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A comparative study of young 'Thompson Seedless' grapevines (*Vitis vinifera* L.) under drip and furrow irrigation. II. Growth, water use efficiency and nitrogen partitioning

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Abstract

The response of 3-year-old grapevines (*Vitis vinifera* L. cultivar 'Thompson Seedless') to furrow and drip irrigation was quantified in terms of water status, growth, and water use efficiency (WUE). Drip irrigation was applied daily according to best estimates of vineyard evapotranspiration while furrow irrigations were applied when 50% of the plant available soilwater content had been depleted. Drip and furrow irrigated vines showed similar water status (midday leaf water potential, Ψ_l) and shoot growth patterns throughout the season. Dry weight partitioning was not significantly different between treatments but root mass was somewhat larger for the furrow than drip irrigated vines. Nitrogen concentrations of the fruit and roots were significantly ($P<0.05$) less for the drip irrigated vines when compared with the furrow treatment. Similar WUE (kg water kg^{-1} fresh fruit wt.) were obtained for both treatments indicating that furrow irrigation was as efficient as drip irrigation under the conditions of this study. The data indicate that drip irrigation may increase the potential for control of vine growth by making vines more dependent on irrigation and N fertilization than furrow irrigation.

Keywords: Root growth; Leaf water potential

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1. Introduction

Furrow is the most common method used for vineyard irrigation, although the use of drip irrigation has increased in recent years. With furrow irrigation, the soil is considered a storage vessel for water and the objective of the irrigation is to replenish the soil water after a certain degree of depletion has occurred that only causes minimum stress to the plants (Stegman, 1983). The concept of water storage capacity of the soil is less relevant for high frequency (less than 7 day interval) drip irrigation where the possibility of applying small amounts of water at a low rate makes it feasible to irrigate the plants according to their evapotranspiration (ET) (Phene and Beale, 1976; Elfving, 1982; Stegman, 1983). Provided that the water requirements of well-watered plants are the same regardless of the irrigation method used (Bucks et al., 1974; Doorenbos and Pruitt, 1977), the efficiency of a particular method will depend upon the capability of supplying sufficient water to the plants while reducing water losses.

The efficiency of drip irrigation has been reported to be greater than that of furrow irrigation in grapevines and other crops (Bernstein and Francois, 1973; Smart et al., 1974; Freeman et al., 1976; Peacock et al., 1977). It is not clear whether the potential for maximum efficiency of furrow irrigation treatments was fully exploited in all the aforementioned experiments. Timing criteria for furrow irrigation generally was based on either tensiometers or on the accumulation of certain amounts of estimated crop ET without considering the actual soilwater content in the root zone and its relationship with soil matric potential. This may result in decreased irrigation efficiency where improper timing increases water loss by evaporation and deep percolation. It should be noted that there are data indicating that water use efficiency of furrow irrigated crops may be similar to those irrigated via low volume methods such as drip (Sammis, 1980).

A small portion of the soil volume around the plant is wetted using drip irrigation when applied water amounts are keyed to actual crop ET. The majority of root growth is confined to the wetted zone in grapevines (Goldberg et al., 1971; Safran et al., 1975; Araujo et al., 1994) and other woody perennials (Black and Mitchell, 1974; Willoughby and Cockcroft, 1974; Levin et al., 1979). Root confinement due to drip irrigation does not seem to affect shoot growth significantly as yield, quality, and vegetative growth have been shown to be similar between drip and surface or sprinkler irrigated plants (Goldberg et al., 1971; Bernstein and Francois, 1973; Smart et al., 1974; Natali and Xiloyannis, 1975; Peacock et al., 1977). Though quantitative data are lacking, the above data would indicate a shift in the root/shoot ratio under drip irrigation.

Plants with a confined root system may deplete water and mineral nutrients more quickly in the restricted root zone and thus become more dependent on proper irrigation and fertilization than plants with unrestricted roots (Atkinson, 1980; Elfving, 1982). Chalmers et al. (1981) suggested that root confinement, similar to that obtained under drip irrigation, may significantly improve the effectiveness of using irrigation to regulate plant growth via plant water status. Root confinement using drip irrigation also may lead to greater control of plant growth with N fertilizer when compared with other irrigation methods.

