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ORIGINAL PAPER

Diurnal effects on the efficiency of drip irrigation

Warwick R. Adams[2] **· Ketema T. Zeleke**[1,2]

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Abstract Drip irrigation is widely used in viticulture and other field crops. However, there has been little evidence to date regarding the net effects of diurnal factors on drip irrigation and whether or not irrigating early morning compared to in the afternoon changes the water use efficiency. A field experiment was undertaken to investigate the diurnal factors and to quantify any effects on irrigation efficiency. It showed that, for soil depths >15 cm, drip irrigation efficiency is not affected by the time of day of watering—there were no diurnal effects and the results did not support a long-held belief that watering in the heat of the day should be avoided. At shallow depths (from 0 to 15 cm), afternoon irrigation actually resulted in a higher moisture content in this layer, with some of that difference persisting over the following 72 h. This finding also has the potential to be applied to irrigation scheduling for salad vegetables and similar shallow-rooted crops where, by irrigating in the afternoon rather than early morning, water usage could be reduced while at the same time potentially increasing the yield.

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✉ Warwick R Adams
warwick@harvest.com.au

[1] Graham Centre for Agricultural Innovation (An Alliance Between NSW Department of Primary Industries and Charles Sturt University), Wagga Wagga, Australia

[2] School of Agriculture and Wine Sciences, Charles Sturt University, Wagga Wagga, Australia

Introduction

The majority of winegrowing regions worldwide are located in semi-arid and arid regions with low rainfall, meaning that irrigation is required. Climate change is expected to result in higher temperatures and higher evapotranspiration rates in those regions, putting additional pressure on limited water supplies for domestic use, industry and agriculture (Monaghan et al. 2013). Dwindling water supplies, increasing drought frequency and uncertainties associated with a changing climate mean that the irrigated viticulture sector needs to improve water efficiency.

Trickle ('drip') irrigation, a widely utilised irrigation method in viticulture, involves application of water at a slow rate from regularly spaced point sources (or emitters) above the soil surface. It is a relatively efficient means of irrigation, especially when combined with techniques such as regulated deficit irrigation, partial rootzone drying, subsurface drip irrigation and application of mulches. However, one aspect that requires further investigation is the potential for water savings by irrigating at only particular times of the day, to take advantage of diurnal factors. A long-held belief, dating back to the fourteenth century, has been that 'you should not water in the heat of the sun' (Power 1928) on the basis that this wastes water, but the evidence for any such claim needs to be tested.

The efficiency of irrigation depends on the losses which take place during and following the irrigation—losses above-ground (wind drift and evaporation losses or WDEL), at the soil surface, from plant root uptake (transpiration) and from percolation within the soil. Under windy conditions, a considerable portion of the spray droplets from sprinkler systems can be carried away from the spray area and lost. Yazar (1984) found that WDEL ranged from 1.5 to 16.8% of the total sprinkled volume, with wind velocity and vapour pressure deficit being the most significant factors. Importantly, they found that air temperature is not a factor itself and can be omitted and this finding was supported by Playán et al. (2005). In order to minimise WDEL, night sprinkler irrigation has long been practised in many areas of the world, as night wind speeds are generally lower and humidity is higher. For drip irrigation on the other hand, because of the small vertical distance between the emitter and the soil surface, the low droplet velocity and relatively large droplet sizes, losses from WDEL are minimal, meaning that overall losses will be from other causes.

The soil physics of the coupled transport of water, water vapour and heat in a soil are well understood for both isothermal and non-isothermal conditions, as are the mechanisms of evaporation. Soil water movement in unsaturated soils was initially studied under isothermal conditions based on Richards' 1931 equation (Deb et al. 2011). Early non-isothermal studies demonstrated that moisture movement in response to thermal gradients through an unsaturated soil occurs mainly in the vapour phase. Philip and De Vries (1957) subsequently developed a moisture migration model (PDV) within homogeneous soil temperature profiles to account for the effects of temperature gradients on moisture migration. Nearly 60 years later, the PDV model still remains the basis for most soil–atmosphere continuum modelling, although today's version of the that model has been modified through numerous studies such as those by Milly (1982, 1984, 1986), Sophocleous (1979), Braud et al. (1995), Shurbaji et al. (1995) and Nassar and Horton (1997).

Because of the complexity of the coupled water and heat transport in the unsaturated zone and the difficulties associated with field measurements, especially near the soil surface, numerical models are often used to analyse these processes (Deb et al. 2011), along with modelling tools such as Hydrus (PC-Progress 2015). However, there has been little focus on the dynamics which occur during the infiltration of irrigation water where the conditions are non-isothermal, vary by the time of day due to diurnal factors and also undergo quite rapid changes in the soil heat and moisture fluxes as the irrigation wetting front proceeds downwards through the soil. The result is that there is little evidence to date regarding the net effects of diurnal factors on drip irrigation, especially whether irrigating overnight or early morning, compared to in the afternoon, will result in higher water use efficiency, either during the irrigation period itself or over subsequent days.

A field experiment was undertaken to investigate the diurnal factors and to quantify any effects both during and after water application by drip irrigation. The findings were also applied to the case of drip irrigation of shallow-rooted crops such as salad vegetables.

Materials and methods

Location

The experimental site was located in a vineyard at Belgrave Park Pty Ltd (Bega, NSW, Australia), at latitude 36.41°S, longitude 149.86°E and an elevation of 150 m above sea level. The climate of the site, from a viticultural perspective, is classified as warm and moderately maritime, with a mean January temperature (MJT) of 20.6 °C (Bureau of Meteorology 2013b) and a summer-dominant rainfall pattern with an annual rainfall of 960 mm (Fig. 1). The annual pan evaporation for the area is 1360 mm (Bureau of Meteorology 2013a), with the aridity classified as low.

The topology of the area has rolling to undulating low hills on granodiorite (Tulau 1997). The soil comprised moderately deep, moderately well-drained leached yellow earth with:

A Horizon: Sandy clay loam, 30 cm deep, with a pH of 6.5.

B Horizon: Decomposed granite, orange to light brown, structured light clay, with the clay

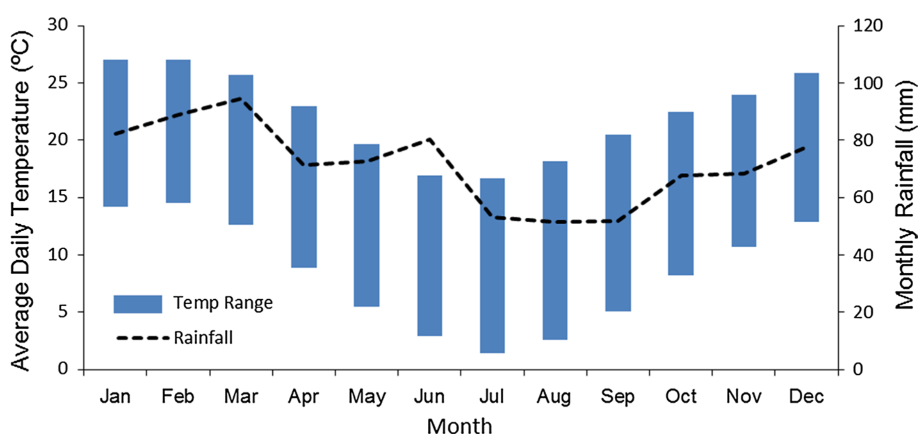


Fig. 1 Monthly temperatures and rainfall totals, Bega, NSW, Australia

content increasing with depth, partly dispersive and with a variable, acidic pH.

Experimental design: Part A

The objective of Part A of this experiment was to measure the effect of time of day on the volume of drip irrigation water that is needed to infiltrate and wet the soil (to various soil depths) and the main features of the design are shown in Fig. 2.

The experimental site comprised bare soil, in order to eliminate the effect of plant transpiration, but retained all other vineyard soil characteristics such as grapevine roots, other plant roots and worm channels. The experiment used a series (8) of above-ground 2.2 L/h low-pressure Toro Turbo Plus II drip emitters (Toro Australia Pty Ltd. 2003) spaced along a short section of vineyard row at between 2- and 3-m intervals, in order to prevent any interaction between the wetting zones. The water supply pressure was regulated to 180 kPa, which was well within the pressure compensation range of the emitters.

Each emitter had an 80 cm long Enviropro subsurface soil moisture and temperature probe (Measurement Engineering Australia 2013) buried vertically alongside, providing for measurements at eight soil depths (5, 15, 25, 35, 45, 55, 65 and 75 cm). The probes were connected to a Plexus mesh-networking radio system, comprising 4 field stations and a hub (Measurement Engineering Australia 2015) which in turn transmitted the readings to a web-based Green Brain database. This provided both a visual interface to view real-time temperature and moisture data from each station, as well as the ability to export raw data to a CSV file. The Enviropro probes measured volumetric soil moisture content from 0 to 50% with an accuracy of ±2% and temperature from −10 to 60 °C with an accuracy of ±1 °C. The probes were preloaded with a calibration based on a standardised calibration media (fine sand) (Apcos Pty Ltd 2015). Even though the values returned in other soil types would differ in accordance with the average particle size distribution in the soil, this was not a consideration for this experiment where all measurements were differential (A.M. compared to P.M.). The various temperatures (ambient, soil surface, irrigation water) and relative humidity were also recorded.

The system was set up with a data-logging interval of 5 min. All emitters and their associated probes (stations) were positioned within a total horizontal distance of 20 m in order to minimise any differences in soil characteristics or profile. There was also a small horizontal separation of 10 cm between the emitter and probe centrelines at each station in order to prevent any irrigation water running directly down the outside surface of the probes.

