FUNDACION PARA LA INNOVACION AGRARIA

PROGRAMA DE FORMACIÓN PARA LA INNOVACIÓN AGRARIA

APOYO A LA PARTICIPACIÓN EN ACTIVIDADES DE FORMACIÓN

PROPUESTA FIA-FP-V-2003-1-A-019

ACTUALIZACIÓN EN MANEJO DE RIEGO Y RELACIONES HÍDRICAS EN FRUTALES

INFORME TECNICO

NOVIEMBRE 2003

GOBIERNO DE CHILE
FUNDACIÓN PARA LA INNOVACIÓN AGRARIA

CONTENIDO DEL INFORME TÉCNICO

PROGRAMA DE FORMACIÓN PARA LA INNOVACIÓN AGRARIA

1. Antecedentes Generales de la Propuesta

Nombre :
Actualización en manejo de riego y relaciones hídricas en frutales

Código

FP-V-2003-1-A-019

Entidad Responsable Postulante Individual
Instituto de Investigaciones Agropecuarias

Coordinador

Gabriel Selles van Schouwen

Lugar de Formación (País, Región, Ciudad, Localidad)

Davis, California U.S.A0

Tipo o modalidad de Formación

- Asistencia al 4th International Symposium on Irrigation of Horticulture Crops de la ISHS.
- Visita Técnica al Kearney Agricultural Center en Parlier, California

Fecha de realización

30 Agosto al 9 de Septiembre 2003

Participantes: presentación de acuerdo al siguiente cuadro:

Nombre	Institución/Empresa	Cargo/Actividad	Tipo Productor (si corresponde)
Gabriel Selles	INIA	Investigador	
Nelson Pereira	CNR	Jefe Dpto Estudios	

Problema a Resolver: detallar brevemente el problema que se pretendía resolver con la participación en la actividad de formación, a nivel local, regional y/o nacional.

Esta actividad se plantea como una de formación que permita actualizar y poner al día en las actuales tendencias del manejo del riego en cultivos hortofrutícolas s e intercambiar experiencia con investigadores y profesionales de otros países.

Objetivos de la Propuesta

- Asistir a un Symposium Científico Internacional que permita actualizarse en las avances y tendencias de la investigación en el área del riego, y promover la interrelación y/o cooperación con grupos de investigación líderes en el mundo.
- Conocer en detalles los trabajos de investigación en manejo del riego y relaciones hídricas de la Universidad de California, Davis.
- 5. Fortalecer el conocimiento en manejo de riego en frutales de los agricultores a través de las actividades de transferencia tecnológica que se realicen

2. Antecedentes Generales: describir si se lograron adquirir los conocimientos y/o experiencias en la actividad en la cual se participó (no más de 2 páginas).

El Simposium al cual se asistió fue organizado en conjunto por la Universidad de California, Davis, y la Sociedad Internacional para la Ciencia Hortícola (ISHS). La Sociedad Internacional para la Ciencia Hortícola (ISHS) fue oficialmente registrada como tal el 27 de abril de 1959, formalizando una red global de cooperación hortícola internacional, aunque el primer Congreso Hortícola Internacional fue organizado en 1864 en Bruselas (Bélgica). Luego se crean dentro de ISHS comisiones según las temática hortícolas, que corresponden a diferentes ramas de las ciencias y tecnologías hortícola, lo que da garantía de alto nivel de los talleres internacionales, simposios y congresos que son organizado cada año por Universidades y/o institutos con el auspicio de la ISHS. La ISHS publica una revistas científicas Acta Hortuculturae de gran impacto en el área.
Por otra parte el Departamento de Suelo, Aire y Recursos de Agua (LAWR) de la Universidad de California, Davis, se creó en 1975 cuando el antiguo Departamento de Suelo & Nutrición de la Planta y Ciencia de Agua & Ingeniería se unieron con el programa de la Ciencia Atmosférico del Departamento de Ingeniería Agrícola para promover coordinación interdisciplinaria y integración en la enseñanza e investigación. En 1990 la facultad de LAWR votó subdividir en los departamentos de Ciencia Atmosférica, suelos y Bioquimica, y Hidrología. Los tres programas tienen una historia larga en el campus de Davis. El enfoque multidiciplinario de los departamentos permiten dar solución a complejos problemas agrícolas y medioambientales locales, nacionales, e internacionales. La Universidad de California tiene varios centro de investigación de los cuales uno de los mas importantes en riego es Kearney en Parlier, condado de Fresno. Este centro se ubica en una zona eminentemente frutícola

En el seminario se realizaron más de 140 ponencias, en los siguientes temas

- Secado parcial de raíces
- Uso de riego deficitario controlado
- Evapotranspiración
- Relaciones hídricasManejo de Riego
- Economía del agua
- Calidad de aguas

Adicionalmente el día 6 de septiembre se participó en una visita a terreno que permitió conocer la estación lisimetrica de la Universidad de California, en Davis, una de las estaciones de la California Irrigation Management Information System (CIMIS), y visitar huertos de almendros bajo riego localizado en distintas modalidades : goteo superficial, goteo enterrado y microaspersión

Un listado detallado de los trabajos presentados se adjunta en anexo, y en el cd adjunto los resúmenes de los mismos.

Por otra parte se realizó una visita técnica al Kearney Agricultural Center en Parlier, Fresno, donde se tuvo la oportunidad de conocer los trabajos realizados en vides para mesa y para vinos (Dr. Larry Williams).

Se discutieron aspectos relacionados con estrategias de manejo y uso de la cámara de presión para el control del riego en ambos tipos de cultivo. Por otra parte se visitó el lisimetro de pesada, donde se realizan los estudios de evapotranspiración para determinar los coeficientes de cultivo (kc) para esta especie. En anexo se adjunta copia de los artículos técnicos recopilados en esta visita recopilados en esta visita. Se adjunta además anexo con fotografías digitales en CD

3. **Itinerario Realizado**: presentación de acuerdo al siguiente cuadro:

Fecha	Actividad	Objetivo	Lugar
30/8/03	Salida desde Santiago		
1-5/09	Asistencia a Symposium	Puesta al día en las actuales tendencias en manejo de riego en cultivos hortofrutícolas	Davis ,California
8/09	Kearney Agricultural Center	Conocer los trabajos de investigación en riego de vides	Fresno, California

Señalar las razones por las cuales algunas de las actividades programadas no se realizaron o se modificaron.

4. Resultados Obtenidos: descripción detallada de los conocimientos adquiridos. Explicar el grado de cumplimiento de los objetivos propuestos, de acuerdo a los resultados obtenidos. Incorporar en este punto fotografías relevantes que contribuyan a describir las actividades realizadas.

Los resultados de esta actividad de formación son los siguientes:

a) Symposium

En el Symposium se presentaron trabajos principalmente en los siguientes temas:

Secado Parcial de las Raíces

En este tema se presentaron trabajos en Vides para vino, Perales y Manzanos. Se concluyo que esta técnica produce estrés en las plantas, por lo cual se cuestionaron la información obtenida en Australia que indicaban que esta técnica podría reducir el agua aplicada en vides en un 50% sin afectar los rendimientos. Los trabajos realizados en Australia indicaban que señales químicas producidas en el sector seco de las raíces reducirían la apertura estomática, pero al mismo tiempo las raíces que están en condiciones adecuadas de humedad, mantendrían un estado hídrico favorable en la parte aérea de la planta. Este fenómeno permite mantener niveles adecuados de fotosíntesis y por lo tanto el crecimiento de la fruta, mientras se disminuye la transpiración

Déficit hídrico controlado

En este tópico se presentaron trabajos en vides viniferas (Merlot, Sangivense, Chardonnay), Duraznos y olivos.

Esta técnica consiste en regar en forma deficitaria (cantidades de agua menores a la evapotranspiración del cultivo) durante períodos que no son considerados críticos para el desarrollo de las plantas, por lo cual no se afectan los rendimientos, lográndose una economía de agua.

Al mismo tiempo esta técnica se utiliza para inducir efectos de calidad, en particular en vides viníferas. La aplicación de déficit hídrico controlado en vides de variedades tintas permite un claro incremento en la calidad organoléptica de los vinos, mejorando el contenido de fenoles y antocianinas.

Programación y controladores del riego

En este tema se presentaron trabajos relacionados con el uso de de indicadores fisiológicos del estado hídrico de las plantas como herramientas para controlar el riego de los cultivos. Se considera que los indicadores fisiológicos integran el sistema suelo- planta –atmósfera, siendo más dinámicos y representativos que las mediciones de humedad del suelo, en particular bajo condiciones de riego localizado, donde solo una fracción de suelo es mojada por el riego y existe una distribución espacial de la humedad al interior de los bulbos de mojamiento.

Dentro de estos indicadores se consideran los dendrometros (captores de desplazamiento lineal) y Potencial hídrico xilematico medido a medio día. Los dendrómetros permiten medir las microvariaciones de diámetro que presentan los órganos de las plantas a escala diaria (crecimiento y contracción) y a nivel estacional (crecimiento) . Las mediciones de potencial xilemático consisten en la determinación de la tensión del agua en el xilema de las plantas utilizando la cámara de presión. La información disponible hasta el momento permite concluir que ambos indicadores son muy buenos controladores de riego en especies frutales, donde existe mayor experiencia. Los dendrometros presentan una mayor sensibilidad en la determinación de deficits hídricos, incluso moderados, que el potencial hídrico xilematico, sin emabargo su variabilidad pero más variables. Se presentaron trabajos en vides, Almendros, ciruelos y vides.

Evapotraspiración y coeficientes de cultivo.

Se presentaron trabajos en varios cultivos, concluyendo que los coeficientes de cultivos disponibles actualmente (Fao 56) tienen errores de 30 a 40% de sub o sobre estimación, principalmente debido a los cambios en las técnicas de cultivo (distancia de plantación entre otras). Por lo cual se cree que es necesario trabajar en este tema pero para hacerlos de una aplicación más amplia se deberían o sombreamiento del suelo o con el porcentaje de cobertura. Esto es importante tanto para el manejo de riego, como para el dimensionamiento de obras de riego (embalses, equipos de riego etc).

En hoja anexa se presenta la nomina de los trabajos presentados al congreso

b) Visita a terreno día Sábado 6 de Septiembre

En el ámbito del Symposium en día sabado 6 de septiembre se participó en una gira técnica, donde se visitaron los siguientes lugares:

Lisimetro de pesada : El Departamento de el Departamento de Suelo, Aire y Recursos de Agua (LAWR) de la Universidad de California, cuenta con un lisimetro de pesada que permite realizar estudios de evapotranspiración de cultivos. Este lisimetro es de forma circular (6 m de díametro), sobre un sistema de balanzas que permite determinar la evapotranspiración diaria de los cultivos con una precisión de 0,0025 mm/día. Este lisimetro es utilizado fundamentalmente en estudios de consumo de agua de cultivos anuales (actualmente con tomates) y permite hacer determinaciones empíricas de coeficientes de cultivo (kc).

CIMIS (California Irrigation Management Information System). El CIMIS es una red de más de 100 estaciones meteorológicas, ubicadas en lugares claves y representativos de los diferentes sectores agrícolas de California. Estas estaciones metereológicas miden velocidad de viento, humedad relativa, temperatura y radiación solar, y calculan la evapotranspiración potencial o de referencia (Eto), utilizando la ecuación de Penman-Monteih. Esta red entrega información a

sus miembros a través de reportes diarios o semanales para que los agricultores puedan realizar sus programas de riego. Por otra parte el CIMIS cuenta con laboratorios móviles para

realizar determinaciones de humedad de suelo y recomendaciones de riego directamente en el campo. Se considera que el mejoramiento en las practicas de riego que se logran con el apoyo del CIMIS permite aumentos de rendimientos y ahorro de energía en las estaciones de bombeo. En anexo se adjunta brochure sobre CIMIS.

Ensayo de riego en almedros

Se visitó un sector, cercano a Davis, donde existen experimentos de diferentes métodos de riego localizado sobre el desarrollo de almendros. Se prueba doble línea de goteo superficial, lineas de goteo enterradas y microaspersión. El sistema de riego por goteo enterrado presenta el inconveniente del taponamiento de emisores por las raicillas de los árboles y la dificultad de detectar los lugares precisos , dentro de la lateral donde se produce la obturación de los emisores. Presenta la ventaja de dejar el suelo libre lo que facilita las labores mecánicas de cosecha. La doble línea y la microaspersión presentan respuestas similares. Llama la atención que se utilice microaspersión con almendros , ya que el mojamiento de los troncos trae asociados enfermedades al cuello, como phytoptora, sin embargo en las condiciones de California, de acuerdo a los expertos, no existe problemas.

c) Visita Kearney Agricultural Research Center

La estación experimental Kearney, de la Universidad de California, se encuentra ubicada en Parlier, Fresno, en una zona eminentemente frutícola (carozos, nogales, almendros y vides). En esta estación experimental se tuvo reunión con el Dr. Larry Williams, experto en fisiología y manejo del agua en vides, de mesa y viníferas

Se tuvo una discusión técnica en torno a los siguientes temas, de interés para el trabajo que desarrollan los investigadores de INIA:
Uva de mesa
- Estimación de los requerimientos de riego en uva de mesa, tanto en plantas jóvenes como plantas adultas
- Indicadores fisiológicos del estado hídrico de las plantas como criterio de riego en uva de mesa. Correlación entre el potencial de base medido al amanecer y el potencial xilemático a medio día
- Relaciones hídricas en vides y el comportamiento de las diferentes variedades
- Distribución de fotoasimilados ,

Uva para vinos
- Comparación de diferentes estrategias de manejo del riego en la producción y la composición de las bayas
- Interacción entre el manejo del riego y el manejo del dosel de la viña y la producción y calidad del vino
- Estrategias de nutrición mineral y fertilización en viñedos

Adicionalmente se realizó una visita a las instalaciones del centro experimental. Especial dedicación tuvo la visita al lisimetro de pesada, que permite determinar la evapotranspiración de las vides con una precisión de 0,025 mm/día. El centro dispone de dos lisímetros de pesada, una en vides de mesa y otro en durazneros. Estos lisímetros han permitido realizar estudios de consumo de agua y determinación de coeficientes de cultivos en estas dos especies.

En anexo se adjunta copias de artículos recientes sobre las materias analizadas.

Foto1.- Arriba . Dendrómetros en troncos de vid. Abajo, cámara de presión

Foto 2.- Lisimetro de pesada Universidad de California, Davis.

Foto 3.- Almendros regados por microaspersión

Foto 4.- Lisímetro de pesada en vides.- Kearney Agricultural Experimental Center, Fresno, California.

5. **Aplicabilidad**: explicar la situación actual del rubro en Chile (región), compararla con la tendencias y perspectivas en el país (región) visitado y explicar la posible incorporación de los conocimientos adquiridos, en el corto, mediano o largo plazo, los procesos de adaptación necesarios, las zonas potenciales y los apoyos tanto técnicos como financieros necesarios para hacer posible su incorporación en nuestro país (región).

La agricultura de riego genera cerca del 60% del PGB agrícola. Dentro de este ocupa gran importancia la fruticultura, con un total aproximado de 253.000 hás, de las cuales unas 70.00 están regadas por goteo.

El gran paso dado por la tecnificación de riego no ha ido asociado, con la misma intensidad en la programación y control del riego, de tal forma de optimizar el uso del agua y obtener productos de calidad.

La asistencia al seminario permitió la puesta al día en las tendencias actuales en las materias señaladas , a saber :

- Secado parcial de raíces (PRD)
- Uso de riego deficitario controlado (RDI)
- Evapotranspiración de cultivos y dterminación de coeficientes Kc
- Relaciones hídricas y Manejo de Riego

La técnica de RDI esta siendo ampliamente utilizada en especies frutales en localidades de recursos hídricos escasos, como una forma de economía de agua, sin afectar rendimientos. Por otra parte esta práctica se utiliza ampliamente en la producción de vinos de calidad. Durante el seminario se realizó también un análisis crítico ala técnica de secado parcial de raíces (PRD), la cual consiste en regar alternadamente el sistema radicular del las plantas por un lado y por otro. De esta forma se postula que el lado que no recibe riego permite que las raíces generen señales bioquímicas que controlen las pérdidas por transpiración al inducir cierr de estomas, sin afectar los calibre y productividad del cultivos, utilizando menores volúmenes de agua. Durante el congreso se demostró que este principio no presenta las virtudes postuladas inicialmente. La técnica del RDI en Consecuencia tiene un gran potencial de aplicación en Chile, en particular en el riego de vides viníferas, ya que induce a aumentos en la calidad de los mostos.

El uso de controladores de riego, basados en indicadores fisiológicos es perfectamente aplicable en Chile. De hecho la cámara de presión esta comenzando a ser utilizada por productores de punta, en particular vides para vinos, luego de la introducción realizada por INIA y la difusión de los resultados de investigación en este rubro. Lo mismo esta sucediendo en uva de mesa donde la técnica está siendo implementada por algunas empresas exportadoras. Al mismo tiempo aparece como tecnología incipientes en agricultores de punta el uso de otras herramientas, como es el uso de dendrómetros, la cua es una muy buena técnica, pero esta limitada por los costos de los equipos y por el nivel de conocimiento de fisiología de las plantas que permita una buena interpretación de la información obtenida.

Por otra parte, aparece también la necesidad de retomar estudios sobre evapotranspiración y determinación de coeficientes de cultivo, lo que pasa a ser un aspecto de relevancia nacional, como se discutió con el Jefe del Departamento de Estudios de la CNR, quien asistió a la gira. Este punto es de particular relevancia, dado que el país anualmente realiza inversiones significativas en obras de riego, donde la presencia de redes de estaciones meteorológicas y coeficientes de cultivos, para estimar la evapotranspiración real permitirá cuantificar mejor las obras y tener una mejor aproximación al dimensionamiento de ellas, a parte de las ventajas asociadas al manejo posterior del riego.

6. Contactos Establecidos: presentación de acuerdo al siguiente cuadro:

Institución/Empresa	Persona de Contacto	Cargo/Actividad	Fono/Fax	Dirección	E-mail
U.C. Davis , California	Richard Snyder	Bioclimatologo	(530) 752-4628	University of California, Davis , California 95616, USA	Rsnyder@biomet.ucdavis.edu
U.C. Davis, Kearney Agric. Expe. Center	Larry Willams	Investigador en viticultura	559-646-6593	Kearney Agricultural Center 9240 South Riverbend Avenue Parlier, CA 93648	Williams@uckac.edu
U.C. Davis, Kearney Agric. Expe. Center	D. Goldhamer	Investigador en riego de frutales		Kearney Agricultural Center 9240 South Riverbend Avenue Parlier, CA 93648	Dagoldhamer@ucdavis.edu
IRTA, España	Joan Girona	Inbestigador en riego de frutales		Rovira Roure, 177.25198, Lleida, España	Joan.girona@irta.es
IVIA – España	Juan Ramón Castel	Investigador en riego de frutales		Apartado 46113, Moncada, Valencia, España	Jrcastel@ivia.es
IAS-CSIC- Univerdidad de Córdoba	Elías Fereres	Investigador riego en frutales		Apartado 4084, 14080, Córdoba, España	
Golan Research Inst.	Amos Naor	Investigador en riego de frutales		Rehovot POB 12 Israel	Bravdo@agri.huji.ac.il

7. Detección de nuevas oportunidades y aspectos que quedan por abordar: señalar aquellas iniciativas detectadas en la actividad de formación, que significan un aporte para el rubro en el marco de los objetivos de la propuesta, como por ejemplo la posibilidad de realizar nuevos cursos, participar en ferias y establecer posibles contactos o convenios. Indicar además, en función de los resultados obtenidos, los aspectos y vacíos tecnológicos que aún quedan por abordar para la modernización del rubro.

La ISHS organiza periodicamente semiarios científicos sobre diferentes materias, el próximo año está contemplado el desarrollo de un seminarios internacional fisología de vides ("June 21-25, 2004, Davis, CA (USA): **VII International Symposium on Grapevine Physiology**. Info: Prof. Dr. Larry Williams, 9240 South Riverbend Ave., University of California - Davis, Kearney Ag Center, Departement of Viticulture and Enology, Parlier, CA 93648, USA. Phone: (1)559-646-6500, Fax: (1)559-646-6593, email: williams@uckac.edu)

Por otra parte con los contactos realizados (ver cuadro anterior) quedaron abiertas las posibilidades para elaborar proyectos de investigación.

Por otra parte se ha señalado la necesidad de comenzar a trabajar en determinación de coeficientes de cultivos, para estimar la evapotranspiración real de la plantas, puestos que los que hoy existen y están en uso (Colección de Riego y Drenaje FAO Nº 24 de 1974, y Colección Riego y drenaje FAO Nº 56), pueden presentar errores del orden del 30ª 40%, prticularmente debido a los cambios que se han producido en las variedades, sistemas de conducción y densidades de plantas y condiciones agroclimáticas propias de las diferentes localidades

8. Resultados adicionales: capacidades adquiridas por el grupo o entidad responsable, como por ejemplo, formación de una organización, incorporación (compra) de alguna maquinaria, desarrollo de un proyecto, firma de un convenio, etc.