This study was conducted in order to determine: (1) the effect of irrigation system on vine water status and vegetative growth from budbreak to fruit harvest, (2) dry weight and nitrogen partitioning for drip and furrow irrigated vines, and (3) water use efficiency of drip and furrow irrigation in a 3-year-old vineyard.

2. Materials and methods

Vitis vinifera L. (cultivar 'Thompson Seedless') rootings were planted in 1984 at the University of California, Kearney Agricultural Center with vine and row spacings of 2.4 m and 3.6 m, respectively and an east–west row orientation. Two soil types of similar area occurred within the 1.2 ha vineyard; a Hanford fine sandy loam and a Hanford sandy loam (coarse–loamy, mixed, non-acid, thermic Typic Xerorthents) with a hardpan at a depth between 0.6 and 1.0 m for both. The trellis system consisted of a cross-arm 0.45 m in width at a height of 1.8 m with a wire at each end of the cross-arm. The vines were pruned to two 12-bud canes in February 1986. No fertilizer was applied.

The vines were furrow irrigated during the first growing season (1984). One-half of the vineyard was changed to drip irrigation on 26 April 1985. One emitter per vine ($3.8\,\mathrm{l\,h^{-1}}$ at 0.14 MPa) was located approximately 0.2 m from the trunk. Drip irrigation was applied daily from 22 April (day of year (DOY) 112) to 15 August (DOY 227) 1986, when irrigation was stopped in order to produce natural raisins. Water was applied to the drip irrigated vines according to the relation:

$$WA = (K_c \times ET_o)0.7 \quad (1)$$

where WA is water applied, K_c is the crop coefficient for grapevines, ET_o is potential evapotranspiration, and 0.7 is the coefficient used in adjusting the crop ET of mature vines to the smaller canopy of the 3-year-old vines used in this experiment (estimated from the number of shoots of mature versus 3-year-old vines). K_c values were those used by Grimes and Williams (1990). ET_o was obtained using meteorological data collected in close proximity to the study site by the California Irrigation Management Information System. 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.

Furrow irrigation was initiated on 7 May 1986 (DOY 128). Two broad-based furrows per row were used for the first four irrigations. Furrow shape was changed to a 'V' shape for the last two irrigations to increase water penetration and reduce soil evaporation. Furrow irrigation was scheduled according to 50% depletion of the soil water available for the vineyard. Soil water available for the vine was considered to be the soilwater content (SWC) between 0.033 and 1.5 MPa of matric suction (Richards and Weaver, 1944; Slater and Williams, 1965). The amount of water to apply per irrigation for the furrow treatment was calculated following the relation:

$$WA = \frac{\Delta \mathrm{SWC}}{100} \times SV \qquad (2)$$

where WA is water applied, ΔSWC is the difference between soilwater content at field capacity (22% v/v) and soilwater content before the irrigation, and SV is the soil volume. Soil volume was determined from surface area and the average soil depth (0.9 m, determined from 38 samples of soil depth, $s^2 = 0.06$ m). The flow rate at the pipe openings to each of the furrows was measured at the start of each irrigation.

Percent volumetric SWC was monitored throughout the experiment in each irrigation treatment by the neutron back-scattering method using a neutron moisture meter (Troxler model 3332 depth moisture gauge). In order to study the response of vines to soilwater deficits 25 replicates, two vines per replicate, were randomly selected within each soil type in the drip irrigated plot. These vines received no water during the experimental period. Midday leaf water potential (Ψ_l), measured with the pressure chamber (Grimes and Williams, 1990), was monitored throughout the study beginning on 13 April (DOY 103). Recent, fully expanded leaves were measured on each sampling date using at least six replicates per treatment.

Primary shoot lengths were measured repeatedly on the same four shoots located at Nodes 3, 6, 9 and 12 from the base of the fruiting canes. A total of 16, 14, and four replicate vines were used for the furrow, drip, and stressed treatments, respectively. Leaf area per vine throughout the season was estimated using the relationship: $y = 0.13 + 0.0044x + 0.0000031x^2$ ($r^2 = 0.88$), where x and y are shoot length and leaf area per shoot, respectively, and the number of primary shoots per vine.

