Cover Crop Enhanced Water Infiltration of a Slowly Permeable Fine Sandy Loam Soil

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ABSTRACT

Infiltration improvement in many sandy to medium texturized soils of California's Central Valley is often hampered by unfavorable soil properties, management practices, and the need to protect perennial crop roots. Minimum-tillage practices using chemical sprays, mulches, and cover crops avoid soil structure deterioration due to high traffic, but some properties of these methods are not universally acceptable. Furrow irrigation water infiltration, water use, and Thompson seedless grape production were evaluated on a Hanford fine sandy loam (mixed nonacid Typic Xerorthents) for three management systems over two years to develop a useful system. The compared systems were: 1) continuous cover crop [winter Blando bromegrass (Bromus mollis L.) followed by summer resident vegetation] (CC); 2) winter bromegrass, herbicide treated to form a summer mulch (CHT); and 3) bare soil, herbicide treated as needed (BHT). Cumulative infiltration for eight-hour irrigation periods, averaged over five irrigations, was 177 mm for CC, 125 mm for CHT, and 74 mm for BHT during the second season. Eight-hour cumulative infiltration was unchanged from the first year to the second for BHT but increased with CC from 107 mm to 202 mm at the first irrigation of each year; the increase for CHT was intermediate. Cover cropping between vineyard rows increased soil water depletion in the between-row zone profile by an average of 14 mm for CHT and 27 mm for CC for each drying cycle between
irrigations. Soil water depletion beneath vine rows was unchanged by treatment.
Slow water penetration into agricultural soils can be a serious production constraint when water stress affects crop vigor and water use efficiency is reduced by longer or more frequent irrigations, increased runoff, and high evaporative loss. In California, more than 20% of all irrigated cropland has water penetration problems (Land, Air, and Water Resources—Cooperative Extension Joint Infiltration Committee, 1984), with the sandy loams and fine sandy loams in the eastern San Joaquin Valley (SJV) of particular economic significance. Deep-rooted annuals and perennials that include alfalfa, cotton, vines, citrus, and fruit and nut trees are especially affected by slow water infiltration.

The severity of this soil problem in this region has been documented by Davis et al. (1968), Christensen et al. (1967) and Gal et al. (1990). During periods of peak crop water use, irrigation water may require ponding in grapevine furrows fully half the time in order to infiltrate enough water into the root zone to meet evaporative demand (L.P. Christensen, 1992, personal communication). Soil impermeability in the eastern SJV has been linked with high surface soil strength (Folorunso et al., 1992), low content of cracking clays (Davis and Schweers, 1971), poor soil aggregation (D.S. Munk, 1989, unpublished data), surface sealing (Grimes, et al., 1976), compaction (Meek et al., 1992), and an unfavorable particle size distribution (Gal et al., 1990).

Recognition of the deterioration of soil structure under high-traffic conventional tillage has given impetus to minimum-
tillage practices utilizing herbicide sprays, mulches, and cover
crops to increase infiltration. These methods are well-suited to
perennial vine and tree crops because they do not cause
mechanical damage to established root systems.

Higher infiltration rates generally have been reported
following cover crops than for herbicide no-till systems. This
has been demonstrated with a wide array of leguminous and non-
leguminous cover crops whether disked under as green manure or
left as permanent cover, whether grown in rainfed or irrigated
conditions, and whether seeded in isolation or into orchards or
vineyards (Williams, 1966; Miller et al., 1963; Scienza and
Miravalle, 1987; Saayman and Van Huyssteen, 1983). In the SJV
region, however, the impact of cover crops and herbicides on soil
permeability in perennial crop systems has been less clear-cut.
Little or no infiltration advantage was gained from chemical
sprays or cover crops over clean-tillage in vineyards (Werenfels
et al., 1963; Aljibury and Christensen, 1972; Christiansen et
al., 1966), while orchard infiltration under perennial cover was
nearly double that of herbicide-treated plots (Folorunso et

Suitability of a specific cover crop depends largely on its
compatibility with the perennial companion crop. Cover crops
have been found to suppress root growth near the soil surface in
vineyards and orchards (Van Huyssteen and Weber, 1980; Morlat,
1981; Haynes, 1980). Cover crops also tend to reduce grape yield
if they are not rotated every few years, especially in young
vineyards and under dryland conditions (Stevenson et al., 1986; Saayman and Van Huyssteen, 1983). Both adverse and beneficial effects can result from biological interactions between cover and perennial crops and competition for water and nutrients must be taken into consideration.