No se contempla este tipo de resultados. Sin embargo la información adquirida será difundida a través de las acciones de transferencia tecnológica y diferentes cursos que se realizan en riego de diferentes cultivos

9. **Material Recopilado**: junto con el informe técnico se debe entregar un set de todo el material recopilado durante la actividad de formación (escrito y audiovisual) ordenado de acuerdo al cuadro que se presenta a continuación (deben señalarse aquí las fotografías incorporadas en el punto 4):

Tipo de Material	Nº Correlativo (si es necesario)	Caracterización (título)
Abstract de artículos presentados (escrito y CD con formato PDF)		Fourth International Symposium on Irrigation of Horticultural Crops
Archivo de fotos en CD		Fotos en formato jpg
Artículo	1	Photoassimilate distribution in plants and crops
Artículo	2	Correlation among redawn leaf, midday leaf and stem water potential
Artículo	3	Vine water relations, gas exchange an vegetative grwth of seventeen vitis species
Artículo	4	Mineral nutrition of grapevines and fertilization guidelines for California
Artículo	5	Interacction of irrigation an canopy mangement practices on winw grape yield and wine quality
Artículo	6	Comparation of irrigation management strategies to optimize wine grape productivity
Artículo	7	Estimation of irrigation requierements for table grape vineyards
Artículo	8	Water use of young Thompson Seddless grapevines in California
Artículo	9	Water use of mature Thompson Seddless grapevines in California
Boletin	10	CIMIS The California Irrigation Management System

10. Aspectos Administrativos

10.1. Organización previa a la actividad de formación

a. Conformación del grupo

_____ muy dificultosa _____ sin problemas __x__ algunas dificultades

(Indicar los motivos en caso de dificultades)

Cambio de la conformación del grupo por parte del FIA. Problemas en la incorporación del profesional de INDAP sugerido por FIA, por no contar con visa para USA

b. Apoyo de la Entidad Responsable

___x_ bueno _____ regular _____ malo

(Justificar)

c. Información recibida durante la actividad de formación

___x_ amplia y detallada _____ aceptable _____ deficiente

d. Trámites de viaje (visa, pasajes, otros)

_____x bueno _____ regular _____ malo

e. Recomendaciones (señalar aquellas recomendaciones que puedan aportar a mejorar los aspectos administrativos antes indicados)

10.2. Organización durante la actividad (indicar con cruces)

Ítem	Bueno	Regular	Malo
Recepción en país o región de destino	x		
Transporte aeropuerto/hotel y viceversa	x		
Reserva en hoteles	x		
Cumplimiento del programa y horarios	x		

En caso de existir un ítem Malo o Regular, señalar los problemas enfrentados durante el desarrollo de la actividad de formación, la forma como fueron abordados y las sugerencias que puedan aportar a mejorar los aspectos organizacionales de las actividades de formación a futuro.

11. Conclusiones Finales

El seminario, de cinco días de duración abarcó una amplia gama de temas, relevantes en el riego de los cultivos: evapotranspiración, control de riego (uso de potencial hídrico xilemático, de uso de dendrómetros) y estrategias de riego para economía de agua y calidad de productos, como son las técnicas de RDI y PRD. Sobre estos aspectos se pudo lograr una amplia información y visiones diferentes respecto de la pertinencia de cada técnica

El programa de formación financiado por FIA cumplió con los objetivos planteados. Permitió a los participantes realizar una puesta al día en aspectos relevantes del manejo de riego en cultivos hortofruticolas. Al mismo tiempo se establecieron contactos con investigadores de alto nivel, con miras a establecer futuros proyectos

Por otra parte, las actividades realizadas permiten la generación de nuevas ideas de investigación en manejo de riego en frutales y vides, en particular en determinación de requerimientos hídricos (determinación de coeficientes kc) controladores de riego, basados en indicadores fisiológicos.

11. **Conclusiones Individuales**: anexar las conclusiones individuales de cada uno de los participantes de la actividad de formación, incluyendo el nivel de satisfacción de los objetivos personales (no más de 1 página y media por participante).

Se incorporan en anexo las conclusiones individuales de los asistentes

Fecha: _____

Nombre y Firma coordinador de la ejecución:

Gabriel Selles van Schouwen
Dr. Ingeniero Agrónomo

ANEXOS

ANEXO 1
CONCLUSIONES INDIVIDUALES

Conclusiones Individuales de Gabriel Selles

La Asistencia al IV Symposium on Irrigation of Horticultural Crops, me ha permitido realizar una puesta al día sobre los grandes temas que en el mundo se están realizando respecto al manejo del riego en frutales y cultivos hortícolas.

.Durante los días que duro el Symposium se presentaron mas de 120 trabajos, de muy buen nivel, en las temáticas de evapotranspiración, riego deficitario, controladores de riego y aspectos económicos de salinidad.

Además se realizó una visita de terreno donde se pudo conocer el sistema de programación de riego utilizado en California, y el lisímetro de pesada del Campus de Davis de la Universidad de California. Al mismo tiempo se pudo conocer algunas prácticas de manejo que realizan en algunas especies frutales, como es el riego localizado subsuperficial

Finalmente, la visita al Kearney Agricultural Research Center, en Parlier, permitió conocer los trabajos que el Dr. Larry Williams, fisiólogo de vides, está realizando en variedades viníferas y de mesa, así como también los trabajos que realiza en control de riego con cámara de presión.

Por otra parte se pudo realizar una serie de contactos con investigadores de diferentes países en el tema de riego en frutales.

En resumen, la gira tecnológica de Formación para la Innovación en "Actualización en manejo de riego y relaciones hídricas en frutales", cumplió plenamente con los objetivos propuestos

Gabriel Selles van Schouwen
Dr. Ingeniero Agrónomo
INIA – La Platina

GOBIERNO DE CHILE
Comisión Nacional
de Riego

INFORME VISITA TECNICA – USA – DE NELSON PEREIRA MUÑOZ

1.- Objetivos del viaje:

Participar en una gira técnica sobre "Actualización en manejo de riego y relaciones hídricas en frutales", financiado parcialmente por FIA, código FIA-FP-V-2003-1-A-019.

2.- Actividades realizadas:

2.1 Participación en el "Cuarto Simposium Internacional sobre Riego en Frutales", organizado por la International Society for Horticultural Science y efectuado en la Universidad de California, Davis.

Se destaca el gran nivel de los trabajos presentados, que me permitió actualizar mis conocimientos profesionales sobre el manejo del riego, economía del agua y respuesta al stress hídrico, fundamentalmente de los frutales. Permitió tener una visión global de estos temas a nivel mundial, dada la amplia gama de países expositores. Lo anterior será de gran utilidad para mi trabajo habitual en la Comisión Nacional de Riego.

Sirvió para estrechar relaciones con otros países en el ámbito del riego. En este sentido, se resalta el hecho que la delegación chilena, con el patrocinio de la Universidad de Talca y la Comisión Nacional de Riego, postuló a Chile como sede de la realización del Quinto Simposium Internacional sobre Riego en Frutales. Lamentablemente la postulación chilena se perdió sólo por tres votos, resultando ganador Australia. Chile recibió fuerte apoyo de varios países, entre los cuales cabe mencionar, por su efectiva participación a España y Portugal.

La sede de este simposium, la Universidad de California, Davis, permitió conocer las instalaciones de esta Universidad, los trabajos de investigación que se realizan en el ámbito del riego y contactos con destacados profesores que están entre los mejores del mundo en el conocimiento y aplicación de las últimas técnicas del manejo del riego.

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2.2 Sistema de Información para el manejo del Riego en California.

Se tomó conocimiento del Sistema de Información para el Manejo del Riego en California (CIMIS, California Irrigation Management Information System) que a través de más de 150 estaciones agrometeorológicas a lo largo del Estado de California, provee de información sobre la Evapotranspiración de Referencia para la programación del riego y el manejo del agua disponible para los agricultores a través de Internet. Los conocimientos adquiridos, serán de gran utilidad en la implementación de un sistema de información similar que la CNR ejecutará en el valle de Limarí, IV Región durante el año 2004.

2.3 Visita Técnica Estación Experimental de Kearny, Universidad de California, en Fresno.

Se conocieron los últimos adelantos en técnicas de manejo de cultivo y de riego en vides. Fue anfitrión el Dr. Larry Williams, experto de categoría mundial en el manejo de vides.

2.4 Visita Técnica Napa Valley.

Se efectuó un recorrido técnico por el Napa Valley, reconocido por el desarrollo de sus plantaciones de vides viníferas, donde se obtuvo una visión general sobre el manejo de este tipo de cultivo.

Nelson Pereira Muñoz
Jefe Departamento de Estudios y Políticas de Riego
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ANEXO 2
DOCUMENTACION RECOPILADA

Photoassimilate Distribution in Plants and Crops

Source–Sink Relationships

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Grape

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I. INTRODUCTION

Grape and wine production has played an important part in Western civilization. Today, grapevines are the number one fruit crop planted worldwide (Mullins et al. 1992). The species *Vitis vinifera* L. accounts for more than 90% of all cultivars planted. Grapes are used for wine, distilled liquors, juice, dried fruit (raisins), fresh consumption (table grapes), and concentrate. Climatic conditions, the end use of grapes, and the means used to harvest them dictate the production practices employed by those who grow grapevines. The ultimate goal of these practices is to produce grapes of high quality, although quality factors can very with type of grape being produced. For example, berry size and sugar/acid ratio are the primary quality factors used to determine harvest date of table grapes; flavor components and high sugar concentrations are quality factors used to harvest wine grapes. In many instances high yields and sugar concentrations are required when grapes are used for raisins or bulk wine production. The production practices used to maximize these quality attributes or yield can have significant effects on source–sink relationships of grapevines.

This chapter deals primarily with source–sink relationships of vines grown in the field, when possible. In addition, specific points are illustrated with various sets of unpublished data collected by the author. Much of what is presented provides quantitative data on vine growth. Thorough reviews of the basic biological characteristics of grapevines (Mullins et al. 1992) and the effects of environmental factors on vine physiological processes (Williams et al. 1994) have recently been published and can be used for further reference.

II. SOURCES OF CARBOHYDRATES

A. Photosynthesis

1. Contribution by Leaves

The C_3 pathway of photosynthesis occurs in gravevines. Therefore, the response of grapevine leaf photosynthesis to various environmental factors is similar to that of other C_3 plant species (Williams et al. 1994). Reported maximum individual leaf net CO_2 assimilation rates for *V. vinifera* and other *Vitis* species approach 20 μmol m^{-2} s^{-1} (During 1991; Gamon and Pearcy 1990; Kriedemann et al. 1970; Liu et al. 1978; Roper and Williams 1989). More commonly reported maximum rates fall in the range of 8

to 13 μmol CO_2 m^{-2} s^{-1} (Archer and Strauss 1990; Correia et al. 1990; Downton et al. 1987). Photorespiratory loss of CO_2 in unstressed grapevines ranges from 13% to 20% of the net CO_2 assimilation rate (During 1988, 1991).

The primary environmental factor limiting maximum rates of individual leaf photosynthesis of nonstressed vines on a diurnal basis is solar radiation (Kriedemann and Smart 1971). In addition to position within the canopy of an individual leaf, age determines its maximum rate of CO_2 assimilation (Kriedemann et al. 1970; Williams and Smith 1985). Schultz (1991) determined the influence of both leaf age and position in the canopy with regard to their CO_2 balance. There was a positive daily carbon balance of both immature and mature leaves irrespective of position in the canopy (Table 1). This study provided important data regarding the contribution of young leaves and shaded leaves to the carbon balance of the entire grapevine. In addition, Buttrose (1966) demonstrated that photosynthesis of shoots on grape cuttings was able to meet growth and respiration demands 17 days after bud break. At this time total leaf area of the shoot was approximately 50 cm^2.

Estimates of whole vine photosynthesis have been determined by modeling or measuring both light interception at the canopy surface and its attenuation within the canopy, the amount of leaf area exposed to those light levels, and the relationship between light intensity and leaf CO_2 assimilation. Smart (1974) concluded that a high proportion of whole vine CO_2 assimilation was due to the interception of direct light, though according to his calculations only 19% of the canopy was illuminated by direct solar radiation. Twelve estimates of canopy assimilation per projected ground area in that study averaged 0.084 mol CO_2 m^{-2} h^{-1} with a maximum value of 0.102 mol CO_2 m^{-2} h^{-1}. Assuming that the ground area subtended by foliage intercepting light in that study was approximately 4 m^2, the average and maximum values of whole vine photosynthesis would be 0.34 and 0.41 mol CO_2 h^{-1}, respectively. The greatest midday value of whole vine photosynthesis estimated by Downton and Grant (1992) for a spur-pruned cultivar was 0.41 mol CO_2 h^{-1}. Maximum photosynthetic capability by those vines was calculated to be 2.56 mol CO_2 $vine^{-1}$ day^{-1} at fruit harvest. Modeled estimates of maximum whole vine photosynthesis were approximately 1.7 mol CO_2 $vine^{-1}$ day^{-1} for vines grown in Switzerland (Wermelinger et al. 1991). The preceding results indicate the variability in whole vine carbon assimilation due to vine size and location where the vines are grown.

The diurnal assimilation of CO_2 by a hypothetical grapevine grown in the San Joaquin Valley, planted in east–west rows, is shown in Fig. 1. This estimate of CO_2 assimilation was based upon the response of grape leaf photosynthesis to light intensity and the amount of solar radiation intercepted by the top, north, and south curtains of the canopy in June (data taken from Figs. 4.2 and 6.2, respectively, in Mullins et al. 1992). The canopy was divided into sunlit and shaded leaf area by using the technique of Williams et al. (1993). Maximum CO_2 assimilation by the canopy at midday was approximately 0.5 mol $vine^{-1}$ h^{-1}, a value comparable to estimates of Smart (1974) and Downton and Grant (1992). The

Table 1 Daily, Estimated Carbon Balance of White Riesling Leaves on a Cloud-Free Day During Midseason[a]

	CO_2 Uptake, mmol day^{-1}		*CO_2 Respired, mmol $night^{-1}$*		*CO_2 Balance, mmol 24 h^{-1}*	
Leaf age[b]	*Sun*	*Shade*	*Sun*	*Shade*	*Sun*	*Shade*
Immature	*165*	*59*	*26*	*16*	*139*	*43*
Mature	*361*	*48*	*9*	*3*	*352*	*45*

[a]Carbon balances were calculated for leaves exposed to direct solar radiation and those growing in the shade.
[b]Immature leaves represent leaves of leaf plastochron indices from 0 to 4. Mature leaves represent leaves of LPIs 6 or greater. Values are expressed on a per square meter leaf area basis. LPI, leaf plastochron index.
Source: Adapted from Schultz 1991.

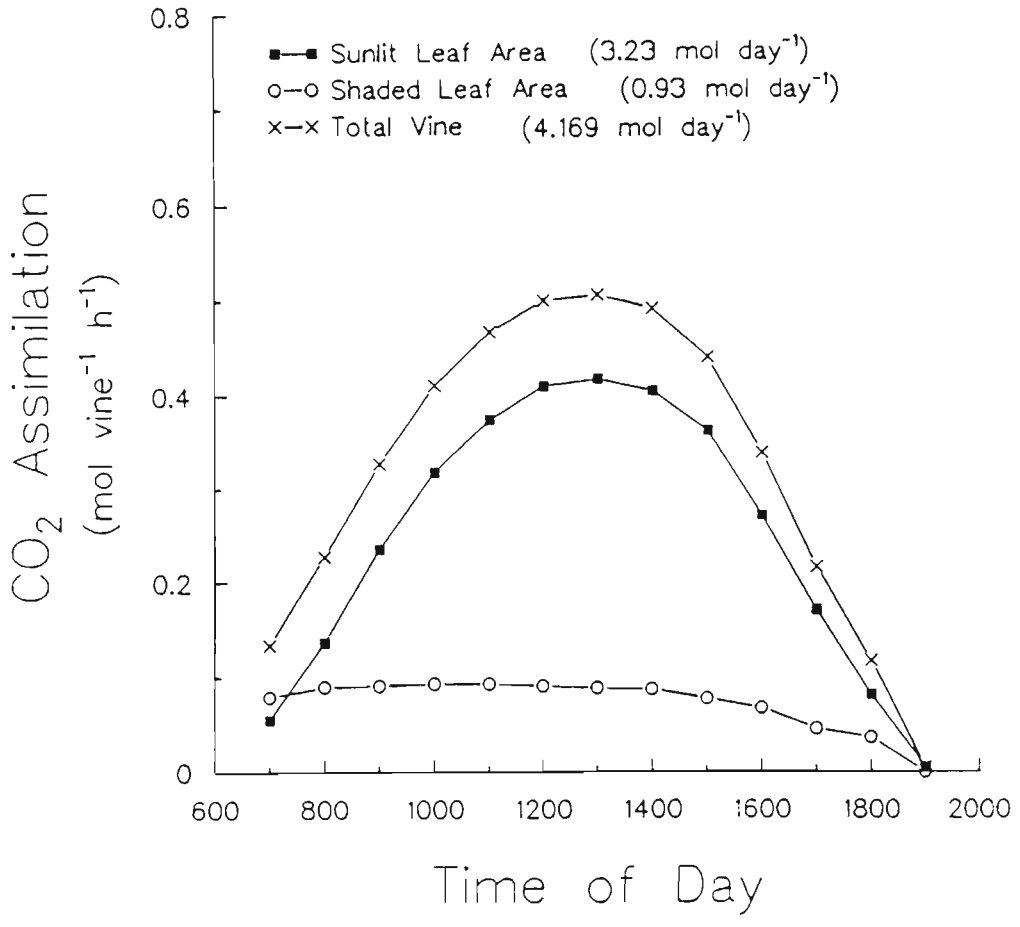

Figure 1 Estimated total vine CO_2 assimilation of a Thompson Seedless grapevine with a full canopy on a cloudless day in June. See text for further details.

daily, estimated amount of CO_2 assimilated by the vine (with 22.3 m^2 leaf area per vine) was 63% greater than that estimated by Downton and Grant (with 23.8 m^2 leaf area per vine). It is interesting to note that 22% of the daily assimilation of CO_2 was contributed by the interior leaves. Smart (1974) calculated that approximately 30% of a canopy's photosynthesis was contributed by leaf area intercepting diffuse light.

2. *Contribution by Other Organs*

Other aerial organs of the grapevine contain chlorophyll, indicating the possibility of photosynthetic activity. Photosynthesis was detected in both immature and mature stems (main axis of the shoot) of grapevines (Kriedemann and Buttrose 1971). Immature stems were able to reduce respiratory CO_2 efflux by 70% in diffuse light and 89% in diffuse + reflected solar radiation. Mature stems (i.e., with periderm) refixed 13% of the respiratory CO_2 efflux. Kriedemann and Buttrose concluded that immature stems are able to refix the bulk of respired CO_2, even if shaded by a leaf. They also hypothesized that after leaf fall, photosynthesis within the stem could compensate for approximately 10% of respiratory carbon loss at 25°C and even greater amounts at lower temperatures.

Organs of the grape cluster also contain chlorophyll and are covered with stomata (Blanke and Leyhe 1987, 1989). In addition to the C_3 pathway of photosynthesis, fruit possess a system which refixes respiratory CO_2 via phospho*enol*pyruvate carboxylase (E.C. 4.1.1.31) (Blanke and Lenz 1989). There is

a net uptake of CO_2 in the light by grape flowers 2 weeks before to anthesis; however, subsequent measurements before anthesis indicate that respiratory losses exceed uptake (Leyhe and Blanke 1989). Photosynthesis by grape berries after set is capable of refixing anywhere from 10% to 90% of the respiratory CO_2 loss in the light; the percentage is dependent upon growth stage (Frieden et al. 1987a; Geisler and Radler 1963; Koch and Alleweldt 1978; Kriedemann 1968). Reported rates of CO_2 assimilation vary from 600 μg CO_2 g^{-1} fresh weight (FW) h^{-1} shortly after anthesis to less than 10 μg CO_2 g^{-1} FW h^{-1} close to fruit maturity. Photosynthesis expressed on a per berry basis ranges from 10 to 120 μg CO_2 h^{-1}.

B. Reserves

The permanent structures of the grapevine are the primary sources of reserve carbohydrate for this perennial crop in the absence of shoots. The relative and absolute amounts of nonstructural carbohydrates have been determined for grapevine, with the results demonstrating seasonal variations in both (Mullins et al. 1992; Winkler and Williams 1945). The absolute amount of nonstructural carbohydrates in vines differs according to cultivar, vine size, age, crop load, environmental conditions, cultural practices, and presence of viral diseases. For example, total nonstructural carbohydrate in the roots, trunk, and cordons of 10-year-old Chenin blanc vines at budbreak was 798 g $vine^{-1}$ compared to 1913 g $vine^{-1}$ for 25-year-old Chenin blanc vines grown at a different location (Mullins et al. 1992; see tables 4.2 and 6.6 in that reference). Thompson Seedless grapevines of different ages grown at the same location using similar cultural practices had 173 and 447 g of nonstructural carbohydrates $vine^{-1}$ in the roots and trunk for vines aged 5 and 20 years, respectively, when harvested on the same date (unpublished data). Root + trunk dry biomass of the 20-year-old vines (3706 g dry wt $vine^{-1}$) was 2.38 times greater than that of the 5-year-old vines. A recent study investigated the influence of pruning method and virus inoculation on the accumulation of carbohydrate reserves in the permanent structures of Cabernet franc grapevines (Ruhl and Clingeleffer 1993). They found that total nonstructural carbohydrates in the permanent structures during dormancy varied from 1680 to 2216 g $vine^{-1}$, depending upon the pruning method. Inoculation of vines in that study with virus reduced total vine carbohydrate amounts in the permanent structures approximately 15% compared to those of the control. The reduction in carbohydrate amount of virus-inoculated vines was due mainly to a reduction in biomass production and not to differences in carbohydrate concentrations.

