Study on evaluation of mulching effect and establishment of irrigation threshold for water-saving production

節水のためのマルチング効果と灌漑時期の評価に関する研究

ZHANG QING TAO

2009

Study on evaluation of mulching effect and establishment of irrigation threshold for water-saving production

節水のためのマルチング効果と灌漑時期の評価に関する研究

ZHANG QING TAO

Doctoral Dissertation

The United Graduate School of Agriculture Sciences,
Tottori University

2009

Contents

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Effects of mulching and sub-surface irrigation on soil moisture and temperature, growth, yield, and berry quality of 'Gros Colman' grapevines

Chapter 5

Chapter 6

Chapter 7

List of figures

List of tables

List of symbols

ADR: amplitude domain reflectometry
A_N: net photosynthesis (μmol CO_2 m^{-2} s^{-1})
CCD: optical coupler
CI: cool night index
C_i: sub-stomatal CO_2 concentration (μmol CO_2 / mol air)
D: berry diameter (mm)
T: transpiration (mmol H_2O m^{-2} s^{-1})
EC: electrical conductivity (dS m^{-1})
Es: soil evaporation (mm)
ET: Evapotranspiration (mm)
ETR: electron transport rate
extrinsic *WUE*: photosynthesis / transpiration
*f*c: focal length
G: gravel mulch
g_s: stomatal conductance (mol H_2O m^{-2} s^{-1})
intrinsic *WUE*: photosynthesis / stomatal conductance
LSD: least significant difference
M: mulch
MS: mulching combined with surface Seeper Hose seepage irrigation
MSS: mulching combined with sub-surface Seeper Hose seepage irrigation
N: no-mulch
R: rice-straw mulch
S: no-mulch combined with surface Seeper Hose seepage irrigation
SDI: sub-surface drip irrigation
SS: no-mulch combined with sub-surface Seeper Hose seepage irrigation
Ts: soil temperature (°C)
WUE: water use efficiency (kg m^{-3})
θ: soil water content (cm^3 cm^{-3})
ψ: soil water potential (kPa)

Summary

Given the current demographic trends and global warming, as much as 60% of the global population may suffer serious water scarcity by the year 2025. Agriculture is likely to suffer the most unless more efficient water management is practiced, particularly in drylands. Mulching is an efficient method controlling evaporation. Reducing evaporation loss helps to conserve soil moisture and control salt accumulation. Since saline water resources are more abundant than fresh water, the careful use of saline or diluted seawater is important for agriculture. Irrigation scheduling also plays an important role in developing water-saving agriculture. Determination of threshold value at which irrigation should be scheduled is necessary for water-use-efficient production. This study was carried out from 2005 to 2008 at the Arid Land Research Center, to evaluate mulching effect for sustainable agriculture and establish irrigation threshold for water-saving production.

In the first part, ameliorative effect of mulching on water use efficiency (*WUE*) of Swiss chard and salt accumulation under saline irrigation was investigated in order to conserve soil water and maintain lower level of salts in the topsoil. A pot experiment was conducted in a greenhouse to evaluate the effects of three mulching types together with diluted seawater irrigation. Seawater was diluted to achieve the electrical conductivity of irrigated water as 4.8 and 7.4 dS m^{-1}. Pots were mulched in the form of gravel, pine-needles and rice-straw, respectively. Mulches significantly reduced evapotranspiration (*ET*) in all the treatments and reduced salt accumulation under high saline irrigation. High diluted seawater irrigation could be used under mulch condition without serious salinity-damage to Swiss chard. Averaged soil temperature (*Ts*) among mulches differed as gravel > rice-straw > pine-needles > no-mulch during winter season, regardless of soil depth. Mulching improved plant biomass as well as *WUE*. Under high saline water, mulches were differed for the dry matter production and *WUE* in the order of gravel > pine-needles > rice-straw > no-mulch. The experiment indicated that mulching practice can be also used favorably for crop production under saline irrigation.

In the second part, the effect of gravel mulch (G) and rice-straw mulch (R) on the soil salinity, *ET*, fresh and dry weight yield and *WUE* of Swiss chard were investigated. Three weighing lysimeters were irrigated with diluted seawater (6.86 dS m^{-1}) from below to allow the water table to keep between 50 cm and 80 cm depth. At the end of the experiment, the electrical conductivity of 1:5 soil extract was measured in four soil depths (5, 10, 15, 25cm). The cumulative *ET* was higher with no-mulch (292 mm) than under R (254.7 mm) and G (216.6 mm). The fresh and dry yields of Swiss chard were, respectively, 76% and 113% higher under R and 49% and 64% higher under G than under no-mulch. The electrical conductivity of 1:5 soil extract in the top 25 cm soil layer was lower under mulching than under no-mulch. Mulching increased the soil temperature slightly. These contributed to the increase of yield under mulching as compared to under no-mulch treatments. RM treatment increased *WUE* by 143% and 10% as compared to no-mulch and G treatment, respectively. Thus mulching using R is recommended for reducing salinity effect under shallow water table of saline water and improving *WUE*.

In the third part, effects of mulching and sub-surface seepage irrigation on soil water, soil temperature, growth, berry quality and yield of grapevines (*Vitis vinifera* L.) were investigated. This experiment was conducted in a greenhouse using 4 weighing lysimeters from 5 June to 21 Sep., 2008. Four treatments: mulching combined with sub-surface Seeper Hose seepage irrigation (MSS); no-mulch combined with sub-surface Seeper Hose seepage irrigation (SS); mulching combined with surface Seeper Hose seepage irrigation (MS); no-mulch combined with surface Seeper Hose seepage irrigation (S), were used. Growing investigation was included of shoot length, leaf area, photosynthesis (A_N), berry diameter, berry sugar content and fresh yield of grapevines. MS gave the highest fresh yield while SS gave the lowest value due to higher θ (upper soil), A_N, *Ts* and diameter for MS as compared with SS. MS gave the higher *WUE* than MSS due to the higher water content at top soil and higher yield for MS. These combination of mulch and seepage irrigation were differed for *WUE* in the order of MS > MSS > SS > S. Compared with SS, the berry diameter, fresh yield, *WUE*, and berry sugar content for MS were enhanced by 2.8 mm, 271.5 g/tree, 33% and 15%, respectively. MSS gave higher berry sugar content than MS, which could be attributed to the higher *Ts* and lower soil water at the top soil layer under the condition of sub-surface irrigation. *Ts* should become an important index for the berry quality of grapevine.

In the fourth part, soil water potential threshold for scheduling irrigation was determined in the last phase of Stage 1 of berry growth based on photogrammetric measurement of berry size. After irrigation, grapevine was allowed to experience decreasing ψ monitored by tensiometers. The instantaneous variations in the berry diameter were measured by photogrammetry simultaneously. Photosynthesis was also measured. Berry diameter increased at night and decreased in the day, and showed sensitivity to developing soil moisture stress. Berry diameter increased rapidly after irrigation till ψ became −3 kPa. In the ψ range of −3 kPa to −5.4 kPa, the growth rate decreased, and as ψ decreased beyond −5.4 kPa, the berry started shrinking and the shrinkage showed a strong linear relationship with decreasing ψ. In contrast, photosynthesis and transpiration remained unaffected by decreasing ψ until it became −9.3 kPa beyond which photosynthesis decreased significantly. Thus, berry diameter was a better indicator of developing moisture stress than photosynthesis and transpiration and −5.4 kPa should be considered as the threshold ψ for scheduling irrigation in the last phase of Stage 1 of berry development in grapevines.

In the fifth part, the critical value of soil water potential was discussed for irrigation scheduling during berry ripening stage (Stage 3) of grapevines. When soil water potential decreased from -13.2 kPa to -14.7 kPa, photosynthesis, stomatal conductance, transpiration, extrinsic *WUE* (= photosynthesis / transpiration) and intrinsic *WUE* (= photosynthesis / stomatal conductance) decreased rapidly and did not recovery thereafter. In contrast, the berry size remained almost unaffected by decreasing soil water potential until it became -16.2 kPa beyond which the berry shrunk significantly. Thus, photosynthesis response was more sensitive to water stress than berry size during the berry ripening stage. When stomatal conductance < 0.03 mol H_2O m^{-2} s^{-1} (corresponding to -14.7 kPa), photosynthesis, intrinsic *WUE* and extrinsic *WUE* decreased rapidly, whereas substomatal CO_2 concentration increased steeply, indicating that non-stomatal limitations to photosynthesis become dormant. A more sensitive response of photosynthesis to water limitation compared to stomatal conductance at this last stage of soil drying led to a decrease in photosynthesis/stomatal conductance. When stomatal conductance > 0.03 mol H_2O m^{-2} s^{-1}, photosynthesis and substomatal CO_2 concentration decreased, whereas extrinsic *WUE* and intrinsic *WUE* usually increased. Therefore, stomatal limitations seem dormant at this stage. In areas where water availability is low or moderate, the critical soil water potential range for irrigation scheduling should be

between -13.2 and -14.7 kPa (corresponding to stomatal conductance range of 0.09 - 0.03 mol H_2O m^{-2} s^{-1}). After irrigation, soil water potential should be kept lower than -6.9 kPa because the highest intrinsic *WUE* occurred in the soil water potential range from -6.9 to -14.6 kPa. In hyper arid and arid areas, the soil water potential threshold for irrigation scheduling should be considered as -16.2 kPa (corresponding to stomatal conductance value of 0.02 mol H_2O m^{-2} s^{-1}) in this important stage of economic yield development and fruit quality in grapevines.

In conclusion, rice-straw mulch was a better option than gravel mulch for improving crop yield and water use efficiency in the long run. The rice-straw mulch combined with surface irrigation exceeded no mulch combined with sub-surface irrigation for enhancing the berry diameter, fresh yield, *WUE* and berry sugar content. Mulching combined with surface irrigation outbalanced mulching combined with sub-surface irrigation in improving yield and *WUE*. Hence when the sub-surface irrigation is used for vineyards, the placement depth of sub-surface irrigation hose should be shallower than 15 cm. Mulching combined with sub-surface irrigation gave higher berry sugar content than mulching combined with surface irrigation due to higher average soil temperature and lower soil moisture at the top soil layer under sub-surface irrigation. Besides the effective mulching cultivation and irrigation methods, the appropriate irrigation scheduling is also very important for saving water. A new photogrammetry system is suitable for measuring berry diameter for irrigation scheduling, therefore photogrammetry could be used for determining the critical point at which the berry contracted under stressful condition. The berry diameter was a better indicator of sensing water stress than photosynthesis in the last phase of Stage 1 of berry growth since the berry contracted under the moderate water stress. Nevertheless, in the ripening stage, the leaf photosynthesis was more sensitive to water stress than berry size, so leaf photosynthesis measurement and photogrammetry technology could be used together to establish irrigation threshold to get cost-effective use of water resources, especially for fruit trees. Since the water demand for vines in various growth stages is not uniform and drought has different effect on fruit development at different stages, further experiments should be conducted to establish critical irrigation values in various growth stages. In addition, further test should be done under open-field conditions.

Acknowledgements

At the outset, I want to thank God for being so merciful during my studies and inspiring me by providence in my life.

This thesis would never be completed without the contribution of many people to whom I would like to express my appreciation.

I want to express my grateful thanks to The Japanese government for granting me a scholarship and Global Center of Excellence (GCOE) program for providing research budget.

I would like to express my deepest appreciation to my supervisor Prof. Inoue Mitsuhiro for his thoughtful supervision, valuable guidance, intellectual encouragement, good advices and critical and constructive comments. I have learned a lot from him in these five years because he has dedicated himself to instruct me and help me in my experiments and during my studies at the Arid Land Research Center. Prof. Inoue also provided me much attention and care which helped my life. It's generous of him to give me so much of his time and show me so much consideration. I want to express my maximum respect to him.

I am also deeply indebted to my associate-supervisor Prof. Koji Inosako and Prof. Kenji Suzuki, whose comments, advice and support were of great value to me. Their intellectual encouragement during the thesis writing is unforgettable.

I am grateful to Dr. Ahmed and Dr. Andry of the GCOE program for their valuable and critical comments during the development of my thesis proposal. Their comments were very beneficial for my study. I do appreciate their help.

I would like to extend my appreciation to the entire Land Conservation division staff for the knowledge they have given me during the period of studies at the Arid Land Research Center. Their advice and help made even the smallest incident important and charming. It is generous of them to take so much interest in my study. I also appreciate their ever-willing attitude to help me solve my personal problems.

Last but not least, I have appreciated the endeavor, advice, help and courage of my wife Li Li, and my daughter Zhang Shi Ran, in coping with me while I was busy for a long time with my experiments and studies, and giving me impetus in my study. I also want to thank my parents for their patience and long-waiting for me in my hometown.

Chapter 1

1.1 Introduction

1.1.1 Drought and salinization in the world and ameliorative effects of mulching

Drought and salinization represent serious threats to the sustainability of irrigated agriculture in many arid and semi-arid regions (Konukcu et al., 2005). The water-use efficiency techniques used with conventional resources have been improved. However, the shortage of water resources of good quality is becoming an important issue in water-scarce countries, which will have to rely more on the use of non-conventional water resources to partly alleviate water scarcity. At the same time, a rapid increase in the population of these areas during the past two decades has significantly increased the need for water, food and fibre. Hence, land and water resources have been put under severe stress (Ghadiri et al., 2005).

Direct evaporation from soil is a major way of water loss because it is not directly related with biomass production. Apparently, there are three main advantages of reducing soil evaporation (*Es*). First, preventing *Es* can help conserve soil moisture and save water. Second, preventing *Es* helps control salt accumulation (Yamanaka et al., 2004). Third, preventing *Es* can also benefit environment since it can reduce leaching of nitrate fertilizers and thus reduce pollution (Romic et al., 2003).

Application of mulch is known to be effective in reducing *Es* (Cadavid et al., 1998). Trees with organic mulch and tree-shelter treatments had a greater survival than trees with plastic mulch and no mulch, particularly when salinity was higher (Sun et al., 1994). In northwest China, use of gravel mulch has been an indigenous farming technique for crop production for over 300 years (Li, 2003), especially in watermelon fields (see **Fig. 1-1**). The farmers usually use 10 mm gravel to mulch the fields and the interval of changing mulch is several decades, so the work of mulching and removing gravel is not an obstacle for the farmers. Increasing water-use efficiency (*WUE*) should be a key issue for research (Al-Kaisi and Yin, 2003) and it is currently a priority for the United Nations policy, what is called the 'Blue Revolution' and summarized as 'more crop per drop'

(Annan, 2000).

Fig. 1-1 Water melon fields covered by gravel mulch in Gaolan in the northwest of China (by Wang Jie Min)

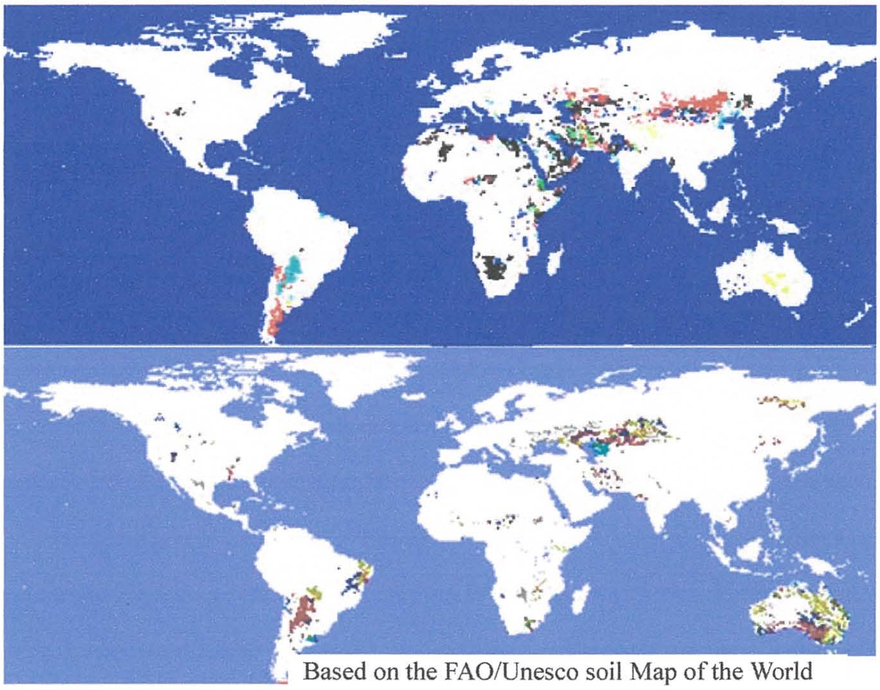
More than 50% of all the existing irrigation systems of the world are more or less affected by soil salinization and alkalinization (Szabolcs, 1989). In the future, one of the consequences of extension of irrigation in arid and non-arid areas would be increasing hazard of secondary salinization, caused by irrigation. The yearly loss of arable land by secondary salinization and alkalinization is more than 10 million hectares and this area is distributed in different developed and developing countries in all the continents. In soils where salinity and alkalinity is a result of improper method of irrigation the amelioration is rather expensive, therefore the prediction and prevention of salinization before construction and exploitation of irrigation systems is necessary (Szabolcs, 1989).

Irrigation-induced salinization is one of the most important reasons of reduced agricultural productivity in many arid and semi-arid regions (Fujimaki et al., 2003). Freshwater resources of these areas, both surface and ground water, have been over-exploited, often at the expense of deteriorating water and land quality. As supplies of good-quality irrigation water are expected to decrease in several regions due to increased municipal industrial agricultural competition, available freshwater supplies need to be used more efficiently (Qadir and Oster, 2004). With limited room for expanding irrigated agriculture due to the lack of extra capacity in freshwater resources, the possible use of saline or sea water has some appeal, especially in coastal areas, such as in Iran (Ghadiri et al., 2005) and Italy (Baccio et al., 2004 and D' Amico et al., 2004).

Saline water was previously considered unusable for irrigation, but new research during the past two decades has helped bringing into practice some large irrigation schemes, which depend on saline water (Beltran, 1999 and Qadir et al., 2001). Irrigation with saline water could provide an interesting opportunity to meet increasing food demands without competing with other pressing needs for fresh water such as domestic and industrial water use in water scarce regions (Karlberg and Vries, 2004). The availability of water resources of marginal quality such as drainage water, saline groundwater, treated wastewater and diluted sea water has therefore become an important consideration. As a consequence of the use of the marginal quality water, however, salts may accumulate in the root zone, damaging the following crops if the rainfall is insufficient to leach them out. In the experiment on use of diluted sea water, soil analysis after harvest showed that the electrical conductivity of the saturation extract had increased significantly in diluted sea water treatments (Ghadiri et al., 2005). This may suggest that the mixing of sea and ground waters at the rates used in these experiments may not be sustainable over a long period of time and soil salinization may occur unless soils are of light texture and sufficient good quality fresh water or winter rain is available to lower the salinity of soil between successive crops (Ghadiri et al., 2005).

Thus, the use of these waters in irrigated lands requires the control of soil salinity by means of leaching and drainage of excess water and salt. An extra quantity of water in excess of that needed for evapotranspiration must be applied as a long-term strategy and the extra quantity of irrigation water must be able to pass through the root zone (Qadir et al., 2003). However, the leaching of salts, soil microelements and agrochemicals can lower the quality of the drainage water in the irrigation scheme. The irrigation return flows with water of poor quality are a source of pollution of the surface water bodies situated downstream of the drainage outlet. Deep percolation could also contaminate the groundwater. Therefore, irrigation with saline water requires a comprehensive analysis (Beltran, 1999).

Salinity generally affects the growth of plants by either producing an ion excess or a water deficits in the expanded leaves (Ghadiri et al., 2005). Water uptake is restricted by salinity due to the high osmotic potential in the soil and high concentrations of specific ions that may cause physiological disorders in the plant tissues (Feigin, 1985) and reduce yields (Verma and Neue, 1984). However, some crops such as wheat and barley can be salt tolerant (Ghadiri et al., 2005). Research suggests that irrigation of barley with up to two-thirds sea water is feasible and may result in economically significant yields.



Based on the FAO/Unesco soil Map of the World

77 million ha of cultivated area is on salt-affected soils

Fig. 1-2 Salt-affected soils in the world

Salinity is a widespread environmental stress for crop plants. It is common in arid, semiarid, and coastal regions (see **Fig. 1-2**). In those environments, seawater infiltrations can occur (Milnes and Renard, 2004) or the sea provides the only source of water for irrigation (Baccio et al., 2004). The use of diluted sea water, saline and/or sodic drainage water and groundwater for agriculture is expected to increase. This warrants modifications in the existing soil, irrigation, and crop management practices used, in order to cope with the increases in salinity and sodicity that will occur (Qadir et al., 2007).

Salts in the soil solution are left behind as soil water evaporates. Therefore, salt accumulation can be reduced by preventing *Es*. Mulching the soil surface with bituminous emulsion up to 75 g m^{-2} decreased the mean salt concentration in the root zone (10% level) (Wahba et al., 1990). Only a few studies have been made about the effects of preventing salt accumulation using mulch (Wahba et al., 1990). Furthermore, there is lack of research on comparing effects of different kinds of mulch on salt accumulation. Residues of wheat and barley have been found to be more effective in decreasing *Es* than those of sorghum or cotton. This is attributed to the thinner stems of wheat and barley than sorghum or cotton (Jalota and Prihar, 1998). Pine-needles are thinner than rice-straw, however, there is lack of research on comparing effects of pine-needle and rice-straw on preventing evapotranspiration (*ET*) and salt accumulation.

1.1.2 Swiss chard and grapevines in drylands and semi-arid regions

Beet (*Beta vulgaris* L.) is an important crop within many arable rotations in the world and it is commonly grown in rotation with wheat (*Triticum* spp.) and barley (*Hordeum* spp.) and sometimes with potato (*Solanum* spp.) (Smith et al., 2001). It is a valuable break crop, preventing the build up of disease and reducing the need for pesticides in the following crops (Tzilivakis et al., 2005). Drought is the most serious cause of yield loss in the UK beet crop (Jaggard et al., 1998). For this reason the availability of water resources of marginal quality such as drainage water, saline groundwater and treated wastewater has become an important consideration. Sugar beet yield was higher in the field irrigated with moderately saline water (5.9–7.0 dS m^{-1}) than in the field irrigated with fresh water (Moreno et al., 2001). Glycine betaine accumulation increased under salinity and this accumulation correlated with higher tissue levels of Na in red-beet (Subbarao et al., 2001). Swiss chard (*Beta vulgaris* L. var. *flavescens*) is a kind of beet. However, there are few studies on effects of mulch and diluted sea water irrigation on Swiss chard (Louvigny et al., 2002).

The grapevine plays a very important role in the economic, social and cultural sectors of many regions; however vineyards are often grown in regions under stressful conditions and thus they are vulnerable to climate change (Santos et al., 2007). In a vineyard, one mulching material of a sewage sludge and bark compost improved water retention capacity of the soil, reduced evaporation and soil temperature fluctuations (Pinamonti, 1998). Nevertheless, the wavelength-selective polyethylene mulch had no detectable effects on vine development, yield components and fruit quality (Bowen et al., 2004). Rice-straw mulching increased *WUE* of Swiss chard by 143 and 10% as compared to no-mulch control and gravel mulching treatment, respectively (Zhang et al., 2009). Unfortunately, there is lack of international literature evaluating effects of the rice-straw mulch on grapevines growth.

Grapevine is a traditionally non-irrigated crop that occupies quite an extensive agricultural area in drylands and semi-arid regions. Recently, irrigation was introduced to increase the low land yield (Escalona et al., 2003), but a good compromise between grape quality and yield is of major importance for the achievement of high-quality products as wine (Cifre et al., 2005).

1.1.3 Sub-surface irrigation

Soon after the conventional surface irrigation, the soil is very wet, resulting in lack of air. Later, this soil becomes dry and hard, causing a degree of salts, and is a continuous cycle. Sub-surface irrigation, in which water is applied below the soil surface, can help conserve water by reducing evaporative water losses in agricultural systems (Siyal and Skaggs, 2009). Sub-surface irrigation has been practiced in various forms, including pitcher or pot irrigation (Bainbridge, 2001; Siyal and Skaggs, 2009), perforated or porous clay pipe irrigation (Ashrafi et al., 2002; Shu et al., 2007) and drip irrigation (Patel and Rajput, 2008). However, reports on the response of grapevines to sub-surface irrigation have not been found.

Sub-surface drip irrigation (SDI) is the most advanced method of irrigation, which enables the application of the small amounts of water to the soil (ASAE Std., 1999) while maintaining a relatively dry soil surface (Patel and Rajput, 2008). Nevertheless, one technological problem is the formation of cavity at the soil surface above the water emission points (Patel and Rajput, 2008). Another problem is spatially dependent reductions in dripper discharge (Ben-Gal et al., 2004). In addition, in many parts of the world, plastic drip tubing and emitters are cost-prohibitive (Siyal and Skaggs, 2009), so some cheap materials for simple micro-irrigation technique should be developed.

Seeper Hose is an absolutely new environmental soil control system which consists of a flexible rubber tubing that contains many micro pores and is laid sub-surface or underground to supply water, air, or fertilizer directly to plants. However, no research has been conducted using sub-surface Seeper Hose irrigation for grapevines. A combination of mulching and sub-surface Seeper Hose irrigation techniques has not been tested on grapevines, and could probably yield even more promising results.

1.1.4 Irrigation scheduling for grapevines based on soil water potential threshold

Improving the efficiency of irrigation is essential for long-term sustainability of grape production and the wine industry. Deficit irrigation in fruit crops can be of value in increasing fruit quality by raising dry matter and sugar content (Chalmers et al., 1981). Several studies have shown that appropriate and moderate water stress is beneficial for berry growth in grapevines, whereas severe water deficit or saline irrigation decreases the production of assimilates, reduces transpiration, shoot growth, and yield and quality of fruit (Shani et al., 1993; Delgado et al., 1995; Pellegrino et al., 2005; Lovisolo and Schubert, 2006; Lovisolo et al., 2008). The potential for water saving by deficit irrigation in orchard crops has remained unexplored so far (Fereres et al., 2003). It is, therefore, important to determine the critical timing for starting irrigation, especially in drylands where drought represents a serious threat to the sustainability of agriculture (Konukcu et al., 2005).

McCarthy (2000) reported that grape berry size was most sensitive to water stress during the post-flowering period, whereas moisture deficit after veraison had only a minor effect on berry weight at maturity and berries were insensitive to water deficit in the month before harvest (McCarthy, 1997a). Imai et al. (1991b) further reported that daily variation in berry diameter might be a useful index for soil moisture control in grape production. The upper limit of ψ in the ripening stage was regarded as $\psi = -12.6$ kPa since the berry swelling was conspicuously affected by soil drying (Imai et al., 1991b). Their study, however, did not indicate the threshold value of ψ at which irrigation should be scheduled during the berry development stages as only two levels of ψ were tested.

Imai et al. (1991b) concluded that in the ripening stage, berry size is affected conspicuously by decreasing ψ. However, McCarthy (2000) reported that moisture deficit after veraison had only a minor effect on grape berry weight at maturity and berries were insensitive to water deficit in the month before harvest (McCarthy, 1997a). The maturation stage is critical for grape berry quality. In the maturation stage, is the berry size sensitive to decreasing ψ? Cifre et al. (2005) reported that stomatal conductance (g_s), sap flow and trunk growth variations could be used as indicators of water stress for grapevine. During the maturation stage of grapevine, which kind of physiological parameter is useful and suitable for irrigation management? Further studies should be done to clear these questions for scheduling irrigation in the maturation stage of grapevine.

There are many studies on the effects of various irrigation regimes on vine growth (Bravdo et al., 1985; Poni et al., 1994; Esteban et al., 2001; Pellegrino et al., 2004; Reynolds et al., 2005). However, what is the threshold ψ at which the grapevine must be irrigated during different berry development stages is not known. We hypothesized that this value could be established by measuring diurnal variations in berry diameter, leaf photosynthesis and stomatal conductance of grapevine experiencing increasing soil moisture stress. It is, however, necessary that the measurements of berry diameter are made with great precision because the changes are rather small.

A new system equipped with automated photogrammetry was developed by Moritani et al. (2006; 2007) to measure soil erosion (Pyle and Richards, 1997). This system consists of two high-precision digital cameras, attached to a computer with an image-analysis program of three-dimensional algorithm. This system can also be applied for measuring fruit size with three major advantages. First, the measurement precision is high. Second, the berry diameter can be monitored automatically. Third, the determination is nondestructive. However, there is lack of information about measuring berry size using the new photogrammetry system.

1.2 Objectives

The objectives of this study were to evaluate mulching effects for Swiss chard and grapevines production and establish irrigation threshold for water-saving management of grapevines. More specifically, the following objectives were addressed in the study:

1) Comparison of the three mulching materials effects (i.e., rice-straw, pine-needles and gravel) under diluted seawater irrigation condition on evapotranspiration, water use efficiency of Swiss chard, soil water content, soil temperature and salt accumulation

2) Evaluation of the rice-straw mulch (M) and sub-surface Seeper Hose irrigation (SS) effects on *ET*, *WUE*, soil water content (θ) and temperature, growth (shoot length, leaf area, photosynthesis and berry diameter), berry quality (sugar content) and yield of 'Gros Colman' grapevines (*Vitis vinifera* L.)

3) Establishment of the critical soil water potential value for starting irrigation in grapevines during the berry-growth stage and ripening stage, based on photogrammetry of berries, photosynthesis of leaf and a tensiometer measurement system of soil water potential, as the water deficit developed in the soil.

Chapter 2 Ameliorative effect of mulching on water use efficiency of Swiss chard and salt accumulation under saline irrigation

2.1 Introduction

In several areas in many countries, irrigation is causing a rapid decline of the groundwater table (Zhang et al., 2003). Application of mulch is known to be effective in reducing evaporation and thus preventing non-beneficial loss of water (Cadavid et al., 1998) because mulch provides resistance to vapor flow from the soil surface to the atmosphere. There are many kinds of mulch material.

In many arid and semi-arid areas, freshwater resources -both surface and ground water- have been over-exploited. The possible use of diluted sea water has some appeal in coastal areas (Ghadiri et al., 2005). But as a consequence, salts may accumulate in the root zone. Thus, the use of these waters in irrigated lands requires the control of soil salinity by means of leaching and drainage of excess water and salt. It is possible that the leaching water requirement might be decreased if mulch was used. However, there is lack of research on effect of application of mulch combined with diluted sea water irrigation on crop performance and salt accumulation in the soil. Hence, this study was conducted using Swiss chard.

2.2 Materials and Methods

A greenhouse experiment was conducted at Arid Land Research Center, Tottori University from Nov. 3, 2005 to Feb. 8, 2006. Clay soil brought from Tohaku Tottori prefecture was used for the experiment. Soil was air dried and sieved via 4 mm sieve. The sand, silt, and clay percentages of the soil were 17.8, 28.3 and 53.9, respectively. The pH and electrical conductivity ($EC_{1:5}$) of the soil were 5.5 and 0.04 dS m^{-1} respectively. The bulk density of the soil was 1.1 g cm^{-3}. Seawater was diluted with tap water to achieve the electrical conductivity (ECw) as 4.8 and 7.4 dS m^{-1}. The chemical composition of seawater is shown in **Table 2–1**. The soil surface in Wagner pot (29 cm depth and 25 cm diameter with the closed outlet) was mulched up to 3 cm thickness either with gravel, pine-needles or rice-straw. The soil layer depth was 26 cm. There was also an unmulched control soil. The densities of gravel, pine-needles and rice-straw were measured as 1.54 g cm^{-3}, 0.052 g cm^{-3} and 0.027 g cm^{-3}, respectively. The diameter of gravel was 0.5 ~ 1.5 cm. The length of pine-needles and rice- straw was about 5 cm. The pots were arranged in randomized complete block design and replicated 3 times. After 15 days two seedlings of Swiss chard (*Beta vulgaris* L. subspp. cycla) were transplanted in every pot. A compound NPK fertilizer (12-12-12) was applied at the rate of 1.8 t ha^{-1} which is equal to 216 kg ha^{-1} of N, P and K respectively. Initially the pots were irrigated with tap water. The diluted seawater irrigation was started after 48 days of transplantation to avoid early shocking effects on plants. The pots were weighed everyday by an electronic balance and the difference in weight was considered as evapotranspiration (*ET*). An equal amount of water to an average value of *ET* across all mulch treatments was applied at 5 days intervals. For no-mulch treatment the pots were irrigated according to their *ET*. Water use efficiency (*WUE*) was calculated by the equation: *WUE* = Plant biomass yield / *ET*.

Table 2–1. Chemical characteristics of seawater (Al-Busaidi et al., 2007).

pH	*ECw*	Na^+	Cl^-	K^+	Ca^{2+}	Mg^{2+}	NO^{3-}	P
	dS m^{-1}	mg L^{-1}						
7.5	38.5	11211	18834	377	266	1976	0.2	2.1

During the growth period, the plants were harvested twice. In the first harvesting 2-3 largest leaves from the base of plants were sampled. The plants were grown for 3 months. The shoots (leaves plus stem) were harvested above the soil surface for fresh biomass yield. Dry biomass was determined after drying the shoots in an oven at 65 °C for 48 h. The post-harvest soils were sampled in 4 layers (0-5 cm, 5-10 cm, 10-15 cm and 15-20 cm) from 36 pots to measure the soil water content and electrical conductivity (*EC*) on Feb. 8, 2006. There were 144 soil samples with 3 replications for each treatment and layer. The soil water content was determined by drying soil samples in an oven at 105 °C. The *EC* of soil water suspension (1: 5) was measured with an *EC* meter (B-173 Horiba Co.). The soil temperature was measured afternoon on daily basis at the depth of 2, 5, 10 and 15 cm by a mercury-in-glass thermometer. The average soil temperature was calculated across the measured data.

An additional experiment was conducted to confirm the effect of mulching on soil temperature using the same pots filled with moist Tohaku clay soil. The soil surface in the pots was mulched up to 3 cm thickness either with gravel, pine-needles or rice-straw. There was also an unmulched control soil. This time the soil temperature was recorded at 15 minutes interval within the soil depth of 5 cm and 10 cm for three days using eight Onset TidbiT v2 Temperature Data Loggers with an accuracy of 0.2 °C.

Data were generally subjected to statistical analysis using SPSS (Version 11.5) software and means were separated by the least significant difference (LSD) method at probability level of 5%.

2.3 Results and Discussion

Evapotranspiration: Evapotranspiration (*ET*) was significantly affected by mulching treatments. Compared with no-mulch, mulch treatments substantially prevented *ET* (**Fig. 2–1**). Among the mulches the magnitude of *ET* was differed in the order of pine-needles ≈ rice-straw > gravel under low saline irrigation. Compared with the treatment of no-mulch in conjunction with tap water irrigation, the *ET* for the treatment of gravel mulch under high saline irrigation was reduced by 56%. The significance of reducing *ET* is to save water whereas crop yield does not decline. Generally transpiration losses from the crops are difficult to control since directly related to the crop growth parameters, whereas the soil evaporation can easily be reduced or modified. Rasiah et al. (2001) reported that gravel mulching was effective in reducing the evaporation losses from the sand dune soil and considerable saving in the irrigation inputs was associated with gravel mulching.

