3
Soilwater content (SWC) before and after furrow irrigations, the volume of water applied each irrigation, and the percent of the water applied (% decrease) not found in the soil when SWC was measured 3 days after irrigation. SWC (% v/v) before and after the irrigation were calculated as the average of all the access tubes and depths. SWC was converted to l per vine using the soil volume per vine[a]

| Irrigation date (month/day) | Soilwater content (% v/v) | | Irrigation water (l per vine) | | |
|---|---|---|---|---|---|
| | Before | After[b] | Applied | Present after irrigation | % Decrease |
| 6/8 | 14.5±3.7 | 19.0±2.9 | 699 | 361.4 | 48.3 |
| 6/23 | 14.7±3.1 | 19.0±4.3 | 639 | 345.3 | 46.0 |
| 7/7 | 13.9±3.2 | 18.2±3.6 | 654 | 345.3 | 47.0 |
| 7/22 | 13.7±2.7 | 17.4±3.8 | 588 | 297.1 | 49.5 |
| 8/7 | 12.8±2.7 | 16.4±4.0 | 540 | 289.1 | 46.5 |
| $\bar{X}$ | 13.9 | 19.0 | 636.5 | 327.6 | 47.5 |

[a] Soil volume per vine: $8.92\ m^2 \times 0.9\ m = 8.03\ m^3$.
[b] Three days after the irrigation, except on 6/8, which was 4 days after.

and downward, but the SWC was always less on the vine side of the wet soil region than on the distal side (Fig. $6B_{4-7}$).

The mean soilwater content for the furrow plot, all depths of all access tubes, decreased from 24.7% to 18.8% before the first irrigation on 8 May (Fig. 4B). The average maximum and minimum soilwater content for subsequent irrigation cycles were 19% and 13.9%, respectively (Fig. 4B and Table 3). Thus, SWC 3 days after irrigation increased an average of 4.08% ($s = 0.4\%$) over that present before irrigation (Table 3). This increase accounted for about 52% of the applied water in each irrigation. The remainder was considered water losses by soil and vine evaporation within the 3 days after irrigation (Table 2), but small amounts may have moved below the measurement depth.

The shape of the furrows was changed in the last two irrigations (Fig. 6) in an effort to reduce evaporative loss by exposing a smaller evaporative surface. Water penetrated to a similar depth beneath the altered furrow, but recharge of more lateral positions was less than in previous irrigations (compare Figs. $6B_5$ and Fig. $6B_{6,7}$) and the total applied water was slightly less (Table 3). However, there was no evidence of increased irrigation efficiency. For each irrigation, the difference between the volume of water applied and the increase in SWC determined 3 days after irrigation indicated a loss of close to 50% of the applied water (Table 3).

Mapping of root intersections showed that the root systems and distribution of drip and furrow irrigated vines differed significantly (Fig. 7). The root system of drip irrigated vines consisted of a highly branched mass of fine, fibrous roots with a horizontal growth pattern. Few roots of drip irrigated vines were observed in deeper soil layers. In contrast, only a few roots were found in the top 0.2 m of soil in furrow irrigated vines where the roots showed a tendency of growing vertically