A data set collected on Thompson Seedless grapevines grown in the San Joaquin Valley of California provides an estimate of the seasonal dynamics of reserve carbohydrates in the permanent structures of the vine (Figs. 2 and 3). From the first of the calendar year until close to fruit harvest the concentration of soluble sugars decreased in both the trunk and the root system (Fig. 2). The starch concentration decreased in the trunk from budbreak until harvest and subsequently increased. The starch concentration in the root system generally increased from budbreak until harvest and then decreased. The seasonal patterns of sugar and starch concentrations in the trunk found here resemble data collected by Winkler and Williams (1945). However, the root data of these Thompson Seedless vines differ greatly from their data. It should be pointed out that a second year's data set collected on vines in the same Thompson Seedless vineyard resembled data found during the first year (Fig. 2). Both the root system and the trunk of these 5-year-old vines contained similar amounts of nonstructural carbohydrate reserves in January (Fig. 3). They both lost approximately 175 g $vine^{-1}$ between January and anthesis. The amount of carbohydrates in the two organs differed considerably after anthesis. These data illustrated that carbohydrate reserves were lower at anthesis than at any other time of the season followed by an increase. The Chenin blanc data (Mullins et al. 1992) also indicted that there was little increase in carbohydrate reserves in the permanent structures until after anthesis.

The current season's vegetative organs may also serve as a source of nonstructural carbohydrates in

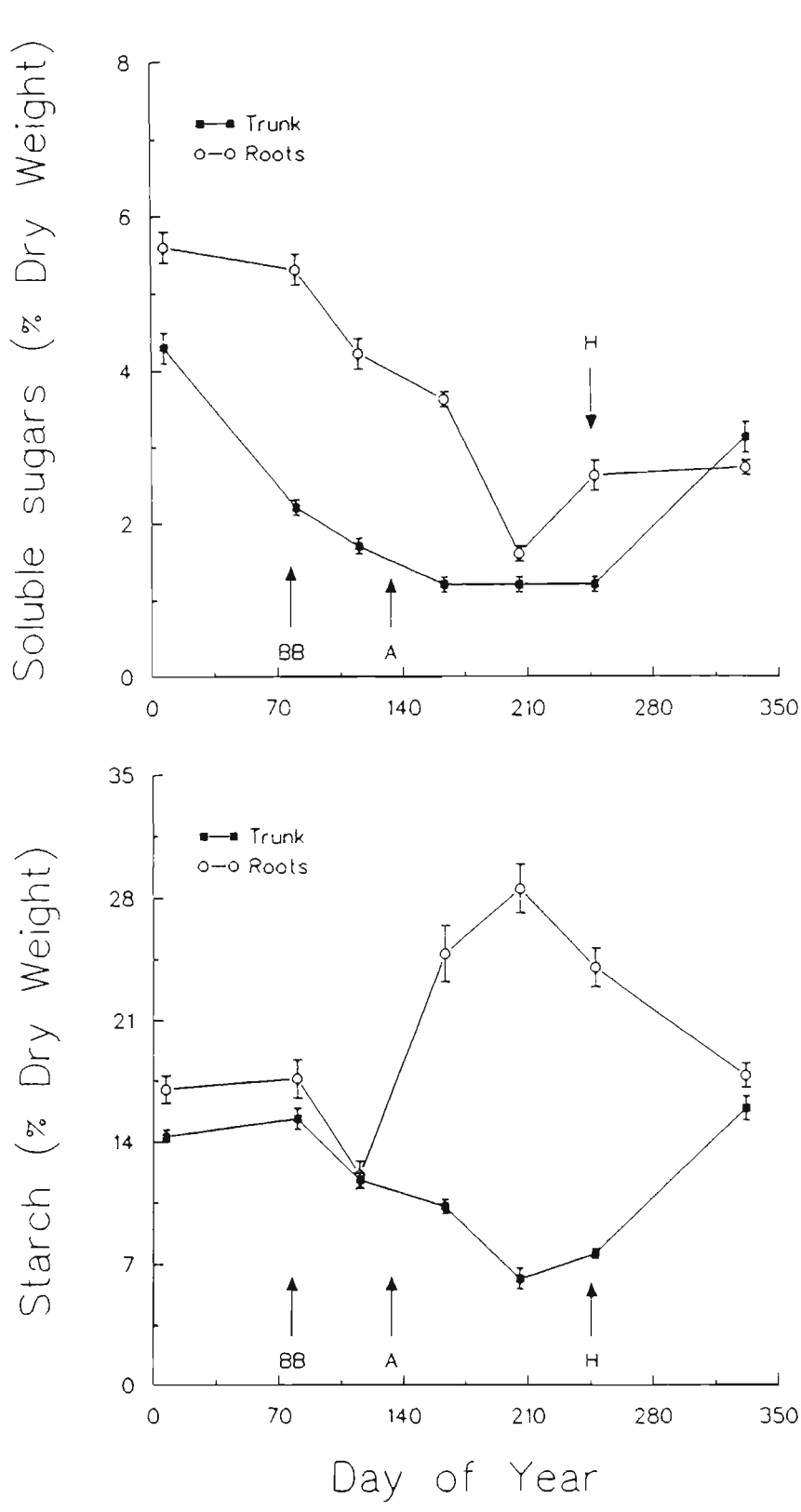

Figure 2 The seasonal change in starch and soluble sugar concentrations of the trunk and root system of Thompson Seedless grapevines. Each data point is the mean of at least six individual vine replicates with bars representing ± one standard error. Glucose, fructose and sucrose comprise the soluble sugars. BB, A, and H represent the dates of 50% budbreak, anthesis, and fruit maturity, respectively.

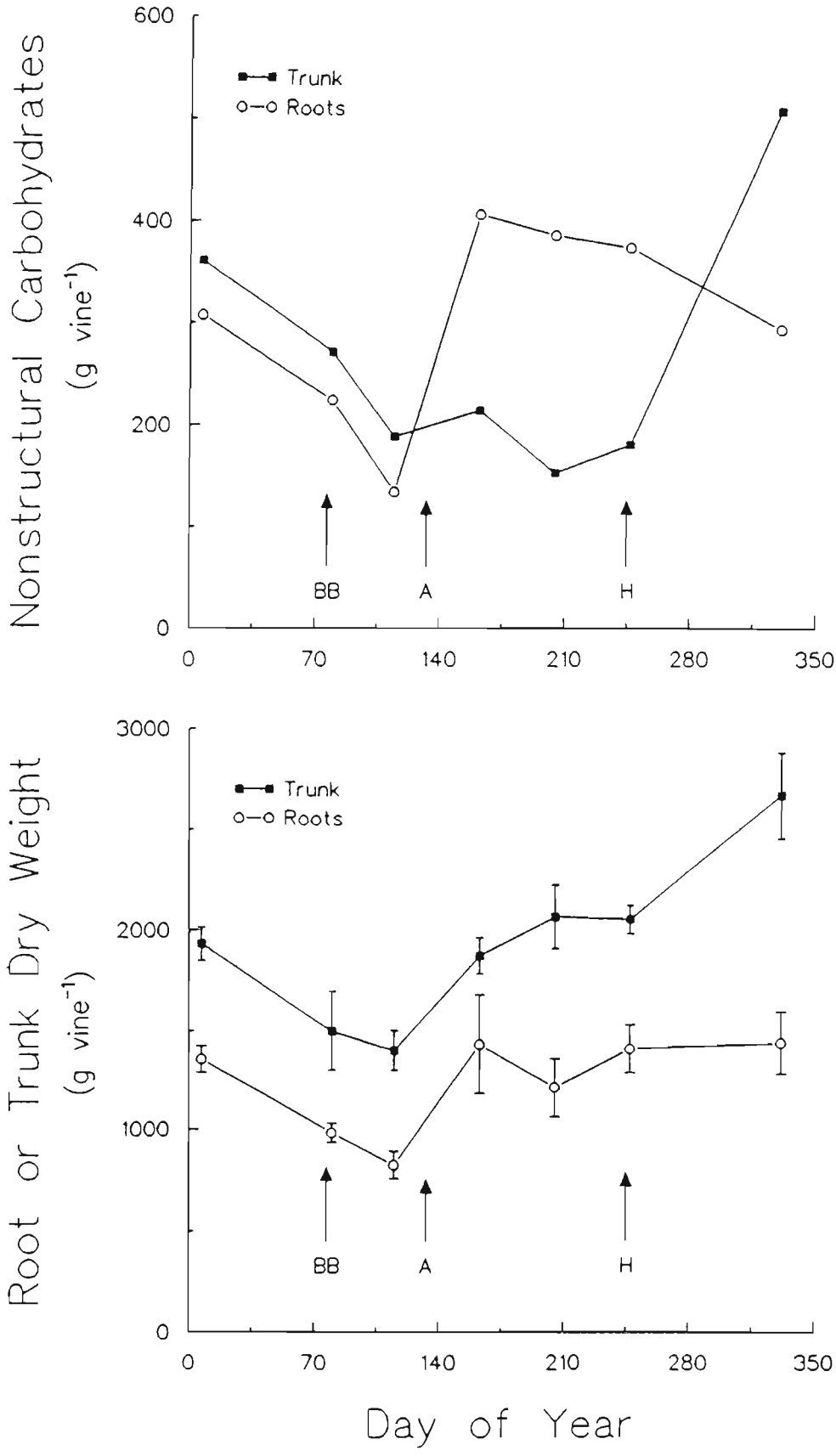

Figure 3 The seasonal change in root and trunk dry weight and total nonstructural carbohydrates of Thompson Seedless grapevines. Other information as in Fig. 2

the grapevine. The concentration of reducing and nonreducing sugars and starch in leaves varies slightly during the day (Roper and Williams 1989) and throughout the season (Kliewer and Nassar 1966; Winkler and Williams 1945). The greatest amount of nonstructural carbohydrates in leaves reported in the literature varied from 45 to 91 g $vine^{-1}$, depending upon time of year (Mullins et al. 1992; Roper and Williams 1989). While the amount of nonstructural carbohydrates found within the current season's growth of the stems will vary with canopy size and time of year, reported values range from 38 to 194 g $vine^{-1}$ (Ruhl and Clingeleffer 1993; Mullins et al. 1992; Roper and Williams 1989).

III. PARTITIONING OF CARBOHYDRATES WITHIN THE LEAF

The metabolism and transport of carbohydrates within the grape leaf are probably similar to those described for other C_3 plant species (Hawker et al. 1991). Leaf age and time during the growing season influence the concentrations of reducing and nonreducing sugars and starch in grape leaves. Kliewer (1966) found that the concentration of glucose and fructose in the leaves of field-grown grapevines increased from unfolding until the individual leaf had expanded to one third of its final leaf area, after which their concentrations leveled off. The glucose/fructose ratio of leaves generally is greater than 1 and sometimes approaches values greater than 2. The concentration of sucrose usually is less than that of either glucose or fructose. The concentration of sucrose in leaf tissue also increases as the leaf ages (Kliewer and Nassar 1966; Sepulveda and Kliewer 1986). In the latter study the concentration of leaf sucrose increased as growth temperature increased. However, it has been shown that increasing growth temperatures decreases the concentration of starch in grape leaves (Buttrose and Hale 1971). The decrease in starch concentration is offset to some extent by an increase in total lipid concentration. Nonstructural carbohydrates in grape leaves increase as a result of CO_2 enrichment when compared to those of vines grown under ambient CO_2 pressures (Johnson et al. 1982). The concentration of starch found in the leaves of grapevines grown in warm environments ranges from 14 to 73 mg g^{-1} dry wt when measured on individual leaves (Roper and Williams 1989; Fig. 4) and from 0 to 93 mg g^{-1} dry weight when all leaves on a vine are sampled (Mullins et al. 1992; Roper and Williams 1989). Values can be considerably higher when vines are girdled to increase berry size (Roper and Williams 1989).

The accumulation of starch in the chloroplasts during photosynthesis is assumed to be an important reserve of carbohydrate for the plant. Starch accumulation in the leaf during the light and its degradation the ensuing evening have been demonstrated by using annual plants grown in environmentally controlled growth chambers (Allen et al. 1988; Potter and Breen 1980) and outdoors (Millhollen and Williams 1986). There appears to be only a slight increase during the day in either sugar or starch concentrations in sunlit leaves of girdled and nongirdled grapevines grown in the field (Fig. 4). The amount of CO_2 assimilated by the sunlit leaves of the control and girdled vines between 800 and 1600 h that day was 0.54 and 0.36 mol m^{-2}, respectively (unpublished data; see also study by Roper and Williams 1989, demonstrating the diurnal pattern of grape leaf photosynthesis in response to girdling). This is equivalent to 0.36 and 0.24 g carbohydrate produced g^{-1} dry wt for the control and girdled vines, respectively. The weight per unit leaf area used to calculate these relationships was assumed to be 45 g m^{-2} (Williams 1987a). The relative constancy of nonstructural carbohydrates during daylight may be due to the fact that an individual leaf, even on the exterior of the canopy, is exposed to direct light only during a small portion of the day. This may be due to mutual shading, leaf angle, row direction, and diurnal course of solar radiation. Another possible explanation is that in woody perennial crops, with significant carbohydrate reserves in the permanent structures, the leaves are not important in supplying carbohydrates to the plant during the evening. The preceding data also indicate that the photosynthate produced in the leaves of these vines was rapidly transported out of the leaf under the conditions of the experiment.

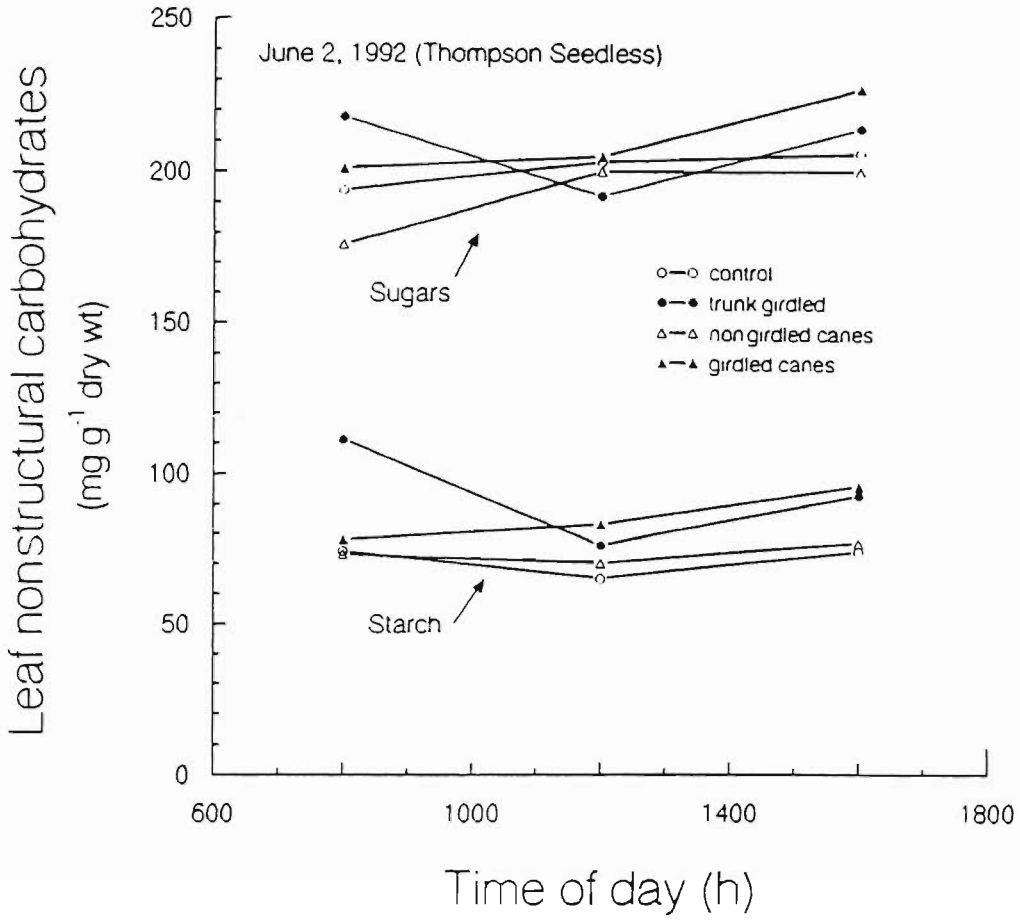

Figure 4 The diurnal change in leaf nonstructural carbohydrates of Thompson Seedless grapevines. Treatments include a control, vines that were trunk-girdled, and vines in which one-half of the fruiting canes were girdled and the other half were not girdled. The upper set of data points are the soluble sugars and the lower set starch. Each value is the mean of six individual leaf replicates. Leaves were killed in liquid nitrogen and then lyophilized. Carbohydrates were determined as described by Roper and Williams (1989).

IV. WHOLE VINE CARBON PARTITIONING

A. Cycle of Vine Growth

1. Seasonal Aerial Vegetative Growth

Shoot growth of grape is initiated in the spring from compound buds, which consist of one primary and two secondary buds. The primary bud usually contains 10 to 12 leaf primordia along with 1 to 2 cluster primordia, located opposite leaf primordia at node positions three to six from the base. Shoot growth generally is initiated from the primary bud and occasionally one of the secondary buds also grows. Secondary bud growth is initiated in the event that the primary bud dies or the primary shoot dies, as occurs after a spring freeze. A low amount of chilling may be needed in breaking dormancy of *V. vinifera* (Antcliff and May 1961). Budbreak generally occurs when the daily mean temperature exceeds 10°C. Subsequent growth of the shoot is dependent upon environmental factors, management practices, and disease or pest problems. The base temperature for vegetative growth has been observed to range from 5°C to 8°C (Moncur et al. 1989). Degree day summations (base temperature >10°C) have also been used successfully to predict the time between various phenological events (Williams et al. 1985b; Williams 1987b). The total number of shoots that develop on a vine is primarily determined by the pruning pattern.

The rate of shoot elongation is greatest early in the growing season and then steadily decreases thereafter (van Zyl 1984). The increase in stem length is sigmoidal when expressed as a function of either calendar days (De La Harpe and Visser 1985) or degree day summations (Williams 1987a). The increase in dry mass of shoots is almost linear until fruit set occurs, with subsequent shoot growth diminishing or leveling off (Gutierrez et al. 1985). Weight per unit stem length, however, continues to increase (Williams 1987a). The amount of biomass partitioned to stems of the same cultivar differs among vineyards (Williams et al. 1985a). In addition, pruning method determines the amount of biomass found in the current growing season's stems. The amount of biomass partitioned to the stems declines as the number of shoots per vine increases (Clingeleffer and Krake 1992). Shoot orientation also influences the partitioning of biomass to the main stem (Kliewer et al. 1989). Shoots positioned downward had less stem biomass than those positioned vertically or horizontally in that study. Finally, the indeterminate growth habit of *Vitis* species, the use of different trellis systems, and the need to drive equipment down the rows in the vineyard may necessitate summer pruning or hedging of the canopy. The loss of shoot dry matter due to summer pruning in modeling grape growth is set at 10% to 25%; the percentage depends upon when hedging takes place (Wermelinger et al. 1991; Williams et al. 1985a).

A similar type of pattern to that described for shoot (stem) growth can also be observed for the increase of leaf weight and area per vine for mature vines (Wermelinger and Koblet 1990; Williams 1987a). Weight per unit leaf area increased linearly as the season progressed in both of the studies mentioned. The increase in weight per unit leaf area is not associated with an increase in nonstructural carbohydrate concentration (unpublished data). Seasonal increments in leaf biomass and leaf area per vine are dependent upon vine age and pruning pattern. Araujo and Williams (1988) found that leaf biomass and area increased throughout the growing season for 2-year-old vines (as the vines were trained up the stake). Leaf biomass and area were shown to increase throughout the season for nonirrigated Cabernet Sauvignon vines grown in the Napa Valley of California (Williams and Biscay 1991). Leaf area development increased more rapidly for minimally pruned vines than for those that were spur-pruned (Downton and Grant 1992). Leaf area per vine 1 month after budbreak was five times greater for the minimally pruned than for the spur-pruned vines. Thus, the concept of a typical pattern of leaf area development of vines under all conditions and situations may not be valid.