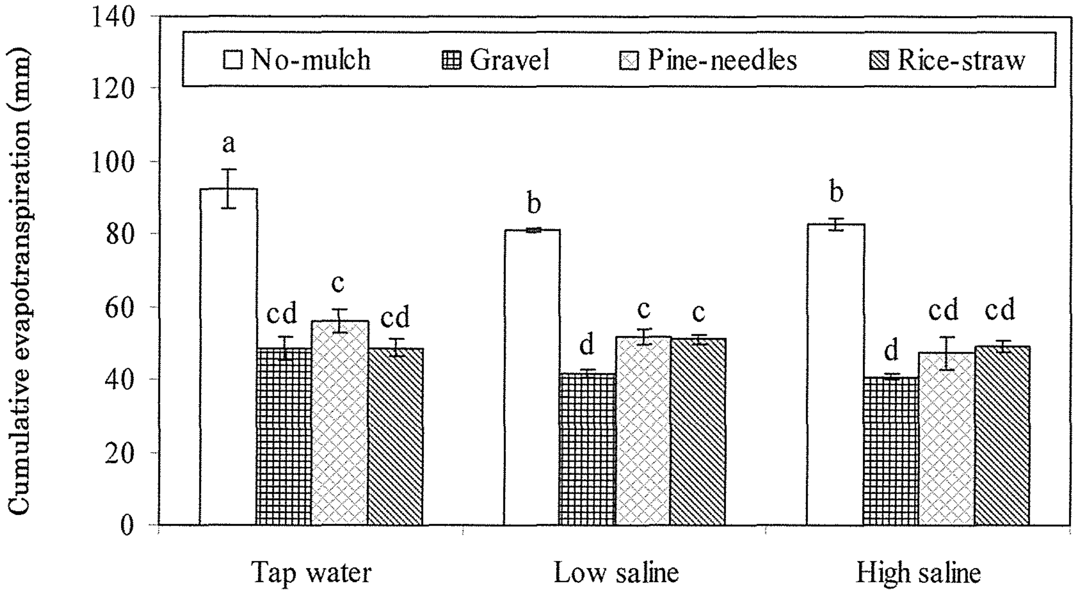


Fig. 2–1. Cumulative evapotranspiration (mm) as affected by saline water and mulching treatments. Alphabets above the bar indicate difference among treatments at p value < 0.05.

The *ET* was lowered in saline irrigation under no-mulch treatment. In other words, the increasing water salinity was negatively associated with the *ET* for no-mulch treatment. The application of water with salts reduced cumulative level of *ET* possibly due to the formation of salt crust on the soil surface from unmulched soils. This phenomenon could be related to the enhanced water density, viscosity and chemical bonds in the soil-salt system. FAO (1998) reported that density, temperature and salinity affected several water characteristics e.g., evaporation and so on. Newson and Fahey (2003) also reported a reduced rate of evaporation due to the development of salt crust on the soil surface. It is also reported elsewhere that soil salinity condition affected crop development and evapotranspiration (FAO, 1998). The *ET* value was insignificantly differed between tap water and saline water among the three mulching materials (**Fig. 2–1**), which could probably be related to the lower evaporation as well as lower accumulation of salts under mulches (**Table 2–2**).

***Soil salinity*:** Salts accumulation in the soil was highly affected by the application of saline irrigation water (**Fig. 2–2**). The *EC* values of the soil reflected the accumulation of salts. As expected the average *EC* of soil increased with the concentration of irrigation water. Blanco and Folegatti (2002) also found a linear association between salinity and application of saline water in the soil profile. Under high saline water various mulching types reduced the average salt accumulation (**Fig. 2–2**). However, there was no effect of mulching on the average soil *EC* under tap water and low saline water conditions, which could be attributed to lower level of salts accumulation.

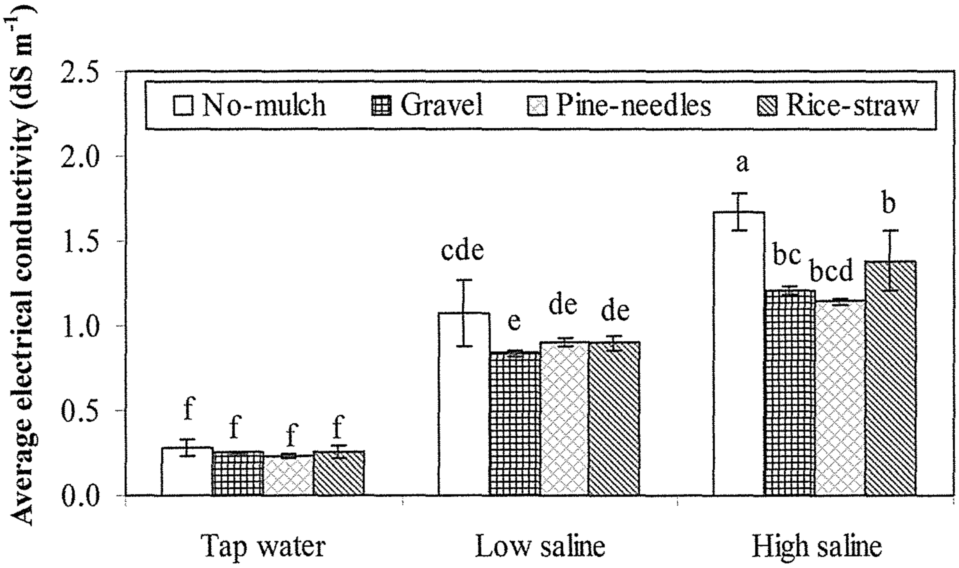


Fig. 2–2. Average soil salinity (dS m^{-1}) as affected by saline water and mulching treatments. The average soil salinity indicates the average of 4 soil layers and 3 replications for each treatment. Alphabets above the bar indicate difference among treatments at p value < 0.05.

Table 2–2. Soil salinity (dS m^{-1}) as affected by mulching under low and high saline water irrigation.

Saline water	Mulching	0-5 cm	5-10	10-15	15-20
Low saline water	No-mulch	2.31 b	0.50 c	0.40 c	1.08 bc
	Gravel	0.97 c	0.97 ab	0.45 bc	0.96 bc
	Pine-needles	1.13 c	0.92 b	0.65 bc	0.92 c
	Rice-straw	1.05 c	0.86 b	0.54 bc	1.15 bc
High saline water	No-mulch	3.90 a	1.18 ab	0.59 bc	1.00 bc
	Gravel	1.50 bc	1.26 a	0.59 bc	1.47 bc
	Pine-needles	1.47 bc	1.18 ab	0.47 bc	1.45 bc
	Rice-straw	1.83 bc	1.29 a	0.86 b	1.55 b

Alphabets in a column indicate difference among treatments in the same column at $p < 0.05$.

The mulch treatments significantly reduced salt accumulation in the upper soil (0-5 cm) whereas unmulched pots accumulated higher salts in the upper soil (**Table 2–2**). In the upper soil (0-5 cm), the *EC* for mulch treatments under high saline water irrigation was no more than that for no-mulch treatment under low saline water irrigation (**Table 2–2**). This suggested that high saline water irrigation could be used under mulch condition without serious salinity-damage for crop. Under high saline water mulching with gravel, pine-needles and rice-straw reduced the *EC* values by 61%, 62% and 50%, respectively in the soil layer of 0-5 cm. In the middle horizon of the soils (5-10 cm and 10-15 cm), the salt accumulation was lowered as compared to the upper or lower zone of the soil (**Table 2–2**). This could suggest that mulching could affect the movement of salts in the soils. In 1987 Yamamoto found that NaCl distribution in soil profiles depended on evaporation rate and soil texture etc. During our experiment higher salinization of soils occurred due to the continuous application of saline water. Water uptake by plants and evaporation from the soil surface were reported the main factors governing salt accumulation in the topsoil layer (Ben-Hur et al., 2001). Salts deposition also depended on the soil moisture depletion and root development due to the plant growth.

Soil water content: Compared with no-mulch treatment, mulch treatment significantly enhanced soil water content in the upper soil (0-5 cm) across all irrigation waters (**Table 2–3**). Under high saline water the soil water contents for gravel and pine-needles were higher than those for no-mulch, regardless of soil depth. The average values of soil water content for gravel mulch were higher than those of rice-straw mulch except tap water irrigation. Irrespective of irrigation water, the average values of soil water contents were improved with the application of gravel, pine-needles and rice-straw by 27%, 18% and 15%, respectively as compared to no-mulch. Several researchers reported mulching as a common practice to conserve soil water in small farms (El-Asswad and Groenevelt, 1985; Groenevelt et al., 1989).

Soil temperature: When compared to the no-mulch treatment the mulching condition enhanced averaged soil temperature (**Table 2–4** and **Fig. 2–3**). These temperature variations of soils could be directly associated to the manipulation of the thermal conditions of soil surface by mulching residues. In addition, greater average temperature was recorded in the soil with gravel treatment under saline condition as compared to rice-straw and pine-needles. Averaged soil temperature among mulches differed as gravel > rice-straw > pine-needles > no-mulch, regardless of soil depth (**Fig. 2–3**). The averaged soil temperature at the depth of 5 cm under gravel mulch was enhanced by 1.2 °C as compared to no-mulch whereas the temperature value increased by 0.5 °C in gravel mulched soil within the soil depth of 10 cm. The differences of soil temperature among mulches in 5 cm soil

Table 2–3. Soil water content (g g^{-1}) as affected by mulching and saline water treatments.

Saline water	Mulching	0-5 cm	5-10	10-15	15-20	Average
Tap water	No-mulch	0.27 c	0.32 cd	0.36 bc	0.38 c	0.33 d
	Gravel	0.37 ab	0.38 bcd	0.40 abc	0.41 abc	0.39 bc
	Pine-needles	0.36 b	0.35 bcd	0.39 abc	0.41 abc	0.38 bc
	Rice-straw	0.37 ab	0.38 bcd	0.39 abc	0.41 abc	0.39 bc
Low saline water	No-mulch	0.29 c	0.32 d	0.36 bc	0.38 c	0.34 d
	Gravel	0.43 a	0.44 a	0.45 a	0.45 a	0.44 a
	Pine-needles	0.41 ab	0.40 abc	0.40 abc	0.44 a	0.41 ab
	Rice-straw	0.35 b	0.36 bcd	0.37 bc	0.38 c	0.37 cd
High saline water	No-mulch	0.27 c	0.32 d	0.35 c	0.37 c	0.33 d
	Gravel	0.43 a	0.44 a	0.44 a	0.44 ab	0.44 a
	Pine-needles	0.40 ab	0.41 ab	0.41 ab	0.44 ab	0.42 ab
	Rice-straw	0.38 ab	0.39 ab	0.39 abc	0.39 bc	0.39 bc

Alphabets in a column indicate difference among treatments in the same column at $p < 0.05$.

Table 2–4. Soil temperature (°C) as affected by mulching and saline water.

Irrigation water	Mulch type	Soil depth (cm) [1]				Mean [2]	Max [2]	Min [2]
		2	5	10	15			
Tap water	No-mulch	13.4	13.1	14.2	14.3	13.7	18.3	1.3
	Gravel	13.8	13.8	14.2	14.4	14.1	18.4	2.4
	Pine-needles	14.0	14.4	14.1	14.3	14.2	18.0	3.5
	Rice-straw	14.0	13.4	14.1	14.6	14.0	18.4	2.3
	Mean	13.8	13.7	14.2	14.4	14.0	18.3	2.4
High saline water	No-mulch	12.3	13.3	13.7	14.1	13.4	18.1	2.5
	Gravel	14.1	15.2	14.3	14.6	14.6	18.5	3.2
	Pine-needles	13.2	13.7	14.1	14.2	13.8	18.7	3.6
	Rice-straw	14.0	14.3	14.3	14.3	14.2	18.4	3.1
	Mean	13.4	14.1	14.1	14.3	14.0	18.4	3.1

[1] The average soil temperature was calculated across the measured data.

[2] Mean, maximum and minimum values of soil temperature show the average values across 4 soil layers out of whole measured data.

depth were more pronounced than temperature differences observed in 10 cm soil depth **(Fig. 2–3)**. These results showed that effect of mulches on heat retention in top soil layer (5 cm) was higher. Li (2003) reported higher soil temperature with a mulch as compared to no-mulch treatment. It is also reported that gravel-mulch had a smaller heat storage capacity than the bare soil (Li, 2003). The higher soil temperature under gravel-mulch could be related to the less evapotranspiration than rice-straw and pine-needles. Warmer soils in the winter season could contribute to an improved plant growth as well.

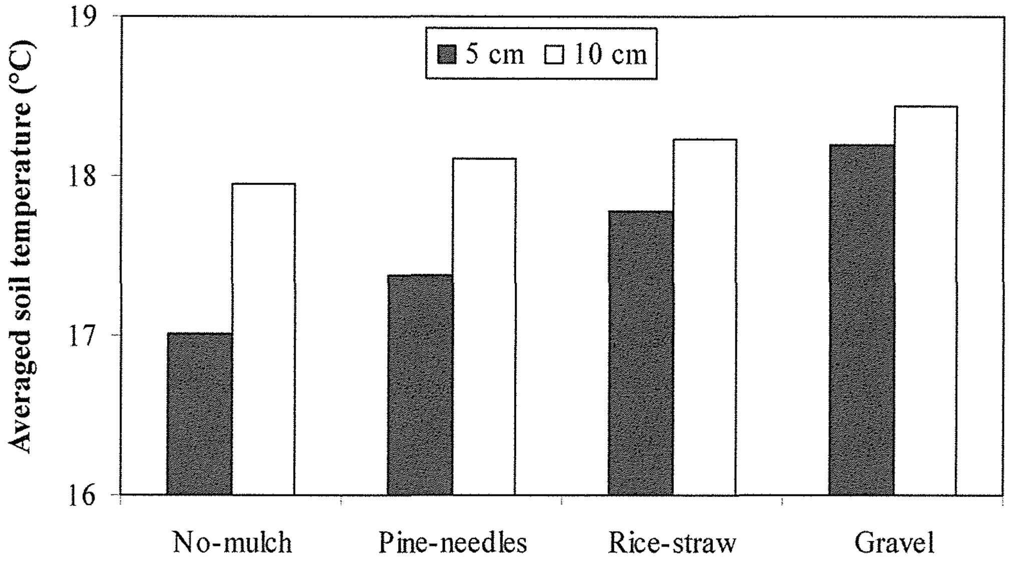


Fig. 2–3. Averaged soil temperature (°C) in 2 soil depths (5 cm and 10 cm) as affected by different mulching treatments. The average soil temperature indicates the average of soil temperature measured during 3 days in 15 minutes interval.

The mulching condition also enhanced the minimum soil temperature, when compared to the no-mulch treatment **(Table 2–4)**. Under tap water irrigation, the minimum soil temperatures under gravel, pine-needles and rice-straw mulches were enhanced by 1.8, 2.7 and 1.7 times, respectively as compared to no-mulch. Mulching condition also increased the maximum soil temperature under high saline irrigation. It is also reported that the mulch layer retained heat, protected plants from frost damage in the early spring and the fall seasons (Li, 2003). It was mentioned elsewhere that straw-mulch reduced soil temperature and delayed crop development under low ambient temperature (Zhang et al., 2005b). Irrespective of mulching types, high saline irrigation increased the minimum soil temperature as compared to ordinary tap water (**Table 2–4**). However, high saline water could not enhance mean soil temperature as compared with ordinary tap water irrigation during the experiment.

Crop biomass: Crop growth was significantly affected by mulching conditions. The application of mulches improved dry biomass yield of Swiss chard irrespective of irrigation treatments (**Fig. 2–4**). Since mulch reduced *ET* and improved soil water content as well as soil temperature in winter season, crop growth may positively be affected. Li (2003) attributed better plant response to gravel–sand mulch due to greater water availability and higher temperature regime. Huang et al. (2005) also reported that straw mulch significantly decreased *ET* and increased yield during both dry and wet seasons. Among the mulches gravel produced the highest crop biomass under saline irrigation (**Fig. 2–4**). The higher biomass under gravel mulch could be related to the lower *ET*, higher soil water content and improved soil temperature during winter.

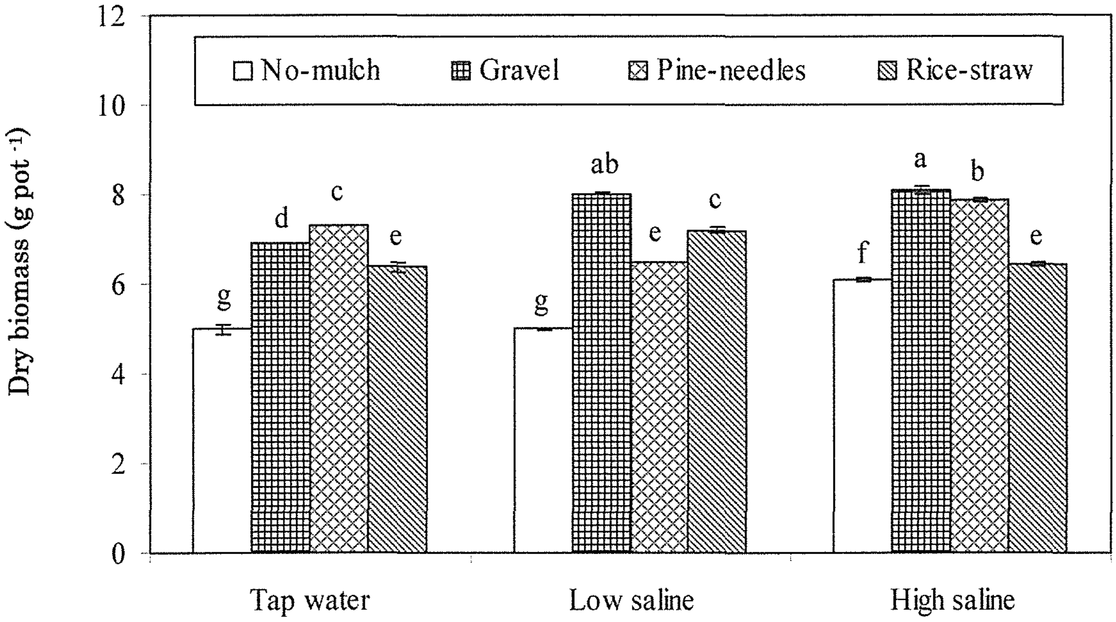


Fig. 2–4. Dry biomass as affected by mulching and saline water treatments. Alphabets above the bar indicate difference among treatments at *p* value < 0.05.

The crop biomass of Swiss chard could not decrease with diluted seawater. This could be attributed to the higher tolerance of Swiss chard towards salts and the presence of essential plant nutrients in the seawater. Since the experiment was conducted during the winter season, the amount of saline water consumed for irrigation was less due to low evapotranspiration rate. In general the crop response to the salinity depends on the plant species, soil texture, water holding capacity and composition of the salts. The inhibitory effects of salinity on growth were also reported to be related to the nutritional status of the plants (Bernstein et al., 1974). Pal et al. (1984) concluded that salt tolerant crop like barley could be grown economically with irrigation water up to the *EC* value of 16 dS m^{-1}. Ghulam et al. (1997) obtained a reasonable barley yield with irrigation water (*ECw*) up to 9.3 dS m^{-1} under 15% excess water as leaching requirement. The depressing effects of salinity on other crops have been reported by some researchers (Abdul et al., 1988; Heakal et al., 1990; Koszanski and Karczmarczyk, 1985).

Water use efficiency: Application of mulches had significant effects on water use of Swiss chard (**Fig. 2–5**). The mulch material gave higher *WUE* regardless to the irrigation treatments. This could be attributed to the higher plant biomass and low *ET* under mulching conditions. For *WUE* the types of the mulches differed as gravel > pine-needles > rice-straw > no-mulch under high saline water whereas under tap water, the mulches remained statistically similar for *WUE*. The *WUE* was increased by more than 100% for gravel mulch as compared to no-mulch under saline water irrigation. The higher plant biomass, lower *ET* and higher conservation of soil water under gravel mulch could be the factors responsible for higher *WUE* when compared with other mulching materials in saline irrigation.

Diluted seawater irrigation maximized *WUE* than ordinary tap water. Higher biomass production and less evaporation from the soil surface under mulching and / or saline irrigation could be the possible reasons for higher efficiency of water use by plants. The increasing level of evapotranspiration has reduced the water use efficiency of plants under no-mulch treatment. Soil management practices like mulching improve soil water and thus increase the availability of water to the crop. These changes would affect evapotranspiration rates and potentially increase crop biomass. The ability of mulch to enhance *WUE* in a soil-plant system could encourage mulching practice for the enhancement of crop production.

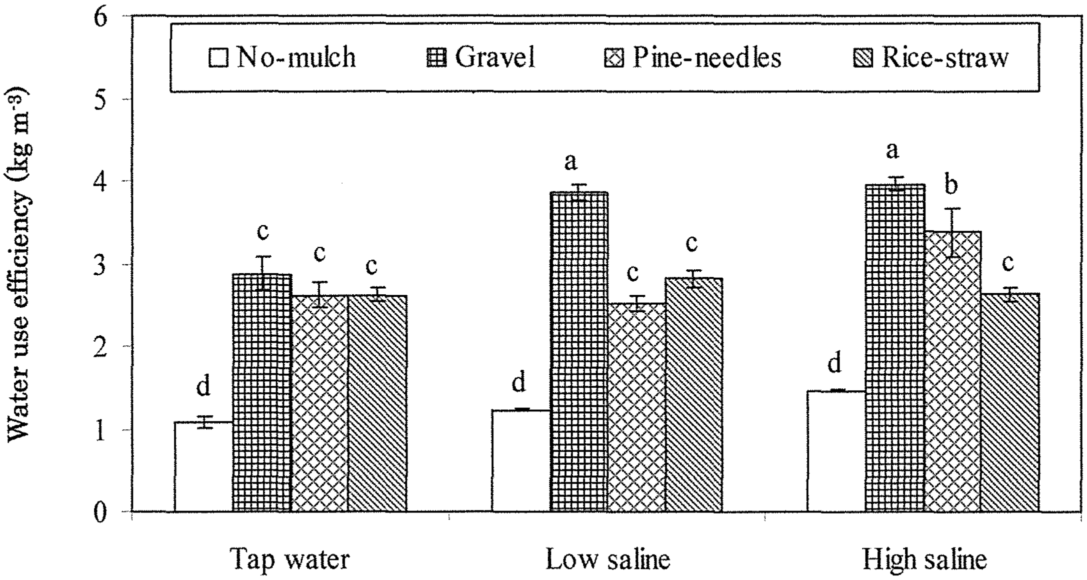


Fig. 2–5. Water use efficiency (*WUE*) as affected by mulching and saline water treatments. Alphabets above the bar indicate difference among treatments at p value < 0.05.

2.4 Conclusions

The findings of the experiment indicated that soil water content, salt level of soil, plant biomass and water use efficiency of Swiss chard were profoundly influenced by mulching and saline water. Mulching of soils significantly reduced the *ET* and accumulation of salts in the topsoil of the pots. The mulching practice improved soil water content, crop biomass yield and *WUE*. The soil temperature was slightly increased with the application of mulches during the winter season. The averaged soil temperature at the depth of 5 cm under gravel mulch was enhanced by 1.2 °C as compared to no-mulch. The enhancement of soil temperature by mulch in 5 cm depth was more than 10 cm depth. Among the mulches gravel mulch followed by pine-needles mulch proved to be effective especially under high saline conditions. Ultimately the crop performance was ameliorated under saline conditions. The mulch induced higher plant growth may provide an opportunity for the safe use of saline water. However, these conclusions were only based on a short-term experiment during winter season when the soil evaporation was relatively low and the crop grew slowly. Hence, the long-term experiments, field and/or laboratory, are needed to assess the impact of saline water use under mulching on evaporation and salinity interrelation for the sustainability of agriculture. The comprehensive understanding also necessitates that we continue to strive for systems that are efficient in their use of water and nutrients in arid and semi-arid areas.

Chapter 3 Effects of mulching on evapotranspiration, yield and water use efficiency of Swiss chard (*Beta vulgaris* L. var. *flavescens*) irrigated with diluted seawater

3.1 Introduction

Some research on sea water irrigation show that a 1:1 mixture of Caspian Sea and well water can be used for irrigation without a significant reduction in the growth and yield of barley, provided that it is not applied earlier than the time of ear formation (Ghadiri et al., 2005). This would promise a significantly reduced demand on the limited ground water resources in many countries for agricultural use.

Comparison of effects of different kinds of mulch on *ET*, salt accumulation, soil temperature, yield and *WUE* in one experiment is very scarce. A long-term experiment (more than half year) using large weighing lysimeters was conducted to further evaluate the conjunctive effects of mulching and saline irrigation. In order to study the effect of different kinds of mulch in detail, this experiment was conducted in three lysimeters in a greenhouse to monitor dynamic variation of *ET* and soil temperature under mulch and no-mulch conditions.

3.2 Materials and Methods

The experiment was carried out in a greenhouse at the Arid Land Research Center, Tottori University, Japan, using three weighing lysimeters. Each lysimeter was 1.2 m high and had a diameter of 0.798 m (surface area 0.5 m^2). The top 40 cm of lysimeter column was filled with the Tohaku clay soil (sand : silt : clay = 17.8% : 28.3% : 53.9%) to achieve a bulk density of 1.1 g cm^{-3}, and the rest of column was filled with a sandy soil with a bulk density 1.58 g cm^{-3}. The *ET* was estimated by measuring the weight changes of the lysimeter with an electronic balance, with a resolution of 50 g, which corresponds to 0.1 mm depth of water. Detailed description of the lysimeter is given by Inoue and Shimizu (1998). Soil temperature was monitored by 4-eletrode sensors at six depths (7, 17, 27, 47, 67 and 97 cm) in each column. A computer continuously recorded the weight of lysimeter and soil temperature data at 15 min time interval.

Swiss chard (*Beta vulgaris* L. var. *flavescens*) seeds were sown on October 01, 2005 in plastic tray containing potting soil to produce seedlings for the experiment. Fourteen seedlings were transplanted in each lysimeter on November 03, 2005. Just before transplanting, a compound NPK fertilizer (12–12–12) was applied at the rate of 1800 kg ha^{-1}. An irrigation tube, 70 cm in height with a small hole in the bottom, was inserted into the center of each lysimeter and used for sub-irrigation. The plants were irrigated with tap water in the first 20 days after transplanting. From November 23, 2005, they were irrigated with saline water (ECw of 6.86 dS m^{-1}) prepared by diluting seawater with tap water. The ground water level was kept between 50 and 80 cm below the soil surface.

Three mulching treatments, no-mulch (control), rice-straw mulch (R) and gravel mulch (G) were compared. Based on the study of Sharma *et al.* (1985), the thickness of mulch was kept 3 cm. During the whole experimental period, which lasted from November 2005 to June 2006 and covered the winter (November to February) and the spring (March to early June) seasons, the Swiss chard was harvested two times. First harvest was done at the end of the winter season, on March 1, 2006, when only the largest four leaves of each plant were cut at their base. Second harvest was done in spring, at the end of the experiment, when all of the above ground material (leaves and stem) were harvested and their fresh and oven-dry weights were determined.

Soil samples were taken from four layers (5, 10, 15 and 25 cm soil depth) at the end of experiment to measure electrical conductivity (1:5 soil extract, $EC_{1:5}$) using a conductivity meter B-173 (Horiba Co.).

Statistical analysis: The statistical analysis software SPSS v11.5 (SPSS Inc, Chicago, IL, USA) was used to analyze data. Means were compared by the *LSD* (least significant difference) at $p < 0.05$ level of significance.

3.3 Results and Discussion

Evapotranspiration: **Fig. 3–1** shows the cumulative *ET* during the winter and spring

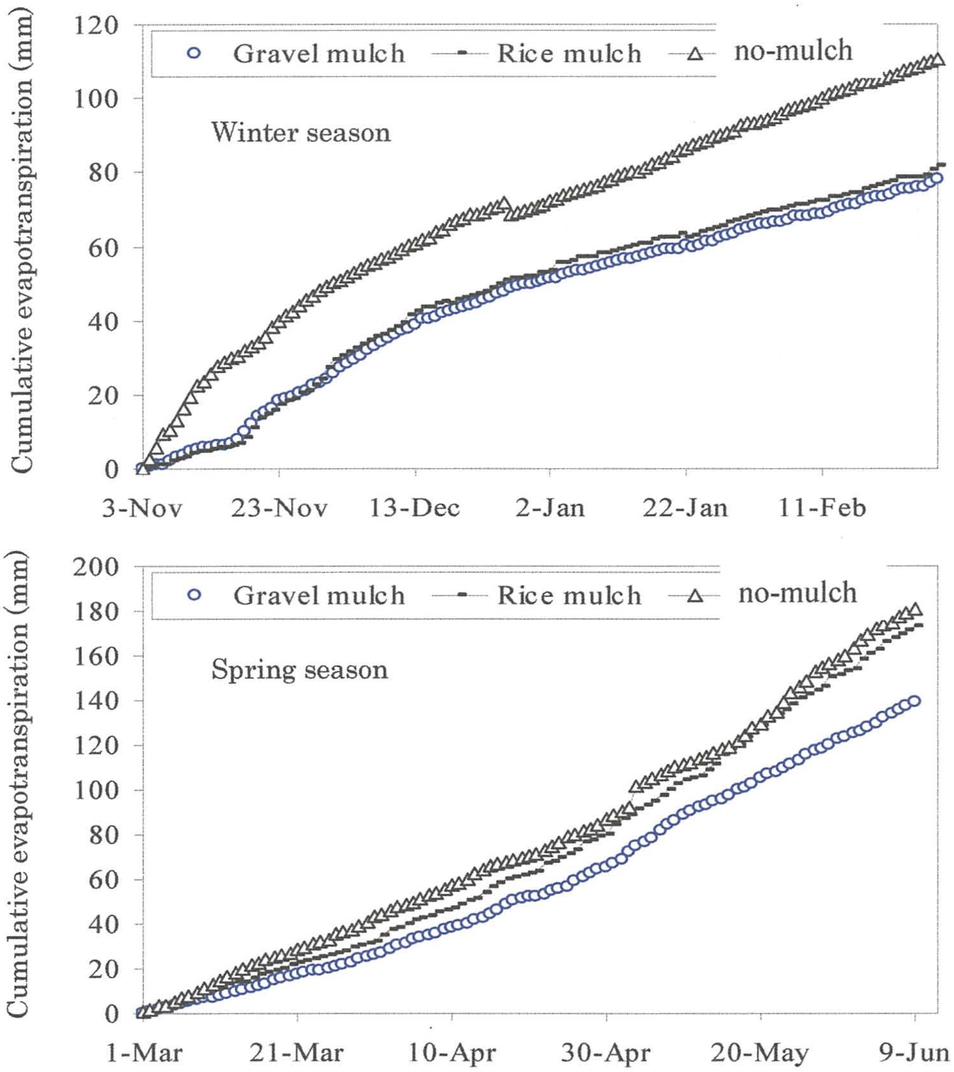


Fig. 3–1. Cumulative evapotranspiration of Swiss chard measured in winter and spring as affected by mulching treatment

parts of the total growth period. The *ET* was higher in spring than in winter under all treatments. This difference can be attributed to low evaporative demand of the atmosphere and smaller growth of the plants in winter than in spring. During winter both the mulching treatments reduced *ET* more or less equally as compared to no-mulch. In contrast, during spring the reduction in *ET* due to mulching was higher under G than under R. The R gave higher *ET* compared to G in spring because the crop grew better under R and would have transpired more water than under the G treatment. These results showing reduction in *ET* because of mulching are consistent with the observations of several other workers (Mao 1998; Rahman et al., 2005; Yang et al., 2006).

Effects of mulching on the hourly change in the cumulative *ET* during each day on three days in both winter (Feb. 27 to 29) and spring (May 20 to 22) are shown in Fig. 3–2. There was no irrigation given on these days, hence the hourly change in *ET* reflected the water balance (Δw) in the lysimeter as the system interacted with the ambient atmosphere. Results showed that for the no-mulch treatment, the Δw increased rapidly before 14:00, then the rate of increase slowed down. We attribute this to higher solar radiation before 14:00. For gravel mulch treatment, the Δw showed nearly the same trend as for the no-mulch. Under RM, however, the Δw value became negative during early morning on the first two days in spring and during afternoon on all the three days in winter, i.e., the weight of the lysimeter increased. The maximum weight increase for R ranged from 0.2 to 1.4 mm day^{-1}. Since there was no irrigation given and the phenomenon occurred only during early morning in spring and during afternoon in winter, when humidity is high, we think that this reflects the capability of R to adsorb water vapor from the air. This was also confirmed by visual observation of the rice straw mulch. As a result, R not only prevented soil evaporation, but also could "catch" water from the air, which would be of benefit for crop growth in drylands. The ability of straw mulch to adsorb water vapor from the air has also been reported earlier (Kosmas et al., 1998; Kosmas et al., 2001).