Since the hypothesis was that the volume of water required would depend on the time of the day that the irrigation took place, the experiment comprised two separate irrigation start times (factor levels) with each factor level applied to a random subset of 4 of the 8 stations. The respective irrigation start times were as follows:

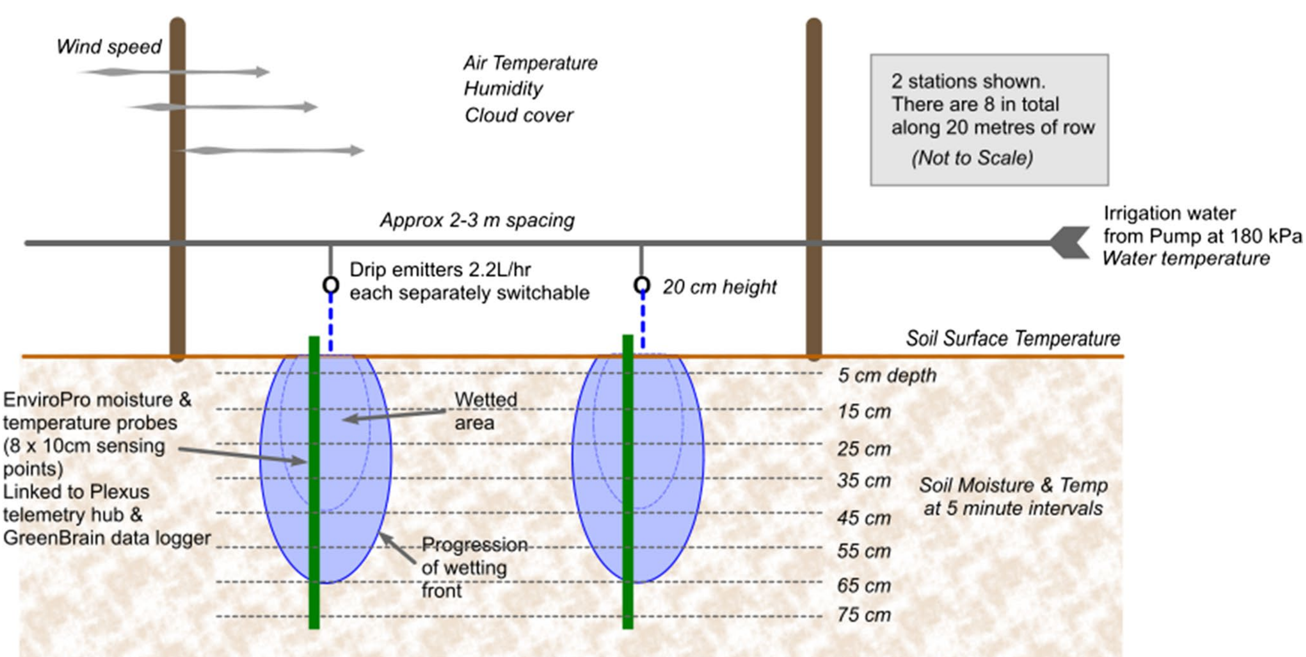


Fig. 2 Experimental design—main features of the drip irrigation set-up and soil sensor probes

(a) Early morning, starting at 06:00 (Eastern Standard Time). This is the period after the soil fluxes have stabilised overnight, but before the surface and shallow soil temperatures begin rising (Fig. 3).
(b) Early afternoon, starting at 14:00. This is approximately the period of day where the soil surface temperature and shallow soil temperature gradients are highest, sometimes exceeding 6 °C/cm between the surface and 5 cm depth at this site.

The measurement was specifically of the volume of water needed to be applied for the wetting front during irrigation to reach 35 cm depth, at A.M. compared to P.M., calculated as:

A.M. Volume Required = Emitter Discharge Rate × A.M. Time to reach 35 cm depth

P.M. Volume Required = Emitter Discharge Rate × P.M. Time to reach 35 cm depth

and the null hypothesis was

A.M. Volume Required = P.M. Volume Required

The 35-cm depth limit was chosen because there is very little diurnal temperature fluctuation below that depth, for example just 1.1 °C at 35 cm and even less at greater depths (Fig. 4). The irrigation was run for a fixed period (90 min), long enough to ensure that field capacity (FC) had been reached to at least 60 cm depth, but limiting the volume of water applied in order to prevent excessive percolation to greater depths.

If there was a difference in the volume of water needed, then that could be attributed to differences in the losses (of any type). In order to eliminate most of the uncontrolled variables (for example surface evaporation), the

Fig. 3 Typical soil temperature profile, without irrigation, at 06:00 and 14:00 (representative day during December 2015)

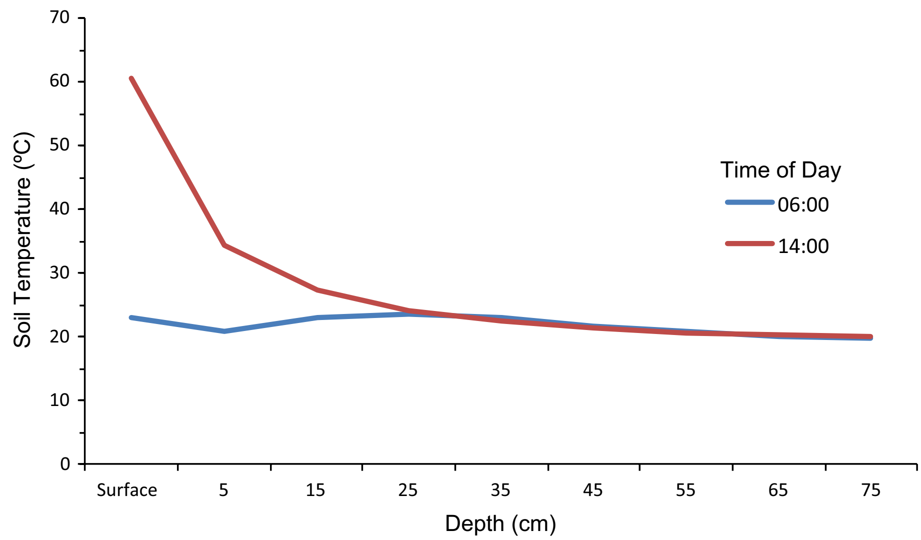


Fig. 4 Diurnal fluctuations of site soil temperature at various depths (31 December 2015)

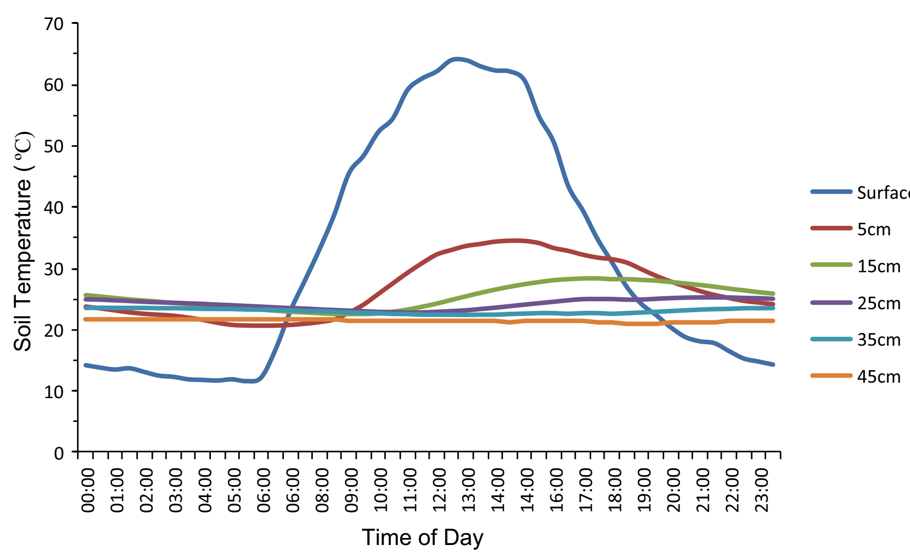


Table 1 Randomised block design for the experiment (comprising eight irrigation stations, with two factors)

Run	Station number								Experiment part
	1	2	3	4	5	6	7	8	
1	P.M.	P.M.	A.M.	P.M.	P.M.	A.M.	A.M.	A.M.	A
2	A.M.	A.M.	P.M.	A.M.	A.M.	P.M.	P.M.	P.M.	A
3	P.M.	A.M.	P.M.	P.M.	A.M.	A.M.	P.M.	A.M.	A
4	A.M.	P.M.	A.M.	A.M.	P.M.	P.M.	A.M.	P.M.	A
5	A.M.	P.M.	P.M.	A.M.	A.M.	P.M.	A.M.	P.M.	B
6	P.M.	A.M.	A.M.	P.M.	P.M.	A.M.	P.M.	A.M.	B
7	A.M.	A.M.	P.M.	A.M.	A.M.	P.M.	P.M.	P.M.	B

experimental design was bounded by both space and time—in essence it comprised a cylindrical soil column 20 cm diameter and 35 cm deep, with the primary hypothesis being tested over an irrigation period of just 90 min.

Each replication comprised all 8 stations, with some being watered at 06:00 (A.M.) and the remainder at 14:00 (P.M.), according to a predetermined randomisation (Table 1). At the start of each run (A.M. or P.M.), the appropriate emitters were turned on or off. Replications only took place on days where the soil moisture content at 5 cm depth was in the range of 13–19% v/v, that is in the 'dry' moisture range and equivalent to approximately −200 to −400 kPa water tension for a loam soil (van Genuchten 1980; Measurement Engineering Australia 2016).

Part of the experiment was to also measure moisture content (at each station and depth) over the ensuing 72 h as redistribution and drying took place. To ensure consistency, the volume of irrigation water applied at each station during each run was kept constant at 3.3 L/station (equating to the 90-min timed application).

Vertical infiltration time as a measure of losses

The experiment measured any difference in the total water losses between A.M. and P.M. by measuring the amount of water needed to be applied to wet the soil to a depth of 35 cm. That is, if the losses were different, then the water volume would be different. Since the experiment was an investigation of diurnal effects only, there was no requirement to identify the sources of losses nor to apportion them. The application rate at each emitter was constant (2.2 L/h), so the volume of water applied was directly related to the elapsed time since start of irrigation.