The development of the canopy and its size is dependent upon the rate of leaf area expansion, shoot growth, and cultural practices that influence the growth of lateral shoots. The production of leaves appears to be a function of temperature, cultural practices, and shoot length. A leaf appearance model of grape, which assumed that appearance rate was dependent upon temperature and that it declined for each subsequent leaf formed, predicted leaf appearance of three of four cultivars grown in the Chianti region of Italy (Miglietta et al. 1992). Leaf initiation rate differed on shoots of Cabernet Sauvignon grapevines when the shoots were oriented in various directions (Kliewer et al. 1989). The growth rate of expanding leaves (younger than 250 degree days [dd]) was shown to be 4.3 mg dd^{-1} followed by a rate of 0.6 mg dd^{-1} (Wermelinger and Koblet 1990). Thompson Seedless leaves were shown to grow at a rate of 2.74 mg dd^{-1} until they were fully expanded (Williams et al. 1985a). Canopy leaf area development was shown to be linearly related to degree days from budbreak until fruit growth rapidly increases (Williams 1987a).

At full canopy, 30% to 85% of the total leaf area can be found on the outside of the canopy depending upon trellis configuration and row spacing (Downton and Grant 1992; Mullins et al. 1992; Smart et al. 1985; Williams 1987a). The proportion of leaf area from lateral shoots that comprise total vine leaf area varies from a low of 6% to 9% to greater than 50% (Smart et al. 1985; Wermelinger and Koblet 1990). The low amount of lateral shoot leaf area in the former study was probably due to the lack of supplemental irrigations, whereas in the latter study primary shoots were summer-pruned several times during the season, thus releasing apical dominance. Canopy development proceeded much more rapidly for minimally pruned vines than for spur-pruned vines (Downton and Grant 1992). However,

canopy leaf area at the end of the season was approximately 40% greater for the spur-pruned than for the minimally pruned vines. Canopy surface area is greater for vines grown at closer row spacings even though leaf area per vine is less at the closer row spacing (Mullins et al. 1992). Finally, various measures of canopy size and density can vary considerably from one site to another for the same cultivar (Dokoozlian 1990).

2. Growth of the Permanent Aerial Structures

The permanent above-ground organs of grapevines consist of the trunk and cordons (horizontal extension of the trunk). The rate of the trunk's increase in diameter reaches a maximum at anthesis, decreasing afterward with a smaller peak after veraison (van Zyl 1984). Total trunk biomass decreases from the middle of dormancy until anthesis (Fig. 3). Subsequent to anthesis trunk biomass increases for the rest of the growing season. This pattern was observed over two growing seasons (Williams 1991). The initial decrease in trunk dry weight is associated with a decrease in nonstructural carbohydrate content (Fig. 3). Trunk biomass was shown to increase from budbreak until fruit harvest for Chenin blanc grapevines (Mullins et al. 1992). A study on 2-year-old vines showed that the trunk tripled in dry weight from budbreak until the first of September (Araujo and Williams 1988).

The seasonal increment in trunk biomass accumulation varies with growing conditions and genotype. Approximately 527 g dry matter vine^{-1} year^{-1} was partitioned to the trunk of Thompson Seedless grapevines from initial planting until the vines were 7 years of age (Fig. 5). Closer examination of the data points indicates large differences in the yearly accumulation of dry matter in the trunk (i.e., yearly accumulations were greater in 1986 and 1988 than in 1987). When averaged over the 18-year life of Cabernet Sauvignon grapevines grafted onto the rootstock 5C, approximately 240 g dry matter was partitioned to the trunk vine^{-1} year^{-1} (Williams and Biscay 1991).

The amount of biomass partitioned to the cordon depends upon the training system used (i.e., unilateral, bilateral, or quadrilateral cordon system). Most studies that have quantified the biomass of cordons used vines trained to bilateral cordons. Approximately 300 g dry biomass vine^{-1} year^{-1} was partitioned to the trunk and cordons of Chenin blanc vines grafted onto 101-14 Mgt rootstock when averaged over a 12-year period (Saayman and van Huyssteen 1980). Ten-year-old Chenin blanc grapevines grown in the San Joaquin Valley partitioned an average of 638 g dry matter vine^{-1} year^{-1} to the trunk and cordons (Mullins et al. 1992). A similar value (612 g dry matter partitioned to trunk and cordons vine^{-1} year^{-1}, calculated from fresh weight data and a dry/fresh weight ratio of 0.45) was obtained for 15-year-old spur-pruned Cabernet franc grapevines grown in the Murray River Valley of Australia (Clingeleffer and Krake 1992).

3. Growth of the Root System

Studies examining the growth of grapevine roots have quantified the periodicity of new root initiation and turnover (Freeman and Smart 1976; McKenry 1984; van Zyl 1984). Results from these studies demonstrate that a flush of root growth occurs shortly after shoot growth begins in the spring, peaking at anthesis. New root initiation decreases rapidly, with few new roots seen between fruit set and harvest. A second, major flush may begin after fruit harvest. Root biomass of Thompson Seedless grapevines decreases during the period from the middle of the dormant portion of the season until anthesis (Fig. 3). As with the trunk, some of the decrease in weight is due to a decrease in nonstructural carbohydrates (Fig. 3). The decrease may also be associated with root death and turnover. After anthesis there is a significant increase in root biomass. The increase in root biomass through the season in this study corresponds to some extent to the observed root flushes. It should be emphasized, however, that root biomass increased throughout the season for young Thompson Seedless grapevines (Araujo and Williams 1988), mature Cabernet Sauvignon grafted on 5C (Williams and Biscay 1991), and own-root

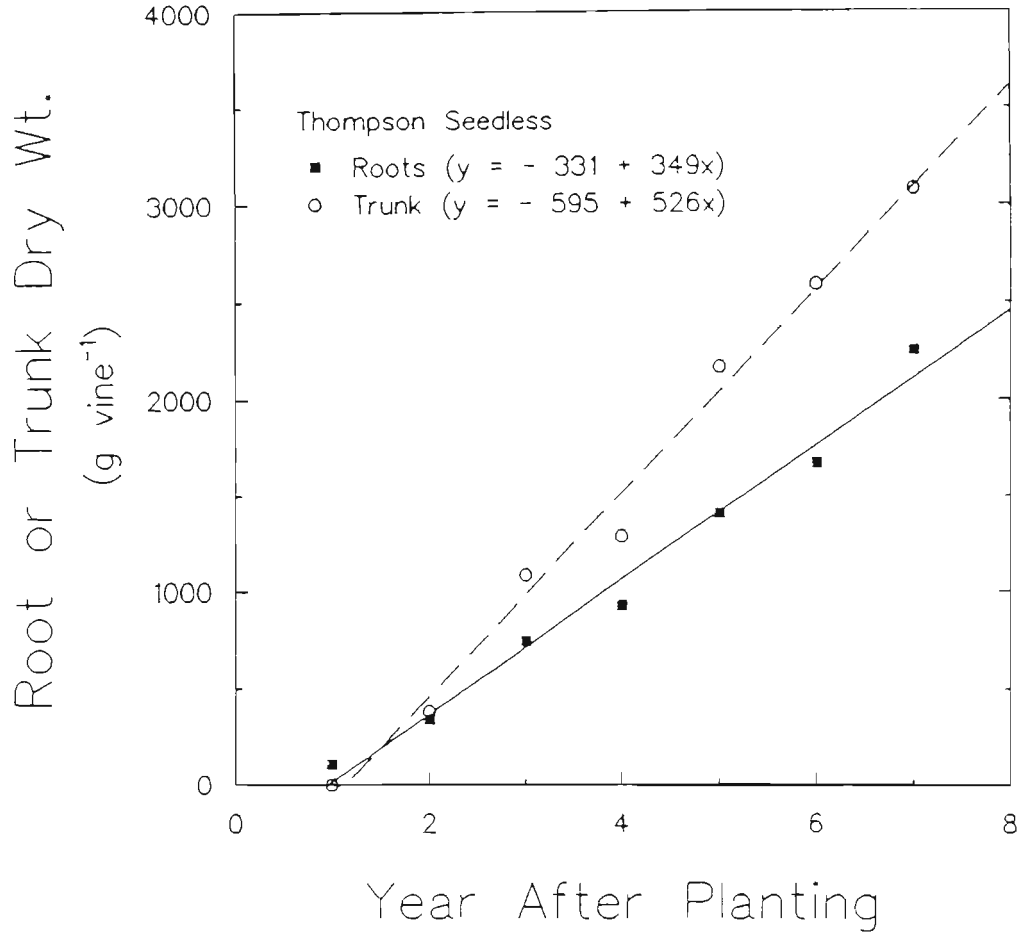

Figure 5 The accumulation of root or trunk biomass of Thompson Seedless grapevines from the time the cuttings were planted through seven growing seasons. Vine and row spacings were 2.44 and 3.66 m, respectively. Biomass was determined each year approximately the first week in September or at fruit maturity. Each value is the mean of six individual vine replicates.

Chenin blanc grapevines (Mullins et al. 1992). These studies would indicate that the seasonal dynamics of root biomass partitioning depend upon the age of the vine and perhaps the cultivar and may not reflect observed root flushes.

The partitioning of biomass to the roots of Thompson Seedless grapevines averaged approximately 350 g dry weight vine^{-1} year^{-1} from the time of planting until the vines were 7 years old (Fig. 5). Up to 20% of this biomass may be nonstructural carbohydrates. Approximately 360 g dry wt vine^{-1} year^{-1} (determined by dividing root biomass by vine age) is the average partitioned to the roots of the Chenin blanc–101-14 Mgt. scion–rootstock combination (Saayman and van Huyssteen 1980). A value of 262 and 130 g dry wt vine^{-1} year^{-1} is the average yearly increment in biomass partitioned to the roots of Chenin blanc–own roots and Cabernet Sauvignon–5C, respectively (Mullins et al 1992; Williams and Biscay 1991). Whole vine harvests of Thompson Seedless grapevines of various ages (from initial planting to vines more than 30 years old) at the University of California Kearney Agricultural Center indicate that the partitioning of biomass to the root system is 60% of that partitioned to the trunk (Fig. 6). Biomass partitioning to the root system of another cane-pruned cultivar was approximately 50% of that partitioned to the trunk when averaged across all harvest dates and rootstock combinations (Williams and Biscay 1991; Williams and Smith 1991). The partitioning of biomass to the root system of Chenin blanc was approximately 40% of that allocated to the trunk + cordons (Mullins et al. 1992); that

fraction was 33% for spur-pruned Cabernet franc (Clingeleffer and Krake 1992). The biomass partitioned to the root system in the Saayman and van Huyssteen study, however, was greater than that partitioned to the trunk + cordons.

4. *Fruit Growth*

Unlike many deciduous tree fruit crops, in which anthesis occurs at budbreak, anthesis in grape does not occur until there is an appreciable vine canopy (Pratt and Coombe 1978; Wermelinger and Koblet 1990; Williams 1987a). The growth of a grape berry does not proceed at a constant rate but rather with periods of ascending and descending growth rates delineated into various phases. Many have characterized berry growth as a double-sigmoid growth curve (Coombe 1976). This type of growth curve has been divided into three, four, and five arbitrarily assigned stages. When three stages are used to describe berry growth, the initial stage (I) consists of rapid growth due to both cell division and expansion. Stage II, a lag phase, is characterized by little berry enlargement; however, maturation of the seed proceeds. The last phase of berry growth (III) is due solely to cell expansion. This phase also is characterized by a massive accumulation of hexose sugars and a decrease in titratable acidity. The double-sigmoid growth curve is also observed for berries of seedless cultivars.

The growth of a berry also can be characterized as occurring in two phases (Staudt et al. 1986). A study reevaluating the double-sigmoid growth curve has concluded that fruit growth of peach (*Prunus persica* L. Batsch) can be divided into two growth stages, based upon relative growth rates (dry weight increment g^{-1} dry weight dd^{-1} or day^{-1}) (DeJong and Goudriaan 1989). Blanke (1992) also concluded that berry growth, based on relative growth rate, can be divided into two growth stages. The lag phase is characterized as a transition between two growth stages rather than a separate growth stage.

The final weight of the flesh of a ripe fruit is determined by cell number, volume, and density. The number and volume of cells at ripeness are influenced by the cell number and volume at anthesis and the subsequent rate and duration of cell division and expansion (Coombe 1976). There are approximately 0.2 million cells in the ovary at anthesis and 0.6 million 40 days later (Harris et al. 1968). Coombe (1976) calculated that the number of cell doublings to achieve these numbers was 17 before anthesis and 1.5 after anthesis. Cell division in the pericarp begins 5 to 10 days before anthesis (Coombe 1960). Harris et al. (1968) concluded that berry pericarp growth was a product of both cell division and expansion up to 3 weeks after anthesis with subsequent growth due to cell expansion alone. Tissue of the pericarp represented 64% of the final volume of the Sultana (syn. Thompson Seedless) berry (Harris et al. 1968).

The majority of berry growth occurs at night. During the day there is no berry expansion; more likely there is contraction (Greenspan 1994). In that study it also was demonstrated that diurnal berry expansion and contraction differed before and after veraison; there was less contraction during the day post veraison. The enlargement of the berry during stages I and II is not associated with dermal tissue extensibility or turgor (Matthews et al. 1987). They also demonstrated that berry expansion subsequent to stage II was not due to changes in berry turgor; however, there was an increase in plastic extensibility of the dermal tissue.

The accumulation of fresh or dry fruit biomass on a whole vine basis occurs rapidly subsequent to berry set. The accumulation of cluster dry biomass has been shown to be a linear function of degree days (Gutierrez et al. 1985; Wermelinger et al. 1991; Williams et al. 1985a; Williams 1987a) and calendar days (Alexander 1958). The accumulation of cluster dry biomass followed a sigmoid curve for Riesling grafted onto rootstock 26G (Lohnertz 1988); it followed an exponential curve for Cabernet Sauvignon grafted onto rootstock 5C (Williams and Biscay 1991); both were based on calendar days. The preceding results indicate that the biphasic growth curve of individual berries is indistinguishable when the growth of all the fruit on a vine is quantified in the field. This may be due to asynchrony in the

growth of individual berries on a cluster and asynchrony in the growth of individual clusters on a vine or to sampling frequency (Coombe, 1992).

5. Daily CO_2 Requirements for Biomass and Carbohydrates

Utilizing the data found in tables 4.1 and 4.2 of Mullins et al. (1992), one can calculate carbon requirements of these grapevines at three stages of vine growth (Table 2). It was assumed that the carbon content of vine dry matter was close to 45% (Downton and Grant 1992). Approximately 98% of the carbon is utilized for dry matter accumulation at anthesis, while during fruit maturation 83% of the carbon is utilized for the accumulation of nonstructural carbohydrates. This demonstrates a shift over the growing season from a vine utilizing carbon for structural purposes to that of a vine accumulating sugars and starch.

B. Source–Sink Relationships in Grape

1. *Fruit as a Sink*

The fruit is the largest sink on the vine once fruit set has occurred (Mullins et al. 1992). The proportion of biomass partitioned to the fruit from budbreak until fruit maturity ranged from 44% to 69% of the total biomass accumulated during that period for Thompson Seedless grapevines (Table 3). This proportion was independent of the cultural practices employed to grow the vines and is probably more a function of the fruitfulness of the canes retained at pruning. The proportion of biomass partitioned to the fruit as a function of standing biomass at fruit harvest is dependent upon the age of the vines and the way in which they were trained. For nonirrigated Cabernet Sauvignon approximately 20% of the standing biomass at harvest was found in the fruit (Williams and Biscay 1991), while for Chenin blanc approximately 30% of the standing biomass was allocated to the fruit (Table 4).

Growth of the fruit after veraison is associated with the uptake of both water and hexose sugars. The uptake of water into the berry after veraison is probably from the phloem sap as there is an apparent loss of xylem function at veraison (During et al. 1987; Findlay et al. 1987). A nearly exclusive role of the

Table 2 The Change in Total Dry Weight and Nonstructural Carbohydrates of Chenin Blanc Grapevines from Budbreak Until Harvest and Calculated Values of CO_2 Uptake Required to Meet Those Demands (g $vine^{-1}$ day^{-1})

			CO_2 required	
Day of year[a]	Δ dry wt	Δ NSC	for dry wt[b]	for NSC[c]
88–147	64.7	1.5	106.8	2.2
148–206	31.0	19.0	51.3	27.9
207–253	10.0	55.3	4.5	81.3

[a]Budbreak, anthesis, and harvest correspond to day of year 88, 141, 253, respectively. Changes in dry wt and NSCs were calculated from tables 4.1 and 4.2 in Mullins et al. 1992. NSC, nonstructural carbohydrate.

[b]Carbon in dry matter was assumed to be 45%. CO_2 required for dry matter was determined by multiplying the dry wt column by 0.45 and that value by 3.67 (molecular wt CO_2/molecular wt C).

[c]CO_2 required for NSC was calculated by multiplying NSC column by 1.47 (molecular wt CO_2/molecular wt CH_2O).

Table 3 Current Year's Dry Biomass Production of Thompson Seedless Grapevines Grown in the San Joaquin Valley of California from Budbreak to Harvest, g vine^{-1}[a]

	1988		1989		1992	
Organ	Dry wt	%	Dry wt	%	Dry wt	%
Roots	495	6	308	2	293	2
Trunk	501	6	828	7	623	5
Stems	2056	26	2227	18	1891	14
Leaves	1458	18	1554	13	1308	10
Clusters	3568	44	7302	60	9173	69
Total	8078		12209		13288	

[a]Vines in 1988 and 1989 were harvested from a furrow-irrigated vineyard planted in 1984. Vines in 1992 were harvested from a drip-irrigated vineyard planted in 1987. Vine and row spacings from the furrow- and drip-irrigated vineyards were 2.44 and 3.66 and 2.1 and 3.55 m, respectively. Each value is the mean of at least five individual vine replicates. The percentage (%) column represents individual values in the dry wt columns divided by total weight.

xylem for water transport to the fruit is evident prior to veraison while the phloem is clearly dominant for the berry's postveraison water budget (Greenspan, 1994). It is unknown whether the uptake of water required for the growth of the berry after veraison is due to that accompanying sugars in the phloem, or to the decrease in berry water potential due to increasing solutes with a subsequent water inflow via the apoplast.

Sucrose is purported to be the primary sugar translocated from the leaves of *V. vinifera* to other organs (During and Alleweldt 1980). The metabolism of sucrose within the cell and its loading into the phloem and subsequent translocation within grapevines are probably similar to those described elsewhere in this book. Individual flowers are served by five or six vascular bundles in the pedicel

Table 4 Standing Biomass at Fruit Harvest and Current Year's Biomass and Nonstructural Carbohydrate Production of Chenin Blanc Grapevines Grown in the San Joaquin Valley of California, g vine^{-1}[a]

	Standing biomass		Current year's production			
Organ	Dry wt	%	Dry wt	%	NSCs	%
Roots	2984	16	220	3	625	17
Trunk	3015	16	263	4	217	6
Cordons	3421	18	−41	0	143	4
Stems	2539	13	2383	33	156	4
Leaves	1732	9	1641	23	91	2
Clusters	5199	28	2696	37	2503	67
Total	18890		7162		3375	

[a]Data were generated from tables 4.1 and 4.2, Mullins et al. 1992. The percentage (%) column represents individual values in the dry wt and NSC columns divided by total of each column.

which separate in the receptacle, giving rise to branches serving the flower parts and the ovary (Mullins et al. 1992). Once fruit set has occurred, the ovary bundles give rise to vascular traces within the developing berry; two serve the seeds and placenta, while the third is the peripheral bundles located between the dermal tissues and the pericarp (berry flesh). The peripheral bundles are joined to the central bundles (Mullins et al. 1992). The vascular strands are composed of tracheids, sieve cells, and elongated cells (Pratt 1971). The number of cells in the pericarp between the periphery and the central vascular bundles after veraison ranges from 15 to 20 cells (Harris et al. 1968).

The concentration of sucrose in *V. vinifera* berries is very low, comprising less than 4% of the total sugars (Hawker et al. 1976). It also was found that the sucrose concentration in easily expressed juice is less than that occurring in the rest of the berry, indicating that sucrose was compartmentalized in tissue that would have included the vascular system. Before veraison the highest concentrations of glucose and fructose are found in the skin and berry center, while after veraison highest concentrations of these two sugars are found in the berry core and below the peripheral vascular bundles (Possner and Kliewer 1985). These results indicate rapid hydrolysis of sucrose once it leaves the vascular tissue.

The majority of the increase in fruit biomass occurs after the inception of veraison (Coombe 1992). Veraison occurs after the lag phase of berry growth and is associated with berry softening and change in color of red- and black-fruited cultivars. The accumulation of glucose and fructose begins suddenly, on the same day that berry softening begins (Coombe 1989). Once it has begun, the concentrations of these two sugars increase linearly. Sugar accumulation rates into berries of field-grown grapevines have been calculated to be 1.1 μmol h^{-1} g^{-1} fresh weight (Hawker 1969). Similar rates have been reported in vitro (Brown and Coombe 1984). Hypotheses about the accumulation of hexose sugars in the pericarp of the berry recently have been reviewed (Coombe 1992). They include (a) active transport of sugars through the tonoplast of pericarp cells, (b) sucrose unloading from the phloem into the apoplast, and (c) sugar flow caused by leakiness of the plasma membrane in the pericarp cells.