Electrical conductivity ($EC_{1:5}$). The electrical conductivity (***$EC_{1:5}$***) of soil at different depths for three treatments at the end of the experiment is shown in **Fig. 3–3**. There were significant differences between no-mulch and the two mulch treatments and the differences were particularly conspicuous in the top 10 cm soil layer, where most of the roots of the

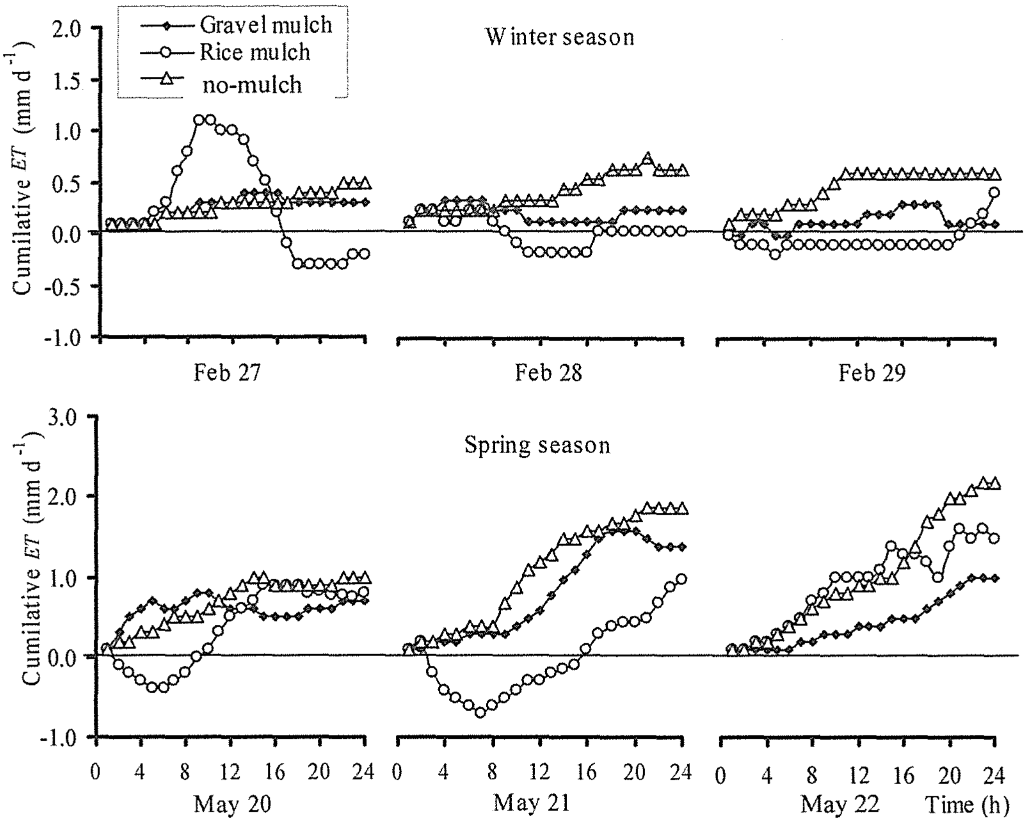


Fig. 3–2. Effects of mulching on hourly change in cumulative *ET* of Swiss chard during each day on 3 consecutive days in winter and spring seasons

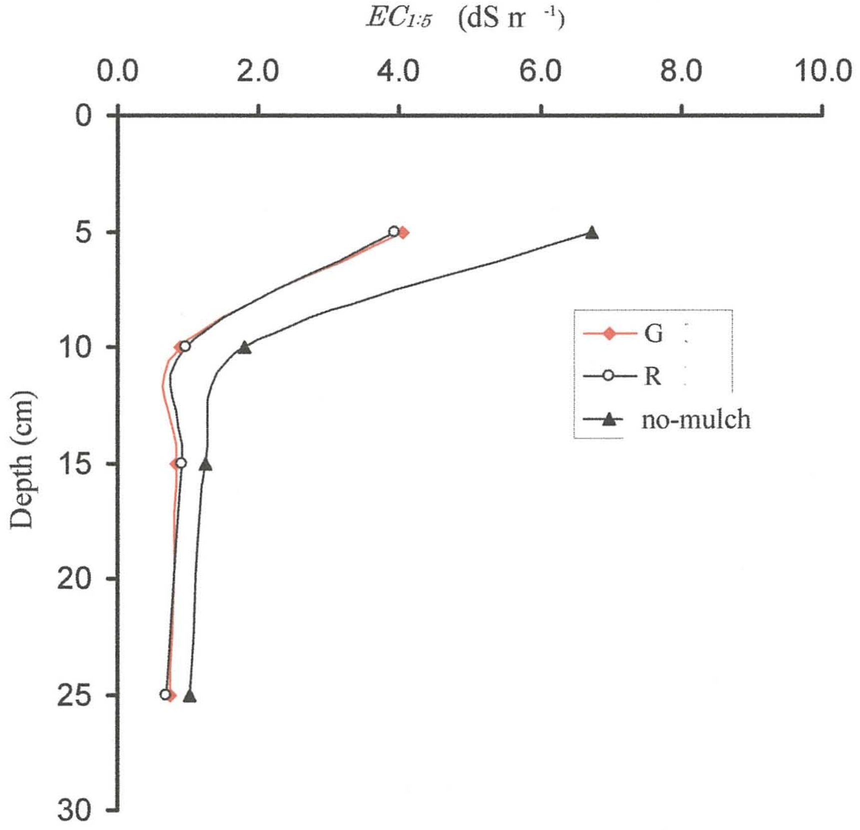


Fig. 3–3. Salt distribution at the end of experiment under different mulching treatments as reflected by electrical conductivity of 1:5 soil extract.

plant are located. This could be attributed to higher evaporation of water from the soil surface under no-mulch, which would have allowed greater upward movement of salt from the sub-irrigation with saline water. There were no differences in the $EC_{1:5}$ values between the RM and GM treatments.

Soil temperature: The average soil temperature (**Table 3–1**) at every depth was higher under G and R than under no-mulch but the difference did not generally reach the level of significance. Only at 17 and 47 cm depths the average temperatures during winter were significantly higher under G than under no-mulch. During spring again, significantly higher average temperatures were recorded for 17 cm depth under mulching treatments than under no-mulch. Mao (1998), Li (2003) and Rahman *et al.* (2005) also reported increase in soil temperature due to mulching in winter cropping season.

Table 3–1. Average soil temperature at different layers measured during the entire winter and spring seasons of the experimental period

Depth (cm)	7	17	27	47	67	97
			Winter season (°C)			
no-mulch	8.30a	8.05b	8.61a	8.97b	7.51a	7.23a
G	9.98a	10.25a	8.82a	9.67a	7.89a	7.82a
R	9.59a	9.87ab	8.23a	9.54ab	8.03a	7.82a
			Spring season (°C)			
no-mulch	22.80a	19.53b	19.26a	18.03a	18.03a	18.06a
G	23.18a	23.11a	20.04a	19.74a	18.74a	18.47a
R	23.14a	23.14a	20.01a	18.92a	18.24a	18.73a

Different letters in a column denote significant differences between treatments at $p < 0.05$.

Yield and water use efficiency: The effect of mulching on total *ET*, fresh and dry matter yield, and *WUE* of Swiss chard, for winter, spring and the whole crop duration is shown in **Table 3–2**. The total seasonal fresh matter yield under R was 76% higher as compared to no-mulch and under G it was 49% higher than no-mulch. The Dry matter yield results showed similar trends. This improvement in the yield because of mulching over no-mulch can be attributed to the reduction in salinization of the surface layer of soil (**Fig. 3–3**) and improved moisture availability to the plants because of lesser *ET* (**Fig. 3–1**).

Table 3–2. Evapotranspiration (*ET*), fresh yield, dry yield and water use efficiency (*WUE*) of Swiss chard as affected by mulching treatment.

Treatment	*ET* (mm)	Fresh matter yield (g plant $^{-1}$)	Dry matter yield (g plant $^{-1}$)	*WUE* (kg m^{-3})
		Winter season		
no-mulch	110.8	14.8±3.1	1.6±0.9	0.23
G	77.9	16.6±2.5	1.9±0.5	0.39
R	81.6	19.2±2.1	2.3±0.9	0.45
		Spring season		
no-mulch	181.2	33.6±6.3	9.5±2.5	0.84
G	138.7	55.5±5.6	16.3±1.8	1.88
R	173.1	66.1±5.9	21.3±4.1	1.97
		Total		
no-mulch	292	48.4±11.3	11.1±3.6	0.61
G	216.6	72.1±14	18.2±2.9	1.34
R	254.7	85.3±13	23.6±4.2	1.48

The relative increases in the yield because of mulching were higher in the spring part of the growing season than in the winter. This can be attributed to higher evaporative demand of the atmosphere in spring, which would have subjected the plants under no-mulch to more stress than the mulched plants. As already indicated, the total seasonal *ET* was highest under no-mulch and it was reduced by 26 and 13% by G and R treatments, respectively. Thus, G was more effective in reducing *ET* as compared to R. As both G and R would have provided nearly the same ground cover to prevent evaporation, the higher *ET* under R should have been because of more transpiration under this treatment, which should have improved photosynthesis and ultimately benefited crop growth and yield (**Table 3–2**).

WUE was improved by mulching treatment (**Table 3–2**) because of reduced *ET* and higher yield than under no-mulch and the highest value was recorded under R. *WUE* increased by 143% under R treatment over no-mulch and by 10% over G treatment. Although both *ET* and yield were higher under R than G, the relative increase in yield under R was higher than in G. Therefore the *WUE* was the highest under R.

3.4 Conclusions

Both gravel mulch (G) and rice-straw mulch (R) could reduce salt accumulation when diluted seawater irrigation was used for irrigation. Compared with no-mulch, the $EC_{1:5}$ of soil under mulches was nearly 38% lesser. The *ET* was 26% lesser under G and 13% lesser under R than under no-mulch. On the other hand, the fresh and dry yields were, respectively, 76% and 113% higher under R and 49% and 64% higher under G than under no-mulch. Therefore, the *WUE* increased by 143% under R and 120% under G as compared with no-mulch treatment. Monitoring of hourly change of cumulative *ET* over three days period when no irrigation was given, indicated that there was small adsorption of water from the atmosphere by the R during the relatively cooler hours of the day, and this could be very useful for crop growth in the arid and semi-arid regions. It can be concluded from this study that mulching was a good strategy for getting good yield and water use efficiency for Swiss chard when grown with saline shallow ground water. Compared with the gravel mulch, the rice straw mulch showed a measure of superiority during this long-term experiment period (about 6-7 months), and given the additional advantage of convenience in managing the material used, therefore, rice straw mulch was a better option than gravel mulch. Further experiments should be conducted to assess the impact of rice-straw mulching on growth of other crops, like grapevines.

Chapter 4 Effects of mulching and sub-surface irrigation on soil moisture and temperature, growth, yield, and berry quality of 'Gros Colman' grapevines

4.1. Introduction

Water is the most limiting resource in drylands. Given current demographic trends and future growth projections, as much as 60% of the global population may suffer water scarcity by the year 2025 (Qadir et al., 2007). Improvements in water use efficiency (*WUE*) of crops are essential under the scenarios of water scarcity. Application of mulch is known to be effective in reducing soil evaporation and saving water (Cadavid et al., 1998; Li, 2003). Several mulching materials improved plant biomass as well as *WUE* of Swiss chard (Zhang et al., 2008). Rice-straw mulching increased *WUE* of Swiss chard by 143 and 10% as compared to no-mulch control and gravel mulching treatment, respectively (Zhang et al., 2009). Besides Swiss chard, grapevines are often grown in arid and semi-arid areas.

The grapevine plays a very important role in the economic, social and cultural sectors of many regions; however vineyards are often grown in regions under stressful conditions and thus they are vulnerable to climate change (Santos et al., 2007). To facilitate adaptation to conditions of limited rainfall and less irrigation water, mulching could provide an alternative means to control grapevine response to irrigation with maximum *WUE*. Compared with the control, soil moistures and nutrient were enhanced and the severity of *Botrytis cinerea* (a saprophytic fungus causes botrytis bunch rot in grapes) infections were reduced for shredded paper and grape marc mulches (Jacometti et al., 2007a). In a vineyard, one mulching material of a sewage sludge and bark compost improved water retention capacity of the soil, reduced evaporation and soil temperature fluctuations (Pinamonti, 1998). In addition, the use of rye mulch could be applied as an effective weed control technique in conventional, as well as organic deciduous tree orchards (Ormenio-Nunez et al., 2008). Nevertheless, the wavelength-selective polyethylene mulch had no detectable effects on vine development, yield components and fruit quality (Bowen et al., 2004). Rice (or Paddy) straw is normally burnt on mechanized farms with air pollution and used as fodder by small farmers having no other alternative feed (Tripathi and Katiyar, 1984). Unfortunately, there is lack of international literature evaluating effects of the rice-straw mulch on grapevines growth.

Grapevine is a traditionally non-irrigated crop that occupies quite an extensive agricultural area in drylands and semi-arid regions. Recently, irrigation was introduced to increase the low land yield (Escalona et al., 2003), but a good compromise between grape quality and yield is of major importance for the achievement of high-quality products as wine (Cifre et al., 2005). Excessive amount of irrigation water not only results in a waste of water, but also causes nutrient loss and promotes excessive vegetative growth at the expense of fruits. Irrigation would give more benefits if schedules and dosages were oriented to maximize *WUE* of grapevines (Fereres et al., 2003). Deficit irrigation in fruit crops can be of value in increasing fruit quality by raising dry matter and sugar content (Chalmers et al., 1981). Several studies have shown that appropriate and moderate water stress is beneficial for berry growth in grapevines, whereas severe water deficit or saline irrigation decreases the production of assimilates, reduces transpiration, shoot growth, and yield and quality of fruit (Shani et al., 1993; Delgado et al., 1995; Pellegrino et al., 2005; Lovisolo and Schubert, 2006; Lovisolo et al., 2008). McCarthy (2000) reported that grape berry size was most sensitive to water stress during the post-flowering period, whereas moisture deficit after veraison had only a minor effect on berry weight at maturity and berries were insensitive to water deficit in the month before harvest (McCarthy, 1997a). The potential for water saving by deficit irrigation in orchard crops has remained unexplored so far (Fereres et al., 2003). The grape cultivar 'Gros Colman' (*Vitis vinifera*) is the later-maturing variety with a handsome grape and large round berries (Hogg, 2007) mainly cultivated in greenhouses (Okamoto et al., 1999). Water-saving research on this variety is surprisingly lacking although nothing is known about the adaptation to water stress of this variety. Similarly like mulching effects, sub-surface irrigation (SS) can also save water.

Soon after the conventional surface irrigation, the soil is very wet, resulting in lack of air. Later, this soil becomes dry and hard, causing a degree of salts, and is a continuous cycle. Sub-surface irrigation, in which water is applied below the soil surface, can help conserve water by reducing evaporative water losses in agricultural systems (Siyal and Skaggs, 2009), similarly like mulching effects. Sub-surface irrigation has been practiced in various forms, including pitcher or pot irrigation (Bainbridge, 2001; Siyal and Skaggs, 2009), perforated or porous clay pipe irrigation (Ashrafi et al., 2002; Shu et al., 2007) and drip irrigation (Patel and Rajput, 2008). However, reports on the response of grapevines to sub-surface irrigation have not been found.

Sub-surface drip irrigation (SDI) is the most advanced method of irrigation, which enables the application of the small amounts of water to the soil (ASAE Std., 1999) while maintaining a relatively dry soil surface (Patel and Rajput, 2008). Today, SDI is used throughout the world to irrigate field crops, vegetables, and fruits (Patel and Rajput, 2008; Camp, 1998). Nevertheless, successful use of SDI system depends on appropriate solutions to a number of technological and economic obstacles. One technological problem is the formation of cavity at the soil surface above the water emission points (Patel and Rajput, 2008). Another problem is spatially dependent reductions in dripper discharge (Ben-Gal et al., 2004). Factors that affect SDI uniformity are emitter clogging, root intrusion, root pinching, mechanical and pest damage, soil overburden and compaction, soil hydraulic parameters, and, possibly, system age (Lamm and Camp, 2007). In addition, in many parts of the world, plastic drip tubing and emitters are cost-prohibitive (Siyal and Skaggs, 2009), so some cheap materials for simple micro-irrigation technique should be developed.

Seeper hose is an absolutely new environmental soil control system which consists of a flexible rubber tubing that contains many micro pores and is laid sub-surface or underground to supply water, air, or fertilizer directly to plants. The seeper hose is made by new materials (special rubber) with outstanding durability. Water seeps out from small holes very slowly, making water control precise and effective. The soil wetness is maintained, will not dry out, avoids unnecessary overflow and conserve water considerably. With a burying machine, the seeper hose can be used in various projects, such as golf courses, nursery plants and soccer fields (Uh uni hose co., LTD). However, no research has been conducted using sub-surface seeper hose irrigation for grapevines. A combination of mulching and sub-surface seeper hose irrigation techniques has not been tested on grapevines, and could probably yield even more promising results. The primary objectives of this study were therefore to:

(a) provide an initial body of knowledge about the soil conditions, growth response and performance of 'Gros Colman' grapevines (*Vitis vinifera* L.) to water stress; and

(b) evaluate the effects of rice-straw mulch (M) and sub-surface seeper hose irrigation (SS) on *ET*, *WUE*, soil water content (θ) and temperature, growth (shoot length, leaf area, photosynthesis and berry diameter), berry quality (sugar content) and yield.

4.2. Materials and methods

4.2.1. Plant and soil materials and experimental layout

The experiment was carried out in 2008 in a greenhouse at the Arid Land Research Center, Tottori University, Japan, using three-year-old 'Gros Colman' grapevines (*Vitis vinifera* L.) grown in large weighing lysimeters. On 25 February 2008, 'Gros Colman' grapevines (*Vitis vinifera*) were transplanted into 4 lysimeters (with 3 vines for each) in the greenhouse under natural conditions of temperature, light and humidity. The amount of water applied was controlled by a time clock-solenoid valve assembly connected with a compressive pump. The grapevines were irrigated according to water requirement till the experiment started. The plants were provided liquid fertilizer containing all essential mineral nutrients (Wang et al., 2001; Thippayarugs et al., 2002) once every week. The experiment started from June 5, 2008. There were four treatments: mulching combined with sub-surface Seeper Hose seepage irrigation (MSS); no-mulch combined with sub-surface Seeper Hose seepage irrigation (SS); mulching combined with surface Seeper Hose seepage irrigation (MS); no-mulch combined with surface Seeper Hose seepage irrigation (S). Based on the study of Sharma et al. (1985), the thickness of mulch was kept 3 cm. Two concentric circles, large circle (outer ring) and small circle (inner ring), were made by the Seeper Hose tube and placed in each lysimeter for irrigation, with the large circle outside three vine trunks and the small circle inside three vine trunks. For sub-surface irrigation, the Seeper Hose rings were placed at 15 cm soil depth. Pumping was used to pump water from a big tank into the Seeper Hose for irrigation. The irrigation amount was determined based on the mean values of actual *ET* in the former week (ET_f). For the control treatment S, vines were irrigated slightly more water than their ET_f, whereas the irrigation amounts for other treatments were only equal to around 90% of their ET_f, respectively.

Each lysimeter was 1.2 m high and had a diameter of 0.798 m (surface area 0.5 m^2). The top 40 cm of lysimeter column was filled with a mixture of sandy soil (sieved through a 2-mm sieve), peat moss, humic allophone soil and lime in a volumetric ratio of 1200 : 600 : 200 : 1, respectively. The mixture had a pH of 6.2 and field capacity of the substrate, which was measured using drying method in an oven, was 0.467 (by volume). A nonwovenes sheet was spread on the bottom of the mixture and around the inner wall of each lysimeter. Root depth was therefore clearly limited in the upper 37 cm. The rest of column was filled with a sandy soil. Imai et al. (1987) and Okamoto and Imai (1989) reported that when the rooting zone of Kyoho and Pione grapevines was restricted in a defined volume by a raised bed or container, shoot growth was reduced and berry set and maturation were improved. In addition, Kyoho vines grown under restriction of rooting zone also showed improvement in accumulation of skin color, juice total soluble solids, favorable vine growth and berry characteristics when rooting-zone depth was 20 cm (Wang et al., 2001).

To encourage uniform vegetative growth, vines were pruned to retain 12 nodes per vine; only two or three shoots per vine were left and were trained horizontally. Eight shoots for each treatments were left and trimmed twice between bloom and the veraison stage of the berries. Lateral shoots were cut back to the first node. At flowering, one cluster was left on each of the two shoots. Each cluster was trimmed to retain only 80-100 florets and once berry-set occurred, further trimming was done to retain only 40–50 berries per cluster. At fruit growth stage, the cluster was protected with a white cover from direct solar radiation. Integrated pest management procedures were used, including manual control and spraying with non-toxic sprays. Ripe grapes are harvested on Sep. 22 by hand. Growing investigation included shoot length, leaf area, photosynthesis, berry diameter, berry sugar concentration, fresh yield of grapevines.

4.2.2. Experimental measurements

The *ET* was estimated by measuring the weight changes of the lysimeter with an electronic balance, with a resolution of 50 g, which corresponds to 0.1 mm depth of water. Detailed description of the lysimeter is given by Inoue and Shimizu (1998). Soil temperature was monitored by 4-eletrode sensors at the soil depth of 7 cm in each column with three replications. A computer continuously recorded the weight of lysimeter and soil temperature data at one hour time interval. Volumetric soil water content (θ) was monitored every 15 minutes by amplitude domain reflectometry (ADR) soil moisture sensors installed at three depths (7, 17 and 27 cm) in each column with three replications. A CR10X data logger and control module (Campbell Scientific Inc., Utah, USA) is used for system programming and automated data storage of ADR sensors.

The shoot length was measured in four days from June 2 to July 7 because shoot growth of vines tends to stop at the end of June or early July in Japan (Wang et al., 2001). Midrib length and leaf width were measured, and leaf area equations were calculated. Thereafter, the midrib length of three vines from each treatment was measured in three days, and the total leaf area was calculated. Twenty days after full bloom, 20 berries per treatment were marked, and the transverse diameter was measured at different intervals.

Net photosynthesis (A_N) and stomatal conductance (g_s) of three healthy primary and lateral leaves of the grapevine for each treatment were measured at 2 hours interval during daytime on August 2 by a portable photosynthesis system (LI-6400, Li-Cor Inc., Lincoln, NE, USA). Measurements were conducted on 2 cm × 3 cm leaf portion in the middle part of a leaf blade confined in the leaf chamber of the system.

Twelve to twenty berries for each treatment were sampled at 7-10 days interval for measuring fresh yield and sugar concentration from July 31 to Sep. 12. These berries were pooled and squeezed by hand in new polythene bags. Samples of juice were taken from these bags and sugar concentration (°Brix) was measured through a digital refractometer (Atago PR-101, 0–45% °Brix ± 0.1% at 5–40 °C; Atago Company Ltd., Japan). At harvest on Sep. 22, 2008, after fresh yield for each treatment was measured, ten berries per treatment were sampled randomly and placed in new polythene bags, squeezed by hand and samples assessed as above.

4.2.3. Statistical analysis

Analysis of variance (ANOVA) was performed on data using "the average ± standard error (SE)" analysis based on excel program.

4.3 Results

4.3.1. Evapotranspiration, soil moisture and soil temperature

Maximum irrigation amount (not shown) and *ET* were recorded for surface irrigation without mulch (**Fig. 4–1**) because S tends to consume more water (including intensive soil evaporation) than mulching or sub-surface irrigation. MSS gave the lowest value of *ET* in the three treatments (**Fig. 4–1**), which could be related to the lowest irrigation amount (not shown) and lower soil evaporation under mulching and sub-surface irrigation. The *ET* was reduced by 1.3, 0.7 and 0.1 mm/day under MSS, compared with S, SS and MS treatments. MS and SS also reduced *ET* by 30.5% and 16.4%, compared with S. The *ET* for SS was higher than that for MS, although irrigation amount for SS was a little lower than that for MS (not shown). This can be attributed to low evaporative demand under the mulching condition.

The highest θ occurred for S at the soil layer of 0-40 cm except a few days (**Fig. 4–2 A, B, C** and **D**) due to the highest irrigation amount (not shown). The differences of θ between S and other treatments became greater in August and September than in June and July. The volumetric soil water contents at the soil depth of 7 cm for mulching treatments (MS and MSS) were higher than that for SS except a few days (**Fig. 4–2 A**) due to the lower *ET* under mulching conditions (**Fig. 4–1**). The θ values at 7 cm depth for MS, MSS and SS on June 15 were 0.207, 0.143 and 0.079, respectively. MS gave higher θ at the top layer than MSS (**Fig. 4–2 A**), which could be attributed to two factors. The first point was that the irrigation pipe was placed at 15 cm soil depth for MSS, whereas on the soil surface for MS, which caused the lower θ at the top layer for MSS. The second point was the lower irrigation amount for MSS, compared with MS. Before Aug. 11, the θ at 17 cm depth for MS was lower than MSS and SS except some days (**Fig. 4–2 B**) because sub-surface irrigation for MSS and SS led to higher soil moistures at the depth just below the irrigation pipes. SS gave higher θ at 17 cm depth than MSS in most of days (**Fig. 4–2 B**) due to the higher irrigation amount for SS. At the depth of 27 cm, for most of days, the lowest θ occurred under SS treatment whereas the θ for MSS was a little higher than that for MS (**Fig. 4–2 C**). This can be attributed to lower *ET* under mulching regime and sub-surface irrigation treatments (**Fig. 4–1**). The average θ was higher for MS and MSS than for SS in most of days (**Fig. 4–2 D**).

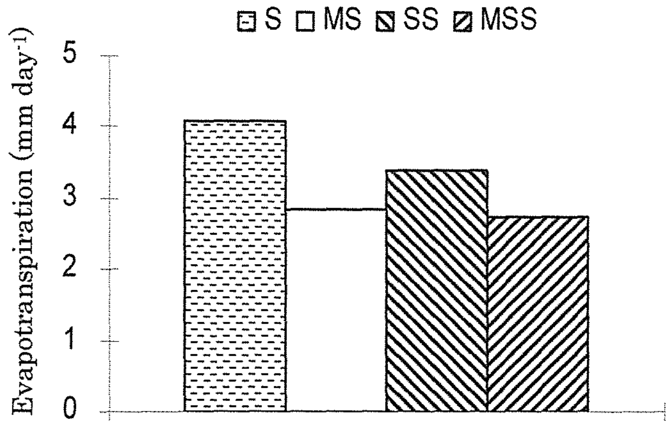


Fig. 4–1. Average evapotranspiration (mm/day) of grapevine for different mulching and irrigation treatments from June 5 to September 21. MSS: mulching combined with sub-surface seeper hose irrigation; SS: no-mulch combined with sub-surface seeper hose irrigation; MS: mulching combined with surface seeper hose irrigation; S: no-mulch combined with surface seeper hose irrigation.

MSS gave the highest average soil temperature at 7 cm soil depth (**Fig. 4–3 A**) due to the lowest *ET* (**Fig. 4–1**) led to the smallest consumed heat energy. There were no significant differences of average soil temperature among other treatments (**Fig. 4–3 A**). Except S, SS gave the highest maximum soil temperature at 7 cm soil depth, with MS the lowest (**Fig. 4–3 A**). The average soil temperature for MSS was 5.1°C higher than SS, while the maximum soil temperature for MS was 3.2°C lower than SS. In addition, compared with MS, MSS enhanced the average soil temperature by 4.6°C (**Fig. 4–3 A**), which could be attributed to the less *ET* under sub-surface irrigation (**Fig. 4–1**). There were no significant differences of minimum soil temperature among different treatments (**Fig. 4–3 A**). On June 27, the mulching regimes enhanced soil temperature from 0:00 to 7:00, whereas reduced it from 11:00 to 20:00, compared with no-mulching treatment (**Fig. 4–3 B**). The highest soil temperature during one day occurred at 14:00 for S, whereas 17:00 for MS and SS (**Fig. 4–3 B**).

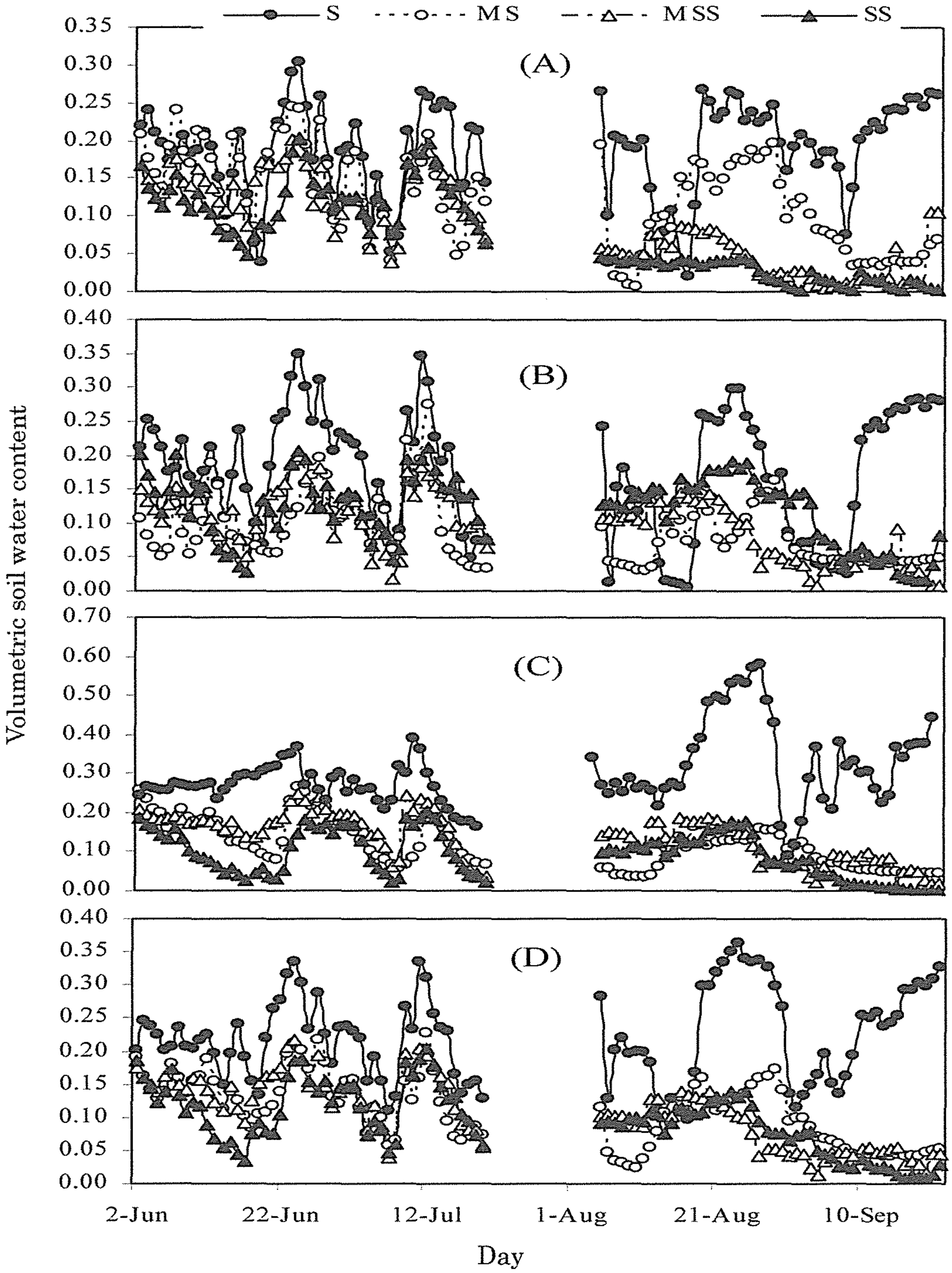


Fig. 4–2. Effects of mulching and irrigation method on volumetric soil water content at three soil depths, where (A): 7 cm; (B): 17 cm; (C): 27 cm; (D): average values of three depths.

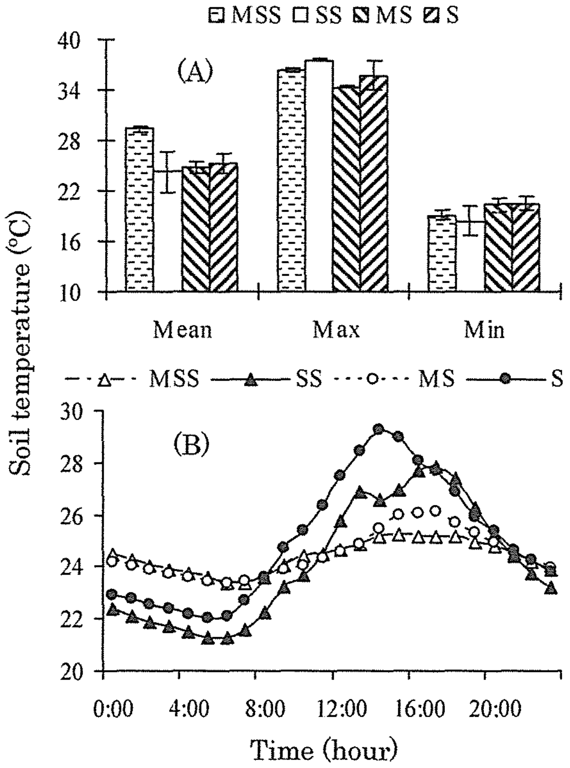


Fig. 4–3. Effects of mulching on mean, maximum (Max) and minimum (Min) soil temperatures at 7 cm soil depth from June 5 to September 21 (A) and daily variation of soil temperature at 7 cm soil depth on June 27 (B). Each symbol in Fig. 4–3 (A) represents the average ± standard error (SE) (n=3).

4.3.2. Shoot length, leaf area, photosynthesis and berry diameter

The primary shoot for S was the lowest on June 2 (**Fig. 4–4 A**). Mulching enhanced primary shoot length than no-mulching on July 7. MS enhanced the primary-shoot length by 7.9, 15.6 and 29.7 cm/mm irri. on July 7, compared with MSS, SS and S (**Fig. 4–4 A**), although the water stress for MS was more severe than S. This could be related to the higher soil temperature during night and improved soil organic matter under MS than under S (**Fig. 4–3 B**) and the higher θ at 7 cm soil depth for MS than for SS and MSS (**Fig. 4–2 A**). Mulching and sub-surface irrigation gave longer lateral shoot than S (**Fig. 4–4 B**). The lateral shoot length for SS was enhanced by 56% on July 7, compared with S (**Fig. 4–4 B**), which indicated that SS enhanced the irrigation efficiency based on the shoot length level.

For primary and lateral leaf area, MS gave higher values than S (**Fig. 4–5 A** and **B**) due to the higher soil temperature during night under MS (**Fig. 4–3 A**) led to well-growth of grapevine leaves under mulching and the shorter shoot length under S (**Fig. 4–4**). On June 30, MS enhanced the primary and lateral leaf area by 69 and 99%, compared with S (**Fig. 4–5 A** and **B**). There were no significant differences of leaf area among other treatments (**Fig. 4–5**).

Under sub-surface irrigation, mulching enhanced the photosynthesis (**Fig. 4–6**) due to the higher θ (**Fig. 4–2 A, C** and **D**), Ts at the upper soil layer (**Fig. 4–3**) and shoot length (for primary leaf) (**Fig. 4–4 A**) than no-mulching. Under surface irrigation, mulching also enhanced A_{N} for primary leaf (**Fig. 4–6**), which could be contributed to the higher soil temperature during night under MS (**Fig. 4–3 A**) led to higher leaf area under mulching (**Fig. 4–5**) and the shorter shoot length under S (**Fig. 4–4**). MSS enhanced A_{N} by 83% at 16:00 as compared with S (**Fig. 4–6**). Sub-surface irrigation treatments gave higher A_{N} than surface irrigation (**Fig. 4–6**). Two peak values of A_{N} occurred for MSS (at 10:00 and 14:00), while only one peak value occurred for MS, SS and S (**Fig. 4–6**). There were no significant differences of g_s among different treatments. MS gave the highest intrinsic WUE in the morning, whereas S gave the lowest value (**Fig. 4–6**) due to lower A_N, higher ET and Ts fluctuation under S. The intrinsic WUE at 10:00 for MS was 3.5 times of that for S.