Subsequent redistribution and drying

Part of the experiment was to compare the soil moisture content reached at various depths at the end of each irrigation run, A.M. and P.M. Then to investigate the decline in moisture content at each of those depths over the subsequent 72 h, as soil moisture distribution and drying took place. In order to achieve this, it was important that each station received the same amount of water during each irrigation in order to establish a consistent baseline. This was the purpose of having a timed 90-min irrigation, which applied 3.3 L of water at each station. At the end of each irrigation period, the soil moisture contents were at their peak, and over the ensuing 72 h period the moisture content at each station and soil depth continued to be measured at 30-min intervals.

Variations in the antecedent moisture content (before irrigation) would affect the peak moisture values reached at the end of the irrigation so, in order to eliminate this effect, (a) all measurements were of the *additional* soil moisture content (that is the current moisture content at any point in time, less the moisture content at the start of irrigation) and (b) each irrigation was only performed when the soil water content at 5 cm depth was in the range of 13–19% v/v.

Other variables

Other variables in the experiment included evaporation, sunlight intensity and cloud cover, ambient temperature, relative humidity, wind speed, rainfall, evaporation, plant transpiration and the temperature of the irrigation water. Of these, plant transpiration and the effect of rainfall were excluded through the experimental design.

(a) *Soil characteristics* Despite the experimental row being restricted to a horizontal distance of <25 m, the soil characteristics would still vary somewhat between stations (for example because of rocks, worm channels, plant roots and the like) and the effect of these variations was mitigated by the use of a paired design so that the A.M. and P.M. applications could be compared for each separate station.
(b) *Antecedent water content* In a soil, plant available water (PAW) cycles between a lower point of permanent wilting point (WP) and upper point of FC. The soils undergo three stages of drying (Hillel 1980) with Stage 3 (being very dry soils) resulting in a much lower rate of evaporation from the surface. For this experi-

Table 2 Field capacities and initial soil moisture contents at various depths at the experimental field site

Horizon	Depth (cm)	Soil type	Field capacity	Soil moisture at start of irrigation (mean of all runs)	
			Soil moisture (vol%)	Moisture (vol%)	Proportion of FC
A horizon	5	Sandy clay loam, pH 6.5	30	15	0.46
	15		50	39	0.76
	25		51	43	0.83
B horizon	35	Structured light clay, variable acidic pH	49	42	0.86
	45		49	–	–

ment, the initial near-surface conditions prior to each irrigation were kept within a soil moisture range of 13–19% v/v (with a mean of 14% v/v at 5 cm depth), that is in the Stage 2 range. At depths of 15 cm and greater, the antecedent moisture content was in the range of 76–86% of FC. (The measured FC's at the experimental site and the mean moisture contents at the start of irrigation runs are shown in Table 2). The irrigation raised the moisture level to FC or greater at each of these depths.

According to Jury and Letey (1979), a large number of separate experimental studies of water transport in response to thermal gradients have shown that the movement is independent of water content over a wide range. This meant that the antecedent water content was not important to this experiment.

(c) *Evaporation* In this experiment, because of the short 90-min duration of irrigation, evaporation during irrigation itself could be ignored (especially as the soil surface temperature cooled rapidly to 35 °C or less at the drip area within 40 min of the start of irrigation). For example, the experimental site had an annual pan evaporation of 1360 mm. For a summer afternoon, compared to the same period in the morning, this equated to an order of 0.25–0.5-mm difference in evaporation during the irrigation period—or just 1–2% of the applied 3.3 L of water (being approximately 26 mm).

Experimental design: Part B

Part A of this experiment focussed on downward infiltration and the effect of diurnal factors on this. However, the effectiveness of drip irrigation in a field situation is three dimensional—including both downward (vertical) and horizontal (lateral) wetting. Thus, the size and shape of the wetted profile under each emitter are an important factor and this was investigated as Part B of the experiment, by measuring the horizontal expansion of the wetting front at various depths and times.

In Part B, at each of the 8 experimental stations the emitter was repositioned so that there was a horizontal separation of 25 cm from the drip line to the centreline of the Enviropro probe. In this way, it was possible to measure how long it took for the wetting front to reach a radius of 25 cm at various soil depths (5, 15, 25, 35 and 45 cm). There have been various studies into wetting patterns and their calculation. In particular, the equations of Philip (1984) have been found to give good predictions by Revol et al. (1997) and Thorburn et al. (2003), and a useful computer application was developed by Cook et al. (2003).

For the purposes of this experiment, the horizontal infiltration distance was calculated by approximating the wetted soil profile as a prolate ellipsoid, in which case the lateral radius increases as the cube root of the elapsed irrigation time. In this manner, the dripper profile at any point in time (3 h was used in the experiment) can be derived from the time taken to reach a radius of 25 cm (at various depths) and the results correlate well with the solution of Revol et al. (1997). Since any approximations apply equally to A.M. and P.M., the profiles can be directly compared and contrasted.

Data analysis

A randomised block design (Quinn and Keough 2002; McKillup 2012) provides a means of isolating treatment effects from spatial variations. In this experiment, each station within the experimental block comprised a drip emitter/probe pair, and the treatment factors—A.M. or P.M.—were applied randomly, with each station receiving one treatment. Hence, a complete experimental replication comprised all eight stations, with half (randomised) receiving A.M. irrigation and the other half P.M. irrigation (Table 1). There were four replications conducted (each with a different randomisation), and an analysis of variance (ANOVA) was run on the 32 result sets.

A paired sample *t* test (McKillup 2012) is intended for experiments where the same variable or variables are measured on each experimental unit under two different conditions. The greatest spatial variation between the stations in this experiment was due to soil characteristics, vine roots, worm channels, rocks and antecedent moisture content. By using a paired *t* test, comparing the difference of the results between consecutive replications for each unit, elimination of the soil-related differences could be achieved. The null hypothesis in this case is that the difference between the values of the two replications at each station is zero.

Inclusion of such a paired *t* test was made possible by having each alternate replication pattern as the inverse of the immediately preceding one; hence, for example, if the first replication irrigated station 3 at 06:00, then the second replication irrigated it at 14:00, and this design is shown as part of Table 1.

All data analyses were performed using Minitab© statistical analysis software (Minitab Inc. 2016).

Table 3 Magnitude of daily soil temperature fluctuations at various depths (31st December 2015)

Depth (cm)	Daily temperature fluctuation (°C)	Lag of peak temperature (h, compared to surface)
Surface	52.4	0
5	13.9	1.5
15	5.8	4.5
25	2.5	8.0
35	1.1	11.5
45	0.7	14.0
55	0.6	16.5
65	0.5	21.0
75	0.3	27.0

Results and discussion

Part A: Irrigation efficiency

Diurnal soil temperatures

For a typical day during the experiment, the fluctuations in soil temperature over a 24-h period are shown in Fig. 4, with corresponding values in Table 3. Note that the experimental runs were only made on sunny days where there was little or no cloud cover (the 5th, 14th, 24th and 30th December 2015).

Soil temperatures during irrigation

The mean temperature of the irrigation water being applied was in the range of 18 °C (at 06:00) and 21 °C (at 14:00) and, as it moved downward from the soil surface, it transferred heat to or from the soil at each depth, subsequently transporting it to lower depths.

At 06:00, the surface soil temperature was beginning to rise and the effect of applying 18 °C irrigation water was simply to slow the rate of heating, as shown in Fig. 5.

At 14:00, the soil surface temperature had typically reached 49 °C or more (Fig. 6) and, during the P.M. irrigation, part of this heat was transferred to the 21 °C irrigation water, which then transported the heat downward to lower levels in the soil as it infiltrated downward. The result was that the soil surface cooled quite rapidly to 35 °C within the first 40 min of irrigation and thereafter continued cooling to reach 30 °C by the end of the irrigation period. The infiltrating water at 5 cm depth in turn cooled the soil to a temperature similar to the surface temperature. However, at 15 cm depth, since the initial soil temperature was 25 °C—cooler than the infiltrating water by the time it reached that depth—the result was

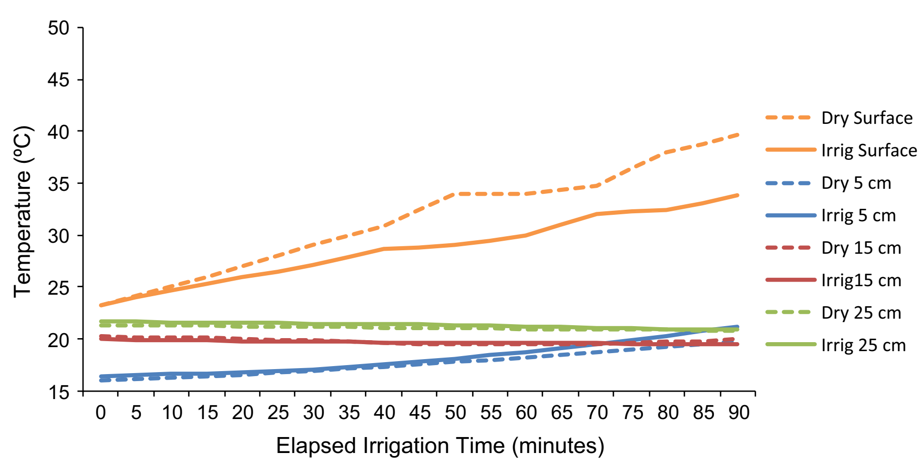


Fig. 5 Soil temperature changes during the 06:00 irrigation period, measured at different depths in both the irrigated and un-irrigated (dry) soil (mean of all runs)