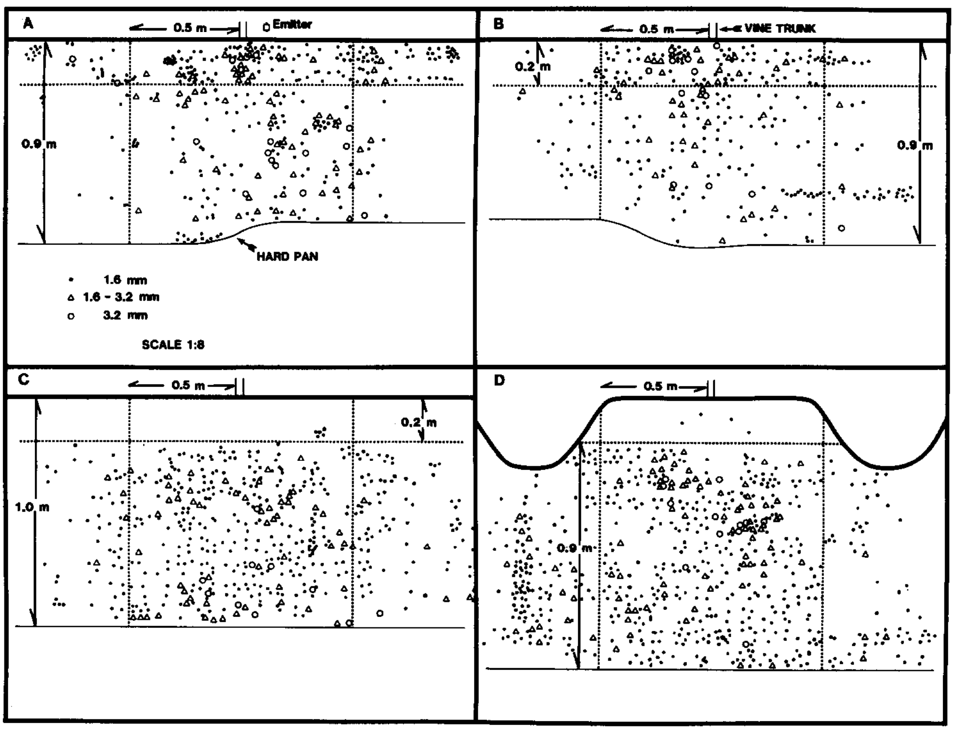


Fig. 7. Root distribution of drip (A and B) and furrow (C and D) irrigated vines. Trenches were open perpendicular to the row (transversal view; B and D) and along the row (lateral view; A and C) 15 cm from the trunk. Root diameter is also indicated.

Table 4
Total number and distribution of roots in the soil profile for 3-year-old drip and furrow irrigated vines. Percentages of the total quantified at the 0–20 cm horizon, 10 cm horizons below 20 cm, and 1 m wide central soil profile (Fig. 7). Data are the mean of the perpendicular and transversal views for each irrigation system, followed by the standard errors

| | Total no. roots | % in 0–20 cm horizon | % in 10 cm horizons below 20 cm | % within ±0.5 m wide profile |
|---|---|---|---|---|
| Drip | 352±37 | 48±7 | 7.5±1 | 78–2 |
| Furrow | 584±67 | 1±0 | 11±0.6 | 70–2 |

toward deeper soil layers. Approximately 50% of the total number of roots counted in the soil profile wall were found in the top 0.2 m of the soil for the drip irrigated vines, compared with 12% for the furrow irrigated vines (Table 4). The root system of furrow irrigated vines was more uniformly distributed throughout the soil profile wall averaging 11% of the total per each 0.1 m horizon below the first 0.2 m horizon (Table 4). Although the lateral distribution of the drip root system was slightly more limited, most of the root system in both types was located within 1 m wide (0.5 m each side of the vine) soil profile (Fig. 7 and Table 4).

## 4. Discussion

The data show that soilwater and root distributions of young (3-year-old) vines differed significantly under drip and furrow irrigation. The initial vertical distribution of soil water became a predominately lateral distribution upon drip irrigation, whereas the distribution remained primarily vertical under furrow. However, the vertical stratification of SWC inverted during each furrow irrigation cycle indicating temporally and spatially dynamic availability of soil water. In contrast, a relatively static and localized region of wet soil was established under drip irrigation. Low SWC was established 1 m away from the drip-irrigated vines early in the season and maintained thereafter.

The differences in soilwater distribution resulted in the development of a localized region of high root density near the soil surface and the emitter under drip compared with the greater lateral and deep growth of roots under furrow irrigation. In addition to reaching greater depth and lateral distance from the vine, roots of furrow-irrigated vines were much more evenly distributed through the soil volume explored by the root system. Root growth and branching proliferated in the wetted zone under drip. In neither irrigation system was the entire soil volume available per vine explored. Few roots and little water uptake at distances greater than 0.75 m away from vine row in furrow indicated limited potential for row-to-row interaction for young vines on these soils, although root systems of more mature vineyards may meet across narrow rows (Gander and Hughes, 1988). Under drip irrigation, the potential for row-to-row interaction appears minimal.

The confinement of the root system to the wetted zone when a restricted soil volume is wetted by drip irrigation has often been observed in grapevine (Goldberg et al., 1971; Safran et al., 1975) and other woody perennials (Black and Mitchell, 1974; Willoughby and Cockcroft, 1974; Levin et al., 1979). Root confinement due to root pruning (Buttrose and Mullins, 1968) or containers (Richards and Rowe, 1977) impairs shoot development. Plants with a confined root system may deplete water and nutrients more quickly and thus become more dependent upon proper irrigation and fertilization than plants with unrestricted root growth (Atkinson, 1980; Elfving, 1982). Although root confinement due to drip irrigation has not been found to affect yield, quality, or vegetative growth of grapes in previous studies (Goldberg et al., 1971; Bernstein and Francois, 1973; Smart et al., 1974; Peacock et al., 1977), the potential for altered nutrient relationships has not been addressed (see Araujo et al., 1994). Gross root structure also differed with drip irrigation resulting in a highly branched mass of fibrous roots and furrow irrigation resulting in thicker, more suberized roots. Other factors, possibly nitrogen uptake and availability, may have also played a role in root distribution under conditions of adequate soil water (Bar-Yosef et al., 1980).