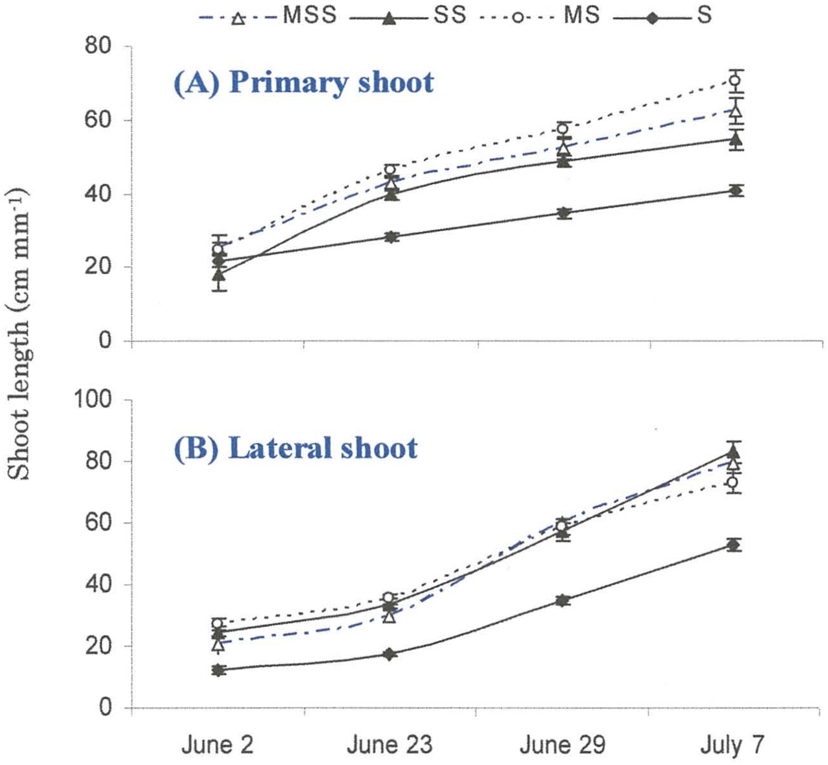


Fig. 4–4. Effects of mulching and irrigation method on shoot length for primary shoot (A) and lateral shoot (B) of grapevine. The Y-ordinate represents the shoot length divided by irrigation amount. Each symbol represents the average (per shoot) ± standard error (SE) (*n*=3).

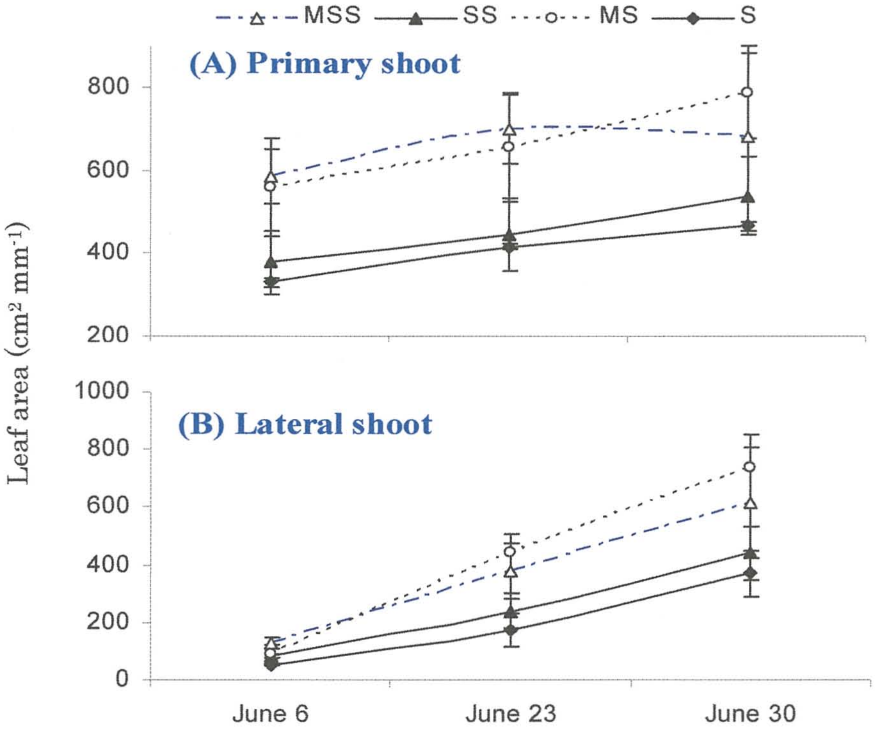


Fig. 4–5. Effects of mulching and irrigation method on leaf area for primary leaf (A) and lateral leaf (B) of grapevine. Each symbol represents the average (per shoot) ± standard error (SE) (*n*=3).

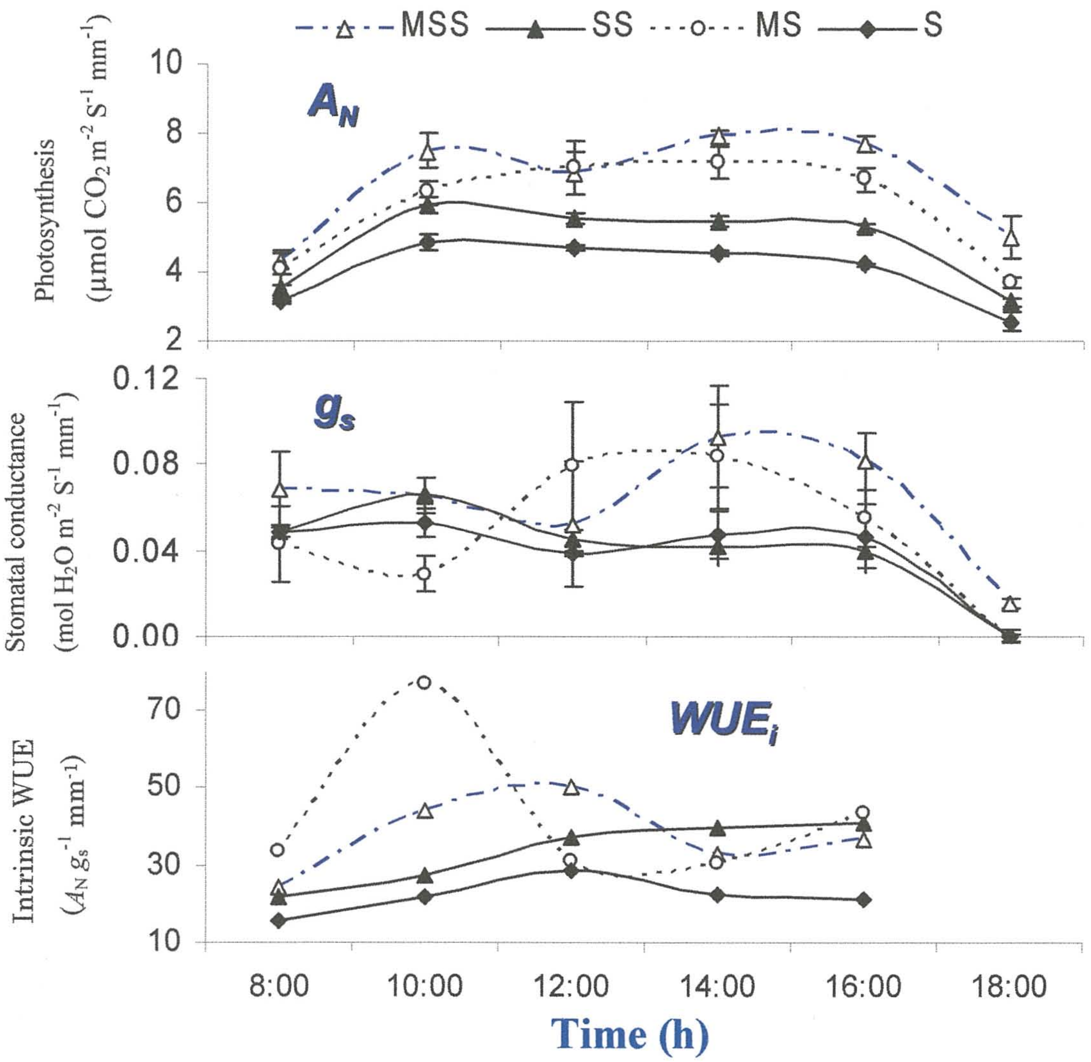


Fig. 4–6. Daily variation of photosynthesis (A_N), stomatal conductance (g_s) and intrinsic *WUE* (A_N g_s^{-1} as μmol CO_2 mol H_2O^{-1}) for primary leaf of grapevine under different mulching and irrigation methods on 2 August, 2008. Each symbol represents the average ± standard error (SE) (n=3).

Mulching and/or sub-surface irrigation regimes also enhanced the berry diameter in most of days (**Fig. 4–7**) due to the improved soil and growth conditions. The berry for

MS was larger than that for S due to higher shoot length, leaf area, A_N and intrinsic *WUE* under mulching. MSS gave larger berry size than SS, which can be contributed to the higher θ, A_N, and average soil temperature for MSS. The higher values of berry size were recorded for SS than S (**Fig. 4–7**), which can be related to higher shoot length, A_N and intrinsic *WUE* of primary leaf for SS. On Sep. 5, compared with MS, S and SS, MSS enhanced the berry diameter by 0.1, 3.5 and 2.3 mm mm^{-1} irri., respectively.

4.3.3. Fresh yield, water use efficiency and berry sugar content

MS gave the highest fresh yield while SS gave the lowest value in four treatments (**Fig. 4–8**). Compared with SS, the fresh yield for MS and MSS increased 271.5 g tree^{-1} and 73.2 g tree^{-1}, respectively, which can be related to the higher θ (at the upper soil layer), A_N, intrinsic *WUE*, the longer shoot and the larger berry diameter for mulching. Under both mulching and no-mulching conditions, the sub-surface irrigation reduced the fresh yield compared with surface irrigation due to the lower θ (at the upper soil layer) under sub-surface irrigation.

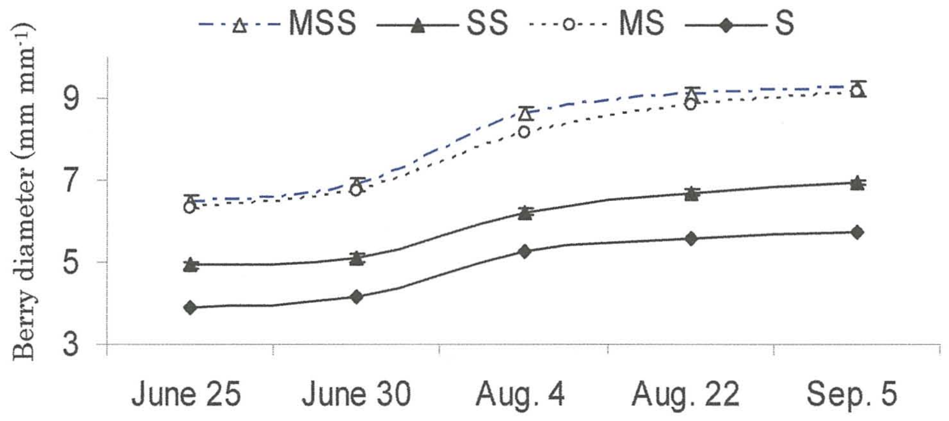


Fig. 4–7. Effects of mulching and irrigation method on berry diameter of grapevine. Each symbol represents the average ± standard error (SE) (n=10).

MS gave the highest *WUE*, followed by MSS and SS, while S gave the lowest value in four treatments (**Fig. 4–9**). Compared with S, MS enhanced *WUE* by 42%, which can be contributed to the improved soil condition (higher soil temperature during night and soil nutrient), the higher A_N, the longer shoot, the larger leaf area, larger berry size, high intrinsic *WUE*, higher yield and lower *ET* under MS led to well-growth of grapevine under mulching. Compared with SS, MSS enhanced *WUE* by 11% due to the higher θ, A_N, average soil temperature, lower *ET* and higher yield under MSS. Compared with MSS, MS enhanced *WUE* by 20% owing to the higher θ (at the upper soil layer) and higher yield under MS. Compared with S, SS enhanced *WUE* by 7%, which can be related to higher shoot length, A_N, intrinsic *WUE* of primary leaf and berry size for SS. Compared with SS, MS enhanced *WUE* by 33% due to the higher θ, A_N and yield, higher soil temperature during night, larger berry size and intrinsic *WUE*, and lower *ET* under MS.

The highest berry sugar content occurred under MSS for most of days (**Fig. 4–10**). At harvest on Sep. 22, the berry sugar contents for mulching conditions were significantly higher than that for SS, which can be related to the ameliorative environmental factors (such as soil temperature and moisture) and plant growth conditions (such as A_N, leaf area, berry diameter, yield and *WUE*) for mulching. Compared with SS, the mulching treatments enhanced berry sugar content by 15% at the harvest time. Higher berry sugar contents were recorded for S than SS in most of days (**Fig. 4–10**), which can be related to far lower θ and soil temperature during night in the upper soil layer under SS. MSS gave higher berry sugar content than MS for some days, which could be attributed to the lower soil moisture at the top soil layer and higher *Ts* under the condition of sub-surface irrigation.

Although grape growing requires less water per value of crop than most plants, the predicted climatic change (i.e. reduced rainfall and increased evapotraspiration rates) will intensify water stress on vines, especially in water-limited regions, affecting the ability of existing varieties to ripen fruit (Jones et al., 2005), the quality of grapes/wine and thus the overall economics of grape production (Santos et al., 2007). Therefore, mulching and /or sub-surface irrigation should be recommended for water-saving production of grapevines.

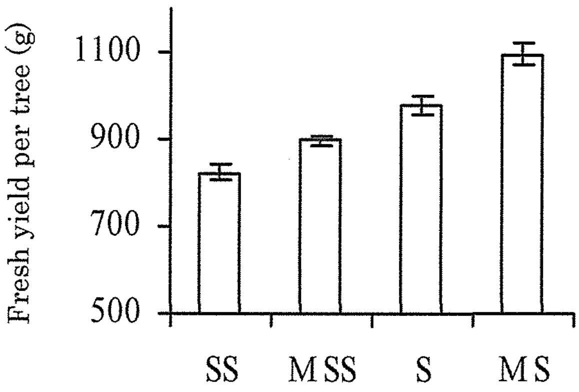


Fig. 4–8. Effects of mulching and irrigation method on fresh yield (per tree) of grapevine. Each symbol represents the average ± standard error (SE) (n=3).

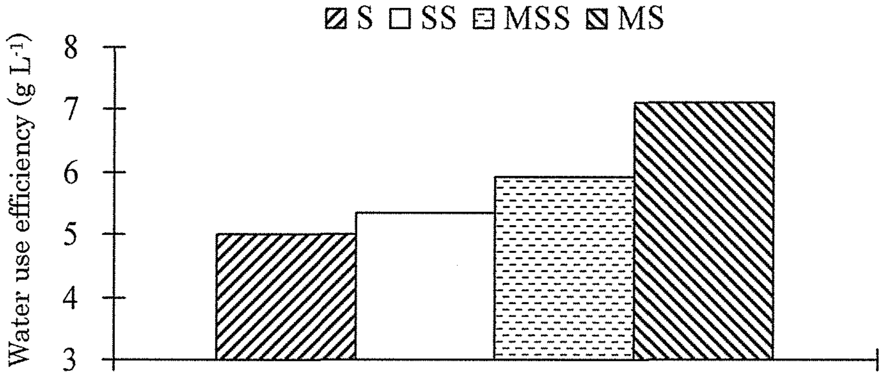


Fig. 4–9. Effects of mulching and irrigation method on water use efficiency ($Y\,ET^{-1}$) of grapevine, where Y is fresh yield (g).

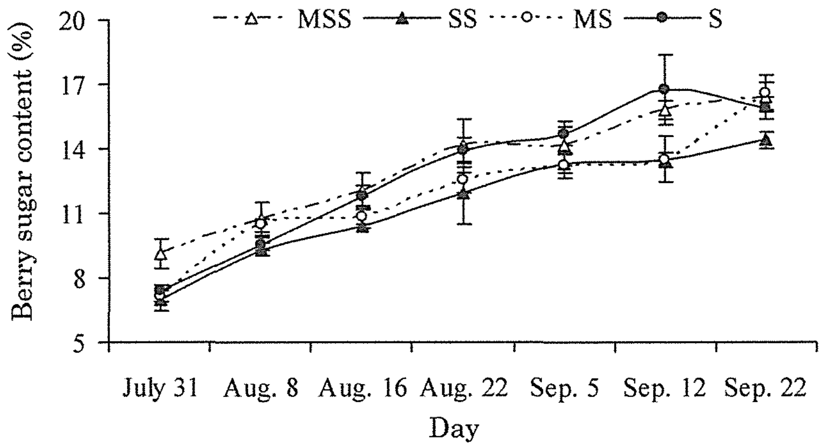


Fig. 4–10. Effects of mulching and irrigation method on berry sugar content of grapevine.
Each symbol represents the average ± standard error (SE) (n=3).

4.4 Discussion

4.4.1. Effects on soil

MS decreased *ET* slightly as compared with SS, although irrigation amount for MS was a little higher than that for SS (**Fig. 4–1**). This can be attributed to low soil evaporative demand under the mulching condition, which is consistent with the finding of Pinamonti (1998) who reported that the compost mulching improved permeability of water, water storage and reduced evaporation.

Under sub-surface irrigation, rice-straw mulching increased θ (**Fig. 4–2**), an effect partially attributed to insulation and lower soil temperatures in the afternoon (**Fig. 4–3**), but also to the high water-holding capacity of the mulches because of their high organic matter content (Li et al., 2004) and low bulk densities (Jacometti et al., 2007b). An increase in soil moisture of 34% was also found under straw, another low bulk density organic mulch, in South Australia (Buckerfield and Webster, 1996).

The mulching regimes increased soil temperature at night, whereas reduced it in the afternoon, compared with no-mulching treatment (**Fig. 4–3 B**). Tripathi and Katiyar (1984) reported that paddy straw enhanced the minimum soil temperature by 3 °C, whereas reduced the maximum value by 7.4 °C as compared with bare soil. Organic mulching reduced soil temperature fluctuations (Pinamonti, 1998; Jacometti et al., 2007a). MS and MSS lowered the maximum soil temperature as compared with SS (**Fig. 4–3 A**), which indicated that mulching could prevent the possible plant damage due to high temperature. Pinamonti (1998) showed that laying the plastic film may turn out to be counterproductive due to the excessive heat which hinders the plants growth (reduced vegetative development along with an increase in dead vines), whereas the compost mulch regulated soil temperatures by reducing seasonal fluctuation and protecting the soil against extremes of temperature.

4.4.2. Effects on the vegetative status of plants

Rice-straw mulching enhanced primary shoot length than no-mulching (**Fig. 4–4 A**), whereas Jacometti et al. (2007a) observed that the mulched paper lowered vine canopy density by up to 1.4 times that of the other treatments. This difference may be related to the higher nutrients under rice-straw mulching led to stronger growth vigor. Mulching tends to enhance the leaf area as compared with S (**Fig. 4–5**). Pinamonti (1998) also reported that the compost mulch improved the general performance and the growth of grapevines during the first year: the pruning weight was 120–140% higher than in the control plots.

The mulching treatments enhanced the photosynthesis (**Fig. 4–6**) due to improved soil condition under mulching. Sub-surface irrigation tends to improve irrigation efficiency based on photosynthesis level (**Fig. 4–6**). Poni et al. (2009) showed that photosynthesis was already limited after 2 days of water stress and this limitation steadily increased for

Lambrusco grapevines which have higher stomatal sensitivity under water stress. However, the g_s for the 'Gros Colman' grapevine seems to be insensitive for water deficit based on our present experiment (**Fig. 4–6**). MS gave the higher intrinsic *WUE* than S in the morning (**Fig. 4–6**) although the soil water content for MS was far lower than that for S. Water deficit treatment was indeed able to consistently increase intrinsic and extrinsic *WUE* as compared to unstressed vines (Poni et al., 2009; Dry and Loveys, 1999; Koundouras et al., 2008). One of the first vine responses to drought is the reduction of leaf stomatal conductance associated with an optimization of intrinsic *WUE*, an indicator of long-term regulation of carbon assimilation under drought (Bota et al., 2001; Cifre et al., 2005).

Under sub-surface irrigation, mulching regimes also enhanced the berry diameter (**Fig. 4–7**), which can be partly contributed to the higher θ under mulching. Wang et al. (2003) also found that berry size and bunch weight are positively correlated with soil moisture, predominantly during the early stages of berry development when they grow rapidly (Wang et al., 2003).

4.4.3. Effects on the productive status (yield and quality) and WUE of plants

Mulching elevated the fresh yield of grapevines regardless the irrigation method (**Fig. 4–8**). The use of straw and mulched cover crops has been also shown to increase yield in grapes by 46～60% and this increase was linked to elevated soil moisture, earthworm presence and additional nutrient sources released slowly (Buckerfield and Webster, 1996; Jacometti et al., 2007a).

The fresh yield of grapevines for MS was higher than that for MSS (**Fig. 4–8**), which can probably be related to the lower θ (at the upper soil layer) for MSS due to the deep placement depth (15 cm below the soil surface) of sub-surface irrigation hose. The placement depth of sub-surface drip laterals has an impact on crop yield and the maximum onion yield was recorded at 10 cm depth of drip lateral in all treatments with 6 depths of placement of drip lateral (Patel and Rajput, 2008). In deeper placement of drip lateral (20 and 30 cm below surface), adequate soil water was found at 30, 45 and 60 cm soil depth (Patel and Rajput, 2008). Our data showed that the θ at 17 and 27 cm depths for MSS was higher than MS except some days (**Fig. 4–2 B** and **C**) because sub-surface irrigation for MSS led to higher soil moistures at the depth just below and near the irrigation pipes. Sub-surface irrigation system should be designed such that the wetted soil volume matches as closely as possible to the crop rooting pattern. Generally, root density was higher in the upper soil layer (0 to 20 cm) than in the deeper soil layers for grapevines (Morlat and Jacquet, 2003), regardless soil types (Soar and Loveys, 2007). Mulches increased grapevine root densities in the upper 20 cm (Smart et al., 2006).

The berry sugar concentrations for mulching conditions were significantly higher than that for SS (**Fig. 4–10**). Marc and paper treatments can also increase grape skin strength by up to 10% in the paper treatment and sugar concentrations by 1.2–1.4 °Brix (Jacometti et al., 2007a). MSS gave higher berry sugar concentration than MS, which could be attributed to the higher *Ts* and lower soil moisture at the top soil layer under the condition of sub-surface irrigation. Pinamonti (1998) showed that the nutrients uptake was more influenced by the physical conditions of the soil (temperature, moisture) than by the availability of nutrients in the soil. Improved wine quality was also usually due to moderate water stress which induced higher concentration of anthocyanins and phenolics in the berries (Zsófi et al., 2009). Organic mulching elevates vine yield and sugar content (Jacometti et al., 2007a), which is influenced by environmental conditions at flowering, fruit set and the early stages of grape expansion (Wang et al., 2003).

The *WUE* for MS was higher than that for S (**Fig. 4–9**) due to lower *ET* and higher yield under MS. Water deficit strategies would increase *WUE* as compared to full irrigation (Dry et al., 1996). In this connection, data reported by Willliams et al. (1994) show that *WUE* (g of dry weight per kg of water transpired) decreased from 5.85 for a treatment irrigated at 20% vine *ET* to 1.84 for plants receiving 140% of vine *ET*. Compared with S, SS reduced yield (**Fig. 4–8**) while enhanced *WUE* by 7% (**Fig. 4–9**) due to the lower *ET* for SS. To give priority to high water-use efficiency over maximum yield, irrigation should be applied only when the indicator parameter drops below a certain threshold value in drylands (Cifre et al., 2005).

4.4.4. General discussion

Although grape growing requires less water per value of crop than most plants, the predicted climatic change (i.e. reduced rainfall and increased evapotraspiration rates) will intensify water stress on vines, especially in water-limited regions, affecting the ability of existing varieties to ripen fruit (Jones et al., 2005), the quality of grapes/wine and thus the overall economics of grape production (Santos et al., 2007). Effective water management in vineyards may attempt to maintain the plants at a limit between water stress and excess water consumption, thus making a rational use of irrigation water. This kind of irrigation may save water with respect to empirical irrigation, improving yield as compared with rainfed grapevines, and maintaining the high fruit quality (Cifre et al., 2005).

Mulching tends to improve the physical conditions of the soil (temperature and moisture) leads to a balance growth performance, higher yield and quality of grapevines. MSS increased the berry sugar concentration on most dates, although the water stress for MSS was far more severe than S. MS gave the higher fresh yield than S, although the water stress for S was far less than MS. SS reduced the fresh yield as compared with S due to the severe water stress under SS. MS should be given a priority for saving water due to its high *WUE*. It is currently a priority for the United Nations policy, what is called the 'Blue Revolution' and summarized as 'more crop per drop' (Annan, 2000).

Different soil water content affects grape quality and reflects in wine quality (Conradie et al., 2002). Jackson and Cherry (1988) show that in regions with a high rainfall the ripening capacity of grapes is lower to that predicted by the climatic thermal indices. A certain lack of water during the ripening period is favorable to the organoleptic wine quality in temperate regions which do not generally suffer droughts (Tonietto and Carbonneau, 2004). Water deficit can also improve fruit and wine quality at a moderate level of stress (Bravdo and Hepner, 1987), which results in larger relative skin mass in the berries (Roby and Matthews 2004) and thus higher concentration of phenolics and anthocyanins (Kennedy et al. 2002b, Ojeda et al. 2002, Sivilotti et al. 2005).

Interestingly, MSS improved berry sugar concentration while decreased the yield as compared with MS, which could be explained that in grapevines, highest crop load is usually linked to low grape quality. Thus, in fact, limitations to grape yield are a common practice (if not compulsory) for a market standard wine production and premium wines (Cifre et al., 2005).

Generally, agronomic vine performance of the 'Gros Colman' grapevines was not impaired severely by water stress. Overall, this outcome fits with previous work showing higher tolerance of grapevine to water deficit imposed after veraison (Poni et al., 1993; Behboudian and Singh, 2001) as compared to preveraison stress, especially as reduced sensitivity of berry growth (Keller et al., 2006). Poni et al. (2009) also showed that water stress did not significantly alter yield or its components while achieving an improvement in must soluble solids and total anthocyanins. Poni et al. (2009) believe that the primary factor that determined the excellent vine performance of the water stress treatment is linked to vine balance. Based on our data, the 'Gros Colman' grapevine is a stress-tolerant variety for severe water deficit. Being an important and extensive crop in drought-prone areas, the variety of grapevine with a high tolerance for water stress is very useful for grapevine production.

Weed growth was also reduced by mulching treatments as compared with control (data not shown). Therefore, the mulch allowed a reduction of herbicide applications (Pinamonti, 1998).

An interesting highlight in this study concerns that the highest average soil temperature led to the highest sugar concentration for MSS. The quality and the typeness of wines depend on natural factors and human factors. In fact, air temperature influences composition and quality of grapes (Coombe, 1987). Tonietto and Carbonneau (2004) developed cool night index (*CI*) as a viticultural climatic indice based on an indicator of night air temperature conditions during maturation. During the ripening period, the air temperature plays a determinant role for grape maturation, including the aroma and the coloration, having an important effect on the characteristics of the wines (Jackson and Lombard, 1993). The day air temperatures influence the coloration (Tonietto and Carbonneau, 2004). The duration of the phenological stages was dependent on vintage temperature characteristics rather than on vineyard site (Zsófi et al., 2009). Therefore, it could be concluded that the average soil temperature should be recommended as an important index for the quality of grapevines, similarly like air temperature.

When the sub-surface irrigation is used for vineyards, the placement depth of sub-surface irrigation hose for 'Gros Colman' grapevine should be shallower than 15 cm since the placement depth of 15 cm decreased yield and *WUE* as compared with surface irrigation under mulching. Further experiments should be conducted about comparing different placement depths of sub-surface irrigation pipe on the performance of grapevines.

The response of soil and grape to different mulching and irrigation treatments could give a useful basis for vine growers for variety selection and choice of viticultural practices, especially in drylands.

4.5 Conclusions

MS gave the highest fresh yield while SS gave the lowest value due to higher θ (upper soil), A_N, Ts and diameter for MS as compared with SS. MS gave the higher *WUE* than MSS due to the higher water content at top soil and higher yield for MS. These combination of mulch and seepage irrigation were differed for *WUE* in the order of MS > MSS > SS > S. Compared with SS, the berry diameter, fresh yield, *WUE*, and berry sugar content for MS were enhanced by 2.8 mm, 271.5 g tree^{-1}, 33% and 15%, respectively. MSS gave higher berry sugar content than MS, which could be attributed to the higher Ts and lower soil water at the top soil layer under the condition of sub-surface irrigation. Ts should become an important index for the berry quality of grapevine.

Chapter 5 Determination of soil water potential threshold for irrigating grapevines in the last phase of Stage 1 of berry growth based on photogrammetric measurement of berry size

5.1 Introduction

Because of increasing population, land and water resources have been put under severe stress (Ghadiri et al., 2005). Given current demographic trends and future growth projections, as much as 60% of the global population may suffer water scarcity by the year 2025 (Qadir et al., 2007). As the agriculture sector is one of the largest consumers of water, it is likely to suffer the most unless more efficient water management is practiced, particularly in semi-arid and arid areas. Grapevine (*Vitis vinifera* L.) is an important fruit crop grown in semi-arid and arid environments. In the drylands of northwest China grape production is common but its sustainability is threatened by unreliable water resources (Du et al., 2005). The problem of water scarcity is going to get further aggravated with climate change, which is also likely to affect the quality of grapes/wine and thus the overall economics of grape production (Santos et al., 2007). Therefore, improving the efficiency of irrigation is essential for long-term sustainability of grape production and the wine industry.

Irrigation management plays an important role in determining water use efficiency in agriculture (Dukes and Scholberg, 2005). Under arid and semiarid conditions, water availability plays the main role in regulation of berry growth and sugar accumulation for vines and, therefore, the highest attention should be paid in these areas to irrigation management, seeking the degree of stress that allows optimizing the combination of yield and berry quality in each situation (Santesteban and Royo, 2006). Horticultural produce is sold by weight, and since water is the major component of most fresh horticultural commodities there is often a marked premium in ensuring that water content is maximised, whilst ensuring that produce quality does not suffer (Jones and Tardieu, 1998).

Traditionally, grape producers tend to use excessive amount of irrigation water during the berry development stage to maximize berry size. This not only results in a waste of water, but also causes nutrient loss and promotes excessive vegetative growth at the expense of fruits. Deficit irrigation in fruit crops can be of value in increasing fruit quality by raising dry matter and sugar content (Chalmers et al., 1981). Several studies have shown that appropriate and moderate water stress is beneficial for berry growth in grapevines, whereas severe water deficit or saline irrigation decreases the production of assimilates, and reduces transpiration, shoot growth, and yield and quality of fruit (Shani et al., 1993; Delgado et al., 1995; Pellegrino et al., 2005; Lovisolo and Schubert, 2006; Lovisolo et al., 2008). In deficit irrigation water application is withheld until the vine has experienced a certain level of water stress, after which a specific volume of water is applied to allow continued sugar accumulation and the maintenance of canopy cover. This practice prevents excessive vegetable growth allowing light to diffuse into the fruiting area improving fruit color and quality while minimizing yield reductions (Prichard et al., 2004). The potential for water saving by deficit irrigation in many orchard crops has remained unexplored so far (Fereres et al., 2003). It is, therefore, important to determine the critical timing for starting irrigation, especially in drylands where drought represents a serious threat to the sustainability of agriculture (Konukcu et al., 2005).

It is well known that the rates of many physiological processes, such as photosynthesis, are more closely related to cell turgor pressure or to cell volume, than to absolute ψ (Sinclair and Ludlow, 1985; Jones, 1992). Water plays a key role in cell expansion and growth. Numerous studies (Bravdo et al., 1985; Poni et al., 1994; Esteban et al., 2001; Reynolds et al., 2005) have focused on irrigation management based on soil water content. However, a local measurement of soil water content may not represent the true picture, especially for drip irrigation. Therefore, the use of physiological indicators of plant water status would be a more appropriate criteria. Besides soil and environment factors, plant physiological parameters would be important indexes for determining when to begin irrigation. During last decades, many plant-related indicators have been widely tested as inputs for precise irrigation control of different crops (Ton et al., 2004a). Plant physiological information has value in estimating the degree of water stress to which fruit trees are subject, using readily accessible measurements. Many growers of various fruit trees have reported substantial savings in water coupled with good yields and quality through fine-tuning irrigation scheduling based on physiological indicators (Ton et al, 2004a). Many of them are based on continuous monitoring of stem diameter (Selles and Berger, 1990; Fereres et al., 1999; Goldhamer and Fereres, 2004) and/or fruit diameter (Gratacos and Gurovich, 2003; Ton et al., 2004a; Avidan et al. 2005). Some of the studies were carried out on grapevines (Myburgh, 1996; Ton and Kopyt, 2004; Ton et al., 2004b; Kopyt et al., 2005), although published information about practical implementation of fruit size measurement results in irrigation control of industrial vineyards is limited. Most of above-mentioned studies about physiological indicators were conducted using phytomonitoring methodology. Nevertheless, Intrigliolo and Castel (2007) reported that trunk diameter was able to detect vine water stress only during a short period of time before veraison.

Severe water stresses due to water deficits may cause retardation of berry growth (Hardie et al., 1981) and damage of plant by reducing photosynthesis through both stomatal and nonstomatal effects (Ennahli and Earl, 2005). Ferreyra et al. (2006) reported that when plants maintained stem water potential (measured at midday) greater than -0.75 MPa, between berry set and veraison, yield and berry size were high. A continuous recording of the micro variations of berry diameter is being considered as a new tool for estimating water stress of grapevines. This seems to be a substantial step ahead to precision viticulture (Ton and Kopyt, 2004). Imai et al. (1991a) reported that the berry diameter of grapevines shrunk in the day time and swelled at night because of the deficit of water content in the day time. In the early stage of berry development, cane and berry diameter shrinkages for grapevines occurred because of the water stress (Imai et al., 1991b). Therefore, berry diameter can become a useful indicator for irrigation management of vineyards when water is limited.

Overall, the berry development of grapevine follows a double sigmoidal shape with a strong increase in diameter early (Stage 1), a slower lag phase (Stage 2), and a rapid growth from veraison (Stage 3) which then gradually slows down (Coombe and McCarthy, 2000; Chatelet et al., 2008). The first period of growth (Stage 1) lasts from bloom to approximately 50-60 days thereafter (Coombe and McCarthy, 2000). During this period, the berry is formed and the seed embryos are produced. Greenspan et al. (1994) have shown that xylem sap is the main source of water for berries during their first growth cycle during which dry matter accumulation is relatively small. Rapid cell division occurs through Stage 1, and by the end of this period, the total number of cells within the berry are established (Coombe, 1987). Thus, the extent of cell division has some bearing on the eventual size of the berry. Also, during the first growth period, the berry expands in volume as solutes such as tartaric and malic acid, tannins and other compounds accumulate. The accumulation reaches an apparent maximum around véraison (Possner and Kliewer, 1985). These solutes are critically important to wine quality. The berry diameter increased 3.5-fold between 12 and 120 days after anthesis (Chatelet et al., 2008). The berry development is the most critical for economic yield as fruit size at harvest is an important aspect of the quality of the fruit (Zhang et al., 2005). McCarthy (2000) reported that water stress during the post-flowering period had most significant effect on berry size, whereas moisture deficit after veraison had only a minor effect on berry weight at maturity and berries were insensitive to water deficit in the month before harvest (McCarthy, 1997a). Imai et al. (1991b) showed that grape berry diameter tends to increase during night and decrease in daytime and the range of diurnal variation increases with decreases in soil water potential (ψ). These authors concluded that berry growth is closely related to ψ.