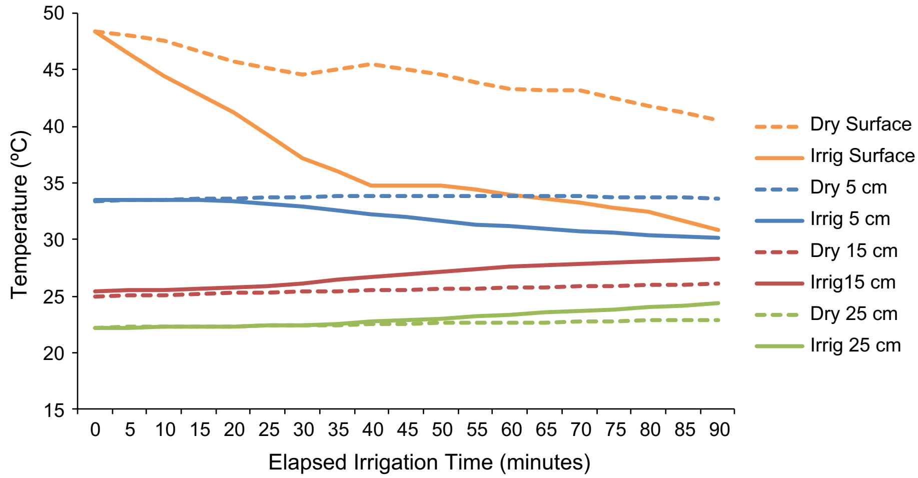


Fig. 6 Soil temperature changes during the 14:00 irrigation period, measured at different depths in both the irrigated and un-irrigated (dry) soil (mean of all runs)

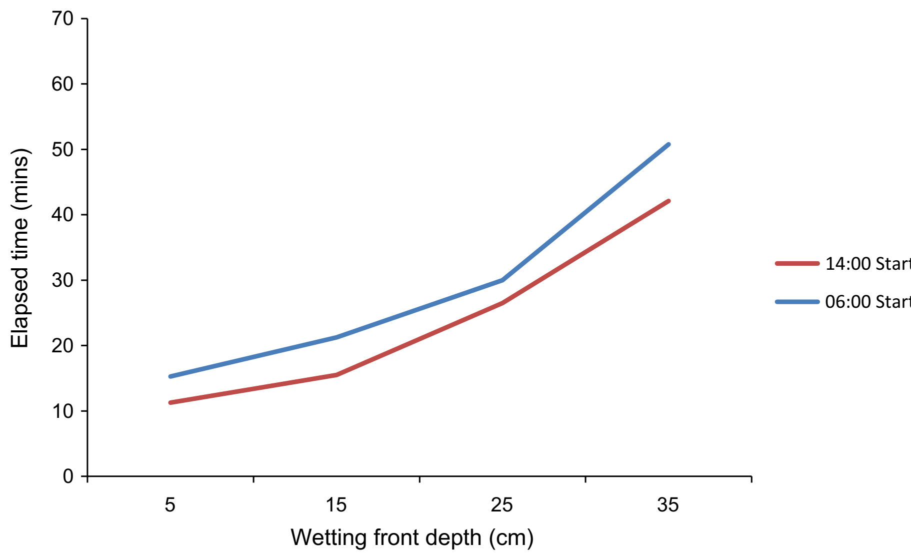


Fig. 7 Vertical infiltration rate of irrigation wetting front to various depths during irrigation, comparing irrigation at 06:00 to that at 14:00 (mean of all runs)

that the soil at 15 cm increased its temperature from 25 to 28.2 °C by the end of irrigation. These changing temperature fluxes at all levels had a significant effect on both the infiltration speed and on the final moisture content at the various depths.

Infiltration

Figure 7 shows the mean vertical infiltration times of the eight stations over four replications. Over the range of soil depths investigated in this experiment, the downward infiltration progressed quite quickly, reaching 35 cm after a mean time of 42 min. The experimental hypothesis was that the time (and hence the water volume) taken to reach 35 cm depth should be the same for both A.M. and P.M.

Figure 7 shows that the P.M. irrigation resulted in infiltration that was slightly more rapid at all depths than that of A.M. A one-way ANOVA was run to compare the effect of time of day (A.M. and P.M.) on the time to infiltrate to 35 cm and hence the volume of drip irrigation water needed to be applied to reach that depth. The ANOVA showed that, at the $p < 0.05$ level, there was no evidence to suggest any difference between the A.M. and P.M. means [$F(1, 37) = 1.0$, $p = 0.323$], and that the amount of water needed to be applied to reach a depth of 35 cm at 06:00 compared to 14:00 was the same.

With regard to near-surface depths though, the situation was different. For 5 cm depth, there was actually less water needed to reach that depth at 14:00 than at 06:00, with a one-way ANOVA showing a difference at the $p < 0.05$ level between A.M. and P.M. [$F(1, 38) = 4.61$, $p = 0.038$]. A paired sample t test (by station) showed this even more clearly with A.M. (M = 13.75, SD = 4.65) and P.M. (M = 10.94, SD = 2.02) conditions; $t(16) = 2.52$, $p = 0.023$.

The soil moisture content increased at each depth as the wetting front progressed downwards. The most noticeable difference between A.M. and P.M. moisture content (Fig. 8)

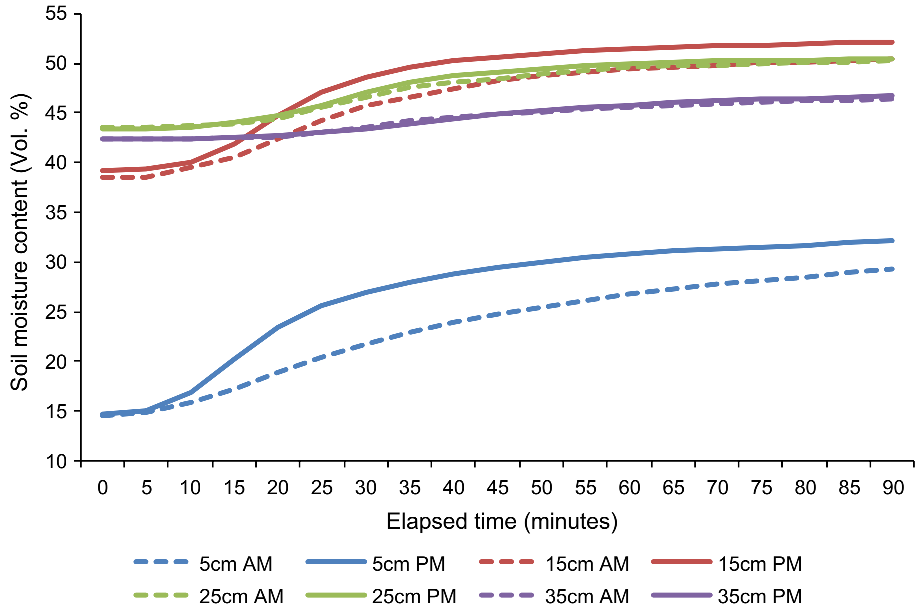


Fig. 8 Changes in soil moisture content at various depths during irrigation, comparing A.M. (06:00) and P.M. (14:00) irrigations (mean of all runs)

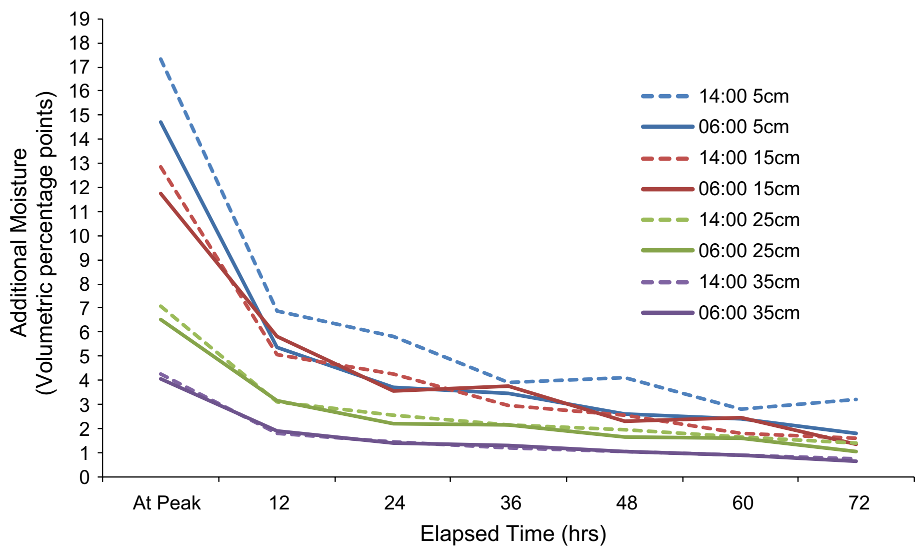


Fig. 9 Retained moisture content at various depths, over the 72-h period following irrigation, for 06:00 and 14:00 irrigation (compared with antecedent moisture content, mean of all runs)

was that there was a more rapid build-up at the 5 and 15 cm depths during P.M. irrigation, and that the final moisture contents at those depths were also higher, for example by 9% at 5 cm depth. More importantly, the incremental moisture content immediately after irrigation (that is the final moisture% − initial moisture%) was higher by 18% at 5 cm and 9% at 15 cm by P.M. irrigation compared to A.M.

Moisture redistribution after irrigation

Following each irrigation, the soil moisture contents were monitored as moisture redistribution and soil drying occurred over the following 72 h (measured from the respective irrigation start times). As shown in Fig. 9, immediately after irrigation the peak moisture contents at 5 cm and 15 cm depths were higher for P.M. irrigation compared to A.M., which seemed both surprising and counterintuitive. A paired sample t test showed this difference was significant at the 95% confidence level for both those depths, with the results at 5 cm depth being [A.M. ($M = 29.48$, $SD = 6.10$) and P.M. ($M = 10.94$, $SD = 2.02$) conditions; $t(16) = -4.8$, $p = 0.000$], and for 15 cm depth being [A.M. ($M = 50.373$, $SD = 2.849$) and P.M. ($M = 52.099$, $SD = 2.928$) conditions; $t(16) = -7.29$, $p = 0.000$].

Much of this initial difference in peak moisture between A.M. and P.M. was retained during all periods throughout the ensuing 72 h at those depths. Even though the rate of soil moisture loss is generally higher at higher soil water content, Fig. 9 shows that this factor is not significant, as the difference between the moisture levels at 5 cm depth after 24 h is similar to that immediately after irrigation. At greater depths than 15 cm, there was no significant difference in either peak moisture content (A.M. compared to P.M.) or in the retained moisture after 72 h.