More uptake of stored water occurred under furrow than under drip irrigation. With a more confined root system under drip, significantly more soil was explored under furrow irrigation, even by young vines. Water recharge and extraction at 0.6–0.9 m, where irrigation and soil evaporation had the least impact on SWC, indicated a greater loss in soil water than can be attributed to irrigation supply. For irrigation cycles after the first one, water extraction from 0.6 to 0.9 m decreased SWC about 6.3%, but irrigation water recharge increased SWC only 3.4%. For the last five irrigation cycles, this amounts to a total soilwater loss of 14.5% that is not attributable to irrigation supply. Also, it appears that significant uptake of stored soil water occurred at all depths early in the season. The average decrease in overall SWC between irrigations was greater (4.6%) than the average increase in SWC after irrigations (4.1%). This contrast was particularly striking following the first irrigation when the decrease in mean SWC for the entire soil volume between irrigations was approximately 100% greater after the first than after subsequent irrigations. Much of this decrease in soilwater content must be due to plant uptake of stored soil water, although surface evaporation and deep percolation undoubtedly also contributed. The SWC in the lower soil profile continued to decrease in drip vines throughout the season also, but the decrease was slight and occurred without recharge.

The water loss from soil drying away from the drip wetted zone is attributed largely to soil evaporation from the upper 0.15 m and to gradual uptake by distal roots. The overall water loss during the season from the dry zone of 10.4% (Fig. 4A) is equivalent to a rate of evaporation of 0.7 mm day$^{-1}$ from that soil volume (accessed by Tubes 7, 8, and 9). Using a clay soil, Ritchie and Burnett (1971) reported soil evaporation rates of 0.25–0.5 mm day$^{-1}$ at similar soilwater contents. Our higher estimate may be due primarily to greater evaporative demand.

On a clay loam soil, Peacock et al. (1977) found that water flow occurred horizontally away from the vine and upward at a distance of 1–1.5 m from the vine row, although this was not necessarily a consequence of surface evaporation.

The difference between the volume of furrow-applied water and the increase in SWC measured 3 days after irrigation indicated large water losses during that interval. Low water infiltration rates are a well established problem on these soils (Department of Land, Air, and Water Resources–Cooperative Extension Joint Committee, 1984) and contribute to increased surface evaporation. Changing the furrow to a deeper, narrower shape did not reduce evaporation loss. Almost the entire soil surface remained wet during the 3 day interval, and free water was observed in the furrows during the second day after irrigation. Thus, evaporation rates comparable with free water surfaces would have occurred (Adams et al., 1976). This can amount to as much as 7–8 mm day$^{-1}$ in this region; thus, over the 3 day period, as much as 21–24 mm could be evaporated. The surface evaporation problem exists, but is clearly diminished under drip irrigation where the wetted soil area is approximately 80% less and the rate and duration of application can be adjusted to the steady state infiltration of the soil.

Similar growth and water status were observed in the two irrigation systems used in this study (Araujo et al., 1994). When water was applied at 0.66–1.70 of the rate required for mature vine canopies at the same site between 10 May (DOY 130) and 1 July (DOY 182), SWC in the wetted zone under drip remained constant. Only 12.5% more water was applied to furrow vines than to drip vines over the growing season. This difference in volume of water required to produce similar growth is small compared with previous comparisons: 20% in grapevines (Smart et al., 1974), 22% in cabbage (Bucks et al., 1974), and 30% in pepper (Bernstein and Francois, 1973). We focused on a young vineyard because that is when the irrigation efficiency of furrow irrigation might be lowest. However, efficiency of furrow irrigation in a mature vineyard that is applied early in the season may decrease further if the vines develop sparse shallow roots.

The results show that with careful use of furrow irrigation supply, irrigation efficiency advantages of drip can be less than previously reported. However, some apparent efficiency under furrow irrigation is attributable to the uptake of stored soil water that did not occur with drip irrigation. More irrigation water was evaporated and more winter precipitation as stored soil water was extracted by furrow vines. As the root system of the perennial vine develops, greater use of stored and furrow applied water may cause further convergence of the efficiencies of drip and furrow irrigation of grapevines, provided there is sufficient winter rains to recharge the soil profile.

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