Water deficits during Stage 1 of fruit growth are thought to reduce potential berry size by reducing the number of cells per berry. The reduction of cell number causes smaller berries and almost always causes a reduced yield (Prichard et al., 2004). Avidan et al. (2005) used daily diameter increment of berry as one of the main indications of grapevine water status for adjusting irrigation and concluded that the direct monitoring of berry growth may help to optimize irrigation rate. Therefore, the use of berry diameter as a key and main plant parameter for reflecting and defining the water potential thresholds for irrigation was considered important. There are many studies on the effects of various irrigation regimes on vine growth (Bravdo et al., 1985; Poni et al., 1994; Esteban et al., 2001; Pellegrino et al., 2004; Reynolds et al., 2005). However, what is the threshold ψ at which the grapevine must be irrigated in the last phase of berry development Stage 1 is not known. This information is critical to optimize water use, prevent nutrient loss and improve yield and quality of grapes. Imai et al. (1991b) already reported that daily variation in berry diameter might be a useful index for soil moisture control in grape production. The upper limit of ψ in the ripening stage was regarded as $\psi = -12.6$ kPa since the berry swelling was conspicuously affected by soil drying (Imai et al., 1991b). Vines watered at $\psi = -15.8$ kPa, from bud burst to seed-hardening, showed slower primary shoot growth, weaker lateral shoot growth, smaller leaf area and slower berry-size increase than those watered at $\psi = -3.2$ kPa (Imai et al., 1991a). Their study, however, did not indicate the threshold value of ψ at which irrigation should be scheduled during the berry development stage as only two levels of ψ were tested. We hypothesize that the threshold value could be established by measuring diurnal variations in berry diameter of grapevine experiencing increasing soil moisture stress. It is, however, necessary that the measurements are made with great precision because the changes are rather small.

A new system of automated photogrammetry has been developed by Moritani et al. (2006; 2007) for continuous measurement of soil erosion (Pyle and Richards, 1997). This system, which consists of two high-precision digital cameras, attached to a computer with an image-analysis program of three-dimensional algorithm, can also be applied for measuring fruit size with three major advantages. First, the measurement precision is high. Second, the berry diameter can be monitored automatically. Third, the determination is nondestructive. There is lack of published information about measuring berry size using photogrammetry.

The goal of this study was to establish the critical soil water potential value for starting irrigation of grapevines in the last phase of Stage 1 of berry growth, based on photogrammetry of berries and a tensiometer system for measuring soil water potential. This was done by examining instantaneous variations in berry diameter, soil water potential and photosynthesis, as the water deficit developed in the soil.

5.2 Materials and methods

The study was conducted in 2008 at the Arid Land Research Center, Tottori (35°15′ N, 133°47′ E), Japan.

5.2.1. Plant and soil materials

On 25 February 2008, 2-year-old Pione grapevines (*Vitis vinifera* L., cv. *V. labrasca)* were transplanted into 34-liter capacity horticultural pots in a greenhouse under natural conditions of temperature, light and humidity. Each pot (39 cm surface diameter, 32 cm depth) contained 28 kg of a mixture of sandy soil (sieved through a 2-mm sieve), peat moss, humic allophone soil and lime in a volumetric ratio of 1200 : 600 : 200 : 1, respectively. The mixture was placed on a 2 cm thick layer of microvesicular pumice to allow free drainage. The mixture had a pH of 6.2. The pots were irrigated with an automatically timed drip irrigation system to ensure optimum moisture regime for the vines. Four emitters per vine were located approximately 10 cm from the trunk. The amount of water applied was controlled by a time clock-solenoid valve assembly. The irrigation amounts for March, April, May and June were 2.4, 3.2, 4.5 and 6.0 L per pot per week, respectively. The plants were provided liquid fertilizer containing all essential mineral nutrients (Wang et al., 2001; Thippayarugs et al., 2002) once every week.

To encourage uniform vegetative growth, vines were pruned to retain 12 nodes per vine; only two shoots per vine were left and were trained horizontally. The anthesis started from May 17, 2008. Shoots were trimmed twice between bloom and the veraison stage of the berries. Lateral shoots were cut back to the first node. At flowering, one cluster was left on each of the two shoots. Each cluster was trimmed to retain only 200–250 florets and once berry-set occurred, further trimming was done to retain only 40–50 berries per cluster.

5.2.2. Experimental details

On 26 June (40 days after flowering), when the berries were in the last phase (the last week) of Stage 1, a pot containing the grapevine was placed in an environmentally controlled growth chamber (type GC-A, Fuji Electric Co. Ltd., Tokyo, Japan) in which temperature was set to 12/12 h (day/night) cycles of 35/20 °C with 12 hours illumination. The relative humidity, air flow and diurnal luminous intensity were set at 50%, 0.3 m s^{-1} and 5000 μmol m^{-2} s^{-1}, respectively. After placement in the growth chamber, the vine was irrigated to saturated condition. From then on till 15:00 h on 28 June the vine experienced deceasing ψ. At 15:00 h on 28 June it was irrigated again to saturation. Thereafter, the plant again faced a deceasing ψ.

Soil water potential was measured every two hours by a pressure transducer system (Marthaler et al., 1983) for field-installed tensiometers with a short section of clear plastic tubing at the upper end. The system consists of a pressure transducer with attached syringe needle, tensiometers and digital read-out. The needle is inserted through the septum stopper which closes the upper end of the tensiometer. A spring guarantees smooth insertion of the needle into the septum as it is forced down. The pressure in the air below the septum stopper, in equilibrium with the water pressure, is read on the digital read-out, which is calibrated in millibars. Upon withdrawal of the needle from the tensiometer, the septum stopper seals the tensiometer. The transducer consists of a steel enclosure with a transducer membrane separating the enclosure in an upper chamber an in a lower chamber. The upper chamber is at atmospheric pressure (Marthaler et al., 1983). The soil water potential was calculated by subtracting the stem length of the tensiometer from the reading on the resistivity meter (calibrated in millibars). Twelve tensiometers (filled with deaerated water) were put in the pot, six at a depth of 10 cm and other six at a depth of 20 cm.

Berry diameter was monitored every hour by a new photogrammetry-system that consists of two digital cameras (Nikon D2H, 16,000 pixels) attached to a computer having an image analysis program of three-dimensional algorithm. The measurement precision of the system was 0.2 mm. Details of this system are described by Moritani et al. (2006).

A rectangular analytical frame with scale was fixed vertically on the grapevine and the grape cluster was placed inside the frame. Three marked berries and two digital cameras were oriented as shown in **Fig. 5–1** and these positions were fixed. The distance between two cameras was 1.2 m. The distance between the camera and the target berries was 1.8 m. Pictures taken by the pair of digital cameras were collected on a computer. The focal length (fc) and resolution of CCD (δccd) of the digital cameras were 50 mm and 0.0094 mm, respectively. The inner orientation factors of the digital cameras are given by Moritani et al. (2006). The relative orientation and gradient of the pair pictures were adjusted to minimize parallax to obtain a rectified photograph. Through rectification and elimination of longitudinal parallax, the y-coordinate of a point in the left rectified image was the same as that in the right one. The same point in the paired images could easily be searched by scrolling the point in the x-axis direction.

Net photosynthesis and transpiration rate of two healthy spur leaves of the grapevine were measured at various intervals by a portable photosynthesis system (LI-6400, Li-Cor Inc., Lincoln, NE, USA). Measurements were conducted on 2 cm × 3 cm leaf portion in the middle part of a leaf blade confined in the leaf chamber of the system. The measurements were repeated three times on each leaf.

5.2.3. Time series analysis of berry diameter data

As the berry diameter showed diurnal variations over the study period, it was necessary to remove the periodic fluctuations by time series analysis (Box et al., 1994; Moran et al., 2009). Periodic fluctuation of berry diameter was filtered by cubic polynomial trend line, and the main secular growth trend part was thus obtained. It was then possible to establish the relationship between the tendency part of berry diameter and soil water potential in the root zone. An example of determining the trend line of the time series of diameter of Berry No. 2 from 29 June to 1 July is given in **Fig. 5–2**. Time-series berry diameter measurements were available for 47 hours. The trend line in this figure can helps in removing the short-term fluctuations in the time series of berry size. The trend values of berry diameter were computed as

$$y_i = 22.831 - 0.0629\, x_i + 0.0066\, x_i^2 - 0.0001\, x_i^3,\ r^2 = 0.67,\ N = 47$$

where x_i is the berry diameter measurement time (i$^{\text{th}}$ hour), y_i is the trend value of berry diameter (mm) at i$^{\text{th}}$ hour, and N is the total hours of measurement in this figure.

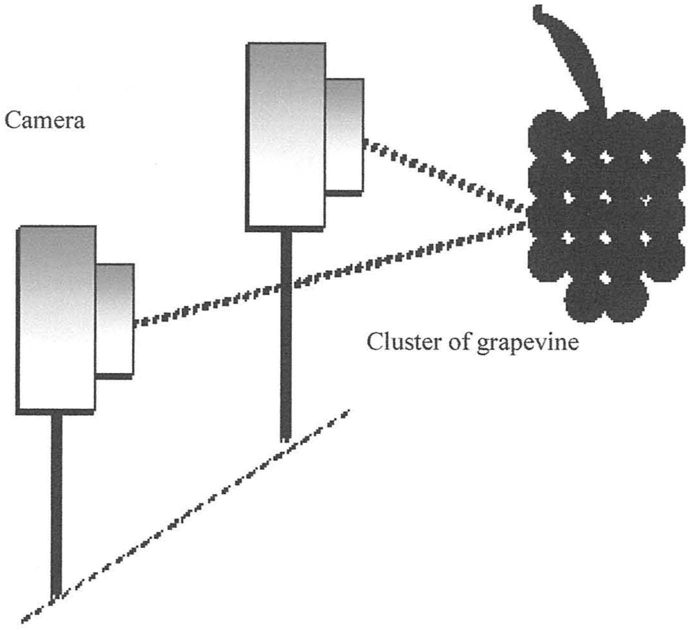


Fig. 5–1. Schematic diagram of two cameras and the marked berries.

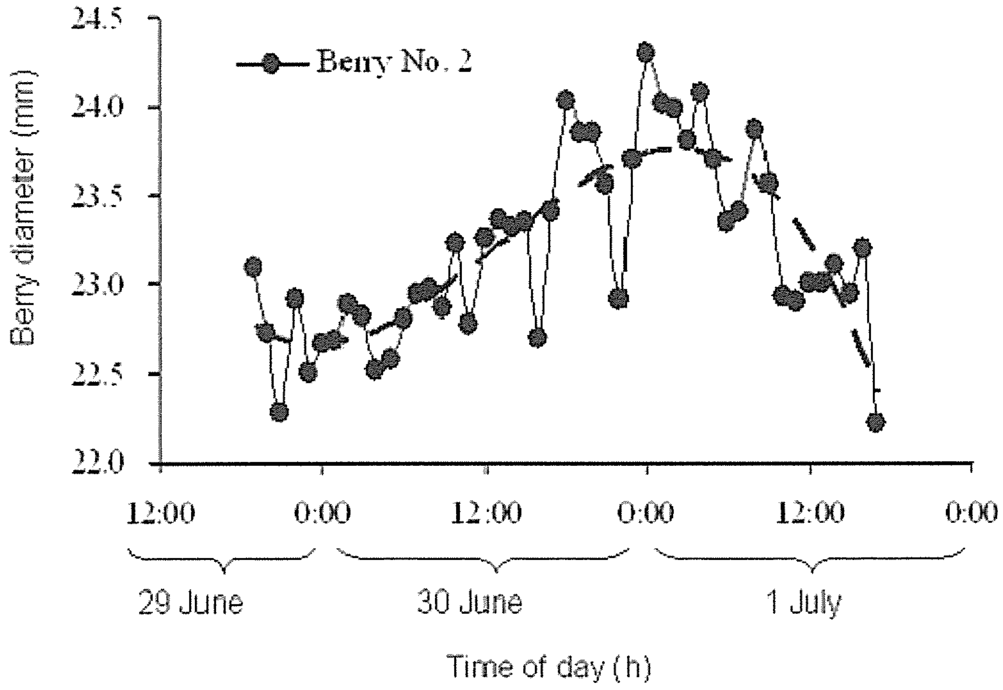


Fig. 5–2. Diurnal variations in a time series of diameter for Berry No. 2 from 29 June to 1 July. The solid line represents measured berry diameter, and the dashed line represents the trend line.

5.2.4. Statistical analysis

Analysis of variance (ANOVA) was performed on data of photosynthesis and transpiration rate using the statistical analysis software SPSS v11.5 (SPSS Inc, Chicago, IL, USA). The data means were compared for any significant differences using Duncan's multiple range tests at a significance level of $P_{0.05}$.

5.3 Results

5.3.1. Daily variation of soil water potential

After irrigation in the afternoon of 28 June, the ψ decreased slowly during the first 2 days (**Fig. 5–3**), but started decreasing rapidly in the afternoon on 1 July when it decreased to –6.2 kPa in the 10 cm soil depth. The rate of decrease of ψ in the daytime was faster than during the night. The trend for the change in ψ at the 10 cm and 20 cm soil depths was similar, although ψ in the 10 cm soil depth was lower than that in the 20 cm soil depth because of evaporative losses from the soil surface.

5.3.2. Daily variation of berry diameter

The diameter of grape berry (average of three berries) tended to increase during night and decrease during daytime (**Fig. 5–4**). During the predawn period on 28 June, the average diameter of grape berries significantly increased by 13% over measurements taken three hours before (**Fig. 5–4A**). The average increase in diameter of the berries from 03:00 h to 06:00 h on 28 June was 2.9 mm. In contrast, the increase during the night between 30 June and 1 July was only 1.6 mm (**Fig. 5–4B**). This difference can be attributed to the lower soil water potential (–13.6 kPa at 10 cm depth) in the afternoon of 28 June (**Fig. 5–3**). Although the grapevine was irrigated to saturated condition afterwards, the berry on 30 June could not retain the previous rapid growth rate. The maximum average berry diameter on 30 June was less than that before the water stress, which also indicated that the exposure to water stress of –13.6 kPa could confine the subsequent natural growth of grape berries even when the soil water potential was improved.

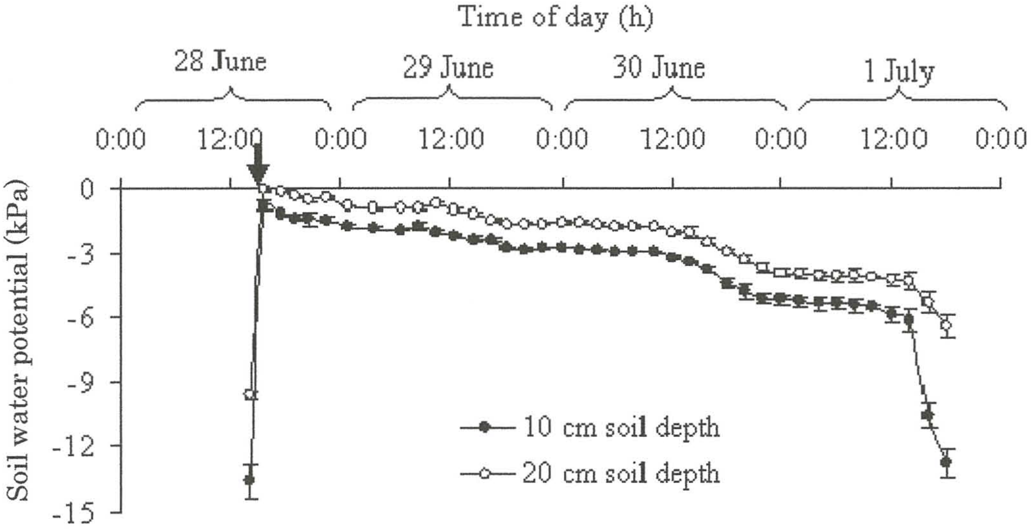


Fig. 5–3. Soil water potential (ψ) of the root zone (10 cm and 20 cm soil depths) after irrigation (shown by arrow) for potted 2-year old Pione grapevine from 28 June to 1 July. Means ± SE ($n = 6$).

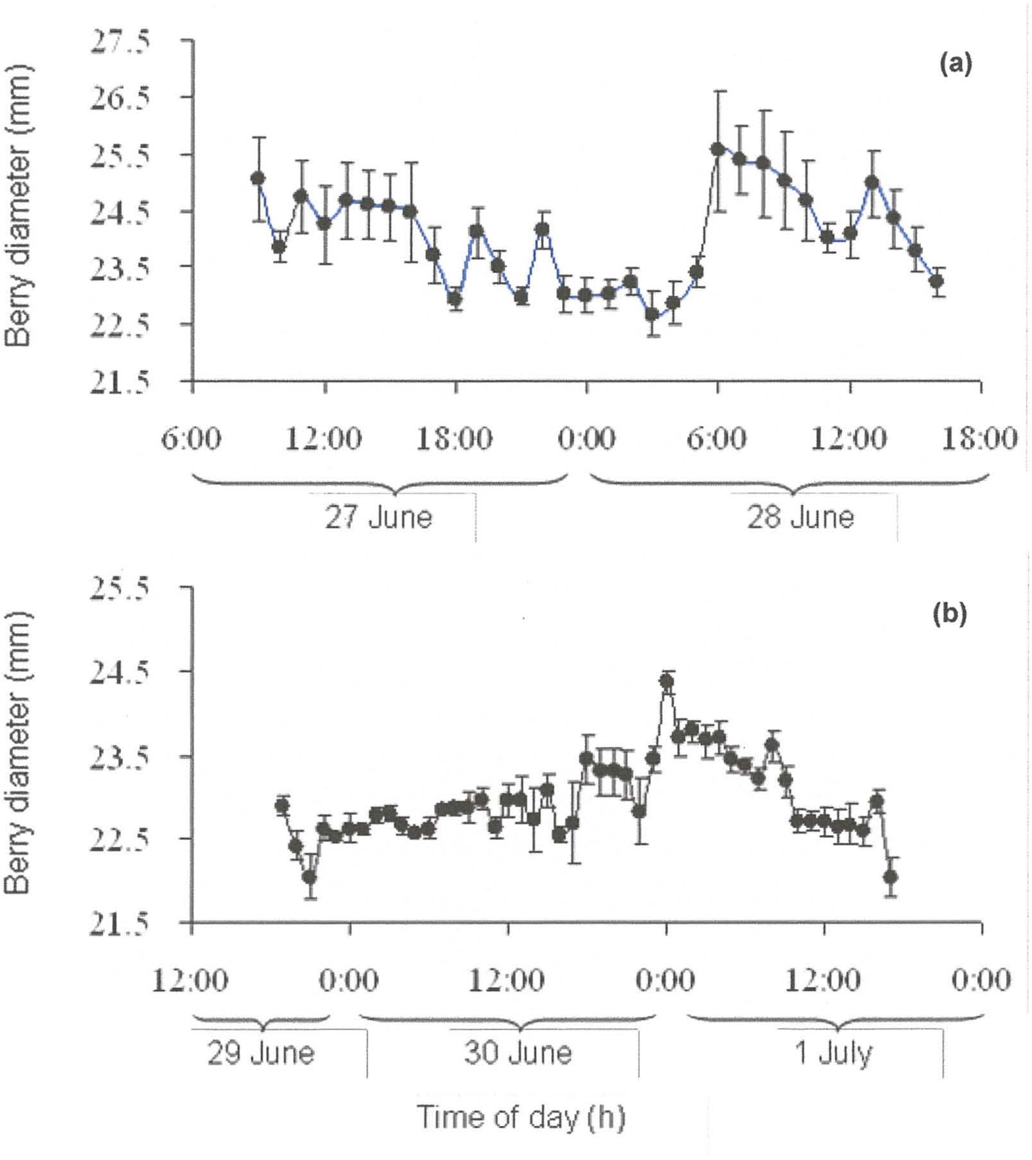


Fig. 5–4. Daily variation of berry size in a 2-year old Pione grapevine in berry-growth stage from 27 June to 28 June (A) and from 29 June to 1 July (B). Means ± SE ($n = 3$)

The diurnal changes in berry size (**Fig. 5–4**) reflected changes in radiation and temperature since the grapevine was placed in the growth chamber where temperature was set to 35 °C in the day of 12 h with the luminous intensity of 5000 μmol $m^{-2} s^{-1}$ while the night cycle of 12 h had temperature set to 20°C.

5.3.3. Relationship between berry size and ψ

The diurnal fluctuations in berry diameter time series data (from 29 June to 1 July) were removed by time series analysis, and the relation between the ψ at 10 cm soil depth and the trend value of berry diameter is shown in **Fig. 5–5**. After irrigation, the berry grew fast till the ψ at 10 cm depth reached –3 kPa. When ψ further decreased from –3 kPa to –5.4 kPa, the berry grew at a slower rate. When ψ decreased beyond –5.4 kPa, the berry started to contract. The absolute value of the slope for ψ-diameter relation curve during 29 June was higher than that during 30 June (**Fig. 5–5**), which indicates that the berry grew faster under the condition of high ψ. When ψ decreased beyond –5.4 kPa, there was a sharp linear decrease in berry size on 1 July (**Fig. 5–5**).

5.3.4. Relationship among ψ, photosynthesis and transpiration rate

Photosynthesis and transpiration rate were not much affected by changes in ψ as long as it did not decrease beyond –9.3 kPa (**Table 5–1**). When ψ reached –9.3 kPa, a significant decrease occurred in photosynthesis. When ψ decreased further (from –10.2 kPa to –13.6 kPa), there was a further significant decrease in photosynthesis. When ψ reached –10.2 kPa, a significant decrease occurred in transpiration.

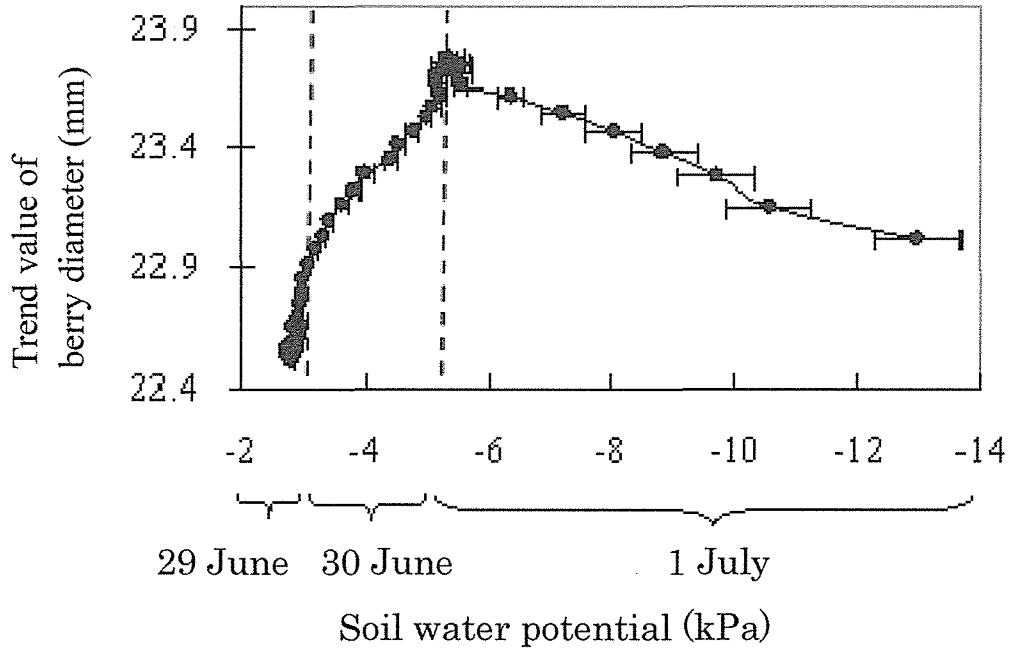


Fig. 5–5. Effect of soil water potential (ψ) (10 cm soil depth) on the trend value of berry diameter. Means ± SE ($n = 6$).

5.4 Discussion

The diameter of grape berry tended to increase during night and decrease during daytime (**Fig. 5–4**) as also reported by Coombe and Bishop (1980), Imai et al. (1991b) and Greenspan et al. (1994), Greenspan et al. (1994) reported that under growth chamber conditions in the Stage 1 of berry development, virtually all berry growth occurred during the night; day periods were characterized by either contraction or absence of expansion.

Irrigation in vineyards is generally scheduled based on either an arbitrarily fixed soil moisture potential as measured by tensiometers or the estimated cumulative crop evapotranspiration (Araujo et al., 1995). The central importance of ψ in irrigation management arises from the fact that differences in water potential between soil and plant provide the driving force for water movement and therefore determine the direction of water flow (Jones and Tardieu, 1998). Applying water at higher ψ value would result in wasteful use (Bowen and Frey, 2002). Under arid and semiarid conditions, water availability plays a main role in regulation of berry growth and sugar accumulation in vines. As shown by Poni et al. (2009), vines subjected to stress by allowing soil-drying for half of the root system improved the composition of grapes in terms of soluble solids and anthocyanin content, without significant change in yield, and this was attributed to earlier shoot growth cessation, enhanced maturity and a leaf to fruit ratio that mitigated the effect of post-veraison stress. However, if ψ is too low, the fresh and dry matter yield of grape would also decrease because of a decrease in the supply of photosynthates due to decreased photosynthesis. Ennahli and Earl (2005) also demonstrated that water stress reduced berry growth and photosynthesis, and Resco et al. (2009) reported that excess water stress even constrained photosynthetic recovery after re-watering. McCarthy (1997b) showed that withholding irrigation for about three weeks after anthesis resulted in a 30% reduction in berry weight compared to fully irrigated grapevines. During most of the contraction of pre-veraison berries, xylem vascular inflow was nil, while water was lost via berry transpiration and backflow from xylem since xylem conduction could be in both directions (Greenspan et al., 1994). It is therefore, necessary to establish only that degree of soil moisture stress which would allow optimizing the combination of yield and berry quality in each situation whilst enhancing the productivity of irrigation water (Santesteban and Royo, 2006). It is in this context that the determination of threshold soil moisture potential for irrigation, as attempted in our studies, becomes important.

Imai et al. (1991a) indicated that the increase in berry size was more rapid in vines watered at $\psi = -3.1$ kPa than in those watered at $\psi = -15.8$ kPa until seed-hardening. Because they only tested two levels of soil water potential, they could not point out the threshold ψ after which the berry would begin contraction. Imai et al. (1991b) sought the relation between ψ and grape berry growth measured by a displacement sensor with rubber string. However, the critical ψ again could not be determined in their study because they measured the ψ starting from about –6 kPa going to –50 kPa. Continuous monitoring of ψ and berry size would provide the early detection of water stress that would be useful for on-line fine-tuning of irrigation regime. In our experiment, we measured instantaneous changes in ψ and berry diameter continuously after saturated irrigation (**Fig. 5–3** and **5–5**), so it was possible to establish this critical ψ for scheduling irrigation. The berry growth continued at fast rate when ψ was above –3 kPa. When ψ further decreased from –3 kPa to –5.4 kPa, the berry grew at a slower rate. When ψ decreased beyond –5.4 kPa, the berry started to contract. It is clear from these results that for scheduling irrigation in grapevines the critical ψ in the active root zone in the last phase of berry development Stage 1 should therefore be –5.4 kPa (**Fig. 5–5**).

It is interesting that decrease in ψ up to –9.3 kPa had no significant effect on the photosynthesis in grapevine while the berry size started showing a shrinkage as the ψ became –5.4 kPa. A significant reduction in the photosynthesis only occurred when ψ reached a value of –9.3 kPa, whereas the berry size showed a linear reduction when ψ decreased from –5.4 kPa to –13 kPa. Therefore, berry size was more sensitive to moisture stress than photosynthesis in grapevine, and thus a better indicator of the soil moisture stress for irrigation scheduling purpose. Bota et al. (2004) showed that limitation to photosynthesis in five C_3 species, including *Vitis vinifera,* by decreased Rubisco activity and RuBP content did not occur until drought was very severe. Primary events of photosynthesis such as the electron transport capacity are very resilient to drought (Cornic et al., 1989; Epron and Dreyer, 1992). Sousa et al. (2005) indicated that sap flow, leaf water potential and leaf transpiration rate in grapevine measured at solar noon had highly significant correlations with soil water content. In our study, berry size was more sensitive to water stress (**Fig. 5–5**) than photosynthesis and transpiration rate (**Table 5–1**), and this could be related to the fact that water deficits during Stage 1 of fruit growth reduced berry size by reducing cell division (Prichard et al., 2004). Continuous monitoring of berry size provided the early detection of water would be useful for on-line fine-tuning of irrigation regime by growers.

Although some growers may prefer a high berry yield, others prefer a high quality product that might require introducing some water stress by partial root zone drying and deficit irrigation. Based on our results on the relationship between ψ at 10 cm soil depth and berry growth, the following suggestions are made for appropriate irrigation under various scenarios in the last phase of berry development Stage 1:

(1) In areas where water availability is low or moderate, the critical point for scheduling irrigation during berry-growth phase should be approximately –5.4 kPa, as this will permit substantial water saving than irrigation scheduled at higher ψ. Because the grape berry contracted in size when the ψ decreased beyond –5.4 kPa (**Fig. 5–5**), the upper limit of soil drying is regarded as approximately –5.4 kPa.

(2) In hyper-arid and arid areas, irrigation water is very scarce and should be used even more economically. In this case, it is possible to set the critical irrigation point lower than –5.4 kPa, because photosynthesis did not decrease rapidly when ψ decreased up to –9.3 kPa (**Table 5–1**). However, permitting development of severe moisture stress might affect the yield, as shown by Hardie and Considine (1976) and Hardie et al. (1981). Therefore, further studies should be done to determine the proper ψ to ensure that any reduction in the economic yield is acceptable in light of the improvement in water use efficiency under drylands.

(3) In the humid and semi-humid areas, a full irrigation strategy with no water stress for vines can be carried out. The critical soil water potential for scheduling irrigation should be –3 kPa (**Fig. 5–5**), as this would permit maximization of berry yield. Some farmers indeed prefer to produce high quantities of berries, such as those who plant grapevines for table grapes sold by weight. There is often a marked premium in ensuring that water content is maximized, whilst ensuring that produce quality does not suffer (Jones and Tardieu, 1998). However, too much water may cause excess growth of shoot and leaf at the expense of economic yield.

Since the water demand for vines in various growth stages is not uniform and drought has different effect on fruit development at different stages, further experiments should be conducted to establish critical irrigation values in various growth stages. In addition, further test should be done under open-field conditions.

5.5 Conclusions

Establishing a critical value of soil water potential for scheduling irrigation is essential for grapevine production in arid and semiarid areas. This critical value for irrigation in the last phase (last week) of berry development Stage 1 was determined by instantaneous measurement of berry size by photogrammetry and soil water potential by tensiometers simultaneously during a drying cycle after irrigation, and establishment of the relationship between these two factors. Berry diameter tended to increase at night and decrease in the day, and the trend value demonstrated sensitivity to developing soil moisture stress in the root zone. Berry diameter increased rapidly after irrigation till ψ became –3 kPa. In the ψ range of –3 kPa to –5.4 kPa, the rate of growth started decreasing, and as ψ decreased beyond –5.4 kPa, berry diameter started shrinking and the shrinkage showed a strong linear relationship with decreasing ψ. In contrast, photosynthesis and transpiration rate remained unaffected by decreasing ψ until it became –9.3 kPa beyond which photosynthesis decreased significantly. Thus, berry diameter was a better indicator than photosynthesis of developing moisture stress in grapevines in the last phase (last week) of berry development Stage 1 and based on this attribute –5.4 kPa should be considered as the threshold ψ for scheduling irrigation in this important stage of economic yield development in grapevines to get cost-effective use of water resources. However, this threshold ψ should not be recommended directly in other stages (including the ripening stage) of grapevines growth because the growth characteristics and water demand are quite different in various growth stages. Therefore, further experiments are needed to establish the soil water potential threshold during the ripening stage for grapevines.

Chapter 6 Establishment of soil water potential threshold for irrigating grapevines during berry ripening based on leaf photosynthesis and photogrammetry technology

6.1 Introduction

The problem of water scarcity is going to get further aggravated with climate change, which is also likely to affect the quality of grapes/wine and thus the overall economics of grape production (Santos et al., 2007). In the drylands of northwest China, grape production is vital for local farmer's life and economic development, but its sustainability is threatened by unreliable water resources (Du et al., 2005). Therefore, improving the efficiency of irrigation is essential for long-term sustainability of grape production and the wine industry.

Deficit irrigation in fruit crops can be of value in increasing fruit quality by raising dry matter and sugar content (Chalmers et al., 1981). The potential for water saving by water-use-efficient irrigation and deficit irrigation in orchard crops has remained unexplored so far (Fereres et al., 2003). It is, therefore, important to determine the critical timing for starting irrigation, especially in drylands where drought represents a serious threat to the sustainability of agriculture (Konukcu et al., 2005).

Overall, the berry development of grapevine follows a double sigmoidal shape with a strong increase in diameter early (Stage 1), a slower lag phase (Stage 2), and a rapid growth from veraison (Stage 3) which then gradually slows down (Coombe and McCarthy, 2000; Chatelet et al., 2008). The third period of growth (Stage 3) lasts from véraison to harvest (Kennedy, 2002a). Fruit ripening is characterized by softening and coloring of the berry. Overall, the berry approximately doubles in size between the beginning of the third growth period and harvest. The phloem becomes the primary source of ingress after véraison (Kennedy, 2002a). The berry development is the most critical for economic yield as fruit size at harvest is an important aspect of the quality of the fruit (Zhang et al., 2005).

The growth characteristics and water demand are quite different in various growth stages. Imai et al. (1991b) showed that the grape berry diameter contracted when ψ decreased from –12.6 to –63.1 kPa during the maturation stage. They further reported that daily variation in berry diameter might be a useful index for soil moisture control in grape production. However, the critical ψ beyond which the berry contracted most obviously during maturation stage could not be determined clearly and sufficiently in their study because they did not measure any other data of ψ between –12.6 kPa and –63.1 kPa. These authors concluded that in the ripening stage, berry size is affected conspicuously by decreasing ψ. However, McCarthy (2000) reported that moisture deficit after veraison had only a minor effect on grape berry weight at maturity and berries were insensitive to water deficit in the month before harvest (McCarthy, 1997a). The maturation stage is critical for grape berry quality. In the maturation stage, is the berry size sensitive to decreasing ψ? Cifre et al. (2005) reported that stomatal conductance (g_s), sap flow and trunk growth variations could be used as indicators of water stress for grapevine. During the maturation stage of grapevine, which kind of physiological parameter is useful and suitable for irrigation management? Further studies should be done to clear these questions for scheduling irrigation in the maturation stage of grapevine.