Part B: Horizontal wetting

The wetted profile of drip irrigation comprises both vertical and horizontal wetting. With regard to this experiment, even if there was no difference in vertical infiltration by A.M. irrigation compared to P.M., there could be a difference in the respective horizontal spreads. This would result in a difference in the wetted profile and/or its volume A.M. and P.M.

The extent of horizontal wetting was measured as a Part B of the experiment (Fig. 10). This shows that, at depths 15 cm and greater, there was no apparent difference in the wetted radius after 3 h of irrigation (between P.M. and A.M.) and that the wetted profile was similar at those depths. For example, at 25 cm depth (the point of maximum wetted diameter) an ANOVA showed there was no evidence to suggest a difference between A.M. and P.M. [$F(1, 22) = 0.11$, $p = 0.743$]. With A.M. application though, there was a significant 'flaring' at the soil surface and down to 5 cm depth, when compared to P.M.

Overall diurnal effect on efficiency

Many growers in the USA traditionally irrigate during predawn or early morning hours (Warren and Bilderback 2001) and, anecdotally, the practice appears to be similarly widespread in Australia. With regard to existing research studies regarding irrigation scheduling, it is rare to find any reference to the time of day of scheduling.

The experimental results of the current investigation have shown that there is no evidence that the efficiency of drip irrigation is affected by the time of day at which it is applied. This means that for deep-rooted crops such as grapevines, irrigation scheduling can be completely flexible—scheduled at any time and not be limited to night time or cooler periods of the day. This is important for minimising the total elapsed time required for irrigating a vineyard, especially for capacity-constrained irrigation systems or heat wave conditions where a water application needs to be completed quickly. The results showed that, at more shallow depths, there were significant beneficial effects from irrigating in the afternoon (as compared to morning)—the peak moisture content achieved by the irrigation was higher and the amount of moisture retained over the ensuing period (for example the next 3 days) was also greater. This is analysed and discussed in more detail in the following sections.

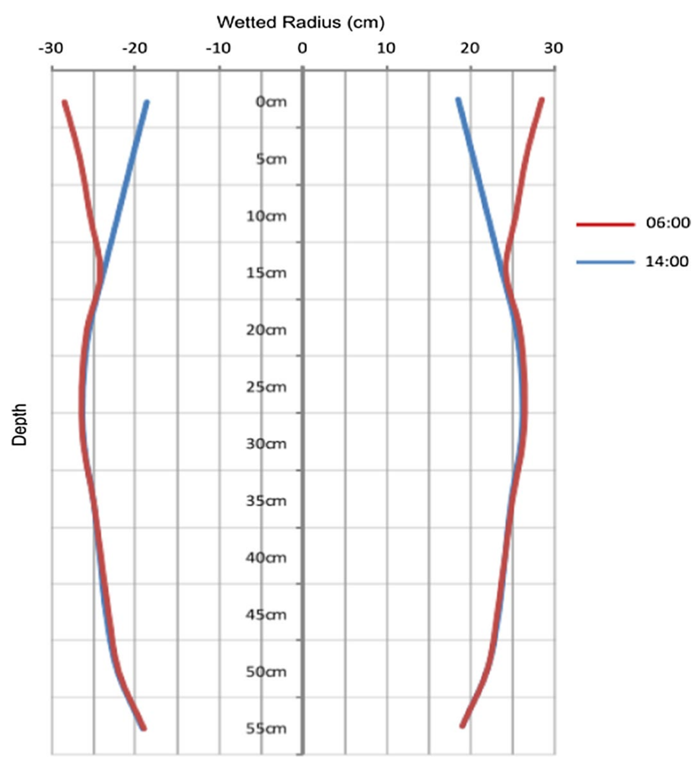


Fig. 10 Horizontal spreading at various depths after 3 h of irrigation, for irrigation start times of 06:00 and 14:00 (mean of all runs)

Diurnal effects on infiltration dynamics

Temperature, liquid and vapour fluxes

The soil surface temperature varied widely in a daily cycle, reaching peaks of 50–65 °C or more in the early afternoon and falling to 10 °C or less overnight. At depths of more than 45 cm or so, the temperature was stable from day to day (Fig. 4). This meant that there were very strong heat fluxes over the first few centimetres of soil depth at particular times of day; the flux changed throughout the day; and there was a temperature 'wavefront' that slowly proceeded downwards through the soil through the hotter parts of day and into the evening.

The transfer of heat in soil is due to radiation transfer (important just at or near the soil surface); convective heat transfer (caused by the water percolation through the soil, especially where there are large differences between the soil temperature and water temperature, such as the P.M. irrigation in this experiment); and conduction (which occurs when liquid water is converted to water vapour through evaporation or condensation processes in the soil). Deb et al. (2011) found that surface energy components and contributions due to heat conduction, convection and vapour transfer were more pronounced with irrigation, and differences between thermal profiles of wet and dry soil conditions before, during and after irrigation were due to the latent heat exchanges. As can been seen from the above, the application of cool irrigation water into a hot soil layer will result in quite different infiltration dynamics depending on the soil temperatures, the temperature gradients between depths and the difference between the temperature of the irrigation water and the soil temperature, and the combination of these factors is reflected in the experimental results between A.M. and P.M.

Soil vapour movement

The transport of moisture in the soil by evaporation and then by re-condensation can be a significant contributor to the net moisture movement in the soil and, because of the large latent energy needed to vaporise water, the water vapour transports a significant amount of energy as it evaporates and re-condenses (Cahill and Parlange 1998). Since vapour pressure is related to the soil temperature (Jury et al. 1991), water vapour will be transported from regions of higher temperature to those of lower temperature—meaning that at some times of the day the temperature gradient will result in this vapour migration being downwards rather than upwards, and not necessarily out through the soil surface to the atmosphere above. Because the soil temperature and heat flux at shallow depths follow a daily cycle with a peak each afternoon, there is a corresponding diurnal variation in water and vapour movement—both in magnitude and direction—and evaporation. The heat flux varies with both depth and the time of day, so the corresponding temperature gradient continually changes in intensity and direction. For example, at night when the shallow soil temperatures become lower than those at greater depths, water vapour in the soil will be transported towards the surface, and in the afternoon the reverse applies and it will tend to move further downward into the soil (Fig. 11). Zeng et al. (2008) found that the thermal water vapour and liquid flux were dominant in uppermost soil layer at night, whereas the isothermal liquid water dominated during the day and in the deeper soil layer and this is evident in Fig. 11. This situation was also investigated by Saito et al. (2005) who found that at noon, even though a large downward thermal water vapour flux occurred due to a large downward temperature gradient, the isothermal liquid water and water vapour fluxes are upward because of an upward pressure head gradient.

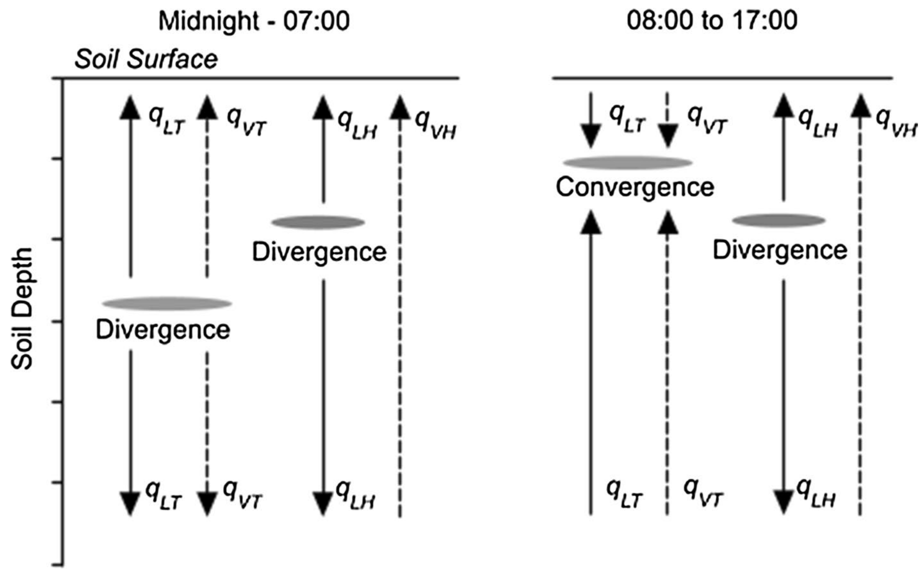
As reported by Parlange et al. (1998), there has never been a satisfactory reconciliation of the Philip and De Vries (1957) theory of water vapour movement in soils with the short-term field observations subsequently made by others (Rose 1968; Jackson et al. 1973; Cass et al. 1984) who found that the vapour flow is perhaps an order of magnitude larger than the theory predicts. Wierenga et al. (1969) reported that 40–60% of the heat flux in the top 2 cm of a bare field soil, and up to 20–25% of the total heat flux at 25 cm depth, was due to water vapour flow and Grifoll et al. (2005) showed that for a near-surface dry soil layer, diffusion and dispersion of water vapour are the significant water transport mechanisms.

In this experiment, during irrigation the temperature of the initially cool irrigation water itself changed as it travelled downward through the soil, gaining or losing heat depending on the temperature of the soil at each depth, and transferring that heat to (or from) the soil at lower depths, causing the heat flux in the soil to be modified rapidly and substantially. As the soil probes recorded temperature and moisture values at each depth every 5 min during the irrigation, the corresponding temperature and moisture gradients between each depth can be calculated. These gradients are not the same as thermal and isothermal fluxes, but it is reasonable to relate the temperature gradient to the thermal liquid and vapour fluxes, and the moisture gradient to the isothermal liquid and vapour fluxes which are shown in Fig. 11.