Six entire vines were harvested from each irrigation treatment on 8 September 1985 and 21 August 1986. Leaf area was determined for each vine with an area meter (LiCor model 3100). A rectangular hole corresponding to the soil volume of each vine (vine in the center) was dug using a backhoe until the uppermost layer of the hardpan was reached. The roots were carefully separated from the soil by hand. The harvested roots were washed to remove any remaining soil particles. All vine parts subsequently were separated and dried at 70°C in forced-air ovens until no further decrease in weight was measured. Total nitrogen concentration was measured on samples of ground tissue of the different vine parts by the Kjeldahl procedure.

Six 100 berry samples per irrigation treatment were taken on 25 August 1986. Measurements of berry weight and °Brix were performed on the same date.

Data were analyzed using analysis of variance for a randomized complete block design. Following a significant F value, mean separation was by Duncan's Multiple Range test. Leaf water potential data for the two treatments were analyzed using the Student t-test.

3. Results

For drip and furrow irrigated vines, timing and volume per application differed greatly but total volume applied over the season differed slightly. The volume of water applied per vine was about 12% less in the drip (3343 l) than in the furrow (3819 l) treatment. A total of six furrow irrigations were applied between 8 May (DOY 128) and 7 August (DOY 219) with an average application rate and frequency of 636.5 l per vine and 18.2 days, respectively. Daily application rate per vine for the drip irrigation treatment increased throughout the experiment, from a minimum of 11.4 l per vine on 22 April (DOY 112) to a maximum of 43.4 l per vine on 10 August (DOY 222). The seasonal average was 29.7 l per vine day^{-1}. The depletion of soil water between budbreak and harvest amounted to 562 and 803 l per vine for the drip and furrow irrigated vines, respectively (calculated from Fig. 4 in Araujo et al., 1994). Therefore, total vine water use between budbreak and harvest was 18% greater for the furrow compared with the drip vines (see Table 2).

Despite the differences in water application, water status was similar for drip

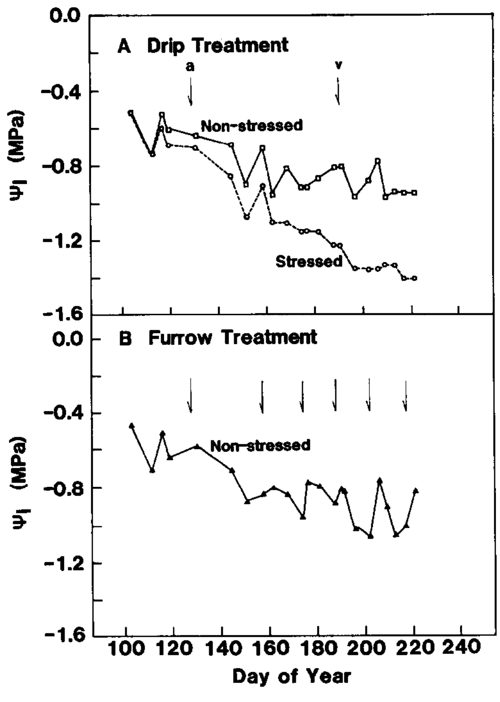

Fig. 1. Midday leaf water potential (Ψ_l) from 13 April (DOY 103) to 9 August (DOY 219) for drip and furrow irrigated grapevines. Each point represents the mean of at least six individual leaf measurements per treatment. The 'stressed' data refer to measurements taken on vines (in the drip irrigated vineyard) in which water was withheld throughout the experiment. The arrows indicate date of irrigation in the furrow treatment. Dates of anthesis (a) and veraison (v) also are indicated.