Infiltration benefits from cover crops must be evaluated in light of their additional water consumption. Central California orchard water use was 10% to 30% higher under continuous cover cropping than when herbicide-treated (Prichard et al., 1989). Shallow-rooted annual grasses are often selected to minimize root overlap with perennial crops, but these fibrous-rooted grasses are also highly competitive for water. A representative California annual grass, Bromus diandrus Roth., depleted soil water to -9 MPa at 0.4 m depth and had deeper roots in field plots than in its range habitat (Gordon et al., 1989). This suggests that water depletion is a primary cause of reports of vine and tree root exclusion beneath grass cover, although its significance under irrigation is uncertain. Prichard et al. (1989) found that a winter annual grass (Bromus mollis L.) formed a surface mulch in orchards during the summer that was very water efficient, with infiltration rates as high as continuous cover and water use as low as a herbicide treatment. Bromus mollis has also been less antagonistic to the growth of young grapevines than other cover crops (McKenry, 1991, unpublished data).

This research was initiated to evaluate the effects of low-traffic vineyard ground management systems on soil infiltration.
Bare soil (herbicide treated) was compared to winter and continuous winter and summer cover crop regimes. Tests were conducted on slowly permeable sandy loams and fine sandy loams which have previously been resistant to structural remediation.
MATERIALS AND METHODS

Field Conditions

A two hectare vineyard was utilized at the University of California Kearney Agricultural Center near Parlier (36°40' N, 119°32' W) in eastern Fresno County. The soil was predominantly Hanford fine sandy loam underlain in most places by a hard substratum of weakly cemented sand at depths varying from 0.5 to 2.0 m. In some areas a silty substratum supplanted or overlay the hard substratum. Surface soil chemical properties at this site were 0.5% organic carbon, 7.8 pH, and 8.0 me/100 g CEC; soil particle size distribution was 10% clay, 45% silt, and 45% sand (Gal et al., 1990). The low electrical conductivity of the irrigation water (0.25 dS/m) was typical for east side groundwater. The 30 year old furrow-irrigated 'Thompson Seedless' grape vineyard had self-rooted vines spaced 2.4 m between vines in rows and 3.7 m between rows that were 260 m long in an east-west direction. Vines were two-wire trellised and cane-pruned. Commercially operated until 1985, the vineyard was used for exploratory furrow infiltration experiments from 1986 to 1988. In preparation for plot establishment the entire vineyard soil was disked and furrowed in late 1988 with two furrows formed between adjacent rows. Furrows were 0.6 m from the vine row, approximately 0.15 m deep, and blocked at the lower end.

Cover Crop and Herbicide Treatments

Rows were assigned in a randomized complete block design containing three replications of three treatments. Each plot
contained one vine row, two middles (zone between adjacent rows), and four furrows as shown in Fig. 1. The treatments are denoted according to winter and summer middle zone management as follows:

CC = continuous cover crop (bromegrass followed by resident vegetation)

CHT = cover crop, herbicide-treated (bromegrass surface mulch)

BHT = bare soil surface (herbicide treated as needed)

Blando bromegrass was seeded in CC and CHT treatments at a rate of 7 kg/ha in early January, 1989. Poor stand establishment due to inadequate rainfall necessitated reseeding in March and December 1989. After seed shattering commenced in May, a natural transition to summer resident vegetation was permitted in treatment CC, whereas all surface vegetation was killed by contact herbicide spray [paraquat (1,1'dimethyl-4,4'bipyridinium dichloride)] in treatment CHT, resulting in a bromegrass surface mulch through the summer. Bromegrass and resident vegetation were mowed as necessary to maintain canopies below 0.3 m height. A bare soil surface was maintained in treatment BHT by five to eight spring and summer applications of paraquat spray.