Infiltration

From the previous sections, it can be concluded that the rate of infiltration from irrigation (for any particular soil characteristics) will be determined primarily by the

Fig. 11 Schematic illustration of the variation (in direction and depth) of liquid and vapour fluxes between **a** night to early morning and **b** through the daylight hours. q_{LT} thermal liquid, q_{VT} thermal vapour, q_{LH} isothermal liquid, q_{VH} isothermal vapour. The figure is from Zeng et al. (2008). With permission



soil temperature and moisture gradients, the differences between those A.M. and P.M. and, importantly, the manner in which they change during the irrigation period itself. The experimental results are discussed in this context below.

(a) Temperature changes during A.M. irrigation. At 3 cm depth, there was initially a downward temperature gradient which increased as irrigation progressed because of the rising soil surface temperature, as shown in Fig. 12. At 10 cm depth, the temperature gradient was initially slightly upward and this changed over the irrigation duration to become slightly downward because of the increasing soil temperature above that depth. The overall effect was that moisture contents at all depths increased steadily during the period of irrigation (Fig. 14).
(b) Temperature changes during P.M. irrigation. The temperature gradients and their effects were more complex in this case (Fig. 13) and combined to result in the peak moisture contents at depths up to 15 cm being higher with P.M. irrigation than with A.M.

It can be seen that, at the start of irrigation, because of the initially high soil surface temperature, there was a very strong downward temperature gradient at 3 cm depth. This gradient decreased rapidly during irrigation, because of the cooling effect of the colder irrigation water at the soil surface and as it percolated downward, halving in value within 20 min of irrigation and thereafter continuing to decline to nearly zero after 40 min. At 10 cm depth, there was initially a slight downward gradient, but this reduced steadily to zero over the irrigation period, again through the cooling effect of the infiltrating water. When P.M. was compared to A.M., it can also be seen that the gradients at 10 cm depth were in opposite directions.

The overall effect was that, at the start of P.M. irrigation, there was initially a rapid downward movement of water (liquid and vapour) due to the strong downward heat flux, but this then slowed as the temperature gradients reduced at shallow depths. It is hypothesised that this caused a more rapid build-up of moisture content at the 5 and 15 cm depths compared to the A.M. situation at the same elapsed time (as shown in Fig. 8) and was a contributing factor to the peak moisture contents at those depths being higher with P.M. irrigation.

Even though the experimental design could not directly measure non-isothermal liquid and vapour fluxes, the moisture gradients and the changes in those were measured. During A.M. irrigation, the moisture gradient at 3 cm depth (Fig. 14) increased rapidly downward in the initial 10 min of irrigation and thereafter declined slowly over the remaining irrigation. At 10 cm depth, there was an upward moisture gradient which did not change significantly, but at greater depths moisture gradients were close to zero. The situation during P.M. irrigation was very similar to that of A.M. (Fig. 15).

Since the overall moisture gradients were similar for both A.M. and P.M. and were dominated by the strong and varying temperature gradients, it was concluded that the moisture fluxes were not a significant contributor to differences between the A.M. and P.M. results. This finding also reinforced the view that antecedent soil moisture was not a significant factor in the experimental design.

This field experiment showed that there are a complex series of factors which change dynamically over the period of irrigation, particularly the effect of cool irrigation water into a relatively hot soil and the role of the irrigation water in the

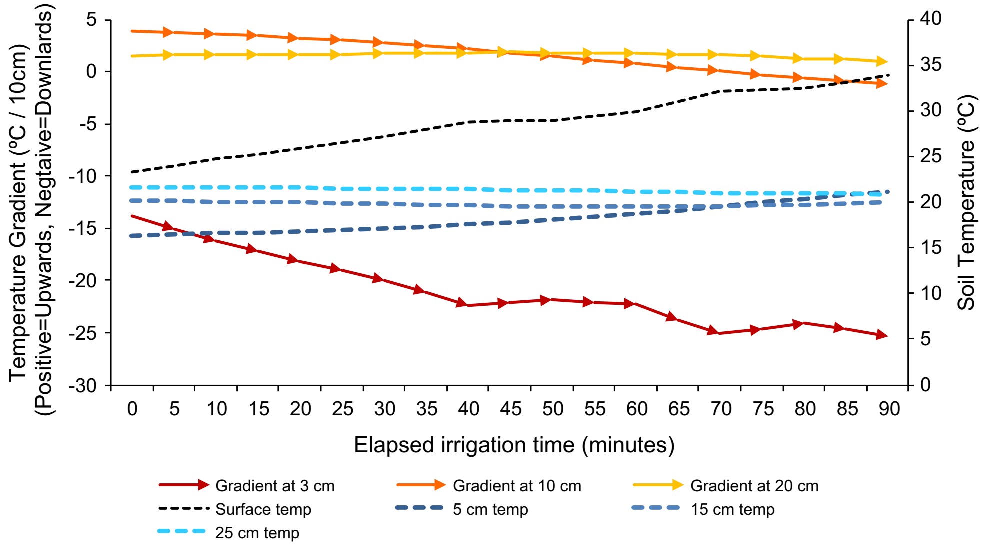


Fig. 12 Changes in temperature and temperature gradients at various depths during A.M. irrigation (06:00, mean of all runs)

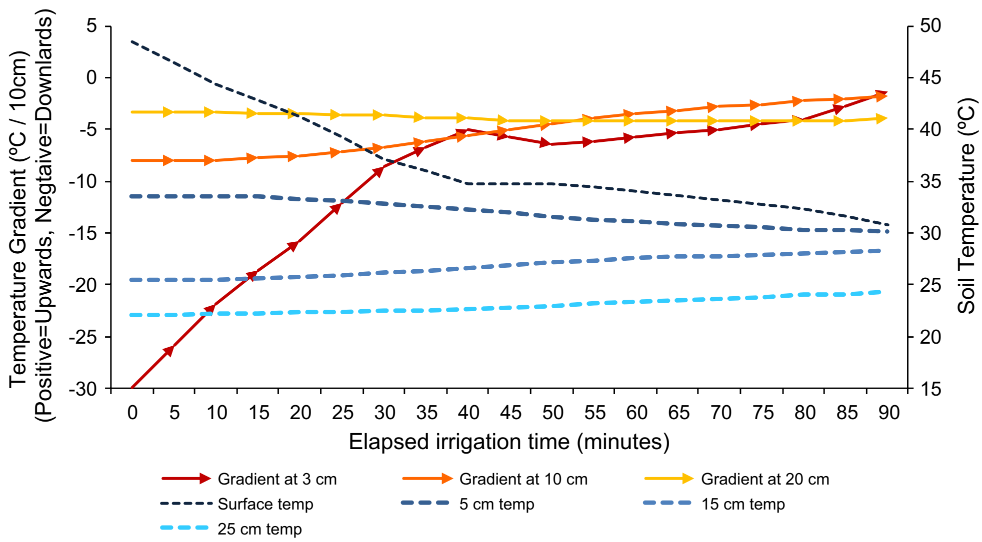


Fig. 13 Changes in temperature and temperature gradients at various depths during P.M. irrigation (14:00, mean of all runs)

heat transfer, and a follow-up 3-D computer simulation would be worthwhile in order to better understand these dynamics.

Horizontal spread

The results showed that the horizontal spreading of irrigation water, and hence the shape of the wetted profile, was the same for both A.M. and P.M. at depths of 15 cm and greater. However, there was an effect at depths up to 15 cm, with A.M. watering having a significantly greater horizontal spread than P.M. (Fig. 10). This can be explained by that fact that the temperature fluxes in the P.M. were directed strongly downward rather than horizontally, whereas in the A.M. any downward soil temperature fluxes were initially small and similar in magnitude to those in a horizontal direction, and these resulted in a higher proportion of lateral spreading. The greater A.M. near-surface horizontal spread would also result in some reduction in the soil moisture content at those depths, since the same amount of applied water was being distributed through a larger soil volume compared to P.M.

Effects on redistribution and drying

For grapevines and other deep-rooted plants, even though P.M. irrigation increases the soil moisture content at

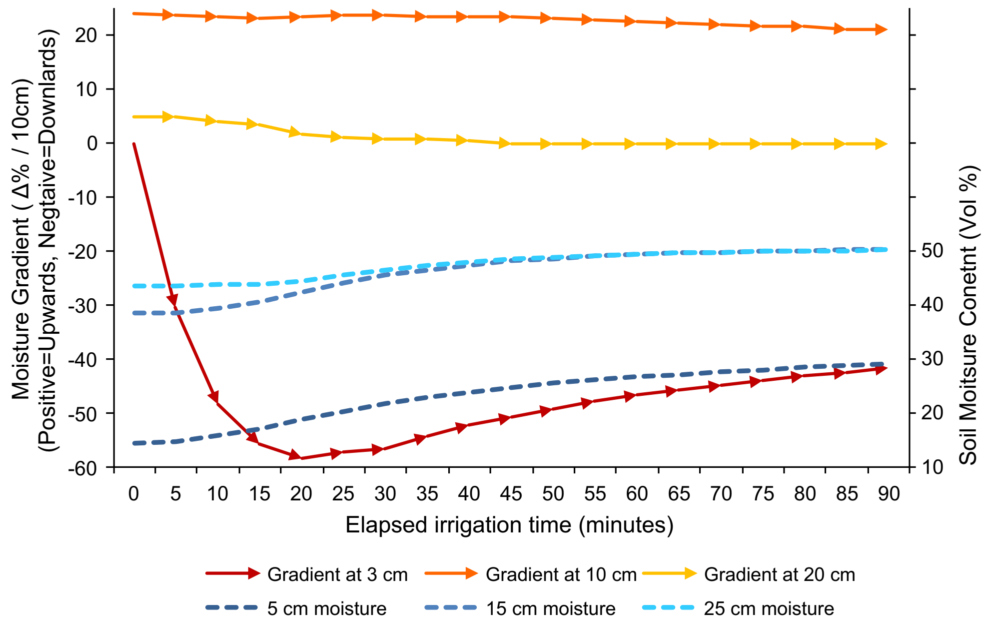


Fig. 14 Changes in moisture content and moisture gradients at various depths during A.M. irrigation (06:00, mean of all runs)