Results derived from compartmental analysis in grape berries indicate that high concentrations of sugars can be found in the apoplast (Coombe 1989). As the concentration of hexose sugars increases during berry maturation, diffusible sugars in dermal segments increased (from 40% to 75%, beginning of ripening to 16% soluble solids), while the compartmented space increased only slightly (Brown and Coombe 1985). These results suggest that active uptake is not responsible for the dramatic sugar increase in pericarp cells but do support phloem loading of the berry. In further support of phloem unloading into the apoplast, Kriedemann (1969) demonstrated that labeled glucose moved from the phloem to the apoplast before entering pericarp cells. Finally, it has been shown that sugar import into the berry can continue after growth ceases (Matthews and Anderson 1988, 1989), even when berry volume decreases (Coombe 1973).

The third hypothesis was proposed by Lang et al. (1986). The breakdown of the apoplast–symplast compartmentation during berry ripening would establish a gradient of water potential between source and sink that would favor the movement of phloem sap into the berry (Coombe 1992). There is some evidence that cells in the pericarp develop some leakiness, such as a decrease in extractable gas, increased proportion of diffusible sugars, and increased translucency of the pericarp after veraison (Coombe 1992). However, the increase in berry sugar late in the growing season without a concomitant increase in volume would indicate that increasing concentrations of sugar in the apoplast of the berry does not create an osmotic gradient which would promote water uptake as implied by this hypothesis.

At present it is unknown what triggers the massive accumulation of sugars in the berry after veraison. Increased invertase activity has been shown to be associated with the increase in berry sugar accumulation (During and Alleweldt 1984). This increase would establish a gradient of sucrose from the phloem to the apoplastic space in the pericarp. Both soluble and cell-wall-associated forms of invertase have been localized in leaf and berry tissues of grape (Hawker 1969; Ruffner et al. 1990). However, invertase activity has been shown to exist in the berry before veraison, arguing against the activation of invertase as the triggering mechanism (Coombe 1989). Finally, phytohormones also have

been implicated as possible triggering mechanisms in other fruit crops (predominantly ethylene in climacteric fruit). The leading candidate for grape (a nonclimacteric fruit) appears to be abscisic acid (ABA) (Coombe 1989).

2. *Seasonal Source–Sink Relationships*

The initial growth of the shoot is dependent upon carbohydrate reserves in the permanent structures of the vine. Between budbreak and anthesis, the decrease in nonstructural carbohydrates amounted to approximately 350 g vine^{-1} for Thompson Seedless grapevines (Fig. 3). It is assumed that the decrease in carbohydrate content in the roots and trunk was utilized to support growth of the new shoots and to meet the respiratory demands of the rest of the vine. This value is similar to the utilization of carbohydrates during this period when modeling the growth of grapevines (Gutierrez et al. 1985; Wermelinger et al. 1991). As mentioned earlier, the shoot is able to meet growth and respiratory demands of a single node cutting once the leaf area exceeds 50 cm^2 (Buttrose 1966). Therefore, when all individual shoots on the entire vine exceed this leaf area, utilization of reserve carbohydrate diminishes and the vine becomes dependent upon recently assimilated photosynthate. This occurs sometime before anthesis (Scholefield et al. 1978; Yang et al. 1980).

The redistribution pattern of recent photosynthate was initially studied with $^{14}CO_2$ labeling and autoradiography, providing qualitative results (Hale and Weaver 1962; Koblet 1977). More recent studies have provided more quantitative data (Hunter and Visser 1988a; Matsui et al. 1985; Yang and Hori 1979, 1980). An interesting result obtained from these studies is the large proportion of ^{14}C label that remains in the source leaf up to 72 hours after exposure to $^{14}CO_2$, whether the vines were potted or were grown in the field. The data indicate a slow turnover of recently assimilated photosynthate in the leaves of grapevines. However, data obtained with both annual and perennial plants demonstrate that carbon export rates range from 5 to 10 μmol C m^{-2} s^{-1} under controlled environmental conditions (Li et al. 1992; Moing et al. 1992; Servaites et al. 1989). An export rate of 5.1 μmol C m^{-2} s^{-1}, averaged over an 8-hour period, can be calculated for field-grown Thompson Seedless grapevines by using the carbohydrate data in Fig. 4 and the net photosynthesis rates given in the text.

Generalizations can be made about the distribution of ^{14}C-labeled photosynthate. Young leaves, less than 50% of their final size, retain most of the carbon they assimilate. Once leaves are larger than 50% of their final size they begin to export carbohydrates (Hale and Weaver 1962; Koblet 1977), although there may be cultivar differences (Yang and Hori 1980). Before anthesis, translocation of photosynthates from grapevine leaves is toward the apical portion of the shoot. Just before and after anthesis movement of photosynthates from the leaves on the basal two-thirds of the shoot is toward the clusters and back into the permanent organs of the vines. After berry set, the fruit becomes a very large sink. Of the ^{14}C-labeled photosynthate that moved from the source leaves, no less than 71% of that label was recovered in the clusters, regardless of the position of the source leaf along the shoot, once berries were 8 to 10 mm in diameter (Hunter and Visser 1988a). The carbon isotope composition of immature berries would indicate that most of the carbon found in the fruit is imported from the leaves (Di Marco et al. 1977); little is derived from berry photosynthesis. After harvest, most of the recently assimilated photosynthate is translocated back to the permanent structures of the vine.

The flush of roots during the growing season, one beginning before anthesis and the other after harvest (McKenry 1984; van Zyl 1984), indicates little allocation of carbon to the root system during initial shoot growth and again once the fruit becomes the major sink. Moreover, dry matter and nonstructural carbohydrates in the root system did not increase until after anthesis, with a smaller increase again after fruit harvest (Williams 1991; Fig. 3). For very young vines, the accumulation of dry matter in the root system did not occur until the canopy was well developed, regardless of treatment (Araujo and Williams 1988). However, once initiated, the growth of the root system for these young vines was maintained throughout the remainder of the growing season. In addition, root dry matter

increased from budbreak to fruit maturity for Chenin blanc vines (Mullins et al. 1992) and from anthesis to fruit maturity for Cabernet Sauvignon vines (Williams and Biscay 1991). It also has been demonstrated that ^{14}C-labeled photosynthate is translocated to the root system during all stages of berry growth (Matsui et al. 1985). In fact, the proportion of label found in the ethanol insoluble fraction in the root system was greater than that found in all other sinks on the vine. While root dry matter increased throughout the season in these examples, it should be stressed that this increase is much less than the dry matter partitioned to the fruit during that time.

There also appears to be an alteration in the partitioning of carbon to the other permanent structures of the grapevine. The increase in trunk diameter during the season mimics root flushes (van Zyl 1984). Trunk biomass does not increase until after anthesis; it levels off during stage III of berry growth and then increases again after fruit harvest (Williams 1991; Fig. 3). Apparently trunk growth does not begin early in the season until there is excess, recent photosynthate. Diminished growth during phase III of berry growth and increased growth after the fruit is removed indicate that the trunk does not compete well for carbon once berries become a strong sink.

Growth of vegetative organs is greater when clusters are removed from the vine compared to those with crop (Table 5). The increased biomass partitioned to leaves, stems, canes, and trunk ranged from 50% to 73%, while the increase in root biomass was 350% greater when the two treatments were compared. The data indicate that the root system is the organ most severely affected because fruit is such a large sink. The results also illustrate that vegetative organs do not have the same sink potential that clusters have, at least under the conditions of this experiment. Total biomass accumulation on vines without fruit, during the period from anthesis to 28 August, was only 53% that of vines with fruit. It should be pointed out that midday, photosynthesis measurements of leaves exposed to direct solar radiation were not different for the two treatments throughout the study (unpublished data). Possible explanations for this apparent anomaly are (1) time of day photosynthesis measurements were made (see Downton et al. 1987), (2) less photosynthesis of leaves elsewhere in the canopy of vines without fruit than on vines with fruit such that whole vine photosynthesis was less, (3) changes in canopy architecture which may reduce whole vine CO_2 assimilation, (4) more shoot biomass removed through mechanical hedging to allow equipment down the row, or (5) higher maintenance respiration rates of vegetative than reproductive organs (see next section).

3. *Utilization of Carbon for Respiration*

It has been estimated 25% to 75% of the CO_2 assimilated by woody plants and perennial crops is lost via respiration (Amthor 1989; Kramer and Kozlowski 1979; Vogt 1991). This would include respiration associated with growth of new tissue, maintenance respiration, and respiration needed for other metabolic processes. Respiration needed for growth has been estimated to be approximately 30% of net

Table 5 The Effect of Crop Removal at Anthesis on Subsequent Growth of 3-Year-Old Thompson Seedless Grapevines

	Organ, Δ g dry wt vine^{-1}[a]						
Treatment[b]	Leaves	Stems	Canes	Trunk	Roots	Fruit	Total
w/Fruit	759	797	237	557	252	6250	8852
w/o Fruit	1137	1358	388	962	872	—	4717

[a]Values represent the increase in biomass after anthesis. Data were generated from six individual vine replicates harvested on 5 September.

[b]Clusters were removed at anthesis (14 May). Dry weights for leaves, stems, canes, trunk, roots, and fruit at anthesis were 524, 474, 370, 561, 481 and 150 g vine^{-1}, respectively.

CO_2 assimilation (Penning de Vries et al. 1983), and this value was recently used to model grapevine growth (Wermelinger et al. 1991). The actual respiratory demand would depend upon tissue composition (Amthor 1989). Maintenance respiration also is dependent upon tissue composition, most notably N content (Ryan 1991). Measurements indicate that "normal values" of maintenance respiration in vegetative tissues range from 0.015 to 0.06 kg CO_2 kg^{-1} dry matter d^{-1} (Penning de Vries 1983) but may be substantially lower in fruit and storage organs. Other factors which would influence respiration rates include temperature and respiratory substrate levels. Schultz (1991) found that shade leaves have a lower specific rate of respiration than leaves grown in full sunlight; the lower rate may have been due to reduced carbohydrate levels in the shade leaves.

Dark respiration rates of grapevine leaves decrease with age; this effect is no longer apparent after vegetative growth ceases (Schultz 1991). This may be due to a decrease in the growth component once the leaves are fully expanded. The Q_{10} of dark respiration is above 3 early in the season and at the beginning of fruit ripening (Schultz 1991). At other times the Q_{10} ranged between 2.4 and 2.7 in that study. Using fully expanded leaves, a Q_{10} of 2 was measured in the temperature range of 10°C to 42°C (Williams et al. 1994). Leaf respiration was negligible at 10°C for Perlette vines grown in the desert, whereas it was measurable down to 5°C for Chardonnay vines grown in a cool climate (unpublished data). Absolute rates of dark respiration in mature leaves at 20°C range from 0.15 to 0.5 μmol CO_2 m^{-2} s^{-1} (Schultz 1991; Williams et al. 1994). Specific respiration rates of other vegetative tissues of grapevine are less well known.

Fruit respiration of grapevines has been studied much more thoroughly (Frieden et al. 1987a; Geisler and Radler 1963; Koch and Alleweldt 1978; Leyhe and Blanke 1989; Kriedemann 1968). Before anthesis individual flower respiration ranged from 1 to 5 μg CO_2 h^{-1}; after set berry respiration ranged from 5 to 60 μg CO_2 h^{-1} (Leyhe and Blanke 1989). Specific berry respiration can be as high as 600 μg CO_2 g^{-1} fresh wt h^{-1} early in berry development, decreasing to approximately 40 μg CO_2 g^{-1} h^{-1} at fruit maturation (Frieden et al. 1987a; Geisler and Radler 1963; Koch and Alleweldt 1978). An increase in berry temperature increases berry respiration, with a Q_{10} of approximately 2.0 (Frieden et al. 1987b).

The estimated daily CO_2 demand of Chenin blanc grapevines grown in the San Joaquin Valley of California is presented in Table 6. The daily requirement of CO_2 for dry matter and nonstructural carbohydrates is taken from Table 2. Maintenance respiration of the trunk and root system was determined by using the starvation method on mature grapevines (unpublished data), while that for

Table 6 Daily, Calculated CO_2 Requirements of Chenin Blanc Grapevines at Three Different Phenological Stages of Vine Growth, mol CO_2 $vine^{-1}$ day^{-1}

			Vegetative[b]		Fruit[c]	
Day of year	Dry matter	NSCs	R_g	R_m	R	Total
147	2.43	0.05	0.73	0.86	0.34	4.41
206	1.17	0.63	0.35	0.98	0.66	3.79
253	0.38	1.85	0.11	1.32	0.58	4.24

[a]See Table 2 for further details.

[b]Growth respiration (R_g) was assumed to be 30% of the cost of dry matter production. Maintenance respiration (R_m) costs were assumed to be 25.9, 11.6, 100.8, and 154.4 ng CO_2 g^{-1} dry wt s^{-1} for roots, trunk, stems, and leaves, respectively. See text for further details.

[c]Specific fruit respiration was taken from Geisler and Radler (1963). Rates for days 147, 206, and 253 were 240, 84, and 40 μg CO_2 g^{-1} fresh weight h^{-1}, respectively.

current season's stems and leaves was taken from a study on peach trees (Grossman 1993). It was assumed that fruit respiration, taken from Geisler and Radler (1963), encompassed both growth and maintenance components, while the accumulation of reserves had no conversion costs (Wermelinger et al. 1991). The costs of carbohydrate translocation were not taken into account. Approximately, 50% of the total CO_2 required by Chenin blanc grapevines on these three dates was used for respiratory purposes. This percentage is similar to the estimates of whole tree respiratory costs mentioned above. The cost of growth respiration diminished as the season progressed; however, as standing biomass increased, so did maintenance respiration. Between days 147 and 253 the increase was 53%. It should be emphasized that the estimates of daily whole vine CO_2 requirements using this data set are similar to the modeled estimates of whole vine photosynthesis presented in Fig. 1.

4. *Root/Shoot Ratios*

The root/shoot ratio is used to provide a quantitative relationship between below- and above-ground growth of plants. However, the usefulness of such a relationship for woody perennial crops under intensive cultivation has yet to be determined. The root to shoot (or aerial) ratio in grapevine varies with vine age, growth stage, environmental conditions, crop load, and management practices. For example, the root/aerial ratio (aerial = trunk, cordons, and shoots) of Chenin blanc grapevines at fruit maturity in South Africa varied from 0.71 to 1.1, depending upon how the soil was prepared before planting (Saayman and van Huyssteen 1980). The calculated root/aerial ratio also varied when vines were planted at different row spacings and trellis heights (Mullins et al. 1992; see table 6.1). The root/aerial ratio (based on standing vegetative biomass) of Chenin blanc vines grown in the San Joaquin Valley of California varied from 0.36 at budbreak to 0.28 at fruit maturity (Mullins et al. 1992). When just the current season's accumulation of biomass is used for the calculation (Table 4), the ratio becomes 0.15 at fruit harvest. The root/aerial, root/shoot (stems + leaves) or root/leaves ratio of the current season's accumulation of Thompson Seedless biomass varied considerably from year to year (data taken from Table 3). The preceding data indicate that when modeling the growth of the grapevine root system, one cannot assume that root growth is a particular fraction of the biomass allocated to the shoots (Gutierrez et al. 1985; Wermelinger et al. 1991). However, as shown in Fig. 6, there appears to be a constant relationship between allocation of biomass to the root system and allocation to the trunk of Thompson Seedless grapevines.

The small amount of biomass allocated to the root system of grapevines (see previous discussion) differs from estimates of C (or biomass) allocated to root systems of trees in a forest (Cannel 1985; Vogt 1991). From 24% to 66% of the assimilated carbon is allocated to the roots of trees, most of this for fine root turnover. However, the amount of carbon allocated to the roots of *Pinus sylvestris* decreased from 59% to 31% with improved soil fertility (Linder and Axelsson 1982). Therefore, high soil fertility and availability of water for irrigation purposes in vineyards (Tables 3 and 4) and orchards (Miller and Walsh 1988), as would be the practice in a commercial situation, may decrease the carbon demand of roots for intensively managed tree and vine crops, resulting in low root/aerial or root/shoot ratios.

V. EFFECTS OF MANAGEMENT PRACTICES ON SOURCE–SINK RELATIONSHIPS

A. Canopy Management and Crop Load

Many different cultural practices are performed on grapevines in order to enhance fruit or wine quality (Jackson and Lombard 1993). These include the use of different trellises, planting densities, pruning practices, leaf and shoot removal, and adjustment of crop load. These management practices will alter the source–sink ratio of the vines. Many of them are used presumably to favor carbon transport to the fruit at the expense of that to the vegetative structures.

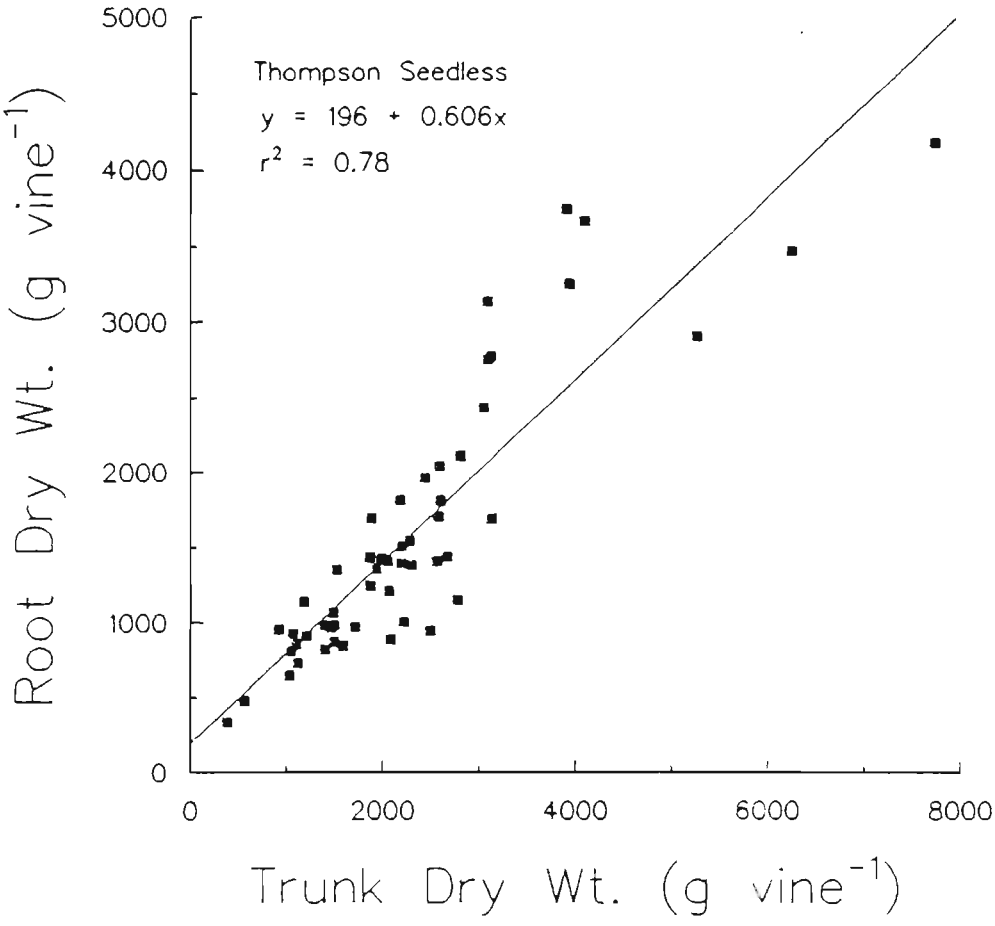

Figure 6 The relationship between trunk and root dry biomass of Thompson Seedless grapevines. Each data point is the mean of at least four individual vine replicates. See text for further details.

The presence or absence of sinks on a grapevine may or may not affect individual leaf net CO_2 assimilation rate. The removal of sinks (either the fruit or actively growing shoot apices) from potted grapevines results in a significant decrease in the net CO_2 assimilation rate of individual leaves (Candolfi-Vasconcelos and Koblet 1991; Hofacker 1978; Kriedemann and Lenz 1972). Net CO_2 assimilation rate of leaves that remain on shoots on which defoliation has occurred is greater than that of leaves on shoots on which no defoliation took place (Candolfi-Vasconcelos and Koblet 1991; Hunter and Visser 1988b). It should be emphasized that fruit removal may have no effect on individual leaf (Williams 1986) or whole vine CO_2 assimilation (Edson et al. 1993). It appears that sink effects on grapevine leaf photosynthesis are a function of the time of day (Downton et al. 1987) and time during the season when measurements were taken (Candolfi-Vasconcelos and Koblet 1991). The presence of other sinks, especially on large, field-grown vines, apparently mitigates any depressing effect fruit removal may have on leaf CO_2 assimilation under those conditions (L. E. Williams and F. Araujo unpublished data).

Crop level affects berry and cluster size, accumulation of sugar and other flavor components in the fruit, and various aspects of vegetative growth (Weaver and McCune 1960; Weaver and Pool 1968; Winkler 1954). As yield per vine increases, berry size and cluster weight decrease (Clingeleffer 1984, 1989; Kliewer and Weaver 1971; Weaver and Pool 1968). It is thought that high yields on vines reduce the quality of the fruit (Jackson and Lombard 1993). This effect is due in part to the fact that "overcropping" delays the accumulation of sugar in the fruit when compared to that of vines with less

crop. However, there are reports indicating that the amount of crop per vine does not affect sugar accumulation and fruit quality (Clingeleffer 1989) or that there is a specific amount of crop a vine will mature before further yield increases delay maturation and affect quality (Bravdo et al. 1985; Kliewer and Antcliff 1970).