Vineyard Maintenance

Surface vegetation was eliminated along a strip extending 0.3 m on either side of each vine row by a winter application of simazine [2-chloro-4,6-bis(ethylamino)-s-triazine] and a spring application of paraquat. Johnson grass (Sorghum halepense L.) was controlled by localized application of glyphosate [N-
(phosphonomethyl) glycine]. Granular fertilizer was broadcast uniformly over the entire zone between rows each year in late April at a rate of 34 kg/ha each of N, P, and K; vines were maintained by standard cultural practices until termination of the experiment following the September 1990 harvest.

All plots were irrigated when 100 mm of soil water was depleted from the soil profile from bud-break in early-March until early-September harvests; five irrigations were required each year. Soil water depletion was estimated as the potential ETc from reference evapotranspiration (ET0) and appropriate crop coefficients (Kc) as described by Grimes and Williams (1990). Precipitation during the growing season was less than 40 mm both years. Due to the physical nature of the water delivery system, furrow inflow rate (0.08 m³ min⁻¹) was constant, but applied water volume varied among treatments according to time required for furrow advance. The constant flow rate was initiated in all plots simultaneously through a single metered riser per plot and rows in each plot were irrigated sequentially by a flexible hose connected to the riser. Irrigation was terminated in any furrow when water had advanced to the blocked furrow end (260 m) and risen to the furrow shoulder there.

Infiltration Procedures

Cumulative water infiltration was measured using a volume balance model with the extended Kostiakov function (Smerdon et al., 1988):
\[ I = A t^B + R_s t \] [1]

where \( I \) is the cumulative depth of infiltrated water, \( t \) is infiltration opportunity time, \( A \) and \( B \) are empirical constants, and \( R_s \) is the steady-state infiltration rate. The appropriateness of this equation for furrow irrigation conditions in California has been confirmed by Hanson et al. (1990).

To determine the steady-state water infiltration rate \( (R_s) \), a recirculating furrow infiltrometer was constructed with a 0.14 m\(^3\) supply reservoir connected by hoses to two 0.5 HP centrifugal pumps for supply and return flow from a 2 m furrow section. The 305 mm diameter capped PVC pipe supply tank was fitted with a piezometric viewing tube and a pressure transducer above the tank outlet as described by Blair and Trout (1989). Furrow section ends were dammed with hemispherical metal plates; inflow at the furrow section head was preset at a constant rate and the return flow hose at the section end was set at a fixed elevation (0.1 m) above the furrow bottom in accordance with Bautista and Wallender (1985). Attachment of a screen shield to the inflow hose end reduced unnatural disturbance of the furrow surface. Field irrigation conditions were simulated by running proximate test sections in adjacent furrows simultaneously and by creating buffer sections at both ends of each test section with additional end plates. Pressure was translated to voltage by a transducer and recorded digitally at 20-second intervals with a data logger. Calibration of pressure against piezometric head reading permitted volumetric conversion. Infiltrometer tests
were run on two treatment row furrows, on either side of a treatment row, of all plots for four hours in October 1989 and six hours in October 1990 to derive one steady-state value \( (R_g) \) per treatment.

The "two-point method" of Wilke (1973) was used to generate coefficients for the power curve

\[
x = pt^r
\]

[2]

employed to characterize water flow advance in furrows where \( x \) is advance distance, \( t \) is advance time to \( x \), and \( p \) and \( r \) are empirical constants. Two equations obtained with the input of furrow advance times at the middle and end of the furrow run were solved simultaneously to determine the constants.

One drawback of the two-point method is that times may be nonrepresentative due to field heterogeneity. To overcome this potential problem, we followed the recommendation of Smerdon et al. (1988) and measured the time of water advance to four furrow stations located at 45.7 m intervals to a distance of 182.8 m from the head of the furrow. Following comparison of several nonlinear regression models, the function

\[
t = a^{bx-a}
\]

[3]

was selected to characterize water flow advance where \( x \) is advance distance, \( t \) is time of advance to \( x \), and \( a \) and \( b \) are empirical constants. For each furrow, the parameters \( a \) and \( b \) were computed by the Gauss-Newton iterative method (SAS
Institute, 1988). Advance times \( t_1 \) and \( t_2 \) for the midpoint and endpoint (taken as the 182.8-m distance) of each furrow were derived from equation 3 and then used in the two-point method.