There are many studies on the effects of various irrigation regimes on vine growth (Poni et al., 1994; Esteban et al., 2001; Reynolds et al., 2005). However, what is the threshold ψ at which the grapevine must be irrigated during the maturation stage is not clear. This information is critical to optimize water use, prevent nutrient loss and improve yield and quality of grapes.

We hypothesize that this value could be established by measuring diurnal variations in berry size and a few physiological parameters of grapevine experiencing increasing soil moisture stress. It is, however, necessary that the measurement of berry size is made with great precision for berry diameter because the changes are rather small.

A new system equipped with automated photogrammetry was developed by Moritani et al. (2006; 2007) to measure soil erosion (Pyle and Richards, 1997). This system consists of two high-precision digital cameras, attached to a computer with an image-analysis program of three-dimensional algorithm. This system can also be applied for measuring fruit size with three major advantages. First, the measurement precision is high. Second, the berry diameter can be monitored automatically. Third, the determination is nondestructive.

The goal of this study was to establish the critical soil water potential value for starting irrigation of grapevines during the maturation stage by examining instantaneous variations in photosynthesis (A_N), stomatal conductance, berry diameter, and soil water potential, as the water deficit developed in the soil.

6.2 Materials and methods

6.2.1. Plant and soil materials

On 25 February 2008, 2-year-old Pione grapevines (*Vitis vinifera* L., cv. *V. labrasca)* were transplanted into 34-liter capacity horticultural pots in a greenhouse under natural conditions of temperature, light and humidity. Each pot (39 cm surface diameter, 32 cm depth) contained 28 kg of a mixture of sandy soil (sieved through a 2-mm sieve), peat moss, humic allophone soil and lime in a volumetric ratio of 1200 : 600 : 200 : 1, respectively. The mixture was placed on a 2 cm thick layer of microvesicular pumice to allow free drainage. The mixture had a pH of 6.2. The pots were irrigated with an automatically timed drip irrigation system to ensure optimum moisture regime for the vines. Four emitters per vine were located approximately 10 cm from the trunk. The amount of water applied was controlled by a time clock-solenoid valve assembly. The irrigation amounts for March, April, May, June, July and August were 2.4, 3.2, 4.5, 6.0, 7.5 and 8.5 L per pot per week, respectively. The plants were provided liquid fertilizer containing all essential mineral nutrients (Wang et al., 2001; Thippayarugs et al., 2002) once every week.

To encourage uniform vegetative growth, vines were pruned to retain 12 nodes per vine; only two shoots per vine were left and were trained horizontally. Shoots were trimmed twice between bloom and the veraison stage of the berries. Lateral shoots were cut back to the first node. At flowering, one cluster was left on each of the two shoots. Each cluster was trimmed to retain only 200–250 florets and once berry-set occurred, further trimming was done to retain only 40–50 berries per cluster.

6.2.2. Experimental details

On 13 August (88 days after flowering), when the berries were in the maturation stage, a pot containing the grapevine was placed in a wind tunnel with a two-layers glass chamber (schematically illustrated in **Fig. 6–1**) in a glass dome building (called "Arid Dome") of the Arid Land Research Center, Tottori University, Tottori (35°15′ N, 133°47′ E), Japan. Natural solar radiation can pass through the glass dome. An artificial light source was set 50 cm higher than the top of the grapevine for supplying enough radiation energy. The diurnal artificial luminous intensity, relative humidity and air flow were set at 3000 μmol m^{-2} s^{-1}, 50% and 0.3 m s^{-1} respectively. The temperature was set to 12/12 h (day/night) cycles of 35/20 °C. These conditions are controlled.

After placement in the wind tunnel, the vine was irrigated to saturated condition. From then on till the end of this experiment no irrigation was applied and the vine experienced deceasing ψ for seven days. Soil water potential was measured every two hours by a pressure transducer system (Marthaler et al., 1983). The system consists of a pressure transducer with attached syringe needle, tensiometers and digital read-out. Twelve tensiometers were put in the pot, six at a depth of 10 cm and other six at a depth of 20 cm.

Berry diameter was monitored every hour by a new photogrammetry-system that consists of two digital cameras (Nikon D2H, 16,000 pixels) attached to a computer having an image analysis program of three-dimensional algorithm. The measurement precision of the system was 0.2 mm. Details of this system are described by Moritani et al. (2006).

A rectangular analytical frame with scale was fixed vertically on the grapevine and the grape cluster was placed inside the frame. Two marked berries and two digital cameras were oriented as shown in **Fig. 6–1** and these positions were fixed. Pictures taken by the pair of digital cameras were collected on a computer. The focal length (fc) and resolution of CCD (δccd) of the digital cameras were 50 mm and 0.0094 mm, respectively. The inner orientation factors of the digital cameras are given by Moritani et al. (2006). The relative orientation and gradient of the pair pictures were adjusted to minimize parallax to obtain a rectified photograph. Through rectification and elimination of longitudinal parallax, the *y*-coordinate of a point in the left rectified image was the same as that in the right one. The same point in the paired images could easily be searched by scrolling the point in the *x*-axis direction.

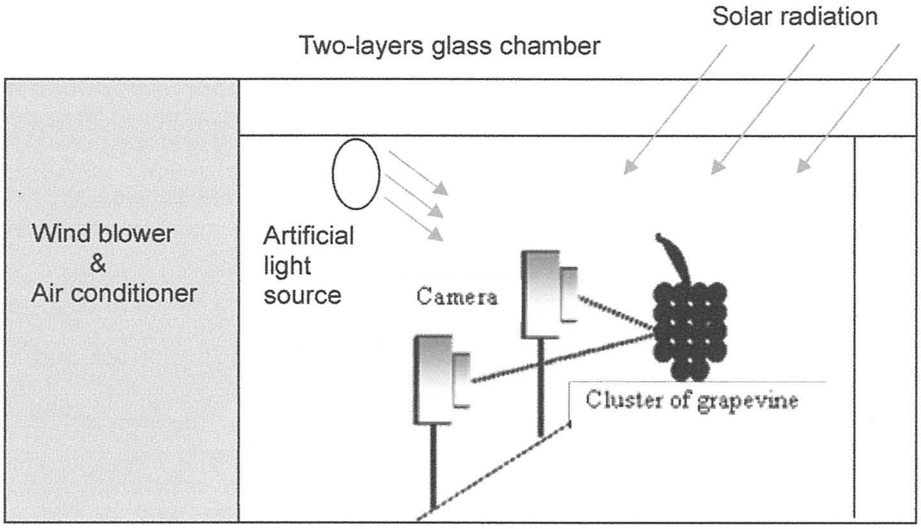


Fig. 6–1. Schematic illustration of experimental setup.

Net photosynthesis (A_N), stomatal conductance (g_s), transpiration (T), sub-stomatal CO_2 concentration (C_i) and leaf temperature of two healthy spur leaves of the grapevine were measured every two hours (from 7:00 to 23:00) per day, simultaneously with ψ measurements, using a portable photosynthesis system (LI-6400, Li-Cor Inc., Lincoln, NE, USA). Measurements were conducted on 2 cm × 3 cm leaf portion in the middle part of a leaf blade confined in the leaf chamber of the system. The measurements were repeated three times on each primary and lateral leaf.

6.2.3. Time series analysis of berry diameter data

As the berry diameter showed diurnal variations over the study period, it was necessary to remove the periodic fluctuations by time series analysis (Box et al., 1994; Moran et al., 2009). Periodic fluctuation of berry diameter was filtered by quartic polynomial trend line, and the main secular growth trend part was thus obtained. It was then possible to establish the relationship between the tendency part of berry diameter and soil water potential in the root zone. An example of determining the trend line of the time series of diameter of Berry No. 2 from 17 August to 19 August is given in **Fig. 6–2**. Time-series berry diameter measurements were available for 48 hours. The trend line in this figure can help us to remove short-term fluctuations in the time series of berry size. The trend values of berry diameter were computed as

$$y_i = 32.267 - 0.0546\, x_i - 0.0032\, x_i^2 + 0.0003\, x_i^3 - 0.000006\, x_i^4,\ r^2 = 0.41,\ N = 48$$

where x_i is the berry diameter measurement time (i$^{\text{th}}$ hour), y_i is the trend value of berry diameter (mm) at i$^{\text{th}}$ hour, and N is the total hours of measurement in this figure.

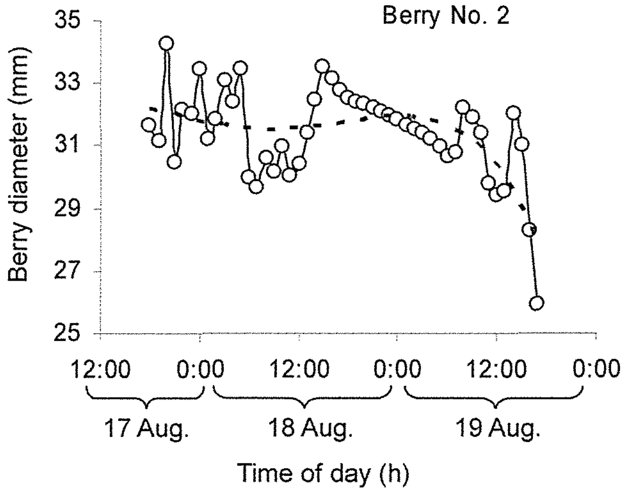


Fig. 6–2. Diurnal variations in a time series of diameter for Berry No. 2 from Aug. 17 to Aug. 19. The solid line represents measured berry diameter, and the dashed line represents the trend line.

6.2.4. Statistical analysis

Values of ψ, A_N, g_s and T for each replicate were averaged for daily variation of these parameters before the mean and the standard error were calculated.

6.3 Results

6.3.1. Effect of soil water potential (ψ) on the trend value of berry diameter

The diurnal fluctuations in berry diameter time series data (17 August to 19 August) were removed by time series analysis, and the relation between the ψ at 10 cm soil depth and the trend value of berry diameter is shown in **Fig. 6–3**. The berry contracted very slowly when the ψ at 10 cm depth decreased from –9.6 kPa to –16.2 kPa. When ψ further decreased from –16.2 kPa to –16.4 kPa, the berry shrunk rapidly. When ψ decreased beyond –16.4 kPa, the berry also shrunk rapidly, but the rate was lower than that when ψ decreased from –16.2 kPa to –16.4 kPa. The differential of trend value of berry diameter on soil water potential ($dD/d\psi$) was highest when ψ decreased from –16.2 kPa to –16.4 kPa (**Fig. 6–3**), which also indicated that the berry shrunk fastest during that stage.

6.3.2. Daily variation of soil water potential, photosynthesis, stomatal conductance and transpiration

After irrigation in the morning of 13 August, the ψ decreased slowly during the first 3 days (**Fig. 6–4**), but started decreasing a little faster when it decreased to –6.2 kPa in the 10 cm soil depth. The trend for the change in ψ at the 10 cm and 20 cm soil depths was similar, although ψ in the 10 cm soil depth was lower than that in the 20 cm soil depth because of evaporative losses from the soil surface.

In the first five days, the highest values of photosynthesis and stomatal conductance occurred during daytime and the lowest values occurred during night (**Fig. 6–4**). Before ψ decreased to –13.2 kPa, A_N, g_s and T fluctuated in a normal range. However, when ψ decreased from –13.2 kPa to –14.7 kPa, A_N decreased from 7.1 to 0.38 μmol CO_2 m^{-2} s^{-1} for primary leaf. In addition, in the following 33 hours, A_N fluctuated in a low-value

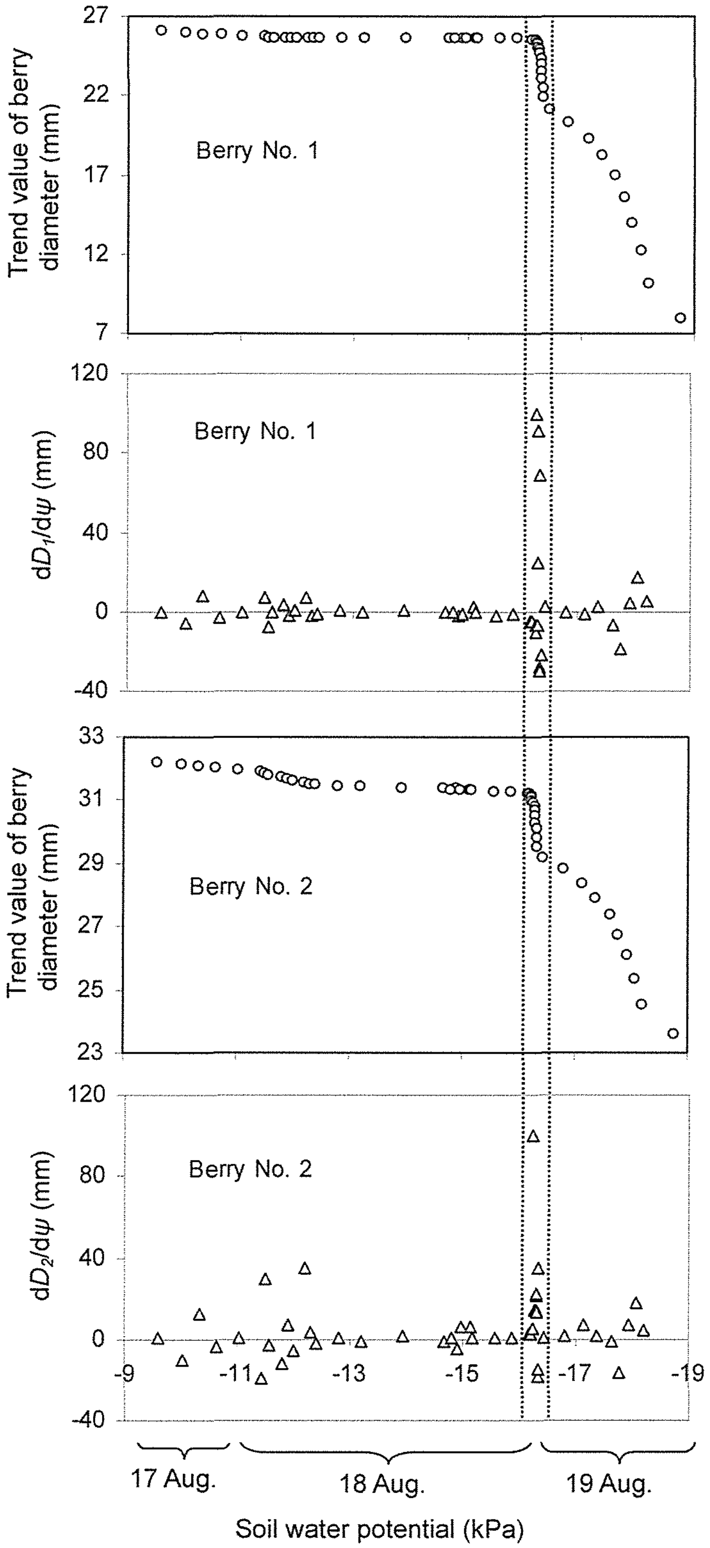


Fig. 6–3. Effect of soil water potential (ψ) (10 cm soil depth, n=6) on the trend value of berry diameter. $dD_1/d\psi$ and $dD_2/d\psi$ represent differential of trend value of berry diameter No.1 and No.2 on soil water potential.

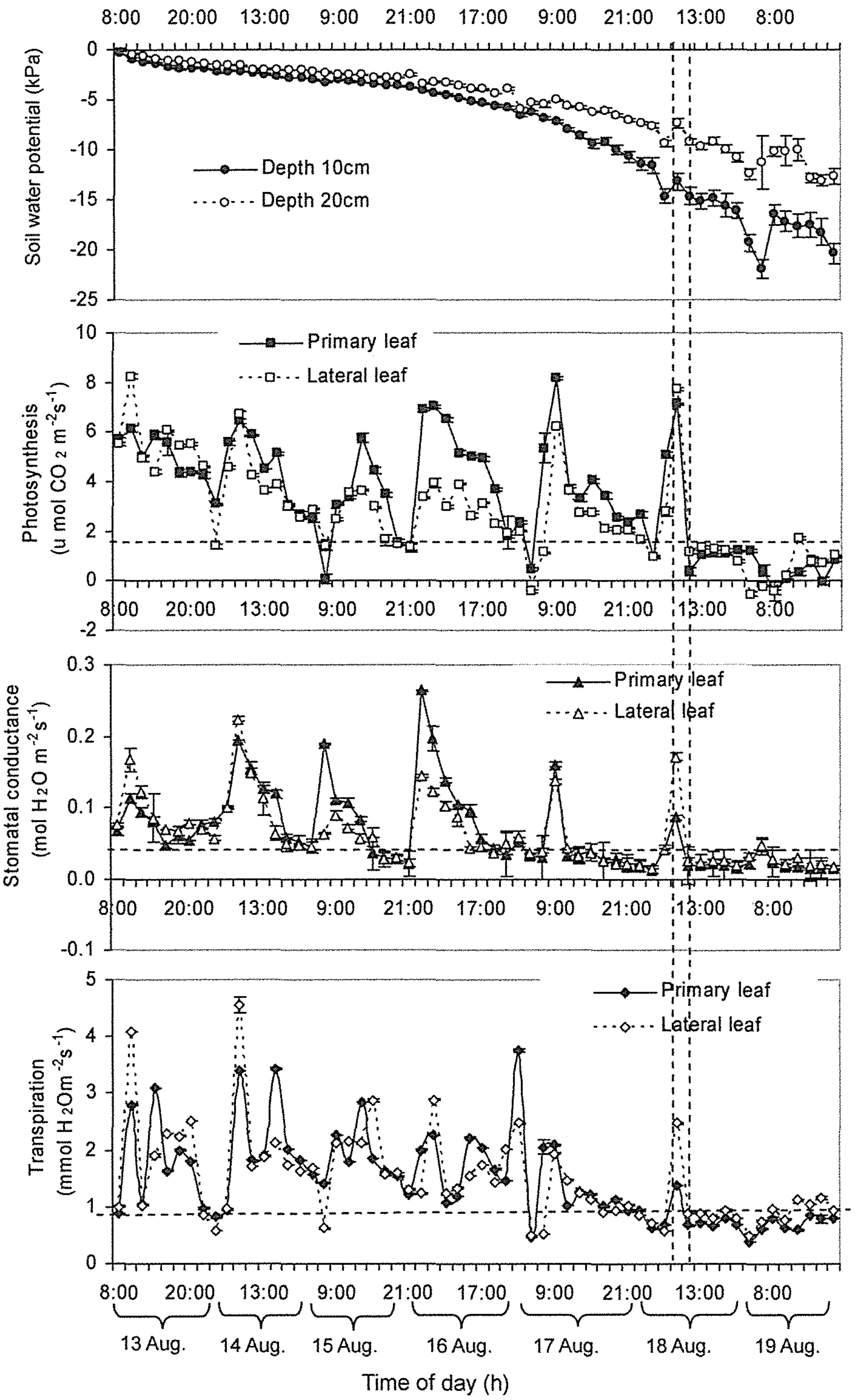


Fig. 6–4. Daily variation of soil water potential (ψ), photosynthesis, stomatal conductance (g_S) and transpiration (T) of grapevine from 13 to 19 August, 2008. Each symbol represents the average ± standard error (SE). There were six replicates of measurements for soil water potential, while three replications were measured for photosynthesis, stomatal conductance and transpiration.

range and did not recovery the high value as before. A_N for lateral leaf, g_s and T for primary and lateral leaf showed the similar trend.

6.3.3. Relationship among ψ, berry diameter and leaf physiological parameters

When ψ decreased from –6.9 to –14.6 kPa, the highest values of intrinsic *WUE* (A_N g_s^{-1} as μmol CO_2 mol H_2O^{-1}) of primary leaf of grapevine (in the morning) occurred (**Fig. 6–5 C**). Before ψ decreased to –14.6 kPa, A_N (in the morning) fluctuated in a range of 3.06 to 8.16 μmol CO_2 m^{-2} s^{-1} for primary leaf (**Fig. 6–5A**). When ψ decreased beyond –14.6 kPa, A_N decreased from 5.1 to 0.38 μmol CO_2 m^{-2} s^{-1} for primary leaf, and furthermore, A_N, extrinsic *WUE* (A_N T^1 as mmol CO_2 mol H_2O^{-1}) and intrinsic *WUE* (n=3) of primary leaf of grapevine (in the morning) decreased fast and could not recover the high value as before (**Fig. 6–5A, B** and **C**). When ψ reached –17.1 kPa, A_N, extrinsic and intrinsic *WUE* became near zero.

Relationship between leaf physiological parameters and berry growth of grapevine was shown in **Fig. 6–6**. When leaf transpiration (in the morning) decreased from 1.38 to 0.69 mmol H_2O m^{-2} s^{-1}, the trend value of berry diameter did not decrease significantly and keep a value of higher than 31 mm. However, the trend value of berry diameter decreased fast (lower than 30 mm) when T decreased beyond 0.69 mmol H_2O m^{-2} s^{-1} (**Fig. 6–4**).

The relationship among berry diameter and A_N, g_s, leaf temperature, intrinsic and extrinsic *WUE* of primary leaf of grapevine in the morning from 13 to 19 August, 2008 also showed the similar trend. When leaf temperature was too high, or A_N, T, g_s, intrinsic and extrinsic *WUE* were too low, the berry contracted obviously (**Fig. 6–6**).

A_N decreased with g_s (Fig. 6–7A) and their relation could be illustrated as

$$y = 2.36\ Ln\ (x) + 10.8,\ r^2 = 0.66,$$

where y is A_N, x is g_s of primary leaf of grapevine in the morning from 13 to 19 August, 2008. A significant decrease occurred in A_N (**Fig. 6–7A**) when g_s (in the morning) decreased from 0.03 to 0.02 mol H_2O m^{-2} s^{-1}, during which ψ reached –14.7 kPa (**Fig. 6–4**).

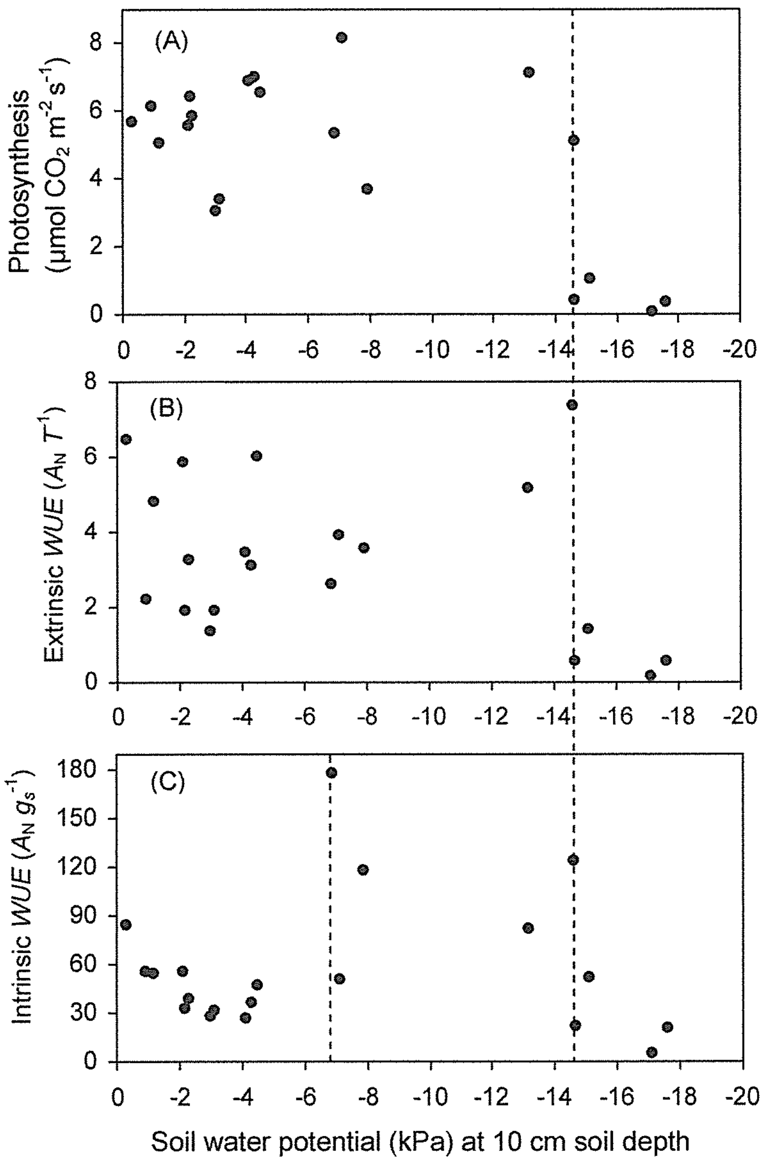


Fig. 6–5. Relationship among soil water potential (at 10 cm soil depth) (*n*=6), photosynthesis (A_N) (*n*=3), intrinsic *WUE* (A_N g_s^{-1} as μmol CO_2 mol H_2O^{-1}) and extrinsic *WUE* (A_N T^{-1} as mmol CO_2 mol H_2O^{-1}) (*n*=3) of primary leaf of grapevine in the morning from 13 to 19 August, 2008.

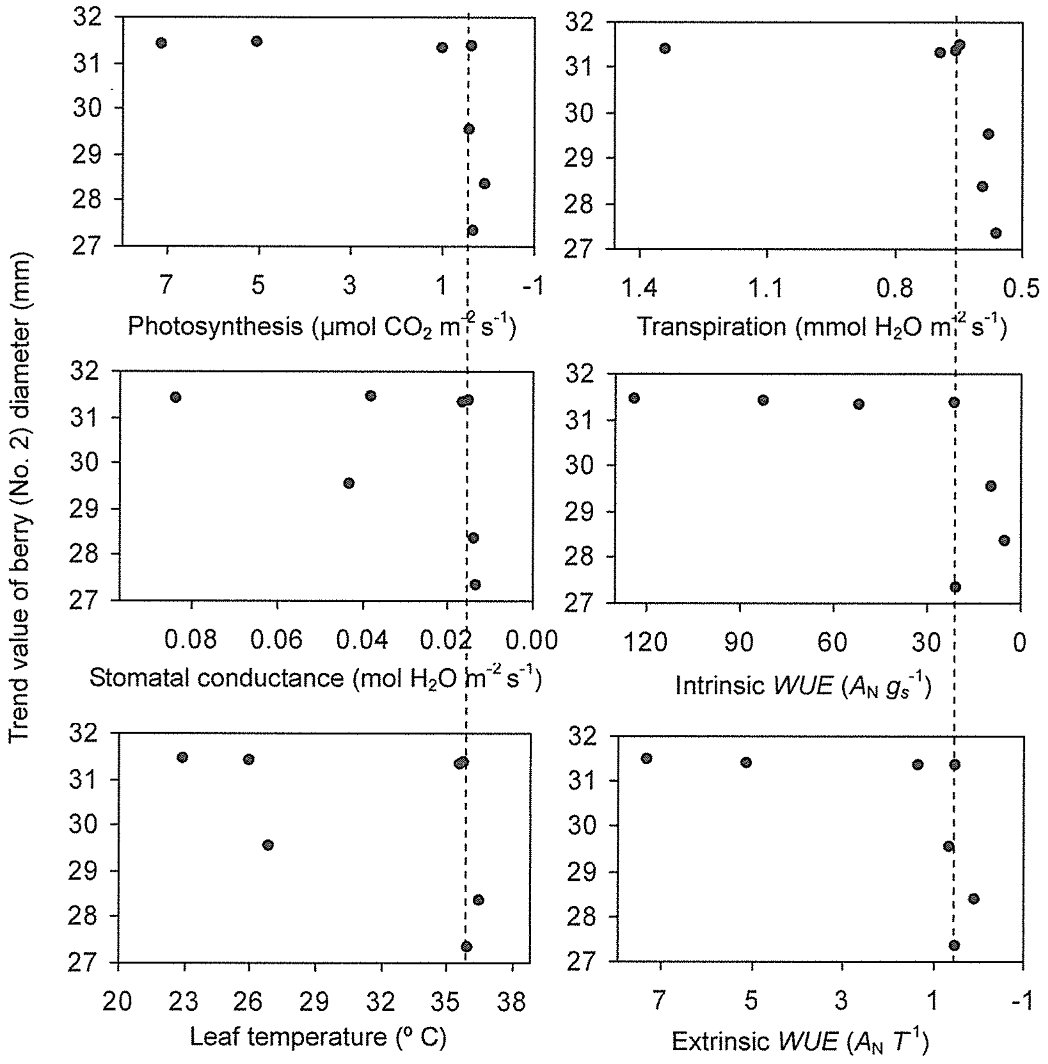


Fig. 6–6. Relationship between trend value of berry (No. 2) diameter and leaf photosynthesis (A_N), stomatal conductance (g_s), transpiration (T), leaf temperature, intrinsic *WUE* (A_N g_s^{-1} as μmol CO_2 mol H_2O^{-1}) and extrinsic *WUE* (A_N T^{-1} as mmol CO_2 mol H_2O^{-1}) of primary leaf of grapevine in the morning from 13 to 19 August, 2008. Values are vine means (n=3).

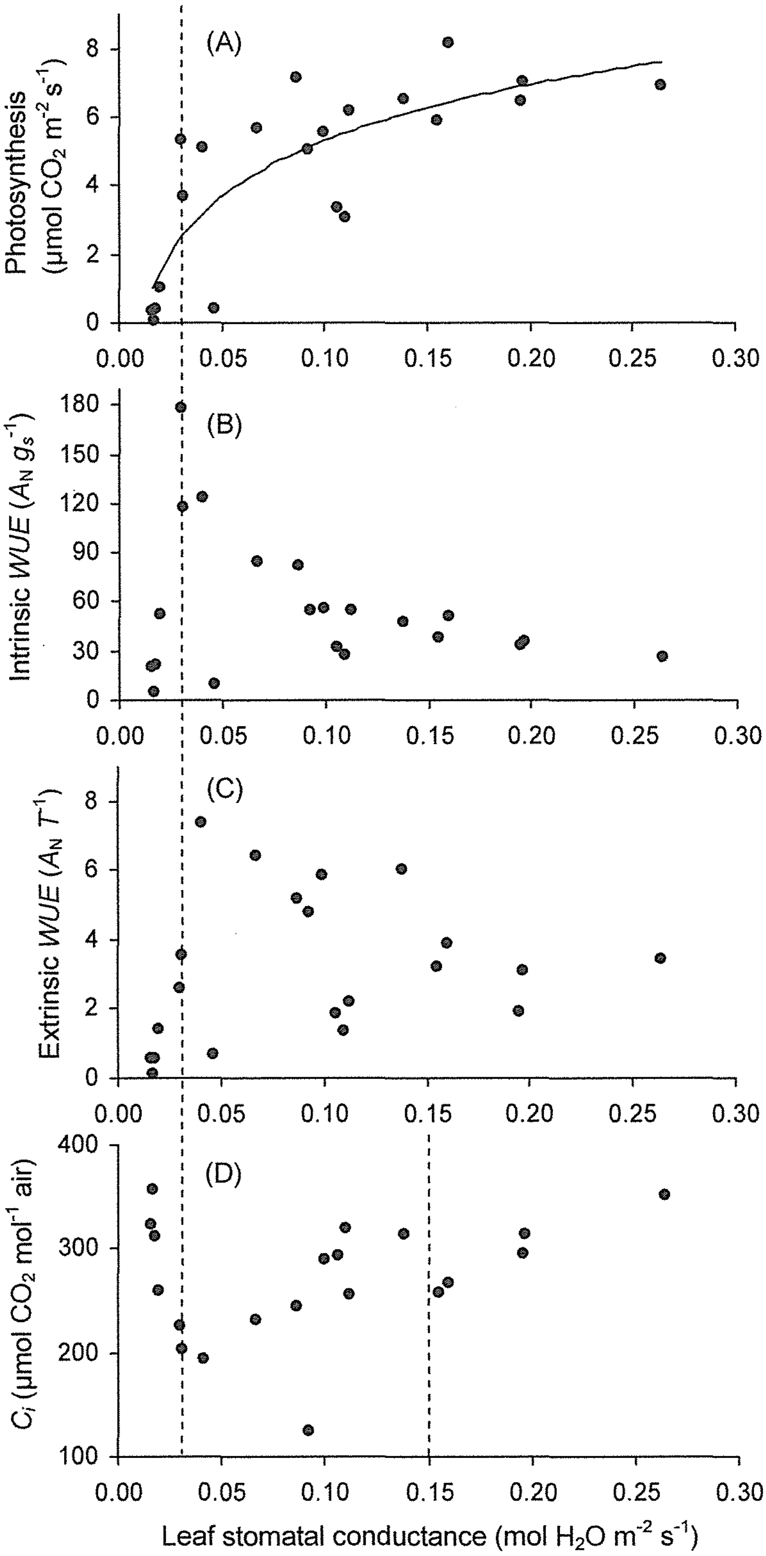


Fig. 6–7. Relationship between leaf stomatal conductance and leaf photosynthesis (A_N), intrinsic *WUE* ($A_N\ g_s^{-1}$ as µmol CO_2 mol H_2O^{-1}), extrinsic *WUE* ($A_N\ T^{-1}$ as mmol CO_2 mol H_2O^{-1}) and sub-stomatal CO_2 concentration (C_i) of primary leaf of grapevine in the morning from 13 to 19 August, 2008. Values are vine means (n=3).

When g_s (in the morning) decreased from 0.26 to 0.03 (or 0.04) mol H_2O m^{-2} s^{-1}, the intrinsic and extrinsic *WUE* increased (**Fig. 6–7 B** and **C**). Thereafter a significant decrease occurred in the intrinsic and extrinsic *WUE* (**Fig. 6–7 B** and **C**) when g_s (in the morning) decreased from 0.03 to 0.02 mol H_2O m^{-2} s^{-1}, during which ψ reached –14.7 kPa (**Fig. 6–4**). When g_s decreased to 0.017 mol H_2O m^{-2} s^{-1}, A_N, intrinsic and extrinsic *WUE* became almost zero (**Fig. 6–7 A, B** and **C**). C_i decreased for decreasing ranges of g_s (in the morning) from 0.26 to 0.15 mol H_2O m^{-2} s^{-1} and from 0.15 to 0.03 mol H_2O m^{-2} s^{-1}, whereas increased steeply when g_s decreased beyond 0.03 mol H_2O m^{-2} s^{-1} (**Fig. 6–7D**).