Differences in results among the studies mentioned indicate the importance of quantifying all aspects of vine growth before concluding that high vine yields decrease fruit quality. As expected, leaf area per vine would be a major determinant in explaining the differences with regard to crop level. This has led many to conduct studies in which vines are defoliated to a certain level to determine the leaf area required to mature a given amount of fruit. A ratio of 0.7 to 1.0 $m^2\ kg^{-1}$ fruit is usually reported to be the value required so that sugar accumulation is not delayed (Jackson and Lombard 1993). Ratios as low as 0.5 have been reported for field-grown Thompson Seedless grapevines in which sugar accumulation is not affected (May et al. 1969; Williams et al. 1987). The usefulness of this ratio in a field situation is probably minimal as trellis type, row direction, seasonal canopy development, and diurnal path of solar radiation alter the proportion of leaves contributing the major portion of a vine's daily production of photosynthate. Indices such as leaf area index (Grantz and Williams 1993), leaf area per meter canopy length, or canopy leaf area to canopy surface area (Dokoozlian 1990) may be more appropriate and useful especially with regard to modeling vine C gain.

It must be stressed that fruit maturation also is affected by the microclimate in the fruiting zone (Williams et al. 1994). One means to increase yield per vine is to leave more buds per vine at pruning. Increased bud numbers without expanding the vine's framework result in more shoots per vine, creating a canopy microclimate that may decrease the accumulation of sugar in the fruit and other aspects of fruit quality, such as color (Smart 1985). The removal of the basal leaves on shoots up to the node positions of the clusters is increasingly being used in California to alter the microclimate in the fruiting zone in the hope of affecting fruit composition. This practice enhances sugar accumulation in the berries through an increase in berry temperature under those conditions (Bledsoe et al. 1988).

Retaining varying numbers of buds on a vine, through differential pruning, usually is the means to assess the effects of crop load on reproductive and vegetative growth (Miller et al. 1993; Weaver and Pool 1968). Current season aerial, vegetative growth and leaf area increase much more rapidly early in the season for vines in which higher number of buds are retained (Downton and Grant 1992). However, leaf area measured at fruit harvest (Downton and Grant 1992) or pruning weight taken during the dormant portion of the season (Clingeleffer and Krake 1992; Miller et al. 1993) is equal to or greater than on vines with low bud numbers retained at pruning than on those that initially have more count buds. Increased vegetative growth and leaf area per vine may be due to increased growth of shoots derived from noncount buds (Table 7). Note that for vines in which two canes were retained half of the entire vine's leaf area originated from the head of the vines and that those shoots also had greater leaf area on lateral shoots. These results would indicate that increased accumulation of sugar in the fruit of vines with lowered cluster numbers is the result of an alteration in the source/sink ratio; much greater source for the vines pruned to two canes. Interestingly, the leaf area (derived only from shoots on the fruiting canes) to fruit ratios for all three treatments were similar, ranging from 0.81 to 0.85 $m^2\ kg^{-1}$.

There have been a few field studies which examined the effects of pruning level on biomass partitioned to the permanent structures of the vine. The root biomass of Cabernet franc vines was significantly less for mechanically pruned compared to spur-pruned vines after the treatments had been imposed for 5 years; however, there were no differences in biomass of the trunk among treatments (Clingeleffer and Krake 1992), there were only slight differences in the concentration of nonstructural carbohydrates in the trunk and roots of these vines (Ruhl and Clingeleffer 1993). Over a 3-year period Thompson Seedless grapevines pruned to four canes produced almost 28 kg more fruit than those pruned to two canes; however, there was almost no difference between the two with regard to the partitioning of biomass to the trunk (Table 8). Biomass partitioning to the root system of vines with yields greater than double those pruned to two canes was reduced by 21% over the 3-year period.

Table 7 Effect of Pruning Level on Yield and Leaf Area of Thompson Seedless Grapevines 3 Weeks Before Fruit Maturity in 1987

Pruning level, (no. of canes)[a]	Yield, kg vine^{-1}	Leaf area (m^2 vine^{-1})				
		Canes[b]		Head[b]		
		1°	2°	1°	2°	Total
2	10.9	6.5	2.8	5.7	5.6	20.6
4	19.3	12.2	3.5	3.8	1.9	21.4
8	25.7	15.4	5.7	3.3	1.3	25.7

[a]Vines were planted in 1968 and were flood-irrigated each growing season. Vine and row spacing were 2.44 and 3.66 m, respectively. Treatments were imposed for a single season.

[b]Leaf area was subdivided into that derived from the fruiting canes (canes) and the head of the vine and from primary (1°) and lateral (2°) shoots.

As demonstrated by Clingeleffer and Krake (1992) there was little effect of pruning level on the partitioning biomass to the trunk. The preceding results would indicate that the extreme, deleterious effect of overcropping reported previously in California may be cultivar-specific (Weaver and McCune 1960) or due to lack of regular irrigation and fertilization programs (Winkler 1954, 1958).

Increasing vine density within the vineyard decreases yield and vegetative growth per vine but increases yield per unit land area without an apparent effect on fruit quality (Archer and Strauss 1991; Lavee and Haskel 1982; Mullins et al. 1992). Increasing vine density from 1120 to 1680 vines ha^{-1} decreased shoot biomass by 30%, but there was no effect on biomass partitioned to the root system (Mullins et al. 1992). However, vine densities greater than 2000 vines ha^{-1} reduced root growth (Archer and Strauss 1985). It has been demonstrated that vines planted to higher densities reduce soil water

Table 8 The Effect of Pruning Level Imposed for Three Growing Seasons on the Increase in Trunk and Root Dry Weight of Thompson Seedless Grapevines During That Period

Pruning level, no. of canes	Yield,[a] kg vine^{-1}	Increase in dry biomass, g vine^{-1}	
		Trunk[b]	Roots[b]
2	12.9	1921	2365
4	22.2	2105	2285
8	29.0	1949	1865

[a]Values in this column are the 3-year mean of each treatment.

[b]Initial biomass, measured at budbreak in 1988, of the trunk and root system was 1981 and 1385 g vine^{-1}, respectively. Biomass at the conclusion of the study was determined after leaf fall, 20 November 1990. Four single-vine replicates were used in determining biomass at the end of the study. Other information is in Table 7.

content more rapidly than those at wider spacings, resulting in more negative leaf water potentials (Archer and Strauss 1989) and reduced rates of photosynthesis (Archer and Strauss 1990). Therefore, the reduction in vine growth at closer spacings may be due to effects of a less favorable vine water status if these density experiments are not irrigated or irrigated with the same amount of water regardless of treatment. The ability to maintain fruit quality at higher densities may be due to a greater leaf area to fruit weight ratio (Archer and Strauss 1991) or to the positive effects of mild water stress (Williams et al. 1994).

B. Irrigation and Fertilization Management

Vineyard water management is probably the best tool with which to manipulate vine growth and fruit quality. Reproductive growth of grapevines appears to be less sensitive to water stress than is vegetative growth (Williams and Matthews 1990; Williams et al. 1994). For example, as applied water decreased from 100% to 80% to 60% of vineyard evapotranspiration (ET), pruning weights decreased 15% and 39% for the latter two irrigation treatments, respectively, compared to the 100% treatment (Fig. 7). However, the corresponding reduction in vine yield was only 1% and 10% for the 80% and 60% irrigation treatments, respectively. Another point illustrated in this data is related to the purported reduction in vegetative growth due to the increasing carbon demands of the fruit as the season progresses (as discussed in previous sections). While there were no significant differences in yield for the 80%, 100%, and 120% irrigation treatments, pruning weights continued to increase linearly. Thus water management and not sink strength of the fruit determined continued growth of the shoots in this study. It should also be pointed out that vines in this study are mechanically hedged in order to facilitate the movement of equipment down the rows. Therefore, pruning weights reported here are less than actual vegetative growth that occurred during the season, especially for vines irrigated at 100% of ET or greater. Finally, the results also indicate that increased leaf area does not always advance fruit maturation as there were no significant differences in soluble solids at fruit harvest for irrigation treatments between 80% and 140% (unpublished data). An alternate conclusion would be that the increased vegetative growth occurring at the higher irrigation levels did not detract from sugar accumulation in the fruit.

Vineyard water stress also will affect the amount of carbon partitioned to the permanent structures of the vine. Root, trunk, and cordon biomass was reduced 31%, 17%, and 26%, respectively, for vines irrigated at 52% of vineyard ET compared to those at 100% ET after 5 years (Mullins et al. 1992; see table 6.6). The concentration of nonstructural carbohydrates in those organs differed only slightly for the two treatments. Water stress generally increased the concentration of carbohydrates in the stems and roots of cuttings of several wine grape varieties (Ruhl and Alleweldt 1990). While the data differ in the preceding two studies with regard to carbohydrate concentrations, it is agreed that total carbohydrate content in those organs decreased on a per vine basis as a result of reduced growth brought about by water stress.

The application of fertilizers in nutrient-deficient soils increases both vegetative and reproductive growth. Continued application of excessive nitrogen fertilizer favors vegetative over reproductive growth. Reduction in the accumulation of sugar in the fruit of vines growing on fertile soils or those fertilized with high rates of N (Spayd et al. 1994) is probably associated with excessive vegetative growth affecting the microclimate in the vine's fruiting zone (Smart 1991).

C. Plant Growth Regulators and Girdling

Plant growth regulators (PGRs) are frequently used in grape culture, especially for the production of seeded and seedless table grapes. The two most commonly used PGRs are (2-chloroethyl) phosphonic acid (Ethephon) and gibberellic acid (GA_3). Ethephon is used to enhance berry color and maturation, induce cluster abscision, and influence budbreak and vegetative growth (Szyjewicz et al. 1984). The

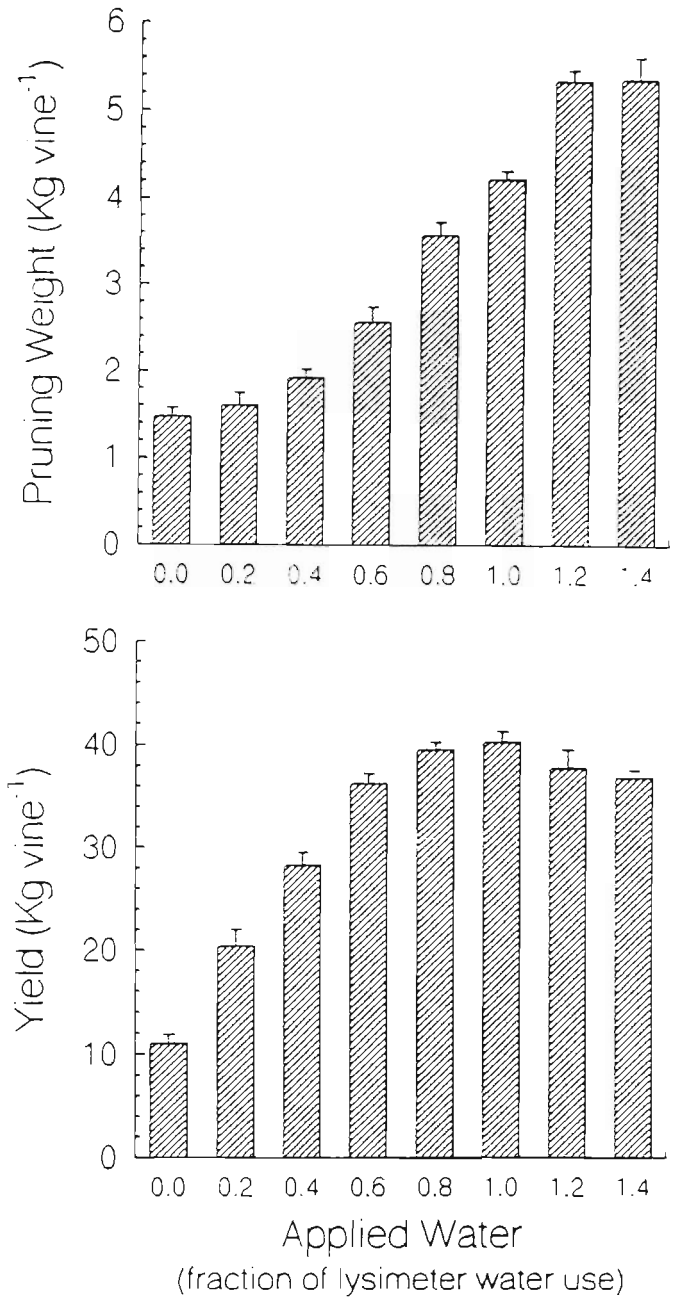

Figure 7 The effect of various amounts of applied water on vine productivity and vegetative growth (pruning weights) of 6-year-old Thompson Seedless grapevines. Full vine ET (1.0 applied water treatment) was determined with the use of a weighing lysimeter (Phene et al. 1991). Vines were irrigated daily at various fractions of the amount of water vines in the lysimeter used.

movement of Ethephon within the vine and its exact mode of action are unclear. Application of Ethephon increases maturity of the fruit in some instances and either has no effect or decreases it in others (Szyjewicz et al. 1984). The contrasting results probably are related to concentration used, time of application, environment, and cultivar. It inhibits the growth of primary and lateral shoots; inhibition wears off with time. It is unknown whether the advancement of berry maturation is due to the inhibition of shoot growth or the maintenance of a canopy microclimate favorable to fruit maturation due to less shoot growth.

The application of GA_3 has long been used in California to increase the size of seedless table grape cultivars (Weaver and McCune 1959). Application at anthesis reduces the number of flowers that set, reducing potential sinks; an additional application a few weeks later also increases berry size by enhancing cell division in the pericarp (Sachs and Weaver 1968). GA_3 also may affect the movement of recent photosynthate (Weaver et al. 1969). For example, its effect on increasing berry size differs, depending on the portion of the vine that is sprayed (Harrell and Williams 1987a; Weaver et al. 1969). Berry size is greater when individual clusters as opposed to entire vines are sprayed with GA_3. It is unknown whether this is due to better coverage of the material when just individual clusters are sprayed or to reduced competition for carbohydrates with shoots, which are covered on whole vine applications. The latter would be the case if GA_3 were able to direct the movement of photosynthate to newly formed vegetative sinks. The application of GA_3 to the vine results in lower concentrations of nonstructural carbohydrates in leaf tissue shortly after treatments are imposed, compared to the control (Roper and Williams 1989). However, no differences in nonstructural carbohydrates were observed in other vegetative organs 2 months later (unpublished data). Therefore, GA_3 is able to increase berry size by decreasing total sink size of the fruit cluster, increasing sink potential by increasing cell division, and possibly manipulating the direction of recent photosynthate. It is interesting to note that berry size and yield of nonirrigated Thompson Seedless grapevines sprayed with GA_3 were similar to those of vines that were irrigated but not sprayed with GA_3 (Williams et al. 1994). This was despite the fact that the leaf area of the nonirrigated vines was less than one third that of the irrigated vines.

Trunk girdling (the removal of a strip of phloem, 6 mm in width) has been used even longer than GA_3 in California to increase the size of seedless table grape cultivars and to advance fruit maturation (Jacob 1929). Girdling is performed at berry set (same time as the second GA_3 application) to increase size and also at veraison to advance fruit maturation. Trunk girdling effectively disrupts the movement of carbohydrates to the root system, resulting in an increase in total carbohydrates above the girdle and a diminishing reserve in the root system (Roper and Williams 1989). Girdles heal under California growing conditions in 4 to 5 weeks. The increased availability of carbohydrates above the girdle is hypothesized to be the reason for the effect on increasing berry size and advancing maturity.

Girdling potted and field-grown grapevines results in decreased rates of photosynthesis as long as the girdle remains open (During 1978; Harrell and Williams 1987b; Hofacker 1978; Kriedemann and Lenz 1972). It is thought that the reduction in photosynthesis is due to the accumulation of carbohydrates in the leaves (Kriedemann and Lenz 1972), but recent work on field-grown vines indicates that this is not the case (Roper and Williams 1989; Fig. 4). The reduction in photosynthesis in response to girdling may be due to the accumulation of ABA in the leaves (During 1978), which decreases stomatal conductance (Downton et al. 1988). When grapevines are both girdled and sprayed with GA_3, the reduction in photosynthesis due to girdling is not as great as with girdling alone (Harrell and Williams 1987b). The specific mode of action of GA_3 on grape leaf photosynthesis under these conditions is unclear.

VI. SUMMARY

There are more than 10,000 cultivars of *V. vinifera* grown commercially under a wide range of climatic conditions. The differences among cultivars presented in this chapter with regard to source–sink relationships would indicate that efforts to model the growth of a specific cultivar under a given set of environmental conditions will require further, extensive studies. In addition, the use of different cultural practices by grape growers indicates that potential sources and sinks of the same cultivar will differ from vineyard to vineyard. Therefore, vine growth (including root growth) must be quantified as a function of vine training, trellis system, and irrigation and fertilization management practices to gain a better understanding of source–sink relationships in grape.

The data presented in this review demonstrate that even during the portion of the growing season

when large amounts of carbohydrate reserves in the permanent structures of the vine continue. This would be expected of this perennial crop as carbohydrates are needed for maintenance of the vine during dormancy and for initial shoot growth in the spring. The ability of vines to partition carbohydrates to the permanent structures during fruit growth would be especially advantageous in cooler regions, where the first freeze may occur shortly after harvest. It was also demonstrated that the amount of carbohydrates found in those structures is only a small portion of the total required to produce the new vegetative and reproductive structures. Therefore, only under extreme pest or disease pressure would one expect the vine not to have adequate carbohydrate reserves. Finally, the amount of reserve carbohydrates found in the permanent structures of grapevines (presented in this chapter) would provide only a small portion of the total C required to grow and mature a grape crop. Therefore, it is doubtful that a vine would deplete these reserves to sustain continued fruit growth in instances in which the vine's canopy could not supply adequate carbohydrates.

Further research is needed to elucidate the mechanism by which grapes accumulate massive amounts of sugars and the stimulus that triggers that event in berries at veraison. The role of phytohormones in regulating sink potential and their effect on carbohydrate translocation need additional study. Grapevines, especially of seedless grape cultivars, may prove to be an excellent system in which to conduct such experiments.

It is hoped that the information presented in this chapter will dispel some of the myths associated with the culture of grapevines. It has been the author's experience that many individuals attribute various maladies of grape growth and delayed sugar accumulation to vegetative sinks' diverting carbohydrates from the fruit. Many of the examples presented indicate that is not the case. More likely, continued vegetative growth alters the microclimate within the fruiting zone, which may then alter berry metabolism (Smart 1985; Williams et al. 1994). Continued quantitative research on vine growth and modeling efforts by viticulturists will provide much needed information on what we do and do not know about this perennial fruit crop.

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Correlations among Predawn Leaf, Midday Leaf, and Midday Stem Water Potential and their Correlations with other Measures of Soil and Plant Water Status in *Vitis vinifera*

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Abstract. A study was conducted to compare three measurements of determining water status of grapevines (*Vitis vinifera* L.) in the field. Predawn leaf water potential (Ψ_{PD}), midday leaf water potential (Ψ_l), and midday stem water potential (Ψ_{stem}) were measured on 'Chardonnay' and 'Cabernet Sauvignon' grapevines grown in Napa Valley, California late in the 1999 growing season. Both cultivars had been irrigated weekly at various fractions (0, 0.5, and 1.0 for 'Chardonnay' and 0, 0.5, 0.75, and 1.5 for 'Cabernet') of estimated vineyard evapotranspiration (ET_c) from approximately anthesis up to the dates of measurements. Predawn water potential measurements were taken beginning at 0330 HR and completed before sunrise. Midday Ψ_l and Ψ_{stem} measurements were taken only between 1230 and 1330 HR. In addition, net CO_2 assimilation rates (A) and stomatal conductance to water vapor (g_s) were also measured at midday. Soil water content (SWC) was measured in the 'Chardonnay' vineyard using a neutron probe. Values obtained for Ψ_{PD}, Ψ_l, and Ψ_{stem} in this study ranged from about −0.05 to −0.8, −0.7 to −1.8, and −0.5 to −1.6 MPa, respectively. All three measurements of vine water status were highly correlated with one another. Linear regression analysis of Ψ_l and Ψ_{stem} versus Ψ_{PD} resulted in r^2 values of 0.88 and 0.85, respectively. A similar analysis of Ψ_l as a function of Ψ_{stem} resulted in an r^2 of 0.92. In the 'Chardonnay' vineyard, all three methods of estimating vine water status were significantly ($P < 0.01$) correlated with SWC and applied amounts of water. Lastly, Ψ_{PD}, Ψ_l, and Ψ_{stem} were all linearly correlated with measurements of A and g_s at midday. Under the conditions of this study, Ψ_{PD}, Ψ_l, and Ψ_{stem} represent equally viable methods of assessing the water status of these grapevines. They were all correlated similarly with the amount of water in the soil profile and leaf gas exchange as well as with one another.