The procedure of Elliott and Walker (1982) was used to apply the two-point method to the volume balance equation of Christiansen et al. (1966):

\[
\frac{V}{x} - A_g = \frac{F}{B+1} A t^B + \frac{R_s t}{r+1}
\]

where \( V \) is furrow inflow volume, \( x \) is advance distance, \( A_g \) is the average cross-section area of surface storage, \( F \) is the "Kiefer correction factor", \( r \) is the power curve exponent, \( A \) and \( B \) are the Kostiakov constants, \( t \) is time of advance to \( x \), and \( R_s \) is the steady-state rate. \( A_g \) was measured from furrow configuration and average water depth. Solution of the simultaneous equations resulting from substitution of advance times at the two furrow locations yields \( A \) and \( B \) of the extended Kostiakov equation.

Cumulative infiltration after eight hours was computed for each plot, irrigation event, and season and statistically evaluated with an analysis of variance.

**Soil-Plant Measurements**

Crop water stress index (CWSI) was determined from infrared thermometer and sling psychrometer readings (Idso et al., 1981) and leaf water potential (LWP) was from midday pressure chamber data (Scholander et al., 1965) in June 1990 just before irrigation.
Volumetric soil water content was measured immediately before and three to five days after each irrigation. Each plot was monitored with a neutron hydroprobe at four access tubes, two placed in the treatment row at the first and third advance stations 0.3 m east of the nearest vine, and two placed 1.8 m south of the in-row tubes midway between treatment and guard rows (middle). The hydroprobe was site-calibrated and volumetric water content was measured at the midpoints of 0.3-m depth increments to a total depth of 1.8 m, except in the surface increment which was read at 0.23 m. Soil water depletion for each depth was obtained from differences between successive post-irrigation readings.

In November, 1990, root trenches were excavated by backhoe from six vines in field plots where CC and BHT were contiguous. Trenches were oriented perpendicular to rows, spanning the two treatments and passing 0.3 m away from the vines. Following the trench-profile method described by Vepraskas and Hoyt (1988), a grid, consisting of 0.15- x 0.30-m horizontally oriented rectangles, was attached to the vertical smoothed wall. Approximately 5 mm of soil was washed from the wall surface by pump sprayer to expose root ends. Vine and cover crop roots were identified and counted separately. Grapevine rooting intensity was summarized as the total number of vine roots counted in a 1.80-m wide, 0.15-m depth increment (0.27 m²).

Soil surface strength of treatments CC and BHT was measured in furrow bottoms with a portable micropenetrometer (Rolston et
al., 1991) in September 1990, four weeks after the final irrigation. Penetration force at 0.1-mm depth intervals to a depth of 5 mm was measured using a 1.59 mm diameter flat-tipped probe penetrating at a rate of 8 mm/min. Measurements were at 50 mm intervals along 1.5 m furrow bottom transects. Two furrows per treatment were tested, with two transects in each selected furrow. Two replications each were measured in CC and BHT.

In September 1990, resident vegetation of treatment CC was surveyed in one meter middle transects located at 23-m intervals along each middle. Percent ground cover of prominent plant species was estimated.

Grape yields were evaluated in early-September of both years from the fresh weight of harvested grape bunches obtained from the entire length (183 m) of treatment rows.

Analysis of variance on all data except root counts and regression statistics were done using a SAS statistical package (SAS Institute, 1988).
RESULTS AND DISCUSSION

Infiltration

Cumulative infiltration during eight hours of opportunity
time was consistently highest in CC and lowest in BHT both years
(Fig. 2). In the second year, cumulative infiltration for
treatment CC was 50% higher than the first year, while increases
were slight in the other two treatments. The magnitude of eight-
hour cumulative infiltration was more than twice as great for CC
as for BHT by the end of the experiment. Cumulative infiltration
decreased by 10 to 20% during each irrigation season except for
CC, which showed an increase in the first season (Fig. 3). This
signifies the importance of continuing cover crop research beyond
a single season to achieve full separation of treatment results.