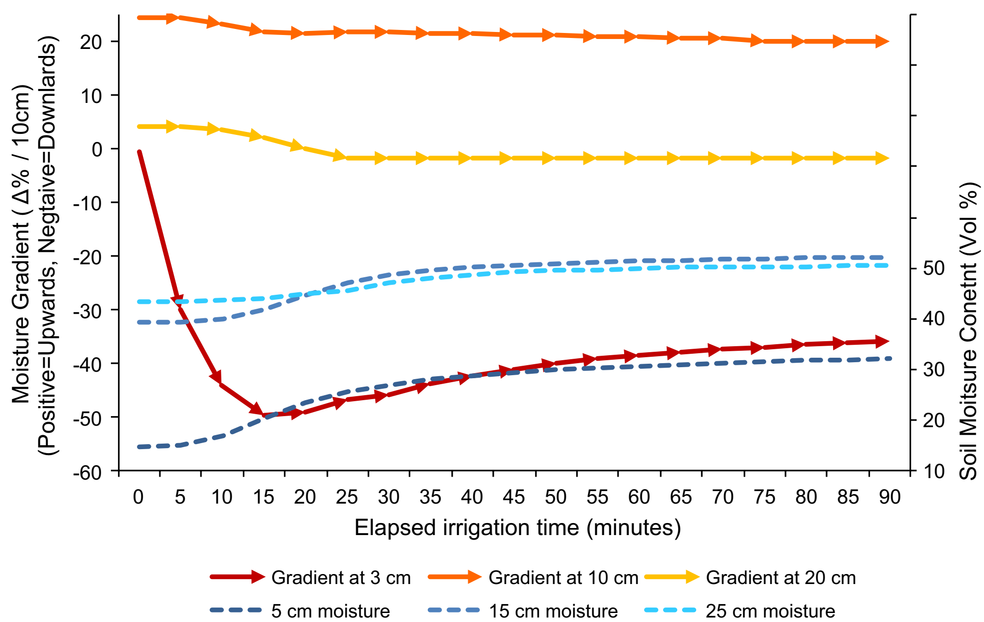


Fig. 15 Changes in moisture content and moisture gradients at various depths during P.M. irrigation (14:00, mean of all runs)

shallow depths compared to A.M., this is of limited benefit to such crops. However, the situation is different for shallow-rooted crops such as salad vegetables (cucumbers, lettuce, tomatoes and the like) which have, in the past, largely been watered by sprinkler or furrow irrigation. For example, spray irrigation is still the principal irrigation type for salad crops in the UK (Doyle and Erickson 2008).

There are a growing number of cases of food contamination worldwide by pathogens such as *Escherichia coli* and *Salmonella* with outbreaks linked to lettuce, spinach and tomatoes (Heaton and Jones 2008). Groundwater, surface water and human wastewater are commonly used for irrigation, and poor-quality water is one way that fruit and vegetables can become contaminated (Steele and Odumeru 2004). There is an increasing trend to use drip irrigation, either surface or subsurface, as a means of both increasing water use efficiency and minimising the transfer of pathogens to the leaves or fruit (by reducing or eliminating splashing, for example).

The current experiment identified some opportunities to improve drip irrigation scheduling for shallow-rooted crops such as salad vegetables, with associated water savings. For crops such as tomatoes, it has been shown by Warren and Bilderback (2002) that applying water at the time of the day when photosynthesis is highest also increases yield—irrigation at midday or in the P.M. produced a 46–56% greater top dry weight than earlier morning irrigation. The current experiment showed that, at depths down to 15 cm, there is an increase in peak moisture content with P.M. irrigation (as compared to A.M.) and that the effect also carries forward over the subsequent days as the soil dries (Fig. 9). This has the potential to be applied to irrigation scheduling for salad vegetables and similar crops, which typically only require irrigation to these shallow depths, to both increase yield and reduce the amount of irrigation water required. For example, by directly applying the experimental results of the rate of drying after irrigation at 5 cm and 15 cm depths (the data shown in Fig. 9) to create an irrigation schedule (Fig. 16), the interval between irrigations can be increased from 6 to 8 days by simply switching to P.M. irrigation rather than A.M. (providing that there is appropriate emitter spacing). This change would still keep the soil moisture content between 20% and FC at all times, but could potentially reduce the water use by up to 25%.

Of course, since the experiment was conducted on a bare site without plant transpiration, the irrigation frequencies shown in Fig. 16 need to be modified for cropping situations with their associated transpiration. By using the same data (Fig. 9), but also applying an arbitrary cropping factor (which has the effect of reducing the soil moisture levels more rapidly from day to day), a hypothetical irrigation schedule can be calculated (Fig. 17) which shows that the interval between irrigations could be 3 days (for A.M. irrigation) and 4 days (for P.M. irrigation), respectively. This demonstrates that there is still a 25% potential saving in the total water usage while keeping the soil moisture in the range of 20% to FC (that is irrespective of the amount of plant transpiration, the relative improvement in scheduling by moving to P.M. irrigation rather than A.M. remains constant).

Conclusion

The experiment showed that, for the soil depths relevant to field crops such as grapevines, drip irrigation efficiency is not affected by the time of day of watering, that is, that there are no diurnal effects. For drip irrigation, the belief that irrigation should not be applied in the heat of the day is not supported by the results of this study. This means that, for deep-rooted crops, drip irrigation scheduling can be completely flexible, can be conducted equally efficiently at any time of the day or night and not be limited to cooler periods of the day. This is important for minimising the total elapsed time needed to irrigate a large vineyard, especially where there are capacity constraints on the irrigation systems. At shallow soil depths, down to 15 cm, irrigating at 14:00 resulted in a higher peak moisture content being reached (a 9–18% increase in moisture added) and much of this difference persisted over the following 72 h of moisture distribution and soil drying. The

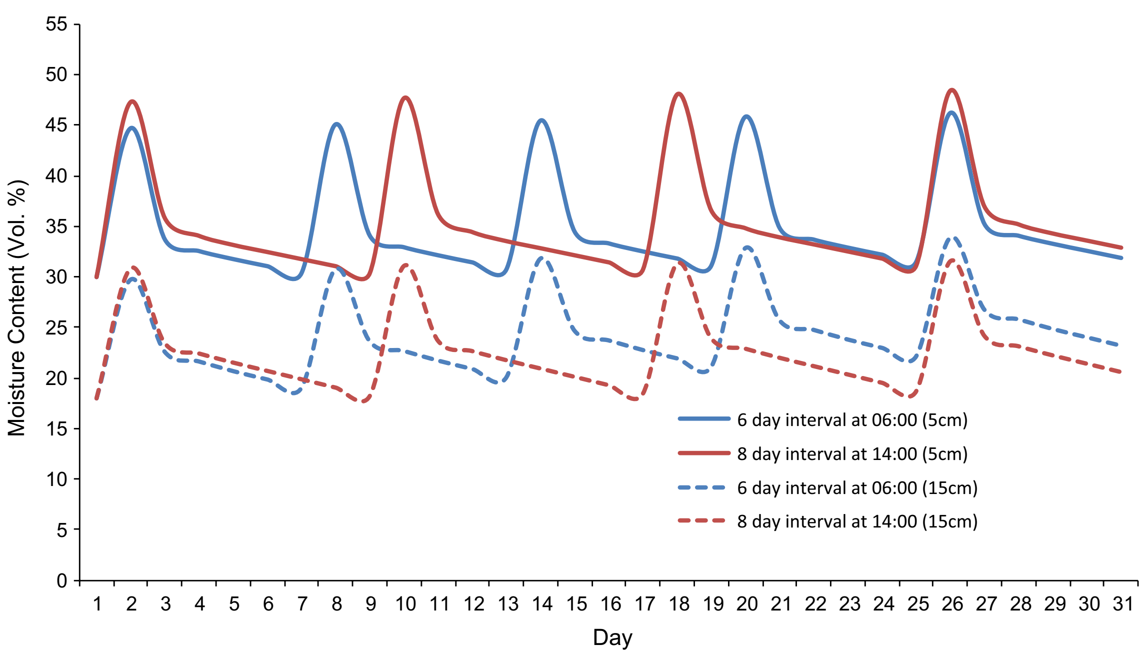


Fig. 16 Differences in the interval between successive irrigations, due to watering at 14:00 compared to 06:00, bare soil conditions and without plant transpiration (typically 8 days compared to 6 days)

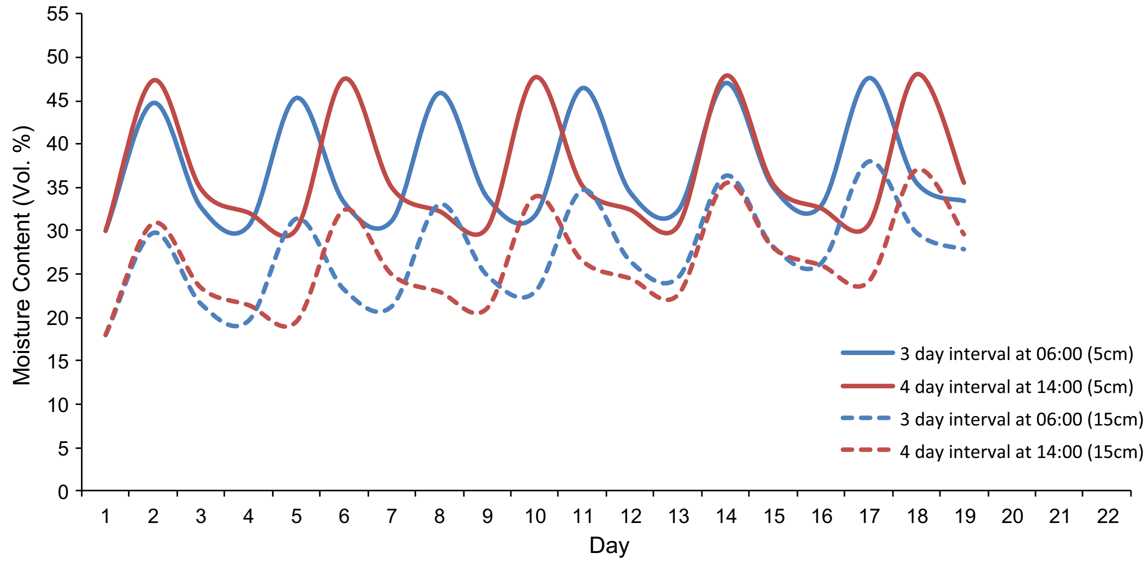


Fig. 17 Hypothetical irrigation interval, including an allowance for crop transpiration, due to watering at 14:00 compared to 06:00 (typically 4 days compared to 3 days)

shape of the wetted soil profile was also investigated and showed that, even though the time of day of irrigation had no effect on the radial wetted distance at depths of 15 cm and greater, at near-surface depths A.M. irrigation did result in a greater wetted radius.