6.4 Discussion

The production of a good quality wine with a sufficient level of yield is dependent on the management of soil water in vineyards. Irrigation in vineyards is generally scheduled based on either soil moisture potential as measured by tensiometers or the accumulation of certain amount of estimated crop evapotranspiration (Araujo et al., 1995). The central importance of ψ in irrigation management arises from the fact that differences in water potential between soil and plant provide the driving force for water movement and therefore determine the direction of water flow (Jones and Tardieu, 1998). Applying water at higher ψ value would result in wasteful use (Bowen and Frey, 2002). Under arid and semiarid conditions, water availability plays a main role in regulation of berry growth and sugar accumulation in vines. As shown by Poni et al. (2009), vines subjected to stress by allowing soil-drying for half of the root system improved the composition of grapes in terms of soluble solids and anthocyanin content, without significant change in yield, and this was attributed to earlier shoot growth cessation, enhanced maturity and a leaf to fruit ratio that mitigated the effect of post-veraison stress. However, if ψ is too low, the fresh and dry matter yield of grape would also decrease because of a decrease in the supply of photosynthates due to decreased photosynthesis (**Fig. 6–4** and **Fig. 6–5**). Ennahli and Earl (2005) also demonstrated that water stress reduced berry growth and photosynthesis, and Resco et al. (2009) reported that excess water stress even constrained photosynthetic recovery after re-watering. It is therefore, necessary to establish a degree of soil moisture stress that would allow optimizing the combination of yield and berry quality in each situation whilst enhancing the productivity of irrigation water (Santesteban and Royo, 2006). It is in this context that the determination of threshold soil moisture potential for irrigation, as attempted in our studies, becomes important.

Physiologically based irrigation tools may attempt to maintain the plants at a limit between water stress and excess water consumption, thus making a rational use of irrigation water. This kind of irrigation may save water with respect to empirical irrigation, improving yield as compared with rainfed grapevines, and maintaining the high fruit quality (Cifre et al., 2005).

Imai et al. (1991a) indicated that the increase in berry size was more rapid in vines watered at ψ = –3.1 kPa than in those watered at ψ = –15.8 kPa until seed-hardening. Because they only tested two levels of soil water potential, they could not point out the critical ψ after which the berry would begin contraction. Imai et al. (1991b) sought the relation between ψ and grape berry growth measured by a displacement sensor with rubber string. They found that the berry diameter contracted when ψ decreased from –12.6 kPa to –63.1 kPa during the maturation stage. However, the critical ψ during maturation stage could not be determined clearly and sufficiently in their study because they did not measure any other data of ψ between –12.6 kPa and –63.1 kPa, so they did not state the accurate value of ψ beyond which the berry contracted most obviously. In our experiment, we measured instantaneous changes in ψ and berry diameter continuously, so it was possible to find this critical ψ for scheduling irrigation. The berry contracted very slowly when the ψ at 10 cm depth decreased from –9.6 kPa to –16.2 kPa (**Fig. 6–3**). When ψ further decreased from –16.2 kPa to –16.4 kPa, the berry shrunk fast. When ψ decreased beyond –16.4 kPa, the berry also shrunk fast, but the rate was lower than that when ψ decreased from –16.2 kPa to –16.4 kPa. The differential of trend value of berry diameter on soil water potential ($\mathrm{d}D/\mathrm{d}\psi$) was highest when ψ decreased from –16.2 kPa to –16.4 kPa (**Fig. 6–3**). Therefore, irrigation should be arranged no later than –16.2 kPa.

It is interesting that decrease in ψ up to –16.2 kPa had no significant effect on the berry size (**Fig. 6–3**) in grapevine while A_{N}, g_s and T started showing an obvious decline as the ψ decreased beyond –13.2 kPa (**Fig. 6–4**). In addition, in the following 33 hours, A_{N}, g_s and T fluctuated in a low-value range and did not recovery the high value as before

(**Fig. 6–4**). Therefore, A_N, g_s and T are more sensitive to moisture stress than berry size in grapevine during the maturation stage, this could be related to the fact that in maturation stage, the berry enlargement may correspond to the berry growth which is due mainly to the photosynthates accumulation and transformation (from leaf to fruit), and the berry growth probably does not caused by the swelling of fresh pulp that depends on the water status. Therefore, photosynthesis parameters (A_N, g_s and T) are thus better indicators of the soil moisture stress than berry size during the maturation stage of grapevine. Zsófi et al. (2009) and Cifre et al. (2005) also believed that g_s is a reliable tool for determining the degree of water stress. Schultz (2003) and Cifre et al. (2005) showed that tight stomatal closure occurred at relatively low soil water deficit in many grapevine cultivars, leading to a rapid reduction of g_s.

A_N is usually higher in the morning than in the afternoon. When ψ decreased beyond –14.6 kPa, A_N, extrinsic and intrinsic *WUE* (in the morning) decreased rapidly and could not recover the high value as before (**Fig. 6–5 A, B** and **C**). In addition, these parameters became near zero when ψ reached –17.1 kPa. Flexas et al. (2002) and Cifre et al. (2005) also reported that A_N and intrinsic *WUE* decreased steeply in the phase of severe water stress. A_N, T, g_s, intrinsic and extrinsic *WUE* had only slight effects on berry growth when they were relative high, whereas berry contracted steeply when these values were too low, during which ψ reached –14.7 kPa (**Fig. 6–4** and **6–6**).

The drought-induced, curvilinear correlation between g_s and A_N (**Fig. 6–7A**) is consistent with Koundouras et al. (2008). A_N decreased rapidly (**Fig. 6–7A**) when g_s decreased beyond 0.03 mol H_2O m^{-2} s^{-1}, during which ψ reached –14.7 kPa (**Fig. 6–4**).

Based on **Fig. 6–7**, three phases of photosynthesis response can be differentiated along a water stress gradient:

(1) A phase of severe water stress takes place when g_s is very low (< 0.03 mol H_2O m^{-2} s^{-1}). During this stress phase, A_N, intrinsic *WUE* (A_N g_s^{-1}) and extrinsic *WUE* decreased rapidly (**Fig. 6–7 A, B** and **C**), whereas C_i increased steeply (**Fig. 6–7 D**), indicating that non-stomatal limitations to photosynthesis become dominant. A similar response was found by Flexas et al. (2002) and Cifre et al. (2005) who reported this character when g_s < 0.05 mol H_2O m^{-2} s^{-1}. This value is a little higher than our data, which

could be related to different grapevine cultivars. Bota et al. (2004) showed that limitation to photosynthesis in five C_3 species, including *Vitis vinifera,* by decreased Rubisco activity and RuBP content did not occur until drought was very severe. Primary events of photosynthesis such as the electron transport capacity are very resilient to drought (Cornic et al., 1989; Epron and Dreyer, 1992). When $g_s < 0.05$ mol H_2O m^{-2} s^{-1}, a general decline in the activity and amount of photosynthetic enzymes is observed (Maroco et al., 2002) and A_N did not recover after irrigation (Quick et al., 1992), indicating that non-stomatal inhibition (metabolic and/or restricted internal CO_2 diffusion) occurred. In addition, our data showed that when g_s decreased beyond 0.03 mol H_2O m^{-2} s^{-1} (corresponding to –14.7 kPa, as shown in **Fig. 6–4**), *T* also decreased rapidly and could not recover. Besides the decrease of *T*, the ratio of A_N T^{1} also decreased (**Fig. 6–7 C**), maintaining the thylakoid electron transport rate (*ETR*) high relative to A_N (Flexas et al., 2002). The curvilinear relationship between g_s and A_N (**Fig. 6–7A**) implies a more sensitive response of A_N to water limitation compared to g_s at the last stage of soil drying, leading to a decrease in A_N g_s^{-1} (**Fig. 6–7 B**), i.e. a decline of carbon assimilation in relation to water supply.

(2) A phase of moderate water stress is defined for a decreasing range of g_s from 0.15 to 0.03 mol H_2O m^{-2} s^{-1}. In this phase, A_N and C_i decreased (**Fig. 6–7 A** and **D**), while extrinsic and intrinsic *WUE* usually increased (**Fig. 6–7 B** and **C**). Flexas et al. (2002) and Cifre et al. (2005) showed the similar phenomenon during intermediate g_s values ($0.15 > g_s > 0.05$ mol H_2O m^{-2} s^{-1}). Zsófi et al. (2009) reported that improved wine quality of grapevine was due to moderate water stress which induced higher concentration of anthocyanins and phenolics in the berries. During this phase, the activity of photosynthetic enzymes, such as Rubisco, is mostly unaffected (Cifre et al. 2005; but see Maroco et al., 2002). Therefore, in this phase, stomatal limitations seem dominant and photosynthesis is rapidly reversed upon rewatering (Flexas et al., 1999), but non-stomatal limitations are already developing (Maroco et al., 2002; Cifre et al. 2005).

(3) A mild water stress phase is characterized by relative high values of g_s (> 0.15 mol H_2O m^{-2} s^{-1}). During this phase, A_N decreased slightly, which results in small increases of intrinsic and extrinsic *WUE* (**Fig. 6–7 A, B** and **C**). A decline of C_i also occurred

(**Fig. 6–7 D**). These characters are consistent with Flexas et al. (2002). At this stage, stomatal closure is probably the only limitation to photosynthesis (Cifre et al. 2005).

During phase (2) and phase (3), i.e. g_s is higher than 0.03 mol H_2O m^{-2} s^{-1}, or ψ is larger than –14.7 kPa, the curvilinear relationship between g_s and A_N (**Fig. 6–7 A**) implies a less sensitive response of A_N to water limitation compared to g_s at the first stages of soil drying, leading to an increase in A_N g_s^{-1} (**Fig. 6–7 B**), i.e. a near optimization of carbon assimilation in relation to water supply (Chaves et al., 2002; Koundouras et al. 2008).

Although some growers may prefer a high berry yield, others prefer a high quality product that might require introducing some water stress by partial root zone drying and deficit irrigation. Based on our results, the following suggestions are made for appropriate irrigation during the ripening stage of grapevines:

(1) In areas where water availability is low or moderate, the critical soil water potential range for scheduling irrigation should be between –13.2 and –14.7 kPa (corresponding to g_s range of 0.09 ~ 0.03 mol H_2O m^{-2} s^{-1}), because A_N, g_s, T, extrinsic and intrinsic *WUE* decreased steeply in the phase of severe water stress (when ψ decreased beyond this range). Furthermore, this will permit substantial water saving than irrigation scheduled at higher ψ. After irrigation, ψ should be kept lower than –6.9 kPa because the highest values of intrinsic *WUE* occurred when ψ decreased from –6.9 to –14.6 kPa. A higher intrinsic *WUE* is in agreement with a higher biomass production for grapevines (Stamatiadis et al., 2007). Some farmers indeed prefer to produce high quantities of berries, such as those who plant grapevines for table grapes sold by weight.

(2) In hyper-arid and arid areas, irrigation water is very scarce and should be used even more economically. The critical point for scheduling irrigation should be approximately –16.2 kPa (corresponding to g_s value of 0.02 mol H_2O m^{-2} s^{-1}), because the grape berry contracted in size steeply when the ψ decreased beyond –16.2 kPa, the upper limit of soil drying is regarded as –16.2 kPa. Although permitting development of severe moisture stress in this case might affect the yield, as shown by Hardie et al. (1981), the limitations to grape yield are a common practice (if not compulsory) for a

market standard wine production and premium wines (Cifre et al. 2005).

Since the water demand for vines in various growth stages is not uniform, further experiments should be conducted to establish critical irrigation values in various growth stages. Our results provide useful information for irrigation management of vines during the maturation stage that could be adopted by growers under different water resource availability scenarios.

6.5 Conclusions

Establishing a critical value of soil water potential for scheduling irrigation is essential for grapevine production in drylands. This critical value for irrigation during the ripening stage was determined by instantaneous measurement of berry size by photogrammetry, photosynthesis by photosynthesis system and soil water potential by tensiometers simultaneously during a drying cycle after irrigation, and establishment of the relationship among these factors. When ψ decreased from –13.2 kPa to –14.7 kPa, A_N, g_s, T, extrinsic and intrinsic *WUE* decreased rapidly and did not recovery thereafter. In contrast, the berry size remained almost unaffected by decreasing ψ until it became –16.2 kPa beyond which the berry shrunk significantly. Thus, photosynthesis response was more sensitive to water stress than berry size during the maturation stage of grapevine. When $g_s < 0.03$ mol H_2O m^{-2} s^{-1} (corresponding to –14.7 kPa), A_N, intrinsic and extrinsic *WUE* decreased rapidly, whereas C_i increased steeply, indicating that non-stomatal limitations to photosynthesis become dominant. A more sensitive response of A_N to water limitation compared to g_s at the last stage of soil drying led to a decrease in A_N g_s^{-1}. When $g_s > 0.03$ mol H_2O m^{-2} s^{-1}, A_N and C_i decreased, while extrinsic and intrinsic *WUE* usually increased. Therefore, stomatal limitations seem dominant in this stage. A less sensitive response of A_N to water limitation compared to g_s at the first stages of soil drying led to an increase in A_N g_s^{-1}.

Based on these results, the following suggestions are made for appropriate irrigation during the ripening stage of grapevines. In areas where water availability is low or moderate, the critical soil water potential range for scheduling irrigation should be between –13.2 and –14.7 kPa (corresponding to g_s range of 0.09 ~ 0.03 mol H_2O m^{-2} s^{-1}). After irrigation, ψ should be kept lower than –6.9 kPa because the highest values of intrinsic *WUE* occurred when ψ decreased from –6.9 to –14.6 kPa. In hyper-arid and arid areas, the threshold ψ for scheduling irrigation should be considered as –16.2 kPa (corresponding to g_s value of 0.02 mol H_2O m^{-2} s^{-1}) in this important stage of economic yield development and fruit quality in grapevines to get cost-effective use of water resources. However, it should be mentioned that this threshold ψ could not be recommended directly in other stages of grapevines growth because the growth characteristics and water demand are quite different in various growth stages. Therefore, further experiments are needed to establish the soil water potential threshold during other growth stages of grapevines.

Chapter 7 General conclusions

Water is the most limiting resource in drylands. Improvements in water use efficiency (*WUE*) of crops are essential under the scenarios of water scarcity. Application of mulch, sub-surface irrigation and irrigation scheduling are effective in reducing soil evaporation and saving water.

Soil water content, salt level of soil, plant biomass and water use efficiency of Swiss chard were profoundly influenced by mulching and saline water. Mulching of soils significantly reduced the *ET* and accumulation of salts in the topsoil of the pots. The mulching practice improved soil water content, crop biomass yield and *WUE*. The soil temperature was slightly increased with the application of mulches during the winter season. The averaged soil temperature at the depth of 5 cm under gravel mulch was enhanced by 1.2 °C as compared to no-mulch. The enhancement of soil temperature by mulch in 5 cm depth was more than 10 cm depth. Among the mulches gravel mulch followed by pine-needles mulch proved to be effective especially under high saline conditions during this short-term experiment (about 3 months). Ultimately the crop performance was ameliorated under saline conditions. The mulch induced higher plant growth may provide an opportunity for the safe use of saline water. The long-term experiments, field and/or laboratory, are needed to assess the impact of saline water use under mulching on evaporation and salinity interrelation for the sustainability of agriculture. The comprehensive understanding also necessitates that we continue to strive for systems that are efficient in their use of water and nutrients in arid and semi-arid areas.

A long-term experiment (more than half year) using large weighing lysimeters was conducted to further evaluate the conjunctive effects of mulching and saline irrigation. Both gravel mulch (G) and rice-straw mulch (R) could reduce salt accumulation when diluted seawater irrigation was used for irrigation. Compared with control, the $EC_{1:5}$ of soil under mulches was nearly 38% lesser. The *ET* was 26% lesser under G and 13% lesser under R than under control. On the other hand, the fresh and dry yields were, respectively, 76% and 113% higher under R and 49% and 64% higher under G than under control. Therefore, the *WUE* increased by 143% under R and 120% under G as compared with control treatment. Monitoring of hourly change of cumulative *ET* over three days period when no irrigation was given, indicated that there was small adsorption of water from the atmosphere by the R during the relatively cooler hours of the day, and this could be very useful for crop growth in the arid and semi-arid regions. It can be concluded from this study that mulching was a good strategy for getting good yield and water use efficiency for Swiss chard when grown with saline shallow ground water. Compared with the gravel mulch, the rice straw mulch showed a measure of superiority during this long-term experiment period (about 6-7 months), and given the additional advantage of convenience in managing the material used, therefore, rice straw mulch was a better option than gravel mulch.

Besides Swiss chard, grapevines are often grown in regions under stressful conditions. Similarly like mulching (M) effects, sub-surface irrigation (SS) can also help conserve water by reducing evaporative water losses in agricultural systems.

MS gave the highest fresh yield while SS gave the lowest value due to higher θ (upper soil), A_N, Ts and diameter for MS as compared with SS. MS gave the higher *WUE* than MSS due to the higher water content at top soil and higher yield for MS. These combination of mulch and seepage irrigation were differed for *WUE* in the order of MS > MSS > SS > S. Compared with SS, the berry diameter, fresh yield, *WUE*, and berry sugar content for MS were enhanced by 2.8 mm, 271.5 g tree^{-1}, 33% and 15%, respectively. MSS gave higher berry sugar content than MS, which could be attributed to the higher Ts and lower soil water at the top soil layer under the condition of sub-surface irrigation. Ts should become an important index for the berry quality of grapevine.

Besides the irrigation method, the appropriate irrigation scheduling is also very important for saving water. Determining a critical value of soil water potential for scheduling irrigation is essential for grapevine production in arid and semiarid areas. This critical value for irrigation during the berry-growth stage was determined by instantaneous measurement of berry size by photogrammetry and soil water potential by tensiometers simultaneously during a drying cycle after irrigation, and establishment of the relationship between these two factors. Berry diameter tended to increase at night and decrease in the day, and the trend value demonstrated sensitivity to developing soil moisture stress in the root zone. Berry diameter increased rapidly after irrigation till ψ became –3 kPa. In the ψ range of –3 kPa to –5.4 kPa, the rate of growth started decreasing, and as ψ decreased beyond –5.4 kPa, berry diameter started shrinking and the shrinkage showed a strong linear relationship with decreasing ψ. In contrast, photosynthesis and transpiration rate remained unaffected by decreasing ψ until it became –9.3 kPa beyond which photosynthesis decreased significantly. Thus, berry diameter was a better indicator than photosynthesis of developing moisture stress in grapevines during the berry-growth stage and based on this attribute –5.4 kPa should be considered as the threshold ψ for scheduling irrigation in this important stage of economic yield development in grapevines to get cost-effective use of water resources. However, this threshold ψ should not be recommended directly in other stages (including the ripening stage) of grapevines growth because the growth characteristics and water demand are quite different in various growth stages. Therefore, further experiments are needed to establish the soil water potential threshold during the ripening stage for grapevines.

During the berry ripening stage, a critical value of soil water potential for scheduling irrigation is established for grapevine production in drylands. This critical value for irrigation was determined by instantaneous measurement of berry size by photogrammetry, photosynthesis by photosynthesis system and soil water potential by tensiometers simultaneously during a drying cycle after irrigation, and establishment of the relationship among these factors. When ψ decreased from –13.2 kPa to –14.7 kPa, A_N, g_s, T, extrinsic and intrinsic *WUE* decreased rapidly and did not recovery thereafter. In contrast, the berry size remained almost unaffected by decreasing ψ until it became –16.2 kPa beyond which the berry shrunk significantly. Thus, photosynthesis response was more sensitive to water stress than berry size during the maturation stage of grapevine. When $g_s < 0.03$ mol H_2O m^{-2} s^{-1} (corresponding to –14.7 kPa), A_N, intrinsic and extrinsic *WUE* decreased rapidly, whereas C_i increased steeply, indicating that non-stomatal limitations to photosynthesis become dominant. A more sensitive response of A_N to water limitation compared to g_s at the last stage of soil drying led to a decrease in $A_N\ g_s^{-1}$. When $g_s > 0.03$ mol H_2O m^{-2} s^{-1}, A_N and C_i decreased, while extrinsic and intrinsic *WUE* usually increased. Therefore, stomatal limitations seem dominant in this stage. A less sensitive response of A_N to water limitation compared to g_s at the first stages of soil drying led to an increase in $A_N\ g_s^{-1}$.

Based on these results, the following suggestions are made for appropriate irrigation during the ripening stage of grapevines. In areas where water availability is low or moderate, the critical soil water potential range for scheduling irrigation should be between –13.2 and –14.7 kPa (corresponding to g_s range of 0.09 ~ 0.03 mol H_2O m^{-2} s^{-1}). After irrigation, ψ should be kept lower than –6.9 kPa because the highest values of intrinsic *WUE* occurred when ψ decreased from –6.9 to –14.6 kPa. In hyper-arid and arid areas, the threshold ψ for scheduling irrigation should be considered as –16.2 kPa (corresponding to g_s value of 0.02 mol H_2O m^{-2} s^{-1}) in this important stage of economic yield development and fruit quality in grapevines to get cost-effective use of water resources. However, it should be mentioned that this threshold ψ could not be recommended directly in other stages of grapevines growth because the growth characteristics and water demand are quite different in various growth stages.

Based on our study, it can be concluded that photosynthesis response was more sensitive to water stress than berry size during the berry ripening stage of grapevine, this could be related to the fact that in ripening stage, the berry enlargement may correspond to the berry growth which is due mainly to the photosynthates accumulation and transformation (from leaf to fruit), instead of the swelling of fresh pulp that depends on the soil water status. However, in berry growth stage, the increase of berry size mainly depended on cell division and swelling that would be strongly related to soil water status.

In conclusion, rice-straw mulch was a better option than gravel mulch for improving crop yield and water use efficiency in the long run. The rice-straw mulch combined with surface irrigation exceeded no mulch combined with sub-surface irrigation for enhancing the berry diameter, fresh yield, *WUE* and berry sugar content. Mulching combined with surface irrigation outbalanced mulching combined with sub-surface irrigation in improving yield and *WUE*. Hence when the sub-surface irrigation is used for vineyards, the placement depth of sub-surface irrigation hose should be shallower than 15 cm. Mulching combined with sub-surface irrigation gave higher berry sugar content than mulching combined with surface irrigation due to higher average soil temperature and lower soil moisture at the top soil layer under sub-surface irrigation. Besides the effective mulching cultivation and irrigation methods, the appropriate irrigation scheduling is also very important for saving water. Photogrammetry system is suitable for measuring berry diameter for irrigation scheduling, therefore photogrammetry could be used for determining the critical point at which the berry contracted under stressful condition. The berry diameter was a better indicator of sensing water stress than photosynthesis in the last phase of Stage 1 of berry growth since the berry contracted under the moderate water stress. Nevertheless, in the ripening stage, the leaf photosynthesis was more sensitive to water stress than berry size, so leaf photosynthesis measurement and photogrammetry technology could be used together to establish irrigation threshold to get cost-effective use of water resources, especially for fruit trees. Since the water demand for vines in various growth stages is not uniform, further experiments should be conducted to establish critical irrigation values in other growth stages.

References

Abdul K. S., Alkam F. M. and Jamal M. A., 1988. Effects of different salinity levels on vegetative growth, yield and its components in barley, *ZANCO*, 1, 21–32

Al-Busaidi, A., Yamamoto, T., Inoue, M., Irshad, M., Mori, Y. and Tanaka, S., 2007. Effects of seawater salinity on salt accumulation and barley (*Hordeum vulgare* L.) growth under different meteorological conditions, Journal of Food, Agriculture and Environment, 5, 84-93

Al-Kaisi M.M., Yin X., 2003. Effects of nitrogen rate, irrigation rate and plant population on corn yield and water use efficiency. Agron. J. 95, 1475–1482.

Annan, K., 2000. UN Millennium Summit. http://www.un.org/millennium/summit.htm.

Araujo, F., Williams, L.E., Matthews, M.A., 1995. A comparative study of young 'Thompson Seedless' grapevines (*Vitis vinifera* L.) under drip and furrow irrigation. II. Growth, water use effkiency and nitrogen partitioning. Sci. Hortic. 60, 251–265.

ASAE Std., 1999. Soil and Water Terminology. S 526.1. ASAE Standards. American Society of Agricultural Engineers, St. Joseph, MI.

Ashrafi, S., Gupta, A., Singh, M.B., Izumi, N., Loof, R., 2002. Simulation of infiltration from porous clay pipe in subsurface irrigation. Hydrol. Sci. J. 47 (2), 253–268.

Avidan A., Hazan A., Kopyt M., Ton Y., 2005. Application of the phytomonitoring technique for table grapes. Proceedings of the International Workshop on Advances in Grapevine and Wine Research. Venosa (Italy), September 15 – 17.

Baccio D. D., Navari-Izzo F. and Izzo R., 2004. Seawater irrigation: antioxidant defence responses in leaves and roots of a sunflower (*Helianthus annuus* L.) ecotype. Journal of Plant Physiology. 161, pp. 1359-1366

Bainbridge D.A., 2001. Buried clay pot irrigation: a little known but very efficient traditional method of irritation. Agric. Water Manage. 48 (2), 79–88

Behboudian M.H., Singh Z., 2001. Water relations and irrigation scheduling in grapevine. Hortic. Rev. 27, 189–225.

Beltran J.M., 1999. Irrigation with saline water: benefits and environmental impact. Agric. Water Manage. 40, pp.183-194

Ben-Gal A., Lazorovitch N. and Shani U., 2004. Subsurface drip irrigation in gravel-filled cavities. Vadose Zone Journal 3: 1407-1413

Ben-Hur, M., Li, F. H. Keren, R., Ravina, I. and Shalit, G., 2001. Water and salt distribution in a field irrigated with marginal water under high water table conditions, *Soil Sci. Soc. Am. J.,* 65, 191 - 198

Bernstein, L., Francois, L. E. and Clark, R. A., 1974. Interactive effects of salinity and fertility on yields of grains and vegetables, *Agron. J.,* 66, 412-421

Blanco, F. F. and Folegatti, M. V., 2002. Salt accumulation and distribution in a greenhouse soil as affected by salinity of irrigation water and leaching management. *Revista brasileira de engenharia agricola e ambiental*, 6, 414–419

Bota, J., Flexas, J., Medrano, H., 2001. Genetic variability of photosynthesis and water use in Balearic grapevine cultivars. Ann. Appl. Biol. 138, 353–361.

Bota, J., Flexas, J., Medrano, H., 2004. Is photosynthesis limited by decreased Rubisco activity and RuBP content under progressive water stress? New Phytol. 162, 671–681.

Bowen P.A., Bogdanoff C.R., Estergaard B., 2004. Impacts of using polyethylene sleeves and wavelength-selective mulch in vineyards. II. Effects on growth, leaf gas exchange, yield components and fruit quality of *Vitis vinifera* cv. *Merlot.* Canadian Journal of Plant Science 84, 555-568

Bowen, P., Frey, B., 2002. Response of plasticultured bell pepper to staking, irrigation frequency, and fertigated nitrogen rate. HortScience 37, 95–100.

Box, G.E.P., Jenkins, G.M., Reinsel, G.C., 1994. Time series analysis: forecasting and control. 3rd ed., Prentice-Hall International, Inc. Page 1.

Bravdo B.-A. and Hepner Y., 1987. Irrigation management and fertigation to optimize grape composition and vine performance. In: Proceedings of the Symposium on Grapevine Canopy and Vigour Management. Acta Horticulturae 206, 49–67. Eds. W.M. Kliewer (Davis: California).

Bravdo, B., Hepner, Y., Loinger, C., Cohen, S., Tabacman, H., 1985. Effect of irrigation and crop level on growth, yield and wine quality of Cabernet Sauvignon. Am. J. Enol. Vitic. 36, 132–139.

Buckerfield, J.C., Webster, K.A., 1996. Earthworms, mulching, soil moisture and grape yields: earthworm response to soil management practices in vineyards, Barossa Valley, South Australia, 1995. Aust. NZ Wine Indus. J. 11 (1), 47–53.

Cadavid L. F., El-Sharkawy M. A., Acosta A. and Sanchez T., 1998. Long-term effects of mulch, fertilization and tillage on cassava grown in sandy soils in northern Colombia. Field Crops Research. 57, pp. 45-56

Camp, C.R., 1998. Subsurface drip irrigation: a review. Trans. ASAE 41, 1353–1367.

Chalmers, D.J., Mitchell, P.D., van Heek, L., 1981. Control of peach tree growth and productivity by regulated water supply, tree density, and summer pruning. J. Am. Soc. Hortic. Sci. 106, 307–312.

Chatelet D.S., Rost T.L., Matthews M.A. and Shackel K.A., 2008. The peripheral xylem of grapevine (*Vitis vinifera*) berries. 2. Anatomy and development. Journal of Experimental Botany 59: 1997-2007

Chaves, M.M., Pereira, J.S., Maroco, J., Rodrigues, M.L., Ricardo, C.P.P., Osório, M.L., Carvalho, I., Faria, T., Pinheiro, C., 2002. How plants cope with stress in the field. Photosynthesis and growth. Ann. Bot. 89, 907–916.

Cifre, J., Bota, J., Escalona, J.M., Medrano, H., Flexas J., 2005. Physiological tools for irrigation scheduling in grapevine (*Vitis vinifera* L.) An open gate to improve water-use efficiency? Agric. Ecosyst. Environ. 106, 159–170.

Coombe, B.G., 1987. Distribution of solutes within the developing grape berry in relation to its morphology. Amer. Jour. of Enology & Viticulture 38: 120-127.

Coombe, B.G., McCarthy, M.G., 2000. Dynamics of grape berry growth and physiology of ripening. Australian Journal of Grape & Wine Research 6: 131-135.

Conradie W.J., Carey V.A., Bonnardot V., Saayman D., Schoor van L.H., 2002. Effect of different environmental factors on the performance of Sauvignon blanc grapevines in the Stellenbosch/Durbanville districts of South Africa. I. geology, soil, climate, phenology and grape composition. South African J. Enol. Vitic. 23 (2), 79–91.

Coombe B.G., 1987. Influence of temperature on composition and quality of grapes. In: Proceedings of the Symposium on Grapevine Canopy and Vigor Management. Acta Hortic. 206, 23–35.

Cornic, G., Le Gouallec, J.L., Briantais, J.M., Hodges, M., 1989. Effect of dehydration and high light on photosynthesis of two C_3 plants (*Phaseolus vulgaris* L. and *Elatostema repens* (Lour.) Hall (f.). Planta 177, 84–90.

D'Amico M. L., Navari-Izzo F., Sgherri C. and Izzo R., 2004. The role of lipoic acid in the regulation of the redox status of wheat irrigated with 20% sea water. Plant Physiology and Biochemistry. 42, pp. 329-334

Delgado, E., Vadell, J., Aguilo, F., Escalona, J.M., Medrano, H., 1995. Irrigation and grapevine photosynthesis. In: P. Mathis, Editor, Photosynthesis: From Light to Biosphere IV, 693–696.

Dry P.R., During H., Botting B.G., 1996. Effects of partial root-zone drying on grapevine vigour, yield composition of fruit and use of water. In: Lee, T., et al. (Eds.), Proceedings of the 9th Australian Wine Industry Technical Conference, Adelaide, Australia, pp. 128–131.

Dry, P.R., Loveys, B.R., 1999. Grapevine shoot growth and stomatal conductance are reduced when part of the root system is dried. Vitis 38, 151–156.

Du, T.S., Kang, S.Z., Xia, G.M., Yang, X.Y., 2005. Response of grapevine growth and water use to different partial root-zone drying patterns under drip irrigation. Trans. Chin. Soc. Agric. Eng. 21, 43–48.

Dukes, M.D., Scholberg, J.M., 2005. Soil moisture controlled subsurface drip irrigation on sandy soils. Appl. Eng. Agric. 21, 89–101.

El-Asswad R. M. and Groenevelt P. H., 1985. Hydrophysical modifications of a sandy soil and its effect on evaporation. *Trans. ASAE.,* 26, 1927-1931

Ennahli, S., Earl, H.J., 2005. Physiological limitations to photosynthetic carbon assimilation in cotton under water stress. Crop Sci. 45, 2374–2382.

Epron, D., Dreyer, E., 1992. Effects of severe dehydration on leaf photosynthesis in *Quercus petraea* (Matt.) Liebl.: photosystem II efficiency, photochemical and nonphotochemical fluorescence quenching and electrolyte leakage. Tree Physiol. 10, 273–284.

Escalona, J.M., Flexas, J., Bota, J., Medrano, H., 2003. From leaf photosynthesis to grape yield: influence of soil water availability. Vitis 42, 57–64.

Esteban, M.A., Villanueva, M.J., Lissarrague, J.R., 2001. Effect of irrigation on changes in the anthocyanin composition of the skin of cv Tempranillo (*Vitis vinifera* L) grape berries during ripening. J. Sci. Food Agric. 81, 409–420.

FAO, 1998. Crop evapotranspiration. FAO Irrigation and Drainage Papers No. 56. Rome

Feigin A., 1985. Fertilization management of crops irrigated with saline water. Plant Soil.

82, pp. 285–299

Fereres E., Goldhamer D., Cohen M., Girona J. and Mata M., 1999. Continuous trunk diameter recording can reveal water stress in peach trees. California Agriculture. 53: 21-25.

Fereres, E., Goldhamer, D.A., Parsons, L.R., 2003. Irrigation water management of horticultural crops. HortScience 38, 1036–1042.

Ferreyra R., Selles G., Silva H., Ahumada R., Muñoz I., Muñoz V., 2006. Effect of applied water on water relations and productivity of 'Crimson Seedless' table grapes. Pesq. agropec. bras., Brasília, v. 41, n. 7

Flexas, J., Escalona, J.M., Medrano, H., 1999. Water stress induces different levels of photosynthesis and electron transport rate regulations in grapevines. Plant Cell Environ. 22, 39–48.

Flexas, J., Bota, J., Escalona, J.M., Sampol, B., Medrano, H., 2002. Effects of drought on photosynthesis in grapevines under field conditions: an evaluation of stomatal and mesophyll limitations. Funct. Plant Biol. 29, 461–471.

Fujimaki H., Shiozawa S. and Inoue M., 2003. Effect of salty crust on soil albedo. Agricultural and Forest Meteorology. 118, pp. 125-135

Ghadiri H., Dordipour I., Bybordi M. and Malakouti M.J., 2005. Potential use of Caspian Sea water for supplementary irrigation in Northern Iran. Agric. Water Manage. 79, pp. 209-224

Ghulam H., Al-Jaloud A. A., Al-Shammary S. A., Karimulla S. and Al-Asawad S. O., 1997. Effect of saline irrigation on germination and growth parameters of barley *(Hordeum Vulgare* L.*)*., Agric. Water Manag., 34, 125-135

Goldhamer D. and Fereres E., 2004. Irrigation scheduling of almond trees with trunk diameter sensors. Irrigation Science. 23: 11 – 19.

Gratacos E. and Gurovitch L., 2003. Phytomonitoring in Kiwifruit orchards as a plant water status indicator and its use in irrigation scheduling. Cien. Inv. Agr. 30: 113-137.

Greenspan, M.D., Shackel, K.A. and Matthews, M.A., 1994. Developmental changes in the diurnal water budget of the grape berry exposed to water deficits. Plant, Cell and Environment 17, 811–820.