Greater cumulative infiltration with cover crop reflected
higher infiltration rates during steady state as well as in the
initial stages of irrigation. Steady-state infiltration rates at
the end of the second season were 2.9 (BHT), 3.7 (CHT), and 5.5
(CC) mm/hr (Table 1).

Inflow time needed for water to reach furrow end for CC was
twice that of BHT in 1989 and four times greater in 1990 (Table
1). Optimal irrigation distribution and efficiency requires
selection of appropriate furrow inflow rates and opportunity
times that were best reflected in CHT in this study.

First-year gains in water infiltration occurred despite
delayed cover stand establishment. Since bromegrass had to be
reseeded, full cover was not provided until early spring.
Resident vegetation, left to fill in naturally following bromegrass, did not provide as complete a cover the first summer as the second. Had the summer cover been seeded, as the winter cover was, infiltration differences between CC and other treatments would probably have been more pronounced the first year. Grasses appeared to be distributed along the length of middles according to differential furrow water recession. Late summer cover consisted chiefly of the annuals green bristlegrass \textit{(Setaria viridis L.)} and cupgrass \textit{(Eriochloa gracilis L.)}, however, knotgrass \textit{(Paspalum distichum L.)} and crabgrass \textit{(Digitaria sanguinalis L.)} were prominent at the lower end. Grass cover was evenly distributed between and within furrows.

Exploratory studies at this site (unpublished data of the authors) showed surface sealing to be a major limiting factor to water infiltration for this soil. Also, post-season surface soil strength in furrow bottoms for BHT was double that of CC (data not shown), however, with only two replications measured, this difference was not statistically significant at a 0.05 probability level. With BHT refurrowed before each irrigation season, BHT cumulative infiltration declined 10 to 20\% over the course of each season between the first and fifth irrigations (Fig. 3). This modest decline from the first to last irrigation suggests that infiltration became impeded by surface sealing during the initial season irrigation due to the low structural integrity of the BHT treatment soil surface.
Statistical separation of steady-state infiltration rates in this study confirms the effectiveness of recirculating furrow infiltrometry on reasonably uniform soils. Elliott and Walker (1982) found this method inconsistent and recommended basing $R_s$ on the soil classification or on inflow-outflow techniques. Blocked-end furrows precluded use of the inflow-outflow method in our study and reliance on texture-based rates, reported in the soil survey (Soil Conservation Service, 1971), would have resulted in an overestimation of $R_s$ by an order of magnitude.

**Yield**

Grape yields, unaffected in 1989, were inversely related to soil permeability in 1990 with highest yield observed with BHT and the lowest with CC (Table 1). These results, however, appear to require cautious interpretation.

Water stress prior to irrigation did not differ significantly among treatments (CWSI and LWP in Table 1) and water deficit stress achieved before irrigation in this study has been associated with maximum production (Grimes and Williams, 1990). Wildman et al. (1976) recorded the highest grape yields in soil profiles of moderate depth and they attributed lower observed yields where the profile was shallow to a temporally perched water table. The physical nature of the study site made it desirable to maintain furrow inflow rate constant among treatments. As a result, the increased length of run time needed for the CC treatment (Table 1) to have adequate water at the end of the furrow run provided substantially more water than for BHT.
or CHT. Water requirement ($ET_c$) for full production at this location is about 690 mm annually (Grimes and Williams, 1990). The applied water for CC plus that in the profile at bud break exceeded this amount by about 53% in 1990. This excess water, coupled with the variable-depth, subsurface impervious layer, likely caused transient perched water. The yield reduction for CC appears to have resulted from transient profile oxygen depletion and possibly some nutrient leaching (especially NO$_3$) over a significant part of the row length; also, competition between grapevines and cover crop cannot be excluded. To explore this hypothesis further, a detailed examination of root distribution for CC and BHT was done following the 1990 harvest.