Since development of the pressure chamber (Scholander et al., 1965), measurement of leaf water potential (Ψ_l) has been used as a tool to assess the water status of plants (Jones, 1990; Koide et al., 1989). Accordingly, leaf Ψ_l has been used to monitor the water relations of grapevines (*Vitis* L. sp.) (Smart and Coombe, 1982; Williams et al., 1994). It has been correlated with various aspects of grapevine physiology (Naor et al., 1994; Williams et al., 1994), vegetative growth (Schultz and Matthews, 1988, 1993), and reproductive growth and yield (Greenspan et al., 1996; Grimes and Williams, 1990). Grapevine Ψ_l has been shown to be fairly consistent up and down the axis of the shoot of *Vitis labruscana* Bailey when leaves are uniformly exposed to solar radiation (Liu et al., 1978). Lastly, Ψ_l has also been used as a factor in a functional model of stomatal conductance of grapevines (Winkel and Rambal, 1990).

There have been reports in which it was suggested that midday or diurnal measurements of Ψ_l did not provide a reliable estimate of plant water status. This was due to lack of correlation between Ψ_l with other physiological parameters, measures of growth, or amounts of applied water (Chone et al., 2001; Garnier and Berger, 1985; Higgs and Jones, 1990; Naor, 1998). Therefore, other methods of measuring plant water status in the field, such as predawn leaf water potential (Ψ_{PD}) and stem water potential (Ψ_{stem}) are being used. Measurements of Ψ_{PD} have been used in grape studies since it is assumed that before sunrise the vine is in equilibrium with the soil's water potential (Correia et al., 1995; Schultz, 1996; Winkel and Rambal, 1993). Correia et al. (1995) found significant differences in vine Ψ_{PD} among three watering treatments but no differences in Ψ_l were found when measured at 1000 and 1600 HR. They concluded that Ψ_{PD} better reflected soil water availability than Ψ_l. van Zyl (1987) concluded that Ψ_{PD} detected the onset of water stress in grapevines earlier and more accurately than Ψ_l.

Stem water potential is determined by enclosing a leaf in a plastic bag that is surrounded by aluminum foil, stopping transpiration, enabling that leaf to come into equilibrium with the water potential of the stem (Begg and Turner, 1970). The reported amount of time between enclosing the leaf in plastic and foil, and measuring Ψ_{stem} for trees and grapevines, has been from 45 to 120 min (Garnier and Berger, 1987; McCutchan and Shackel, 1992; Naor et al., 1997). Some have bagged leaves from 14 to 24 h before measuring Ψ_{stem} in grape (Liu et al., 1978; Stevens et al., 1995). Stem water potential has been shown to be less variable than Ψ_l and improved the ability to detect small, but statistically significant differences among treatments (McCutchan and Shackel, 1992). It was also found that a clear difference in Ψ_{stem} between two irrigation treatments occurred at an earlier date (1 week) during the growing season than differences in Ψ_{PD} and Ψ_l for the same treatments (Selles and Berger, 1990). In addition, Ψ_{stem} has been shown to be a linear function of applied water (Lampinen et al., 1995) and soil water availability (Stevens et al., 1995). Lastly, Ψ_{stem} has been highly correlated with tree (Olien and Lakso, 1986) and fruit (Naor et al., 1995) size in apple [*Malus sylvestris* (L.) Mill var. *domestica* (Borkh.) Mansf.].

It has been suggested that for a measure of plant water status (such as Ψ_l) to be a sensitive indicator of water stress, it must be responsive to differences in soil moisture status and/or resulting growth differences due to water applications (Higgs and Jones, 1990). It should also be closely related to short- and medium-term plant stress responses (Shackel et al., 1997) and less dependent upon changes in environmental conditions (Jones, 1990;

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McCutchan and Shackel, 1992). The specific examples given above for grape would indicate that Ψ_{PD}, Ψ_l, or Ψ_{stem} may all be possible candidates. Only a few studies have actually compared one of the three methods of measuring Ψ with one another for determination of plant water status. Stevens et al. (1995) found that diurnal measures of Ψ_l and Ψ_{stem} of grape were highly correlated ($r^2 = 0.97$) with one another. Conversely, Naor et al. (1995) found that the correlation between Ψ_l and Ψ_{stem} of apple resulted in a r^2 of 0.35. Therefore, the purpose of this study was to measure Ψ_{PD}, Ψ_l, and Ψ_{stem} of two *Vitis vinifera* cultivars and compare the three with one another and with measures of leaf gas exchange, soil water content, and reproductive growth. Grapevines at two sites were chosen as they had been irrigated at various fractions of estimated vineyard evapotranspiration (ET_c) from the initial irrigation of the season onward, providing plant material expected to exhibit large differences in soil and vine water status.

Materials and Methods

Two *Vitis vinifera* cultivars were used for the study, 'Chardonnay' and 'Cabernet Sauvignon'. The 9-year-old 'Chardonnay' vineyard was located in the southern portion of Napa Valley (Carneros District), in California within 10 km of San Francisco Bay. The 10-year-old 'Cabernet Sauvignon' vineyard was also located in Napa Valley, 3 km from Oakville (≈25 km from the Carneros site). Two rootstocks were used in the 'Chardonnay' vineyard, '5C Teleki' (5C) and '110 Richter' (110R). One rootstock was used in the 'Cabernet Sauvignon' vineyard, 5C. Vine and row spacings for the 'Chardonnay' and 'Cabernet Sauvignon' vineyards were 1.52 and 2.13 m and 1.0 and 1.83 m, respectively. The trellis system used in both vineyards was the vertical shoot positioned (VSP). Row directions in the 'Chardonnay' and 'Cabernet Sauvignon' vineyards were approximately east–west and north–south, respectively. The soil in the 'Chardonnay' vineyard was a Diablo fine, montmorillonitic, thermic Chromic Pelloxerert and that in the 'Cabernet' vineyard was a Bale fine-loamy, mixed, thermic Cumulic Ultic Haploxeroll. The soil pH of both vineyards was 5.5 and there were no apparent restrictions to root exploration of the profile.

Both vineyards used for this research were also being used in an irrigation study investigating relationships among applied quantities of water, rootstock, and productivity. Three irrigation treatments were used in the 'Chardonnay' vineyard. Vines received applied amounts of water at 0, 0.5, and 1.0 times estimated ET_c. The plot size of an individual irrigation–rootstock treatment consisted of 18 vines down the row using a single border vine and a border row receiving no applied water between plots. Vine water use was calculated as the product of potential ET (ET_o) and the crop coefficient (k_c). Potential ET was obtained from a California Irrigation Management Irrigation System (CIMIS) weather station located 8 km from the vineyard site. The seasonal crop coefficients (k_cs) used were those developed by L.E. Williams in 1994 for a VSP trellis planted on 2.13-m row spacings (unpublished data) and expressed as a function of degree-days from budbreak using a base of 10 °C. Four irrigation treatments were used in the 'Cabernet Sauvignon' vineyard: 0.0, 0.5, 0.75, and 1.5 times estimated ET_c. The plot size of an irrigation treatment at this location was the entire row (78 vines). The k_cs used to calculate ET_c were similar to those in the 'Chardonnay' vineyard but were adjusted for the narrower row spacing (i.e., the k_cs were ≈16% greater than for the 2.13 m row spacing). Potential ET for the 'Cabernet' vineyard was obtained from a CIMIS weather station located 3 km from the site. Differences in applied water amounts in both vineyards were obtained by using different numbers and/or sizes of in-row emitters using drip irrigation.

Soil water content (SWC) was measured only in the 'Chardonnay' vineyard using a neutron probe (model 503 DR hydroprobe moisture gauge; Boart Longyear Co., Martinez, Calif.). Six access tubes were installed to a depth of 3 m in one quarter of an individual vine's rooting volume. One tube was placed close to the trunk of the vine and another midway between vines within the row. Two access tubes were placed midway between rows, in line (perpendicular) with the two in-row tubes. The last two access tubes were placed midway between the four tubes, mentioned previously (i.e., 1/4 the distance between rows). There was one access tube site per irrigation treatment–rootstock combination. Measurements of SWC began at a depth of 0.15 m from the soil surface and at each 0.3-m depth, thereafter. The neutron probe was calibrated with the vineyard's soil type and expressed as percentage volumetric water content. Soil water content used in the study was the mean of all access tubes at an individual site and at all depths measured.

Vine water status and leaf gas exchange were measured on two dates (24 Aug. and 21 Sept. 1999) in the 'Chardonnay' vineyard and one date (25 Aug. 1999) in the 'Cabernet' vineyard on randomly selected vines only in block 1 of the larger irrigation study at both locations. Soil water content was also measured only in block 1 of the 'Chardonnay' vineyard both days. All dates were cloud free. Water potential readings were conducted according to the procedures of Padgett-Johnson et al. (2000) and Koide et al. (1989). Specifically, predawn Ψ measurements began at ≈0330 HR and were finished before sunrise using a pressure chamber (PMS Instruments Co., Corvallis, Ore.). Midday measurements of Ψ_l and Ψ_{stem} occurred between 1230 and 1330 HR, Pacific Daylight Time. Leaf blades for Ψ_{PD} and Ψ_l determinations were covered with a plastic bag, quickly sealed, and petioles then cut within 1 to 2 s. The time between leaf excision and chamber pressurization was generally <10 to 15 s. Leaves, chosen for midday Ψ_l determinations, were fully expanded, mature leaves exposed to direct solar radiation. These leaves were located on the south side of east–west rows and the west side of the north–south rows. About 90 to 120 min before midday measurements, leaves for determination of Ψ_{stem} were enclosed in black plastic bags covered with aluminum foil. Leaves chosen for Ψ_{stem} measurements were of similar age and type as those used for Ψ_l but were located on the north side of the vines in east–west rows and the east side of vines in north–south rows to minimize any possible heating effects. Leaves for midday determinations of Ψ_l and Ψ_{stem} were taken from the same vine and simultaneously measured. One leaf from an individual vine was used for each measurement.

In Aug. 2001, midday Ψ_l was measured on the cultivar Merlot grown in the San Joaquin Valley, comparing leaves covered with a plastic bag before excision, covered with a plastic bag just after excision, and leaves not covered with plastic. All other procedures were as described above for midday Ψ_l. A single leaf replication of each method to measure Ψ_l was taken from the same vine using six different vines. Vines were irrigated at 40% and 120% of estimated vineyard ET, weekly.

Measurements of net CO_2 assimilation rates (A) and stomatal conductance (g_s) were taken subsequent to the measurements of midday leaf Ψ and completed by 1400 HR. Both measures of gas exchange were made with a portable infrared gas analyzer, LCA2 (Analytical Development Co., Hoddeson, United Kingdom) using the broad leaf chamber. Leaves chosen for gas exchange were similar to those used for Ψ_l. Solar radiation, net radiation, photosynthetic photon flux (*PPF*), ambient temperature and, relative humid-

Table 1. Effects of applied water amounts on predawn leaf (Ψ_{PD}), midday stem (Ψ_{stem}), and midday leaf (Ψ_l) water potentials for selected grape cultivars, dates of measurement, and rootstock. Applied quantities of water were various fractions of estimated full ET_c. Each value is the mean of a single leaf replicate measured on six different vines for data collected on 24 Aug. and five different vines for the other two measurement dates.

Cultivar	Date	Rootstock	Applied water (fraction of ET_c)	Ψ_{PD}	Ψ_{stem}	Ψ_l
				MPa		
'Chardonnay'	24 Aug.	5C	0.0	–0.45 c[z]	–1.17 c	–1.50 c
			0.5	–0.16 b	–0.92 b	–1.25 b
			1.0	–0.10 a	–0.74 a	–1.04 a
		110R	0.0	–0.60 c	–1.44 b	–1.64 b
			0.5	–0.24 b	–0.98 a	–1.28 a
			1.0	–0.14 a	–0.86 a	–1.13 a
'Chardonnay'	21 Sept.	5C	0.0	–0.46 b	–1.29 b	–1.54 b
			0.5	–0.05 a	–0.82 a	–1.06 a
			1.0	–0.02 a	–0.72 a	–1.02 a
		110R	0.0	–0.62 b	–1.64 c	–1.81 c
			0.5	–0.06 a	–0.69 b	–0.98 b
			1.0	–0.02 a	–0.60 a	–0.86 a
Cabernet	25 Aug.	5C	0.0	–0.75 c	–1.39 c	–1.71 c
			0.5	–0.57 b	–1.11 b	–1.37 b
			0.75	–0.51 b	–1.11 b	–1.39 b
			1.5	–0.26 a	–0.96 a	–1.29 a

[z]Means within a column followed by a different letter for a specific cultivar, date and rootstock are significantly different at $P < 0.05$.

ity were measured 1 m above the canopy and averaged hourly with a datalogger. Canopy temperature (to calculate canopy to air vapor pressure difference) was measured hourly with a hand-held infrared thermometer (model 39650-04; Cole-Parmer Inst. Co., Chicago, Ill.).

Data were analyzed via regression analysis using linear, quadratic, and cubic terms. Since there were no improvements using either quadratic or cubic terms for analysis of any of the relationships obtained herein only linear regressions are presented. The relationships between midday measurements (Ψ_l and Ψ_{stem}) and Ψ_{PD} were analyzed using the means of an individual treatment (scion–rootstock combination, irrigation treatment, and date, n = 16). This was due to the fact that measurement of Ψ_{PD} was not necessarily determined on the same vines within the plot as done for Ψ_l and Ψ_{stem}. The relationship between Ψ_l and Ψ_{stem} was of individual leaf replicates (n = 6 for each scion–rootstock combination, irrigation treatment in the 'Chardonnay' vineyard on 24 Aug. while n = 5 for each treatment in the 'Chardonnay' vineyard measured on 21 Sept. and for the 'Cabernet Sauvignon' vines measured on 25 Aug.; total n = 86). The relationships between A and g_s and water potentials were also determined using treatment means as A and g_s were not necessarily determined on the same leaves and/or vines as Ψ measurements were within block 1 at each location. Differences in water potential among irrigation treatments at either site were analyzed via analysis of variance and means separated using Duncan's multiple range test. An analysis of covariance was used to test for heterogeneity of slopes for the relationship between Ψ_{stem} and Ψ_l among the three different measurement dates.

Results

There had been no significant rainfall since anthesis at either site in 1999. Irrigations commenced at both locations in the middle of June and water was applied once per week. The 'Chardonnay' vines had been irrigated 5 d before measurements of vine water status in August, while in September the vines were irrigated the previous day. Potential ET the weeks of 23 Aug. and 20 Sept. at the Carneros CIMIS station (used for calculating ET_c for the 'Chardonnay' vineyard) was 30.7 and 21.9 mm, respectively. Applied amounts of water at 100% of ET_c in the 'Chardonnay' vineyard the week measurements were taken were 63.8 L/vine (19.7 mm) in August and 49.6 L/vine (15.3 mm) in September. Ambient temperatures and canopy to air vapor pressure difference at the time of the midday measurements in the 'Chardonnay' vineyard were 26 °C and 2.5 kPa in August and 27 °C and 1.9 kPa, in September, respectively. *PPF* measured in the 'Chardonnay' vineyard was in excess of 1,700 $mmol \cdot m^{-2} \cdot s^{-1}$ at solar noon. It should be pointed out that the irrigation pump in the 'Cabernet' vineyard broke 2 weeks before 25 Aug. 1999, and it had not been fixed on the date measurements were

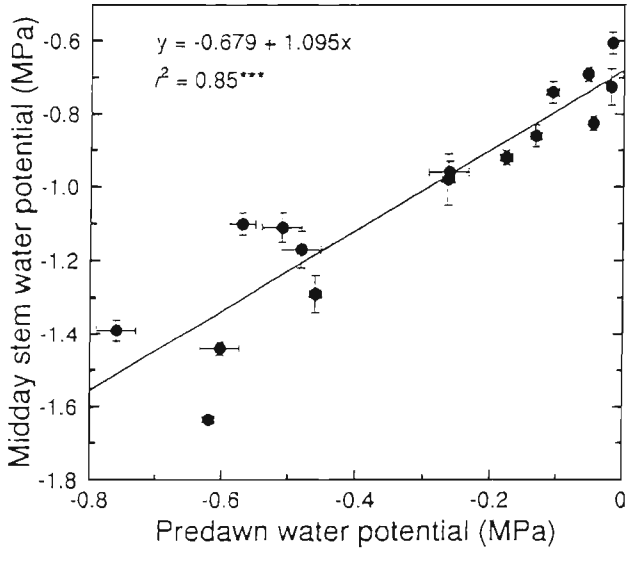

Fig. 1. Relationship between midday stem water potential (Ψ_{stem}) and predawn leaf water potential (Ψ_{PD}) of 'Chardonnay' and 'Cabernet Sauvignon' grapevines. An individual data point is the mean of either five or six individual leaf replicates (See Materials and Methods). Bars larger than the symbols represent ± 1 SE. ***Significant at $P < 0.001$.

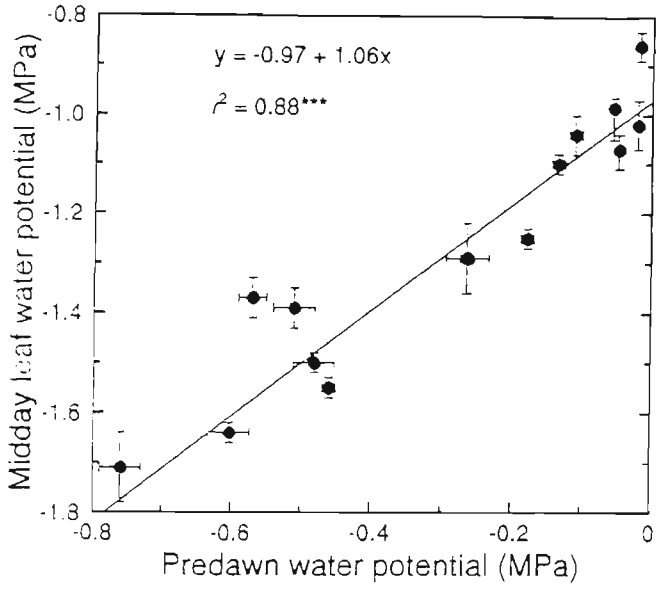

Fig. 2. Relationship between midday leaf water potential (Ψ_l) and predawn leaf water potential for the vines used in the study. See Fig. 1 for additional information. ***Significant at $P < 0.001$.

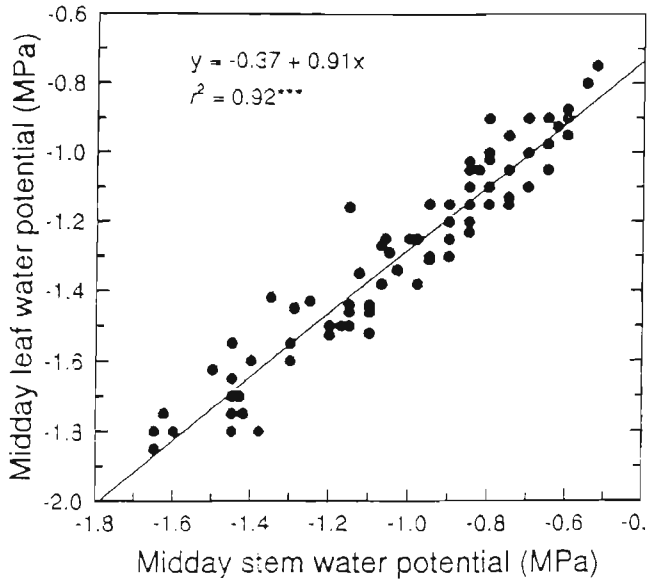

Fig. 3. Relationship between midday leaf water potential and midday stem water potential of 'Chardonnay' and 'Cabernet Sauvignon' grapevines. Each value is an individual leaf replicate. The coefficient of determination for a linear regression of the data using treatment means (such as used in Figs. 1 and 2) equals 0.96. The slopes and intercepts for the three different measurement dates were not significantly different. ***Significant at $P < 0.001$.

taken. Ambient temperature at midday on 25 Aug. was 36.7 °C (maximum temperature that day was 41.3 °C) and midday canopy to air vapor pressure difference was almost 5.0 kPa (maximum that day was 7.4 kPa). The *PPF* at 1300 HR was 1679 mmol·m^{-2}·s^{-1} on 25 Aug.

Use of irrigation treatments at both locations resulted in a wide range of vine water statuses (Table 1). The lowest values of Ψ_{PD}, Ψ_l, and Ψ_{stem} recorded for an individual leaf were –0.85, –1.85, and –1.65 MPa, respectively. The highest values of Ψ_{PD}, Ψ_l, and Ψ_{stem} recorded for an individual leaf were –0.02, –0.75, and –0.55 MPa, respectively. In most cases, significant differences among irrigation treatments for one measure of vine water status were also similarly different for the other two (Table 1). The exceptions were for the 110R rootstock measured on both dates. On 24 Aug. Ψ_{PD} was significantly different between the 0.5 and 1.0 irrigation treatments but Ψ_{stem} and Ψ_l were not. On 21 Sept., Ψ_{PD} between the 0.5 and 1.0 irrigation treatments was not significantly different, but Ψ_{stem} and Ψ_l were.