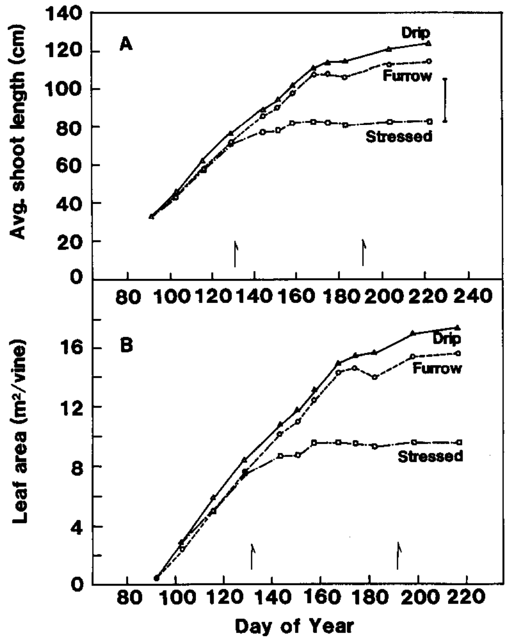

Fig. 2. Average primary shoot length (A) and estimated total vine leaf area (B) for drip and furrow irrigated grapevines and vines in which water was withheld throughout the growing season (stressed). Each point in A represents the mean of 14, 16 and four vines (four shoots per vine) for drip, furrow and stressed vines, respectively. Average shoot length was significantly ($P<0.05$) less for stressed vines than vines in either irrigation treatment after 17 June (DOY 168). Total vine leaf area was estimated from the relationship between shoot length and leaf area of the shoot and number of shoots per vine. The arrows indicate dates of bloom (left arrow) and veraison (right arrow).

Table 1
Dry weight (g per vine) of drip and furrow irrigated 'Thompson Seedless' grapevines at fruit harvest of third leaf. There were no significant differences between the two treatments. Data are means of $n=6$

Treatment	Leaves	Shoots (s)	Fruit[a]	Canes	Trunk	Roots (R)	Vine	R/S
Drip	1224	1616	4098	235	1029	647	8850	0.08
Furrow	1109	1357	4837	213	1101	854	9471	0.10

[a] Cluster fresh weights for the drip and furrow irrigated vines were 21.3 kg per vine and 25.2 kg per vine, respectively.

and furrow vines irrigated throughout the season. Midday leaf water potential (Ψ_l) decreased from −0.5 MPa to about −0.9 MPa between 13 April (DOY 103) and 31 May (DOY 151) for both treatments (Fig. 1). This decrease occurred despite a relatively high SWC for both irrigation treatments and reflects the increasing climatic evaporative demand during that period. After 31 May Ψ_l for the furrow irrigated vines was positively correlated ($r^2=0.73$) with the soil-

Table 2
Vine water use, total dry matter production per vine, and water use efficiencies for the 1986 growing season

Treatment	Vine water use[a] (kg per vine)	Total dry wt. accumulation in 1986[b] (kg per vine)	WUE[b] ($kg\ kg^{-1}$ dry wt.)	WUE[c] ($kg\ kg^{-1}$ dry wt.)	WUE[d] ($kg\ kg^{-1}$ fresh wt.)
Drip	3905	7.9	494	953	183
Furrow	4622	8.5	544	956	183

[a] Vine water use is the sum of applied water amounts and the contribution of soil water to ET_c (calculated from Fig. 4 in Araujo et al., 1994).
[b] Total dry weight produced during 1986 was estimated by subtracting from the 1986 vine weight at fruit harvest the dry weight of 1986 canes (2-year-old wood, from Table 1) and the 1985 dry weight of the permanent parts (roots and trunk) measured at fruit harvest. (Root dry weights at fruit harvest in 1985 were 365 g and 312 g for drip and furrow vines, respectively. Trunk dry weights at fruit harvest in 1985 were 362 g and 400 g for drip and furrow vines, respectively.) Water use efficiency was calculated dividing values in the first column by the corresponding weights.
[c] Water use efficiency for cluster dry weight production.
[d] Water use efficiency for cluster fresh weight production.

Table 3
Leaf area, mean total primary and lateral shoot length per vine, mean primary and lateral shoot number per vine, berry weight, and soluble solids of fruit of drip and furrow irrigated vines at harvest of 3-year-old 'Thompson Seedless' grapevines

Treatment	Leaf area (m^2 per vine)	Primary shoot length (cm)	Primary shoot number (no. per vine)	Lateral shoot length (cm)	Lateral shoot numbers (no. per vine)	Berry weight (g)	Soluble solids (°Brix)
Drip	18.9a	155.9a	34.4a	31.1a	109a	1.37a	21.2a
Furrow	15.1a	129.5b	40.7a	23.6a	97a	1.29a	20.3b

Means within a column followed by a different letter are significantly different at the 5% level.