Groenevelt P. H., Van Straten P., Rasiah V. and Simpson J., 1989. Modifications in evaporation parameters by rock mulches, Soil Tech., 2, 279-285

Hardie, W.J., Considine, J.A., 1976. Response of grapes to water-deficit stress in particular stages of development. Am. J. Enol. Vitic. 27, 55–61.

Hardie, W.J., Johnson, J.O., Weaver, R.J., 1981. The influence of vine water regime on ethephon-enhanced ripening of zinfandel. Am. J. Enol. Vitic. 32, 115–121.

Heakal M. S., Modaihsh A. S., Mashhady A. S. and Metwally A. I., 1990. Combined effects of leaching fraction salinity and potassium content of waters on growth and water use efficiency of wheat and barley, Plant and Soil, 125, 177–184

Hogg R., 2007. Grapes. Synopsis Of Grapes. Part 19, in: The Fruit Manual: Containing The Descriptions And Synonyms Of The Fruits And Fruit Trees Of Great Britain. Kessinger Publishing, LLC.

Huang Y. L., Chen L. D., Fu B. J., Huang Z. L. and Gong J., 2005. The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects. Agric. Water Manag., 72, 209-222

Imai, S., Fujiwara, T., Tanaka, S., Okamoto, G., 1991a. Effect of soil moisture on vine growth and fruit production of Kyoho grapes growing on restricted rooting volume (in Japanese, with English abstract). Environ. Control in Biol. 29, 133–140.

Imai, S., Iwao, K., Fujiwara, T., 1991b. Measurements of plant physiological informations of vine tree and indexation of soil moisture control (3) — Influence of soil moisture on daily variation-characteristics of stem and fruit diameter of vine trees (in Japanese, with English abstract). Environ. Control in Biol. 29, 19–26.

Imai S., Okamoto G. and Endo M., 1987. Effect of dense planting and root system control on attaining greater early production and fruit stability of tetraploid grapes. (in Japanese with English summary) Bull. Hiroshima Fruit Tree Exp. Stn. 12:1-9

Inoue M. and Shimizu T., 1998. Experimental set-up to continuously monitor water flow and solute transport in unsaturated large weighing lysimeters. Annual Report 1997–1998. Arid Land Research Center, Tottori University, pp. 1–14

Intrigliolo D. S. and Castel J. R., 2007. Evaluation of grapevine water status from trunk diameter variations. Irrigation Science. 26, 49-59

Jackson, D.I., Cherry, N.J., 1988. Prediction of a district's graperipening capacity, using a latitude-temperature index (LTI). Am. J. Enol. Vitic. 1, 19–28.

Jackson, D.I., Lombard, P.B., 1993. Environmental and management practices affecting grape composition and wine quality: a review. Am. J. Enol. Vitic. 4, 409–430.

Jacometti M.A., Wratten S.D., Walter M., 2007a. Understorey management increases grape quality, yield and resistance to *Botrytis cinerea*. Agric. Ecosyst. Environ. 122, 349–356.

Jacometti, M.A., Wratten, S.D., Walter, M., 2007b. Management of understorey to reduce the primary inoculum of *Botrytis cinerea*: Enhancing ecosystem services in vineyards. Biol. Control. 40, 57–64.

Jaggard K.W., Dewar A.M. and Pidgeon J.D., 1998. The relative effects of drought stress and virus yellows on the yield of sugarbeet in the UK, 1980–1995. J. Agric. Sci. 130, pp. 337-343

Jalota S.K. and Prihar S.S., 1998. Reducing soil water evaporation with tillage and straw mulch. Iowa State University Press, Ames, Iowa, USA, 120 pp.

Jones, G.V., Michael, A.W., Owen, R.C., Storchmann, K., 2005. Climate change and global wine quality. Climatic Change 73, 319–343.

Jones, H.G., 1983. Estimation of an effective soil water potential at the root surface of transpiring plants. Plant Cell Environ. 6, pp. 671–674

Jones, H.G., 1992. Plants and Microclimate. Cambridge Univ. Press, Cambridge, 428 pp.

Jones, H.G., Tardieu, F., 1998. Modelling water relations of horticultural crops: a review. Sci Hortic 74, 21–46.

Karlberg L. and Vries F.W.T.P., 2004. Exploring potentials and constraints of low-cost drip irrigation with saline water in sub-Saharan Africa. Physics and Chemistry of the Earth, Parts A/B/C. 29, pp. 1035-1042

Keller M., Smith J.P., Bondada B.R., 2006. Ripening grape berries remain hydraulically connected to the shoot. J. Exp. Bot. 57, 2577–2587.

Kennedy J., 2002a. Understanding grape berry development. Practical Winery and Vineyard. 58-D Paul Drive, San Rafael, CA

Kennedy J.A., Matthews M.A. and Waterhouse A.L., 2002b. Effect of maturity and vine water status on grape skin and wine flavonoids. American Journal of Enology and Viticulture 53, 268–274.

Konukcu F., Gowing J.W. and Rose D.A., 2005. Dry drainage: A sustainable solution to waterlogging and salinity problems in irrigation areas? Agric. Water Manage. 83, pp. 1-12

Kopyt, M., Ton Y. and Tsadok S., 2005. Chardonnay trunk diameter growth and microvariations: four-year trial results and outlook for irrigation control. The Australian and New Zeeland Grapegrower and Winemaker. 493: 23-25.

Kosmas C., Danalatos N.G., Poesen J., van Wesemael B., 1998. The effect of water vapour adsorption on soil water content under Mediterranean climatic conditions. Agric. Water Manage. 36; 157-168.

Kosmas, C., Marathianou, M., Gerontidis, St., Detsis, V., Tsara, M., Poesen, J. 2001. Parameters affecting water vapor adsorption by the soil under semi-arid climatic conditions. Agric. Water Manage. 48; 61-78.

Koszanski Z. and Karczmarczyk S., 1985. Use of saline water for irrigation of spring barley and oats. Zeszyty-Naukowi-Akademii-Rolniczej-w-Szczecinie, Rolnictwo 36, 95-105

Koundouras, S., Tsialtas, I.T., Zioziou, E., Nikolaou, N., 2008. Rootstock effects on the adaptive strategies of grapevine (*Vitis vinifera* L. cv. Cabernet–Sauvignon) under contrasting water status: Leaf physiological and structural responses. Agric. Ecosyst. Environ. 128, 86–96.

Lamm F. R. and Camp C. R., 2007. Subsurface drip irrigation, in: Microirrigation for crop production - design, operation, and management. Developments in Agricultural Engineering. 13, 473-551

Li H., Parent L.E., Karam A., Tremblay C., 2004. Potential of sphagnum peat for improving soil organic matter, water holding capacity, bulk density and potato yield in a sandy soil. Plant and Soil 265 (1–2), 355–365.

Li X.Y., 2003. Gravel–sand mulch for soil and water conservation in the semiarid loess region of northwest China. Catena, 52, pp. 105-127

Louvigny N. de., Dürr C., Fiès J. C. and Bruckler L., 2002. Emergence of sugar beet (*Beta vulgaris* L.) from seedbeds after glass waste deposition on soil. Soil and Tillage Research. 66, pp. 35-46

Lovisolo, C., Schubert, A., 2006. Mercury hinders recovery of shoot hydraulic conductivity during grapevine rehydration: evidence from a whole-plant approach. New Phytol. 172, 469–478.

Lovisolo, C., Perrone, I., Hartung, W., Schubert, A., 2008. An abscisic acid-related reduced transpiration promotes gradual embolism repair when grapevines are rehydrated after drought. New Phytol. 180, 642–651.

Mao X.S., 1998. A study of effect of concrete mulch on movement of soil water and salt in salinized region. Chin. Agrc. Meteorol. 19(1); 26-29.

Maroco, J.P., Rodrigues, M.L., Lopes, C., Chaves, M.M., 2002. Limitations to leaf photosynthesis in field-grown grapevine under drought – metabolic and modelling approaches. Funct. Plant Biol. 29, 451–459.

Marthaler, H.P., Vogelsanger, W., Richard, F., Wierenga, P.J., 1983. A pressure transducer for field tensiometers. Soil Sci. Soc. Am. J. 47, 624–627.

McCarthy, M.G., 1997a. The effect of transient water deficit on berry development of cv. Shiraz (*Vitis vinifera* L.). Aust. J. Grape Wine Res. 3, 2–8.

McCarthy, M.G., 1997b. Effect of timing of water deficit on fruit development and composition of *Vitis vinifera* cv. Shiraz. PhD thesis, University of Adelaide.

McCarthy, M.G., 2000. Developmental variation in sensitivity of *Vitis vinifera* L. (Shiraz) berries to soil water deficit. Aust. J. Grape Wine Res. 6, 136–140.

Milnes E. and Renard P., 2004. The problem of salt recycling and seawater intrusion in coastal irrigated plains: an example from the Kiti aquifer (Southern Cyprus). Journal of Hydrology. 288, pp. 327-343

Moran, M.S., Scott, R.L., Keefer, T.O., Emmerich, W.E., Hernandez, M., Nearing, G.S., Paige, G.B., Cosh, M.H., O'Neill, P.E., 2009. Partitioning evapotranspiration in semiarid grassland and shrubland ecosystems using time series of soil surface temperature. Agric. For. Meteorol. 149, 59–72.

Moreno F., Cabrera F., Fernández-Boy E., Girón I. F., Fernández J. E. and Bellido B., 2001. Irrigation with saline water in the reclaimed marsh soils of south-west Spain: impact on soil properties and cotton and sugar beet crops. Agric. Water Manage. 48, pp. 133-150

Moritani, S., Yamamoto, T., Henintsoa, A., Muraki, H., 2006. Monitoring of soil erosion using digital camera under simulated rainfall (in Japanese, with English abstract). Trans.

of JSIDRE. 244, 143–149.

Moritani, S., Yamamoto, T., Henintsoa, A., Muraki, H., 2007. Monitoring of soil erosion using digital camera under simulated rainfall. American Geophysical Union, Fall Meeting, abstract #H41G–0847.

Morlat R. and Jacquet A., 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. Am. J. Enol. Vitic. 54, 1–7.

Myburgh, P. A. 1996. Repsonse of "*Vitis vinifera*" L. cv. Barlinka/Ramsey to soil water depletion levels with particular reference to trunk growth parameters. South African Journal for Enology and Viticulture, Stellenbosch. 17, 3-14.

Newson T. A. and Fahey M., 2003. Measurement of evaporation from saline tailings storages. Eng. Geology, 70, 217-233

Ojeda H., Andary C., Kraeva E., Carbonneau A. and Deloire A., 2002. Influence of pre- and postveraison water deficit on synthesis and concentration of skin phenolic compounds during berry growth of *Vitis vinifera* cv. Shiraz. American Journal of Enology and Viticulture 53, 261–267.

Okamoto G. and Imai S., 1989. Promotion of seeded berry set of 'Pione' grape by restricting root zone. (in Japanese with English summary) Rep. Agri. Okayama Univ. 74:15-20

Okamoto G., Miki Y., Suyama A., Inubushi H., Hirano T., 1999. Fruit Quality of 'Gros Colman' Grapes Produced on Virus-free Vines. Scientific Reports of the Faculty of Agriculture, Okayama University. 88, 65–71

Ormenio-Nunez J., Pino-Rojas G., Garfe-Vergara F., 2008. Inhibition of yellow nutsedge (*Cyperus esculentus* L.) and bermudagrass (*Cynodon dactylon* (L.) Pers) by a mulch derived from rye (*Secale cereale* L.) in grapevines. Chilean Journal of Agricultural Research 68: 238–247

Pal B., Singh S., Singh H., 1984. Barley yield under saline water irrigation, Plant and Soil, 81, 221-228

Patel N. and Rajput T.B.S., 2008. Dynamics and modeling of soil water under subsurface drip irrigated onion. Agric. Water Manage. 95, 1335–1349

Pellegrino, A., Lebon, E., Voltz, M., Wery, J., 2004. Relationships between plant and soil water status in vine (*Vitis vinifera* L.). Plant Soil 266, 129–142.

Pellegrino, A., Lebon, E., Simonneau, T.M., Wery, J., 2005. Towards a simple indicator of water stress in grapevine (*Vitis vinifera* L.) based on the differential sensitivities of vegetative growth components. Aust. J. Grape Wine Res. 11, 306–315.

Pinamonti F., 1998. Compost mulch effects on soil fertility, nutritional status and performance of grapevine. Nutrient Cycling in Agroecosystems 51: 239–248

Poni, S., Lakso, A.N., Turner, J.R., Melious, R.E., 1994. Interactions of crop level and late season water stress on growth and physiology of field-grown Concord grapevines. Am. J. Enol. Vitic. 45, 252–258.

Poni, S., Bernizzoni, F., Civardi, S., Gatti, M., Porro, D., Camin, F., 2009. Performance and water-use efficiency (single-leaf vs. whole-canopy) of well-watered and half-stressed split-root Lambrusco grapevines grown in Po Valley (Italy). Agr. Ecosyst. Environ. 129, 97–106.

Poni S., Lakso A.N., Turner J.R., Melious R.E., 1993. The effects of pre- and post-veraison water stress on growth and physiology of potted Pinot noir grapevines at varying crop levels. Vitis 32, 207–214.

Possner, D.R.E., Kliewer, W.M., 1985. The localization of acids, sugars, potassium and calcium in developing grape berries. Vitis 24: 229-240.

Prichard T., Hanson B., Schwankl L., Verdegaal P., Smith R., 2004. Deficit irrigation of quality winegrapes using micro-irrigation techniques. Handbook. University of California Cooperative Extension, San Joaquin County.

Pyle C.J., Richards K.S., 1997. Digital photogrammetric monitoring of river bank erosion. Photogramm. Rec. 15, 753–764.

Qadir M., Boers Th. M., Schuberta S., Ghafoorb A. and Murtaza G., 2003. Agricultural water management in water-starved countries: challenges and opportunities. Agric. Water Manage. 62, pp. 165-185

Qadir M., Ghafoor A. and Murtaza G., 2001. Use of saline-sodic water through phyto-remediation of calcareous saline-sodic soils. Agric. Water Manage. 50, pp. 229-241

Qadir M. and Oster J.D., 2004. Crop and irrigation management strategies for saline-sodic soils and waters aimed at environmentally sustainable agriculture. Science of The Total Environment. 323, pp. 1-19

Qadir M., Sharma B.R., Bruggeman A., Choukr-Allah R. and Karajeh F., 2007. Non-conventional water resources and opportunities for water augmentation to achieve food security in water scarce countries. Agric. Water Manage., 87, 2-22.

Quick, W.P., Chaves, M.M., Wendler, R., David, M., Rodrigues, M.L., Passaharinho, J.A., Pereira, J.S., Adcock, M.D., Leegood, R.C., Stitt, M., 1992. The effect of water stress on photosynthetic carbon metabolism in four species grown under field conditions. Plant Cell Environ. 15, 25–35.

Rahman M.A., Chikushi J., Saifizzaman M., and Lauren J.G., 2005. Rice straw mulch and nitrogen response of no-till wheat following rice in Bangladesh. Field Crops. Res. 91, 71-81.

Rasiah, V., Imai, M., Yamamoto, T. and Inoue, M., 2001. Evaporation losses from sand dune -Influence of column and gravel mulch size-. J. Arid Land Stud., 11, 177-186

Resco, V., Ewers, B.E., Sun, W., Huxman, T.E., Weltzin, J.F., Williams, D.G., 2009. Drought-induced hydraulic limitations constrain leaf gas exchange recovery after precipitation pulses in the C_3 woody legume, *Prosopis velutina*. New Phytol. 181, 672–682.

Reynolds, A.G., Lowrey, W.D., Savigny, C.D., 2005. Influence of irrigation and fertigation on fruit composition, vine performance, and water relations of Concord and Niagara grapevines. Am. J. Enol. Vitic. 56, 110–128.

Roby G. and Matthews M.A., 2004. Relative proportions of seed, skin and flesh, in ripe berries from Cabernet Sauvignon grapevines grown in a vineyard either well irrigated or under water deficit. Australian Journal of Grape and Wine Research 10, 74–82.

Romic D., Romic M., Borosic J. and Poljak M., 2003. Mulch decreases nitrate leaching in bell pepper (*Capsicum annuum* L.) cultivation. Agric. Water Manage. 60, pp. 87-97

Santesteban, L.G., Royo, J.B., 2006. Water status, leaf area and fruit load influence on berry weight and sugar accumulation of cv. '*Tempranillo*' under semiarid conditions. Sci. Hortic. 109, 60–65.

Santos, T.P., Lopes, C.M., Rodrigues, M.L., Souza, C.R., Ricardo-da-Silva, J.M., Maroco, J.P., Pereira, J.S., Chaves, M.M., 2007. Effects of deficit irrigation strategies on cluster microclimate for improving fruit composition of Moscatel field-grown grapevines. Sci. Hortic. 112, 321–330.

Schultz, H.R., 2003. Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown Vitis vinifera L. cultivars during drought. Plant Cell Environ. 26, 1393–1405.

Selles G. and Berger A., 1990. Physiological indicators of plant water status as criteria for irrigation scheduling. Acta Horticulturae. 278: 87-100.

Shani, U., Waisel, Y., Eshel, A., Xue, S., Ziv, G., 1993. Responses to salinity of grapevines with split root systems. New Phytol. 124, 695–701.

Sharma R.A., Upadhay M.S., and Tomar R.S., 1985. Water use efficiency of some rainfed crops on a Vertisol as influenced by soil and straw mulching. J. Indian Soci. Soil Sci. 33:387-391.

Shu Q.S., Liu Z.X., Wang Z.Y., Liang H.J., 2007. Simulation of the soil wetting shape under porous pipe sub-irrigation using dimensional analysis. Irrig. And Drain., 56: 389-398.

Sinclair, T.R. and Ludlow, M.M., 1985. Who taught plants thermodynamics? The unfulfilled potential of leaf water potential. Aust. J. Plant Physiol. 12, pp. 213–217

Sivilotti P., Bonetto C., Paladin M. and Peterlunger E., 2005. Effect of soil moisture availability on merlot: From leaf water potential to grape composition. Am. J. Enol. Vitic. 56, 9–18.

Siyal A.A. and Skaggs T.H., 2009. Measured and simulated soil wetting patterns under porous clay pipe sub-surface irrigation. Agric. Water Manage. 96, 893–904

Smart D.R., Schwass E., Lakso A., Morano L., 2006. Grapevine rooting patterns: A comprehensive analysis and review. Am. J. Enol. Vitic. 57, 89–104

Smith D. C., Beharee V. and Hughes J. C., 2001. The effects of composts produced by a simple composting procedure on the yields of Swiss chard (*Beta vulgaris* L. var. *flavescens*) and common bean (*Phaseolus vulgaris* L. var. *nanus*). Scientia Horticulturae. 91, pp. 393-406

Soar C.J. and Loveys B.R., 2007. The effect of changing patterns in soil-moisture availability on grapevine root distribution, and viticultural implications for converting full-cover irrigation into a point-source irrigation system. Aust. J. Grape Wine Res. 13, 1–13

Sousa, T.A., Oliveira, M.T., Pereira, J.M., 2005. Physiological indicators of plant water status of irrigated and non-irrigated grapevines grown in a low rainfall area of Portugal. Plant Soil 282, 127–134.

Stamatiadis, S., Christofides, C., Tsadila, E., Taskos, D., Tsalidas, C., Schepers, S., 2007. Relationship of leaf stable isotopes (delta ^{13}C and delta ^{15}N) to biomass production in two fertilized Merlot vineyards. Am. J. Enol. Vitic. 58, 67–74.

Subbarao G. V., Wheeler R. M., Levine L. H. and Stutte G. W., 2001. Glycine betaine accumulation, ionic and water relations of red-beet at contrasting levels of sodium supply. Journal of Plant Physiology. 158, pp. 767-776

Sun D., Dickinson G. and Bragg A., 1994. The establishment of *Eucalyptus camaldulensis* on a tropical saline site in north Queensland, Australia. Agriculture, Ecosystems & Environment. 48, pp. 1-8

Szabolcs I., 1989. Amelioration of soils in salt affected areas. Soil Technology. 2, pp. 331-344

Thippayarugs, S., Suzuki, K., Katsuta, Y., Yoshida, A., Matsumoto, N., Kabaki, N., Wongwiwatchai, C., 2002. Vegetable production using energy-saving hydroponic system in Khon Kaen. JIRCAS Working Report 30, 161–165.

Ton Y. and Kopyt M. 2004. Phytomonitoring in realization of irrigation strategies for wine grapes. Acta Horticulturae. 652:167-173.

Ton, Y. M. Kopyt, I. Zachs and Z. Ben-Ner. 2004a. Phytomonitoring technique for tuning irrigation of fruit trees. Acta Horticulturae. 646, 127-132.

Ton Y., Kopyt M., and Nilov N., 2004b. Phytomonitoring technique for tuning irrigation of vineyards. Acta Horticulturae. 646: 133-139.

Tonietto J. and Carbonneau A., 2004. A multicriteria climatic classification system for grape-growing regions worldwide. Agricultural and Forest Meteorology 124, 81–97.

Tripathi R.P. and Katiyar T.P.S., 1984. Effect of mulches on the thermal regime of soil. Soil and Tillage Research. 4, 381–390

Tzilivakis J., Jaggard K., Lewis K.A., May M. and Warner D.J., 2005. Environmental impact and economic assessment for UK sugar beet production systems. Agriculture, Ecosystems & Environment. 107, pp. 341-358

Verma T.S. and Neue H.U., 1984. Effect of soil salinity level and zinc application on growth, yield, and nutrient composition of rice. Plant Soil. 82, pp. 3–14

Wahba S.A., Abdel Rahman S.I., Tayel M.Y. and Matyn M.A., 1990. Soil moisture, salinity, water use efficiency and sunflower growth as influenced by irrigation, bitumen mulch and plant density. Soil Technology. 3, pp. 33-44

Wang, S.P., Okamoto, G., Hirano, K., Lu, J., Zhang, C.X., 2001. Effects of restricted rooting volume on vine growth and berry development of Kyoho grapevines. Am. J. Enol. Vitic. 52, 248–253.

Wang, Z.P., DeLoire, A., Carbonneau, A., Federspiel, B., Lopez, F., 2003. Study of sugar phloem unloading in ripening grape berries under water stress conditions. J. Inter. des Sci. de la Vigne et du Vin 37 (4), 213–222.

Willliams L.E., Dokoozlian N.K., Wample R.L., 1994. Grape. In: Schaffer, B., Andersen, P.C. (Eds.), Environmental Physiology of Fruit Crops. vol. I. Temperate Crops. CRC press, Boca Raton, Florida, USA, pp. 85–134.

Yamamoto T., 1987. Dynamic analysis of water and salt in soil column under a constant ground water table. Sand Dune Res., 25, 19-26 (in Japanese with English summary).

Yamanaka T., Inoue M. and Kaihotsu I., 2004. Effects of gravel mulch on water vapor transfer above and below the soil surface. Agric. Water Manage. 67, 145-155

Yang Y.M, Liu X.J, Li W.Q, and Li C.X., 2006. Effect of different mulch materials on winter wheat production in desalinized soil in Heilonggang region of North China. J. Zhejiang Uni. Sci. B. 7(11); 858-867.

Zhang, C.X., Tanabe, K., Tamura, F., Itai, A., Wang, S.P., 2005a. Partitioning of ^{13}C-photosynthate from spur leaves during fruit growth of three Japanese pear cultivars differing in maturation date. Ann. Bot. 95, 685–693.

Zhang Q.T., Ahmed O.A.B., Inoue M., Saxena M.C., Inosako K., Kondo K., and Suzuki K., 2009. Effects of mulching on evapotranspiration, yield and water use efficiency of Swiss chard (Beta vulgaris L. var. flavescens) irrigated with diluted seawater. Journal of Food, Agriculture & Environment, 7 (3&4), October. (Accepted)

Zhang Q.T., Inoue M., Inosako K., Irshad M., Kondo K., Qiu G.Y. and Wang S. P., 2008. Ameliorative effect of mulching on water use efficiency of Swiss chard and salt accumulation under saline irrigation. Journal of Food, Agriculture & Environment, 6, 480 – 485

Zhang Q.T., Qiu G.Y., Inoue M. and Yasuda H., 2005b. The combined effects of straw mulch intensity and cropping density on soil evaporation, evapotranspiration, water-use efficiency and soil water content — case study of winter wheat in the North China Plain. Proceedings of the 60th meeting of the JSIDRE (The Japanese society of irrigation, drainage and reclamation engineering) annual branch meeting in Chugoku and Shikoku. pp. 173-175

Zhang X.Y., Pei D. and Hu C.S., 2003. Conserving groundwater for irrigation in the North China Plain. Irrig Sci. 21, 159-166

Zsófi, Z., Gal, L., Szilagyi, Z., Szucs, E., Marschall, M., Nagy, Z., Balo, B., 2009. Use of stomatal conductance and pre-dawn water potential to classify terroir for the grape variety Kékfrankos. Aust. J. Grape Wine Res. 15, 36–47.

Summary in Japanese

要旨

本研究では、持続的な節水農業のために、種々のマルチング効果を評価し、灌漑時期開始点（灌漑閾値）を評価することを目的とした。

乾燥地では良質の水が少なく節水が重要である。そこで、希釈海水を灌漑に使用し、さらに、灌漑後の土壌面蒸発を軽減するためにマルチングを行い、供試作物には耐塩性のあるフダンソウを用いた。1/2000a のワグネルポット内に東伯土壌(粘土 54%)を充填し、いずれも厚さ 3cm の砂利マルチ、松葉マルチ、稲ワラマルチとマルチなしの条件で、冬期にポット栽培試験を行った。電気伝導度（*EC*）が 4.8 dS m^{-1} と 7.4 dS m^{-1} の希釈海水を用いた塩水灌漑条件下で、砂利による保温効果もあり、砂利マルチが水利用効率、乾物量ともに高く、マルチング効果が認められた。

地下水位を初期に 50cm に保ち、希釈海水（*EC* = 6.9 dS m^{-1}）による地下灌漑条件下で、東伯土壌にいずれも厚さ 3cm の砂利マルチ、稲ワラマルチを施し、11 月から 2 月の冬、3 月から 6 月の春にウェイイングライシメータを用いたフダンソウの栽培試験を行った。いずれの時期でも、マルチなしは積算蒸発散量と土壌中の塩分濃度が高いこと、マルチなしと比較して乾物重は稲ワラマルチが 113%、砂利マルチが 64%高いこと、稲ワラマルチはマルチなしと比較して水利用効率が 143%高く、砂利マルチと比較しても水利用効率が 10%高いことがわかった。以上の結果から、稲ワラマルチを用いたマルチングは塩を含んだ浅い地下水面の条件下で、塩類集積を軽減し水利用効率の向上に貢献することが認められた。

乾燥地ではブドウは高収入が期待される果樹であるが不適切な灌漑による水資源の枯渇が問題となり節水栽培が急務である。上述の実験で効果が認められた稲ワラマルチを用いて、東伯土壌に浸潤型多孔質チューブを地上と地中深さ 15cm に設置し、6 月から 9 月にウェイイングライシメータを用いたブドウ（*Vitis vinifera* L.）栽培試験を行った。マルチなしと比較して稲ワラマルチは水利用効率が高いこと、稲ワラマルチと多孔質チューブを地上に設置した場合が水利用効率、新鮮重、果粒径、果粒糖度ともに高いことから、節水と品質向上が期待できた。

さらに節水を考える場合、灌漑時期の判定が重要となる。温湿度を制御したグロースチャンバー内に鉢植えのブドウを置いて、2 台の高性能デジタルカメラを用いた画像解析で果粒径とテンシオメータで根群域の土壌水分ポテンシャルを測定した。ブドウの成長期において、果粒は昼に縮小し夜に肥大する日変化を示し、灌漑後に果粒は徐々に肥大し、さらに、土壌水分ポテンシャルがある閾値を過ぎると水分ストレスによって果粒が縮小することが明らかになった。ブドウの果粒径と土壌水分ポテンシャルの関係が、灌漑開始時期を評価する判断材料になることがわかった。

同様に，グロースチャンバー内で、葉の光合成と気孔抵抗の変化を測定して、ブドウの成熟期の栽培試験を行った。深さ 10cm の土壌水分ポテンシャルが-13.2kPa から-14.7kPa に

減少したときから、光合成と気孔コンダクタンスが著しく減少し、回復しなかった。その後、土壌水分ポテンシャルが-16.2kPa に減少したときに果粒径が減少した。このように、ブドウの成熟期の場合、光合成などの反応が果粒径の変化よりも水分ストレスに敏感であることを明らかにした。

本研究は、いくつかのマルチ資材の中から、塩を含む水で灌漑した場合の稲ワラマルチによる節水効果と塩類集積軽減効果を示したこと、稲ワラマルチと灌漑強度の低い浸潤型多孔質チューブを用いた栽培実験でブドウの収量と品質に対するマルチング効果を示したこと、灌漑開始時期を判定する方法に新たにデジタルカメラを用いた画像解析を採用し、その有効性を示したことなどの新しい知見は、乾燥地農学に貴重な情報を提供したものであり、乾燥地の持続的農業に貢献するものと期待される。

Abstract in English

This study was carried out to evaluate mulching effect for sustainable agriculture and establish irrigation threshold (based on a new photogrammetry system) for water-saving production.

Water-saving is important since freshwater resources have been over-exploited in many areas. Therefore a pot experiment was conducted to evaluate the effects of three mulching types (gravel, pine-needles and rice-straw with 3 cm thickness) together with diluted seawater irrigation during winter season. Seawater was diluted to achieve the electrical conductivity of irrigated water as 4.8 and 7.4 dS m^{-1}. High diluted seawater irrigation could be used under mulch condition without serious salinity-damage to Swiss chard. Gravel mulching enhanced soil temperature, biomass and water use efficiency (*WUE*) under saline irrigation.

From November to June, the effect of gravel mulch (G) and rice-straw mulch (R) (3 cm thickness) on Swiss chard were investigated. Three weighing lysimeters were irrigated with diluted seawater (6.9 dS m^{-1}) from below. The cumulative *ET* and soil salinity were higher with no-mulch than mulches. The dry yield was 113% higher under R and 64% higher under G than under no-mulch. R increased *WUE* by 143% and 10% as compared to no-mulch and G, respectively. Thus mulching using R is recommended for reducing salinity under shallow water table of saline water and improving *WUE.*

The grapevine plays an important role in enhancing income in drylands with the problems of water scarcity and improper irrigation, hence water-saving production is on urgent business. Based on the results of above-mentioned experiment, effects of rice-straw mulching and sub-surface seepage irrigation (at 15 cm soil depth) on growth of grapevines (*Vitis vinifera* L.) in weighing lysimeters were investigated from June to September. Mulching combined with surface irrigation gave the highest berry size, fresh yield and WUE, while mulching combined with sub-surface irrigation gave the highest sugar content.

It is also essential to determine the critical timing for starting irrigation in drylands. When the berries were in the last phase of Stage 1, a potted grapevine was placed in an environmentally controlled growth chamber. Berry diameter was monitored by a new photogrammetry-system that consists of two digital cameras attached to a computer having an image analysis program. Soil water potential was measured by a pressure transducer system for tensiometers. Berry diameter increased rapidly after irrigation till ψ became –5.4 kPa, beyond which the berry started shrinking and the shrinkage showed a strong linear relationship with decreasing ψ. Berry diameter was a more sensitive indicator of moisture stress than photosynthesis and –5.4 kPa should be considered as the threshold ψ for scheduling irrigation in this growth stage.

In the similar way, when the berries were in the ripening stage (Stage 3), leaf photosynthesis and stomatal conductance were monitored from a potted grapevine in a growth chamber. When soil water potential (at 10 cm soil depth) decreased from -13.2 kPa to -14.7 kPa, photosynthesis, stomatal conductance and transpiration decreased rapidly and did not recovery thereafter. Afterwards the berry shrunk significantly as soil water potential became -16.2 kPa. Thus, photosynthesis was more sensitive to water stress than berry size during the ripening stage.

In conclusion, rice-straw mulch was a good option in several mulching materials for preventing soil salinity and improving *WUE*. Furthermore, the rice-straw mulch combined with seepage irrigation could influence yield and quality of grapevines. A new photogrammetry system is suitable for measuring berry diameter for irrigation timing scheduling, therefore this effective method could be used to get cost-effective use of water resources, especially for fruit trees under stressful conditions. The valuable information provided here will benefit the sustainable agriculture, especially in arid and semi-arid areas.

List of related publication

Ameliorative effect of mulching on water use efficiency of Swiss chard and salt accumulation under saline irrigation

Authors: Qing Tao ZHANG, Mitsuhiro INOUE, Koji INOSAKO, Muhammad IRSHAD, Kensuke KONDO, Guo Yu QIU and Shi Ping WANG

Publication: Journal of Food, Agriculture & Environment

Date, Volume, Pages: 2008. 6, pp. 480 - 485

This paper covers the chapter 2.

Effects of mulching on evapotranspiration, yield and water use efficiency of Swiss chard (*Beta vulgaris* L. var. *flavescens*) irrigated with diluted seawater

Authors: Qing Tao ZHANG, Bouya Ahmed OULD AHMED, Mitsuhiro INOUE, Mohan Chandra SAXENA, Koji INOSAKO, Kensuke KONDO and Kenji SUZUKI

Publication: Journal of Food, Agriculture & Environment

Date, Volume, Pages: 2009. 7 (3&4), October, 2009. Accepted (This manuscript will be published in this upcoming journal issue)

This paper covers the chapter 3.

List of related conferences papers

1. ZHANG Qingtao, WANG Shiping, MORITANI Shigeoki, INOUE Mitsuhiro, XIE Qiang, TSUJI Wataru, TANABE Kenji, 2008. Establishment of irrigation critical value in berry growth stage of grapevines based on photogrammetry. Proceedings of the 63rd meeting of the JSIDRE (The Japanese society of irrigation, drainage and rural engineering) annual branch meeting in Hiroshima, Chugoku and Shikoku, Japan. pp. 32-133

2. ZHANG Qingtao, INOUE Mitsuhiro, KONDO Kensuke and YAMAMOTO Tahei, 2006. Effects of various mulching materials on salt accumulation and water use efficiency of Swiss chard irrigated with diluted sea water. Proceedings of the 2006 meeting of the JSIDRE (The Japanese society of irrigation, drainage and rural engineering) annual meeting in Utsunomiya, Japan. pp. 728-729

3. WANG Shiping, INOUE Mitsuhiro, ZHANG Qingtao, MORITANI Shigeoki, TSUJI Wataru, TANABE Kenji, TAMURA Fumio, 2009. Establishment of irrigation critical value in berry maturity stage of grapevine based on photosynthesis and its transformation. Hort. Res (Japan). 8 (suppl.1): 91 pp (in Japanese)

4. WANG, S.P., ZHANG, Q.T., INOUE, M., ZHANG, C.X., 2009. A New Self-Watering Technique for Container-Grown Grapevine ---Capillary Wicking Water Cultivation (CWWC), American Society for Horticultural Science, St. Louis, USA