Root Distribution

Grapevine root distribution appeared interactive between cover crop treatments and the position of the restrictive layer (Fig. 4). Two zones of elevated root proliferation occurred in both BHT and CC, between 0.15 and 0.45 m and immediately above the restrictive layer. In the CC treatment, root counts were about four times higher above deep (1.35 m) than shallow (0.6 and 0.75 m) restrictive layers. In BHT, total root counts were approximately twice as high above shallow as deep layers. This reversal in root proliferation with restrictive layer depth was consistent under both rows and middles at all depths. It was not caused by random variation in root competition from the cover crop, since the pattern of cover crop root density was consistent at all sites. The excess water applied to treatment CC appears
to have been beneficial to root growth where it redistributed through a deep soil profile but detrimental where confined to excess in a shallow root zone. Since root growth is closely associated with crop water uptake and metabolic vigor, it appears reasonable to conclude that root systems and grape production declined in tandem in the overwatered CC treatment.

Cover crop roots were relatively shallow when compared to grapevine roots and roughly one-fifth as prolific at a 0.5-m depth as at the surface.

**Water Use**

Despite differences between treatments in applied water, measured water depletion within vine rows did not differ significantly among treatments (Table 2). Treatment differences were pronounced in middles, however, especially in the surface 0.3 m where row/middle depletion ratios were 2.1 in BHT, 1.5 in CHT, and 1.1 in CC. Water depletion was similar in CC rows and middles throughout the profile and in the surface zone exploited by bromegrass and resident vegetation. This likely resulted because of greater middle wetting at irrigations for CC than was achieved by BHT.

Differences in water depletion over the two-years were most apparent in the 0.9-1.5-m depth zone where considerably less recharge and depletion occurred in the BHT treatment than in CC and CHT (Fig. 5). Treatment differences at this depth under middles were most dramatic in 1989 (Fig. 6). The average of row
and middle water depletion in the 0 to 1.8-m depth (Table 2) was increased over BHT by 46% for CC and 19% for CHT.

When water application substantially exceeds root zone water depletion over the course of the season, as it did in CC and slightly (10% in 1990) in CHT, the discrepancy must be accounted for as migration beyond the root zone in the three day post-irrigation redistribution period before measurement of soil-water content. Since vertical drainage below the root zone was limited by a restrictive layer underlaying much of the field, lateral redistribution from the wettest treatment (CC) to the driest (BHT) probably occurred to some extent. This would account for the unexpectedly high level of recharge shown in Fig. 6 for middles at the bottom of the BHT profile during 1990.

Lateral redistribution into the BHT treatment likely counteracted the effects of sluggish infiltration and alleviated potential grapevine water stress that would have otherwise lowered BHT grape yield since only 75% of the ET$_c$ needed for full production was applied directly to BHT.
CONCLUSIONS

This experiment demonstrated that winter and perennial cover crops can increase summer soil permeability to irrigation water even on intractable Central California soils. Striking improvement in furrow water penetration was achieved during the first study year on a fine sandy loam vineyard soil. Differences in cumulative infiltration doubled the second year and were two and one-half times higher in CC than in the BHT treatment; results in the CHT treatment were intermediate.

Enhanced water infiltration had a cost in overall increased water use by the cover crop. This cost was modest (19% increase in ET\textsubscript{c}) where the bromegrass cover crop was killed by a contact herbicide in the spring with the residue mulch maintained throughout the summer months (CHT). Eight-hour cumulative infiltration was nearly double that of BHT during the second study year. Maintaining a live continuous cover through the summer (CC) increased infiltration slightly over CHT, but ET\textsubscript{c} was increased disproportionately.

With cover crop use and increased initial and steady-state infiltration, increased furrow inflow rates are required to achieve proper furrow advance for optimum distribution and system efficiency. An upward adjusted inflow rate would avoid excess infiltrated water due to the reduced intake opportunity time and allow maximum crop productivity.
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Table 1. Cover crop treatment effects on grape yield, water stress levels, irrigation water furrow advance, and cumulative infiltration.