These findings regarding the benefits of P.M. irrigation at shallow depths suggest that they have the potential to be applied to irrigation scheduling for salad vegetables and similar crops, which typically take up most of their plant water from depths <25 cm. By irrigating in the afternoon, rather than early morning, the frequency of irrigation could be reduced without impacting soil moisture content in the rootzone, resulting in significant savings in irrigation water. At the same time, the crop yield could potentially be increased through better matching of moisture availability with daily peak photosynthesis periods.

There are opportunities for further research, in particular by using 3-D computer simulations to model both the diurnal effects (considering heat, water and vapour flows) and the irrigation dynamics (resulting from the application of cool water into a hot soil) and also to further investigate the potential of P.M. irrigation for shallow-rooted crops.

References

Apcos Pty Ltd (2015) User manual—enviropro sub-surface soil probe, 5.1 edn. ETS Envirotek Solutions, Lyrup,South Australia. http://www.envirotek.com.au/images/ep200/User_Manual_EnviroPro_Series_E_SDI12_1.pdf

Braud I, Dantas C, Vauclin M, Thony L (1995) A simple soil plant atmosphere transfer model (SiSPAT): development and field verification. J Hydrol 166(3):213–250

Bureau of Meteorology (2013a) Average annual, monthly and seasonal evaporation. Retrieved 1 Nov 2015, from http://www.bom.gov.au/jsp/ncc/climate_averages/evaporation/index.jsp?#maps

Bureau of Meteorology (2013b) Monthly climate statistics (Bega). Retrieved 7 Feb 2016, from http://www.bom.gov.au/climate/averages/tables/cw_069002.shtml

Cahill AT, Parlange MB (1998) On water vapor transport in field soils. Water Resour Res 34(4):731–739

Cass A, Campbell GS, Jones TL (1984) Enhancement of thermal water vapor diffusion in soil. Soil Sci Soc Am J 48(1):25–32

Cook F, Thorburn P, Fitch P, Bristow K (2003) WetUp: a software tool to display approximate wetting patterns from drippers. Irrig Sci 22(3–4):129–134

Deb SK, Shukla MK, Sharma P, Mexal JG (2011) Coupled liquid water, water vapor, and heat transport simulations in an unsaturated zone of a sandy loam field. Soil Sci 176(8):387–398

Doyle MP, Erickson MC (2008) Summer meeting 2007—the problem with fresh produce: an overview. J Appl Microbiol 105(2):317–330

Grifoll J, Gasto JM, Cohen Y (2005) Non-isothermal soil water transport and evaporation. Adv Water Resour 28(11):1254–1266

Heaton JC, Jones K (2008) Microbial contamination of fruit and vegetables and the behavior of enteropathogens in the phyllosphere: a review. J Appl Microbiol 104(3):613–626

Hillel D (1980) Environmental soil physics—fundamentals. Academic Press, New York

Jackson RD, Kimball BA, Reginato RJ, Nakayama FS (1973) Diurnal soil–water evaporation: time-depth-flux patterns. Soil Sci Soc Am J 37(4):505

Jury WA, Letey J (1979) Water vapor movement in soil: reconciliation of theory and experiment 1. Soil Sci Soc Am J 43:823–827. https://www.soils.org/publications/sssaj/abstracts/43/5/823

Jury WA, Gardner WR, Gardner WH (1991) Soil physics. Wiley, New York

McKillup S (2012) Statistics explained: an introductory guide for life scientists, 2nd edn. Cambridge University Press, Cambridge

Measurement Engineering Australia (2013) Enviropro. Retrieved 8 Feb 2016, from http://mea.com.au/upload/Brochures/SoilMoistureMonitoring/EnviroPro_Web.pdf

Measurement Engineering Australia (2015). Plexus. Retrieved 14 Feb, 2016, from http://mea.com.au/upload/Brochures/SoilMoistureMonitoring/Plexus_Web_2.pdf

Measurement Engineering Australia (2016) Comparing soil moisture tension and soil moisture content. Retrieved 8 Feb 2016, from http://mea.com.au/soil-plants-climate/soil-moisture-monitoring/learning-centre/comparing-soil-moisture-tension-and-soil-moisture-content

Milly PCD (1982) Moisture and heat transport in hysteretic, inhomogeneous porous media: a matric head-based formulation and a numerical model. Water Resour Res 18(3):489–498

Milly PCD (1984) A simulation analysis of thermal effects on evaporation from soil. Water Resour Res 20(8):1087–1098

Milly PCD (1986) An event based simulation model of moisture and energy fluxes at a bare soil surface. Water Resour Res 22(12):1680–1692

Minitab Inc. (2016) Minitab 17. Retrieved 22 Feb 2016, from https://www.minitab.com/en-us/products/minitab/

Monaghan JM, Daccache A, Vickers LH, Hess TM, Weatherhead EK, Grove IG, Knox JW (2013) More “crop per drop”: constraints and opportunities for precision irrigation in European agriculture. J Sci Food Agric 93(5):977–980

Nassar IN, Horton R (1997) Heat, water, and solution transfer in unsaturated porous media: I—theory development and transport coefficient evaluation. Transp Porous Media 27(1):17–38

Parlange MB, Cahill AT, Nielsen DR, Hopmans JW, Wendroth O (1998) Review of heat and water movement in field soils. Soil Tillage Res 47(1–2):5–10. http://www.sciencedirect.com/science/article/pii/S016719879800066X

PC-Progress (2015) Hydrus 2D/3d. Retrieved 21 Mar, 2015, from http://www.pc-progress.com/en/?hydrus-3d

Philip JR (1984) Travel times from buried and surface infiltration point sources. Water Resour Res 20(7):990–994. doi:10.1029/WR020i007p00990

Philip JR, De Vries DA (1957) Moisture movement in porous materials under temperature gradients. Eos Trans Am Geophys Union 38(2):222–232

Playán E, Salvador R, Faci JM, Zapata N, Martínez-Cob A, Sánchez I (2005) Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agric Water Manag 76:139–159

Power E (trans) (1928) The goodman of Paris (Le Ménagier de Paris), a treatise on moral and domestic economy by a citizen of Paris. Harcourt, Brace, & Co., New York, pp 195–204. http://search.proquest.com.ezproxy.csu.edu.au/docview/757325001/fulltextPDF/6D589545B92042BEPQ/1?accountid=10344

Quinn G, Keough M (2002) Experimental design and data analysis for biologists. Cambridge University Press, Cambridge. doi:10.1017/CBO9780511806384

Revol P, Clothier BE, Mailhol J, Vachaud G, Vauclin M (1997) Infiltration from a surface point source and drip irrigation: 2. An approximate time-dependent solution for wet-front position. Water Resour Res 33(8):1869–1874

Rose CW (1968) Water transport in soil with a daily temperature wave. I. Theory and experiment. Soil Res 6(1):31–44

Saito H, Šimůnek J, Mohanty BP (2005) Numerical analysis of one-dimensional coupled water, vapor and heat transport in the vadose zone using HYDRUS. In: Proceedings of the workshop on HYDRUS applications, p 22

Shurbaji A-RM, Phillips FM, Campbella AR, Knowlton RG (1995) Application of a numerical model for simulating water flow, isotope transport, and heat transfer in the unsaturated zone. J Hydrol 171(1):143–163

Sophocleous M (1979) Analysis of water and heat flow in unsaturated-saturated porous media. Water Resour Res 15(5):1195–1206

Steele M, Odumeru J (2004) Irrigation water as source of foodborne pathogens on fruit and vegetables. J Food Prot 67(12):2839–2849

Thorburn PJ, Cook FJ, Bristow KL (2003) Soil dependent wetting from trickle emitters: implications for systems design and management. Irrig Sci 22(3–4):121–127

Toro Australia Pty Ltd. (2003) Toro turbo plus II drip emitters. Retrieved 8 Feb 2016, from http://www.toro.com.au/product/toro-turbo-plus-ii-drip-emitters?c3=drip-3&c4=online-emitters

Tulau MJ (1997) Soil landscapes of the Bega-Goalen point. Department of Land and Water Conservation, Sydney. Retrieved from http://www.environment.nsw.gov.au/soils/bega.htm

van Genuchten MT (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44(5):892

Warren SL, Bilderback TE (2001) Irrigation timing: Effect on plant growth, photosynthesis, water-use efficiency and substrate temperature. In: International symposium on growing media and hydroponics, vol 644, pp 29–37

Warren SL, Bilderback TE (2002) Timing of low pressure irrigation affects plant growth and water utilization efficiency. J Environ Hortic 20(3):184–188

Wierenga PJ, Nielsen DR, Hagan RM (1969) Thermal properties of a soil based upon field and laboratory measurements. Soil Sci Soc Am J 33(3):354–360

Yazar A (1984) Evaporation and drift losses from sprinkler irrigation systems under various operating conditions. Agric Water Manag 8:439–449

Zeng YJ, Wan L, Su ZB, Saito H, Huang KL, Wang XS (2008) Diurnal soil water dynamics in the shallow vadose zone (field site of China University of Geosciences, China). Environ Geol 58(1):11–23