Table 4
Nitrogen concentration (% dry wt.) of different tissues for vines which received drip or furrow irrigation. Samples were taken at fruit harvest of third leaf (season). Data are the means of $n=6$

Treatment	Leaves	Shoots	Fruit	Canes	Trunk	Roots	Vines
Drip	2.19a	0.36a	0.46a	0.24a	0.33a	0.66a	0.68a
Furrow	2.20a	0.41a	0.55b	0.27a	0.34a	0.87b	0.72a

Means within a column followed by a different letter are significantly different at the 5% level.

water content. Between 31 May and 9 August (DOY 221), Ψ_l averaged -0.9 MPa for both treatments ($s^2=0.03$ and 0.1 MPa for drip and furrow treatments, respectively). The Ψ_l of drip irrigated vines was significantly greater ($P<0.05$) than the Ψ_l of furrow irrigated vines on Days 158, 202 and 213 and significantly lower on Days 130, 162 and 176. The Ψ_l of vines that received no water decreased throughout the experimental period from -0.5 MPa to a minimum of approxi-

Table 5
Nitrogen content (g N per vine) of different vine parts for vines which were watered either by drip or furrow irrigation. Data are means of $n=6$

Treatment	Leaves	Shoots	Fruit	Canes	Trunk	Roots	Vine
Drip	26.8a	5.9a	19.0a	0.57a	3.4a	4.3a	60.0a
Furrow	24.4a	5.5a	26.7b	0.56a	3.7a	7.5b	68.4a

Means within a column followed by a different letter are significantly different at the 5% level.

mately -1.4 MPa. This reduction was described by the equation $y=2.42-0.078x$ ($r^2=0.94$), where y and x are Ψ_l and DOY, respectively.

Shoot length increased linearly for both drip and furrow irrigated vines up to 17 June (DOY 168) after which the maximum length attained was approached curvilinearly (Fig. 2A). Shoot length of the stressed vines increased linearly up to 9 May (DOY 129) and then leveled off after 7 June (DOY 158). Average shoot length on 11 August (DOY 223) was 124 cm, 115 cm, and 83 cm for drip, furrow, and stressed vines, respectively. There was a square root relationship between shoot length and DOY which yielded coefficients of determination of 0.99, 0.99 and 0.97 for drip, furrow, and stressed vines, respectively. The average rate of shoot growth between 3 April (DOY 93) and 7 June was 1.06 and 1.03 cm day^{-1} for drip and furrow irrigated vines, respectively. From 7 June to 11 August the average growth rate was 0.51 cm day^{-1} and 0.28 cm day^{-1} for vines in the drip and furrow irrigated treatments, respectively. The average rate of shoot growth for stressed vines was 0.99 cm day^{-1} and 0.52 cm day^{-1} between 3 April and 26 April (DOY 116) and 26 April and 7 June (DOY 158), respectively.

Leaf area measured on drip irrigated plants on 9 May (DOY 129) and 4 August (DOY 216) was 7.9 m^2 (only one vine) and 17.9 m^2, respectively. Estimated leaf area per vine on the last sampling date (11 August, DOY 223) was 17.3 m^2, 15.6 m^2, and 9.6 m^2 for drip, furrow, and stressed vines, respectively (Fig. 2B). Measured leaf area per vine at harvest, 20 August (DOY 232), was 18.9 m^2 and 15.1 m^2 for drip and furrow vines, respectively (see Table 5).

There were no significant differences in total dry weight (Table 1) and WUE (Table 2) between drip and furrow irrigated vines. In addition, no significant differences were found between leaf, shoot, cane, trunk, root and fruit dry weights and root/shoot ratio of drip and furrow irrigated vines. Although the mean root dry weight was 30% greater for furrow irrigated vines than for drip irrigated vines, large vine to vine variability precluded achieving statistical significance. There were no significant differences in leaf area, average secondary shoot length, number of primary and secondary shoots, and increase in trunk diameter per vine (unpublished data); however, primary shoot length per vine was significantly ($P<0.05$) greater in drip irrigated vines (Table 3).