<table>
<thead>
<tr>
<th>Cover crop treatment†</th>
<th>Yield 1989</th>
<th>Yield 1990</th>
<th>July, 1990 water stress levels‡</th>
<th>Furrow advance to 182.8 m¶</th>
<th>Cumulative infiltration at 8 hours#</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mg/ha</td>
<td></td>
<td>CWSI</td>
<td>LWP</td>
<td>Rs§</td>
</tr>
<tr>
<td>BHT</td>
<td>22.48 a††</td>
<td>23.30 c</td>
<td>0.44 a</td>
<td>-1.00 a</td>
<td>2.9 a</td>
</tr>
<tr>
<td>CHT</td>
<td>20.85 a</td>
<td>19.96 b</td>
<td>0.42 a</td>
<td>-0.98 a</td>
<td>3.7 a</td>
</tr>
<tr>
<td>CC</td>
<td>20.93 a</td>
<td>15.68 a</td>
<td>0.34 a</td>
<td>-0.96 a</td>
<td>5.5 b</td>
</tr>
</tbody>
</table>

† BHT is bare soil surface (herbicide treated as needed).
CHT is bromegrass cover crop, herbicide treated (bromegrass surface mulch).
CC is continuous cover crop (bromegrass followed by resident vegetation).

‡ CWSI is crop water stress index.
LWP is pressure chamber measured leaf water potential.

§ Rs§ is the steady state infiltration rate at the end of the 1990 season.

¶ Data from separate irrigation events are averaged.

# Cumulative infiltration was derived from furrow advance data by the two-point and expanded Kostiakov procedures.

†† Means in a column followed by the same letter are not significantly different at a 0.05 probability level according to Duncan's multiple range test.
Table 2. Soil water depletion within rows (row) and at the center of between-row (middle) water extraction zones.

<table>
<thead>
<tr>
<th>Depth range</th>
<th>Cover crop treatment†</th>
<th>Row</th>
<th>Middle</th>
<th>Average</th>
<th>Ratio: Row/Middle</th>
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</thead>
<tbody>
<tr>
<td>m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>BHT</td>
<td>226 a‡</td>
<td>109 a</td>
<td>168 a</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>CHT</td>
<td>218 a</td>
<td>147 ab</td>
<td>183 a</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>267 a</td>
<td>236 b</td>
<td>251 b</td>
<td>1.1</td>
</tr>
<tr>
<td>11</td>
<td>BHT</td>
<td>427 a</td>
<td>274 a</td>
<td>351 a</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>CHT</td>
<td>447 a</td>
<td>386 ab</td>
<td>417 ab</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>531 a</td>
<td>493 b</td>
<td>511 b</td>
<td>1.1</td>
</tr>
</tbody>
</table>

† BHT is bare soil surface (herbicide treated as needed).
CHT is bromegrass cover crop, herbicide treated (bromegrass surface mulch).
CC is continuous cover crop (bromegrass followed by resident vegetation).

‡ Values in the same depth increment and column followed by the same letter are not significantly different at a 0.05 probability level according to Duncan's multiple range test.
Each entry is the sum of eight depletion periods (four in each of two irrigation seasons).
LIST OF FIGURES

Figure 1. Cross-sectional diagram showing the locations of grapevine rows, furrows in relation to bare soil and cover crop treatment, soil water depletion zones, and root excavation sites.

Figure 2. Cumulative water infiltration during eight hours of opportunity time in a grape vineyard sandy loam soil for bare soil and cover crop treatments in 1989 and 1990. Infiltration characteristics are an average of three replications and five irrigation events each year.

Figure 3. Cumulative water infiltration in a grape vineyard sandy loam soil for CC and BHT treatments compared for the first and last irrigation events of 1989 and 1990.

Figure 4. Effect of restrictive layer depth on grapevine root counts for BHT and CC treatments.

Figure 5. Two year and row-middle average soil profile water depletion by grapevines between irrigation events for bare and cover cropped middles.

Figure 6. Soil water depth depletion profiles for between-row middles of BHT and CC treatments in 1989 and 1990.
Figure 1. Cross-sectional diagram showing the locations of grapevine rows, furrows in relation to bare soil and cover crop treatment, soil water depletion zones, and root excavation sites.
Figure 2. Cumulative water infiltration during eight hours of opportunity time in a grape vineyard sandy loam soil for bare soil and cover crop treatments in 1989 and 1990. Infiltration characteristics are an average of three replications and five irrigation events each year.
Figure 3. Cumulative water infiltration in a grape vineyard sandy loam soil for CC and BHT treatments compared for the first and last irrigation events of 1989 and 1990.
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