Total vine N concentration and content were not significantly different between the furrow and drip irrigated vines (Tables 4 and 5) although both were slightly higher for furrow irrigated vines. The N concentration and content of the roots and fruit were significantly greater for the furrow irrigated vines. Berry weight did not differ between the two treatments, but °Brix was significantly greater for drip irrigated vines. Fruit from the stressed vines were not marketable due to severe berry desiccation.

4. Discussion

The water status of both drip and furrow irrigated vines, as assessed by midday Ψ_l, generally was similar in this experiment. For both treatments, Ψ_l was substantially greater than in non-irrigated (stressed) vines throughout the experiment. The decrease in Ψ_l between 13 April (DOY 103) and 31 May (DOY 151) of about 0.4 MPa for both drip and furrow vines while soilwater content remained high has been observed previously in grapevines (Matthews et al., 1987; Matthews and Anderson, 1989; Grimes and Williams, 1990). This may be the result of increasing evaporative demand (and resulting increase in transpiration), ET_c would require a more negative Ψ_l to draw water through the liquid phase resistance in the plant. The extent to which the decrease in Ψ_l is attributable to lower turgor and solute potential is not known. Stegman et al. (1980) suggested that osmotic adjustment may take place to compensate for increases in liquid phase plant resistance to liquid flow as the season progresses. Schultz and Matthews have shown significant osmotic adjustment in roots (1988) and leaves (1993) in grapevines. Consequently, the Ψ_l required to inhibit shoot growth may change during the growing season.

In this study, the rate of shoot growth of stressed vines decreased after DOY 129 when Ψ_l began a rapid decline. In contrast, the rate of shoot growth of irrigated vines was maintained high to DOY 166 despite a drop in Ψ_l to approximately -0.9 MPa. Similar shoot growth in drip and furrow irrigated vines (Fig. 2) indicates that the water deficit experienced by drip and furrow irrigated vines, if any, was comparable. The high SWC in the wetted zone of drip irrigated vines and in the furrow irrigation treatment after DOY 160 (Araujo et al., 1994) and the maintenance of similar SWC values for both treatments suggests that the reduction in the rate of shoot growth observed after DOY 168 was due to something other than increasing water deficit, perhaps increased photosynthate demand of the developing fruit. While the length of individual shoots was highly variable within a vine it was observed that some shoots stopped growing early in the season and some kept growing until the end of the experiment, without any apparent pattern of behavior.

Similarities between measured and estimated leaf area indicated that leaf area per vine was well estimated using the relationship between shoot length and leaf area of shoots. Thus, shoot length may be used as an alternative to actual measurements of leaf area. This differs from previous studies in that entire vine leaf area was estimated as opposed to estimates of individual leaf area (Smith and Kliewer, 1984; Elsner and Jubb, 1988). Entire vine leaf area would provide a more useful index in assessing canopy management practices and validation of grapevine growth models (Gutierrez et al., 1985; Williams et al., 1985, 1993; Wermelinger et al., 1991).

It appears that the coefficient (0.7) used for these 3-year-old vines, as compared with a coefficient of 1.0 for a mature vine, was sufficient in estimating actual crop ET in this vineyard. In addition, leaf area of drip irrigated vines measured on 4 August was 72% of the leaf area of mature 'Thompson Seedless' vines measured on the same date in a plot next to the experiment (Williams, 1987). However, leaf area is not the sole determinant of the crop coefficient (Burman et al., 1983). Factors such as management practices, soil variability, weather and location will affect the seasonal crop coefficient curve (Ritchie and Johnson, 1990).

Calculated vine ET in this study (Table 2) was less for the drip than the furrow irrigated vines. Vine ET under drip irrigation (3905 l per vine) reported here compares favorably with measured ET (3800 l per vine) using a weighing lysimeter of drip irrigated, 3-year-old vines from budbreak to harvest (Phene et al., 1991). As discussed in the preceding paper, ET of the furrow irrigated vines was greater due to more soil evaporation but also slightly greater utilization of soil water. This would be attributed to the more widespread root system of vines grown under this irrigation system (Araujo et al., 1994).

The amount of water a crop consumes per unit productivity and the various ways in which it is determined have recently been reviewed (Howell, 1990). Early on this relationship was termed the 'transpiration ratio' and was calculated as the amount of water transpired either as a function of net CO_2 assimilation rate or dry matter produced. In a review of the literature by Fischer and Turner (1978), it was concluded that this ratio (kg water transpired per kg dry matter produced) for C_3 plant species was approximately 670. However, this conclusion must be viewed with caution in that many times this ratio was calculated without below-ground dry matter data. A more meaningful term for field studies is that of crop 'water use efficiency' (WUE) defined as the ratio of crop production to ET_c, which includes water loss to both transpiration and soilwater evaporation (Viets, 1962). As vine transpiration was not determined in this study, we calculated WUE for both irrigation treatments and expressed it as a function of either total vine seasonal dry matter accumulation or fruit biomass (dry and fresh weight basis). It should be pointed out that the WUE for seasonal dry matter production in this study included measures of below-ground biomass.

The WUE obtained in this study for the drip and furrow irrigated vines (494 kg kg^{-1} total vine dry wt.and 544 kg kg^{-1} total vine dry wt., respectively) were greater than the transpiration ratio values for C_3 annual plant species presented in Howell (1990) despite the fact that our values included soilwater evaporation. This would indicate that grape is very efficient at utilizing available water when compared with annual plant species or it may indicate that root biomass was not included in those studies. While the furrow irrigated vines used 50 more kg of water to produce a kg of plant dry weight than the drip vines when averaged across the entire season, the WUE for reproductive growth (expressed either on a dry or fresh wt. basis) were almost identical between the two (Table 2). The majority of the vegetative growth of a vine in the San Joaquin Valley occurs prior to fruit set (approximately 1 June (DOY 151) for 'Thompson Seedless'). It was during the period budbreak to set that we obtained the greatest decrease in soil-water content with the decrease greater for the furrow irrigated vine (see fig. 4 in Araujo et al., 1994). This would have been when much of the vegetative growth occurred (prior to DOY 160). The relative constancy of SWC in both treatments after DOY 160 indicates that both sets of vines were receiving irrigation amounts close to vine ET. It is also subsequent to DOY 160 when most of the fruit growth is occurring. Therefore, as there were no significant differences in fruit yields between the treatments, and vines were being irrigated at the amount of water they used, one would expect similar WUE. It is interesting to point out that the calculated WUE for cluster fresh weight production in the study of Phene et al. (1991) was 167 kg kg^{-1} fresh weight. The closeness of values calculated in this study (183 kg kg^{-1} fresh wt.) to that of Phene et al. demonstrates that our estimates of ET_c were very accurate.

More dry weight was partitioned to the root system of the furrow vines than for the drip vines. Root dry weight increased 77% and 175% for the drip and furrow vines, respectively, between 1985 and 1986. Aboveground dry weight production (leaves, stems, and fruit) in 1986, was only 5% greater for furrow irrigated vines than drip vines. The smaller increase in root dry weight of the drip vines compared with furrow vines may be due to the lack of root growth outside the wetted zone in combination with the type of roots of drip vines. The highly branched mass of fine fibrous roots of drip vines may be an adaptive anatomical response to increase the root surface area, and therefore, root soil contact area, in order to supply enough water and mineral nutrients to the vine top from a limited volume of soil. Lastly, it has been demonstrated that roots of small diameter comprise only a minor fraction of the weight of the entire root system (McKenry, 1984; Williams and Smith, 1991). This also may explain the differences in root weights between the two irrigation treatments.

The root to shoot ratio is used in plant studies to provide a quantitative relationship between below and aboveground growth. Root/shoot ratios of woody perennial crops, such as grapevines grown in the field, also includes the annual increase in dry mass of the aboveground permanent structures. Therefore, age of the plant may affect the ratio obtained throughout the season and from year to year. The root/shoot (including the trunk and dry weights) ratios obtained in this study at harvest were 0.08 and 0.1 for drip and furrow irrigated vines, respectively. These values are similar to or slightly lower than those reported for potted vines (Hoffacker, 1977; Conradie, 1980). Comparisons with mature, field-grown vines at fruit harvest indicate that the ratio obtained on 3-year-old vines is much less. The root/shoot ratio for cultivar 'Chenin blanc' vines at harvest, grown in South Africa, varied from 0.9 to 1.4 depending upon how the soil was prepared prior to planting (Saayman and Van Huyssteen, 1980). The root/shoot ratio of non-irrigated cultivar 'Cabernet Sauvignon' vines grown in the Napa Valley of California was 0.38 at fruit harvest (Williams and Biscay, 1991). Lastly, the root/shoot ratio for 'Chenin blanc' vines grown in the San Joaquin Valley of

California varied from 0.36 at budbreak to 0.19 at fruit maturity (Mullins et al., 1992). Therefore, as has been shown for other crops (Russell, 1977; Kramer and Kozlowski, 1979; Richards, 1983), the root to shoot ratio in grapevine will change with plant growth, phenological development, age and management practices. Our data indicate that the type of irrigation used will also impact the root to shoot ratio and possibly as the vineyards mature differences between the two irrigation methods may become larger.

A general trend toward lower N concentration in various vine tissues of drip compared with furrow irrigated vines suggests a reduced N uptake in drip vines. This may be due to partial N depletion of the soil volume occupied by roots. The large root–soil contact area that is expected in the root system of drip irrigated vines would make nutrient mining of the wetted zone extensive, accelerating nutrient depletion. Approximately 15% of the total N accumulated per vine in both treatments was supplied by the irrigation water (water used in this study had an average nitrate concentration of 12 p.p.m.).

Nitrogen concentration of roots and fruit in drip irrigated vines was significantly lower than in furrow irrigated vines. Total N concentration increased in 'Thompson Seedless' berries as a result of increased levels of nitrate in the nutrient solution in which the vines were watered (Kliewer, 1971). The roots and fruit may be the first organs showing reduced vine N status to a mild N deficit, since no difference in the total vine biomass was found between furrow and drip vines. The dependence of dry weight production on plant N concentration, as proposed by Greenwood et al. (1986), would indicate that a N shortage in the root zone of the drip treatment may affect vine performance, particularly biomass production, in subsequent cycles. Hence, N fertilizer may be required on soils using drip when it would not be needed under furrow irrigation.

There was significantly higher soluble solids and a somewhat larger berry weight in drip irrigated vines compared with furrow irrigated vines. This may be due to the significant difference in leaf area/fruit weight ratios which were approximately 0.6 and 0.9 m^2 kg^{-1} for furrow and drip vines, respectively. Reductions in leaf area/fruit weight ratios have been shown to reduce fruit maturity and berry weight in defoliation experiments with 'Thompson Seedless' (May et al., 1969; Kliewer and Antcliff, 1970). However, a reduction in the ratio from 1.0 to 0.5 m^2 kg^{-1} due to interior canopy defoliation of field-grown 'Thompson Seedless' had no adverse effects on berry size and fruit maturation (Williams et al., 1987). Alternatively, the difference between the two treatments may be due to a more stable daily (or weekly) vine water status under drip irrigation.

5. Conclusions

This study demonstrated that comparable and high water use efficiencies under drip and furrow irrigation can be obtained for young 'Thompson Seedless' grapevines. Dry weight partitioning was not significantly affected by the irrigation methods in this experiment; however, nitrogen partitioning was. Nitrogen content of the fruit and roots was significantly lower in drip irrigated vines than in furrow vines partially as a result of the lower N concentration of roots and fruit. This lower N concentration may be attributable to a reduction in the N concentration of the soil solution in the dense and confined root zone of the drip irrigated vines. This confinement would diminish the capacity of soil reserves to act as a buffer and thus would make vines more dependent on irrigation water and N fertilization since the depletion in the root zone would be accelerated. Vine growth would therefore be easier to control with drip irrigation than with surface irrigation methods.

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