All three methods of estimating vine water status were highly correlated with one another (Figs. 1–3). The best correlation was between midday Ψ_l and Ψ_{stem} (Fig. 3). All three methods of estimating vine water status were also significantly correlated with SWC in the 'Chardonnay' vineyard (Table 2).

Maximum and minimum values of A in terms of CO_2 for an individual leaf measured at either location were 13.5 and 1.7 mmol·m^{-2}·s^{-1}, respectively. Maximum and minimum values of g_s in terms of H_2O for an individual leaf measured at either location were 440 and 70 mmol·m^{-2}·s^{-1}, respectively. All three measurements of vine water status were significantly correlated with A and g_s (Table 3). Predawn leaf water potential was more highly correlated with A and g_s than either midday measurements of vine water status. Lastly, all three measures of vine Ψ determined on 24 Aug. were linearly correlated (r^2 values in excess of 0.93) with berry weight and vine yield at the Carneros location when measured on 4 and 6 Oct., respectively (data not presented).

Mean (±SE) midday Ψ_l of the 'Merlot' vines irrigated at 120% of estimated ET_c were –0.93 ± 0.01, –1.04 ± 0.03, and –1.21 ± 0.01 MPa for leaves covered with a plastic bag before excision, covered with a plastic bag just after excision, and leaves not covered with plastic at any time, respectively. Mean midday Ψ_l of vines irrigated at 40% of estimated ET_c were –1.33 ± 0.01, –1.45 ± 0.01, and –1.52 ± 0.02 MPa for the above mentioned treatments, respectively. Differences in Ψ_l between leaves covered with the bag before excision and those not covered at all were greater for the vines irrigated at 120% of ET_c compared to those at 40%.

Table 2. Regression equations of the method of measuring vine water status as a function of soil water content and the coefficient of determination and its significance level of 'Chardonnay' grapevines. Regressions are based on mean values of all measures of water potential. Soil water content was expressed as % vol/vol and water potential in MPa.

Ψ measurement	Regression	r^2
Predawn leaf (Ψ_{PD})	y = –3.81 + 0.099x	0.69**
Midday leaf (Ψ_l)	y = –5.86 + 0.129x	0.68**
Midday stem (Ψ_{stem})	y = –5.77 + 0.134x	0.63**

**Significant at $P < 0.01$.

Table 3. Regression equations of A and g_s as a function of the method of measuring vine water status and the coefficients of determinations and their significance level. Net CO_2 assimilation rate (A) was expressed in terms of CO_2 as mmol·m^{-2}·s^{-1}, stomatal conductance to water vapor (g_s) was expressed in terms of H_2O as mmol·m^{-2}·s^{-1} and water potential was expressed as MPa.

Ψ measurement (x)	Gas exchange (y)	Regression	r^2
Ψ_{PD}	A	y = 11.8 + 14.9x	0.67**
	g_s	y = 298 + 325x	0.69**
Ψ_l	A	y = 24.3 + 13.4x	0.50*
	g_s	y = 600 + 314x	0.58*
Ψ_{stem}	A	y = 19.3 + 12.4x	0.46*
	g_s	y = 485 + 293x	0.54*

*,**Significant at $P < 0.05$ or 0.01, respectively.

Discussion

The combination of irrigation treatments and evaporative demand resulted in large differences in various measures of leaf water potential and gas exchange parameters in this study. Vines that had been irrigated the previous day, depending upon the amount of water applied, had high values of Ψ_{PD}, Ψ_l, and Ψ_{stem} and high rates of A and g_s. Conversely, nonirrigated vines or vines which had not been irrigated due to an irrigation pump malfunction had low values. The mean Ψ_{PD} values of vines irrigated at 100% of ET_c (i.e., –0.02 to –0.1 MPa) the day before measurements were taken was much higher than those of Correia et al., (1995) for well watered vines (Ψ_{PD} = –0.38 MPa) but similar to that reported by Rodrigues et al. (1993). In addition, Ψ_{PD} of vines in a 'wet site' vineyard had lower values (Winkel and Rambal, 1993) than Ψ_{PD} reported herein. However, the lowest Ψ_{PD} recorded in this study, –0.8 MPa, was much higher than the stressed vine's Ψ_{PD} (–1.13 MPa) in the study by Rodrigues et al. (1993) using potted vines.

Vines that received quantities of applied water at 100% of estimated ET_c in this study had midday Ψ_l values generally no lower than –1.0 MPa. This value is similar to the minimum midday Ψ_l of 'Thompson Seedless' grapevines irrigated at full ET_c (Grimes and Williams, 1990; Williams, 2000; Williams et al., 1994). It is much higher than the midday Ψ_l reported for 'Sauvignon blanc' vines growing under nonlimiting soil water availability conditions with daily irrigation (Naor et al., 1997) or for continuously irrigated *V. labruscana* (Naor and Wample, 1994). It is also higher than the midday Ψ_l reported for a wet site in France (Winkel and Rambal, 1993). The minimum Ψ_l values reported herein at midday are similar to minimum Ψ_l values measured on field grown grapevines (Chaves and Rodriques, 1987; Schultz, 1996; Winkel and Rambal, 1993). Lastly, extremes of midday Ψ_{stem} measured in this study were similar in range to that reported on *V. labruscana* (Naor and Wample, 1994; Liu et al., 1978) and *V. vinifera* 'Colombard' (Stevens et al., 1995).

The present investigation is the first study the authors are aware of in which the three 'standard' methods of estimating grapevine water status in the field (i.e., Ψ_{PD}, Ψ_l, and Ψ_{stem}) had been measured and compared specifically with one another. The highest correlation of the comparisons among Ψ_{PD}, Ψ_l, and Ψ_{stem} was that between midday Ψ_l and Ψ_{stem}. This was despite the fact that the correlation was made on individual leaf replicates between these two as opposed to treatment means when Ψ_l and Ψ_{stem} were correlated with Ψ_{PD}. The high correlation between the individual leaf, midday measurements of Ψ may have been due to the fact that the measurements were made simultaneously from leaves on the same vine. van Zyl (1987) found a r^2 of 0.66 when Ψ_l was correlated with Ψ_{PD}. An analysis by the authors of this paper of the Ψ_{PD} and daily minimum Ψ_l reported by Winkel and Rambal (1993) indicate that the two were linearly correlated ($r^2 \approx 0.5$). Stevens et al. (1995) found that diurnal measurements of Ψ_l and Ψ_{stem} of 'Colombard' on 'Ramsey' rootstock were highly correlated with one another. When the diurnal Ψ_l and Ψ_{stem} data in Fig. 4 of Liu et al. (1978) are linearly correlated with each another (performed by the authors of this paper), one obtains an $r^2 > 0.95$. The above would indicate that either measurement of midday Ψ would give a good estimate of the water status of grapevines. This may not hold true for other plant species as Naor et al. (1995) found the correlation between Ψ_l and Ψ_{stem} of apple to have a r^2 of just 0.35. However, it would appear that the Ψ_{stem} and Ψ_l of peach [*Prunus persica* (L.) Batsch (Peach group)] trees presented in Fig. 5 of Seles and Berger (1990), would be highly correlated with one another.

Predawn leaf water potential has been used in many grape studies as the standard to which other measures of the vine's water status are compared (Correia et al., 1995; Rodrigues et al., 1993; Schultz, 1996; van Zyl, 1987; Winkel and Rambal, 1993). It is assumed that the vine is in equilibrium with water potential of the soil at that time (Winkel and Rambal, 1993). The relationships between Ψ_{PD} of 'Chardonnay' and SWC found in this study and a similar comparison by van Zyl (1987) (Ψ_{PD} vs. SWC in that study resulted in a r^2 of 0.39), indicates that measurement of Ψ_{PD} on grapevines may provide a good estimate of the soil moisture status within a vineyard. It has also been demonstrated, though, that season long measurements of midday Ψ_l on 'Chardonnay' (same vines as used in this study) (Williams, 1996) and 'Thompson Seedless' (Williams et al., 1994) are highly correlated (r^2 = 0.82 and 0.67, respectively) with the seasonal change in SWC of treatments irrigated with differing applied amounts of water. That data, along with the data in Table 2 would indicate midday Ψ_l also is reflective of the amount of water in the soil profile under the environmental and soil conditions of this study.

The suggestion that Ψ_{stem} and Ψ_{PD} are better indicators than Ψ_l of grapevine water status is based on correlations of those Ψ measurements with leaf gas exchange (Chone et al., 2001; Naor, 1998) or the convergence of Ψ_l later in the day among treatments that are assumed to have different water statuses (Correia et al., 1995; Naor and Wample, 1994). Naor (1998) found a better linear relationship between Ψ_{stem} and g_s than Ψ_l and g_s for measurements made between 0900 and 1400 HR on 'Sauvignon blanc' grapevines. However, Naor et al. (1994) reported previously that g_s was highly correlated with Ψ_l of 'Sauvignon blanc' grapevines. In addition, Naor et al. (1997) has also reported that the relationship between g_s and Ψ_{stem} of 'Sauvignon blanc' was curvilinear, not linear. The differences noted above for 'Sauvignon blanc,' would indicate that correlation of vine water status (either Ψ_{stem} or Ψ_l) with only a single criterion, such as g_s, can differ from study to study. In the present study, more than one parameter of vine water status was measured, for two different cultivars, on three different dates, in addition to the measurement of soil water content and applied water amounts.

Correia et al. (1995) found differences in Ψ_{PD} between well watered and stressed treatments but no differences in Ψ_l later in the day, at 1000 and 1600 HR. However, it has been found that in some cases Ψ_{PD} of different plant species will come into equilibrium with the wettest portion of the soil in the plant's root zone (Ameglio et al., 1999; Tardieu and Katerji, 1991). Therefore, the soil moisture a plant responds to at midday may differ from that at predawn due to the flux of water occurring while the plant is actively transpiring (Jensen et al., 1989; Stevens et al., 1995). Thus, differences observed at predawn may not necessarily reflect the water status of the plant later in the day, such as observed in the present study (Table 1, 110R rootstock data on 21 Sept.) and the data of Chone et al. (2001).

Other studies which have concluded that either Ψ_{PD} or Ψ_{stem} were better measures of plant water status did not expressly state in the materials and methods that leaves were covered with a plastic bag before leaf excision for measurement of Ψ_l (Chone et al, 2001; Garnier and Berger, 1985; van Zyl, 1987) or covered the leaf only after excision (Naor, 1998). There is a rapid loss of water from actively transpiring leaves within a few seconds of excision such that the Ψ_l of bagged leaves is higher than that of nonbagged leaves (Turner and Long, 1980). This was demonstrated in the

present study using 'Merlot' grapevines grown in the San Joaquin Valley. It was also demonstrated that leaves bagged just subsequent to leaf excision also had more negative Ψ_l than those that were bagged before excision. Therefore, the method used in measuring midday Ψ_l could influence subsequent interpretation of the data regarding its correlation with other means of determining plant water status.

One last factor that may have improved the reliability of using Ψ_l to estimate vine water status in this study was the limitation placed upon time (1230 to 1330 HR Pacific Daylight Time) when midday measurements were taken. It is during this time that maximum diurnal water use (Williams, 2000) or canopy conductance (Williams, 1999) has been measured on nonwater-stressed 'Thompson Seedless' grapevines irrigated at 100% of ET with the use of a weighing lysimeter. Canopy conductance of 'Thompson Seedless' grapevines that had not been irrigated for 15 d is greatest early in the morning but maximum diurnal water use also occurs around solar noon (Williams, 1999). Time periods for measurements of midday Ψ have been from 1100 to 1400 HR for grape (Chone et al., 2001) and 1200 to 1500 HR for trees (McCutchan and Shackel, 1992). Leaf water potential of 'Thompson Seedless' grapevines can vary considerably between 1100 and 1500 HR during the day, possibly due to changes in vapor pressure deficit (VPD) and ambient temperature (Williams et al., 1994) and therefore it is expected that Ψ_l of other *V. vinifera* cultivars and species would be the same. Thus, midday Ψ_l values would have a larger deviation around the mean, resulting in fewer significant differences, as found by McCutchan and Shackel (1992) and Chone et al. (2001), than perhaps measurements taken only 0.5 h on either side of solar noon.

All three methods of estimating vine water status used in this study were similarly correlated with SWC, applied amounts of water and with one another, with only a few exceptions. In addition, they were significantly correlated with midday measurements of leaf gas exchange. Therefore, the criterion that estimates of plant water status should reflect the availability of soil moisture and/or applied water amounts or measures of short- or medium-term plant stress responses (Higgs and Jones, 1990; Shackel et al., 1997) and growth (Naor, et al. 1995), were met for all measures of Ψ under the conditions of this study.

Currently in California, some of the larger wineries and crop consultants are using measurement of vine water status as an aid in vineyard irrigation management decisions. They are using leaf water potential to determine when to start irrigating at the beginning of the season and sometimes for the determination of the interval between irrigation events. Based upon the data collected in this study, critical values of Ψ_{PD}, Ψ_l, or Ψ_{stem} could be established and utilized to assist in making such decisions. However, from a practical standpoint, measurement of midday Ψ_l would be most convenient. One would not have be in the vineyard before sunrise to measure Ψ_{PD} nor arrive in the vineyard 90 min before taking midday Ψ_{stem} readings in order to bag the leaves in plastic and cover with aluminum foil. However, the time frame used to measure midday water potentials in this study was restricted to 0.5 h on either side of solar noon. Such a restriction would limit the acreage or number of vineyards one could measure with limited resources on a daily basis. The extension in the measurement of Ψ_l before or after the 1230 to 1330 HR time frame used herein to a commercial situation could be accomplished with its calibration to environmental variables such as ambient temperature and VPD as done for cotton (*Gossypium hirsutum* L.) (Grimes et al., 1987) and VPD as done for deciduous fruit trees (Shackel et al., 1997). Lastly, it has been demonstrated that the individual making measurements of plant water status is a significant source of variation, even for stem water potential (Goldhamer and Fereres, 2001). Therefore, it is imperative that technicians be well trained in the use of the pressure chamber and the choice of leaves to sample.

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Vine Water Relations, Gas Exchange, and Vegetative Growth of Seventeen *Vitis* Species Grown under Irrigated and Nonirrigated Conditions in California

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Abstract. A comparison was made among 16 native North American *Vitis* species and *Vitis vinifera* L. ('Carignane') grown in the San Joaquin Valley of California with or without irrigation over 2 years. Predawn water potential (Ψ_{pd}), predawn leaf osmotic potential (Ψ_π), midday leaf (Ψ_l), and stem water potential (Ψ_{stem}), stomatal conductance (g_s), net CO_2 assimilation rate (A), and intrinsic water use efficiency (WUE) were measured on five dates during the growing season the first year of the study and pruning weights were evaluated both years. Net gas exchange and water potential components taken on the last measurement date in 1992 and pruning weights of the nonirrigated species were less (or more negative for Ψ components) than those of the irrigated vines. The 17 *Vitis* species were ranked according to their relative drought tolerance based upon their performance without irrigation and when compared to their irrigated cohort. The *Vitis* species considered most drought tolerant were *V. californica*, *V. champinii*, *V. doaniana*, *V. longii*, *V. girdiana*, and *V. arizonica*. Those six species generally had high values of A, g_s, and pruning weights and more favorable vine water status at the end of the study than the other species when grown without irrigation. The drought-induced reductions in the measured parameters also were less for those species when compared to their irrigated cohorts. The least drought tolerant species were, *V. berlandieri*, *V. cinerea*, *V. lincecumii*, *V. riparia*, and *V. solonis*. The drought-tolerant rankings were generally associated with the species' native habitat and probable soil water availability.

Plants subjected to severe water deficits show decreases in stomatal conductance (g_s), net CO_2 assimilation rates (A) and more negative leaf water potential (Ψ) (Jones, 1992). The drought responses of agronomic and perennial crops can include reduced A, g_s, transpiration rates and osmotic adjustment (Chartzoulakis et al., 1993; Martin and Ruiz-Torres, 1992; McCree and Richardson, 1987; Stoneman et al., 1994; Wong et al., 1985). As stem water potential values (Ψ_{stem}) become more negative the more xeric adapted *Prunus* species exhibited higher water use efficiency (WUE) than those of mesic origin (Rieger and Duemmel, 1992). The responses of grapevines (*Vitis* spp.) to drought can include reductions of A, g_s, reduced stomatal frequency, increased root density, and reduction of leaf area and leaf number (Smart and Coombe, 1983).

Differences among *V. vinifera* cultivars in response to water deficits have also been documented. Drought stressed 'Trollinger' grapevines responded to water deficits by reducing A (Düring, 1988), while 'Riesling' vines osmotically adjusted resulting in a higher turgor potential (Ψ_T) than 'Sylvaner' vines (Düring and Loveys, 1982). Additionally, 'Riesling' and 'Sylvaner' grapevines had differing degrees of osmotic adjustment and changes in WUE when subjected to water stress (Düring, 1984; 1987). Grimes and Williams (1990) found that 'Thompson Seedless' vines osmotically adjusted ≈0.4 MPa when deficit irrigated while Düring (1984) found an osmotic adjustment of 0.7 MPa. In another drought response study 'Carignane' had greater maximum g_s and higher stomatal sensitivity to changes in air humidity than did 'Shiraz' or 'Merlot' grapevines (Winkel and Rambal, 1990).

There has been relatively little work done on the effects of soil water deficits on other *Vitis* species. The objective of this study was to rank the relative drought tolerance of 17 *Vitis* species under irrigated and nonirrigated conditions in the San Joaquin Valley of California. This was accomplished by measuring leaf water relations, gas exchange and vine growth and then comparing each species within the nonirrigated portion of the vineyard with one another and with their irrigated cohort. In addition to several North American species, which are used either as commercial rootstocks or parents of other grape rootstocks, this study included several *Vitis* species indigenous to the arid southwestern United States. It was expected that the diverse, native habitats of the 17 species would have selected for a wide range drought tolerance characteristics that may be of use in future rootstock breeding programs.

Materials and Methods

Dormant cuttings of the *Vitis* species listed in Table 1 were taken from vines growing in the United States Department of Agriculture National Clonal Germplasm Repository, Davis, Calif. holdings, in February 1990. Rooted cuttings were initially planted into 0.95 L milk cartons using a 1 sand : 1 compost–vermiculite : 2 peatmoss soil mix. The vines were transplanted into 3.8-L pots of coarse sand, and moved to a lath house for the remainder of the 1990 growing season. The dormant vines were transported to the University of California, Kearney Agricultural Center, near Fresno, California, during the 1990-91 winter. Five individual vine replicates per species were planted in March 1991 in a 0.4 ha vineyard using a completely randomized block design. A buffer vine was planted on either side of each data vine down the row. Vine and row spacings were 2.44 and 3.66 m, respectively. A single wire trellis (1.0 m above the soil surface) was used. The soil was a Hanford fine sandy loam (coarse-loamy, mixed, nonacid, thermic Typic Xerorthent) with a hardpan at 1.2 m. Standard pest control measures were used throughout the

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Table 1. *Vitis* species used in the study, description of their native habitats and ranges in North America or elsewhere and references.

Vitis species	Habitat	Range	Reference[z]
arizonica (Englemann)	Canyons, rocky canyon walls	Ariz., N.M., Trans-Pecos of Texas	1, 5, 6
berlandieri (Planchon)	Limestone soils, moist sites	Texas to Mexico	1, 8
californica (Bentham)	Stream banks	California's coastal mountain range, central valley, Sierra foothills, and southern Ore.	9
candicans (Englemann)	All situations, edge of woods, sandy slopes, disturbed ground, coastal oak woods	East and south central Texas	1, 4, 11
champinii[y] (Planchon)	Dry, chalky, limestone soils	Throughout Texas	8
cinerea (Englemann)	Low woodlands and alluvial soil along streams	Southeast U.S.: Texas to N.C and S.C., Ariz., Mo., Kans., Ill.	3, 12, 13
cordifolia (Michaux)	Along streams and moist wooded areas	Texas to Kans. and southeastern U.S.	2
doaniana[x] (Munson)	Woods, stream bottoms, rocky slopes or alkaline soils	Texas panhandle/east of Pecos River and N.M.	1, 6, 8
girdiana (Munson)	Canyon bottoms and along streams	Coastal to inland Calif. (including Mojave Desert)	9
lincecumii (Buckley)	Woods and thickets, upland wooded soils, riverbeds	Texas to Kans.	1, 3, 11
longii (Prince)	Sandy soils, dry hillsides, dunes, rocky slopes	Kans. and Texas panhandle	1, 3
monticola (Buckley)	Rocky hills, limestone hills, canyons, ridges	N.M. and Texas	1, 6
riparia (Michaux)	Streambanks, low woodlands, alluvial soils	Eastern, central, and northern U.S.	3, 10, 13
rupestris (Scheele)	Sand and gravel bars	Once widely scattered from Tenn. to Texas	1
solonis (Hort. Berol.)	Open woods and rocky canyon slopes	Texas	1
treleasei (Munson)	Glabrous form of *V. arizonica*	Occurs on northern extent of *V. arizonica*'s range	1
vinifera L. 'Carignane'	Indigenous to Eurasia		7

[z]1 = Correll and Johnson, 1970, 2 = Galet, 1979, 3 = Gates, 1940, 4 = Jones, 1975, 5 = Kearney and Peebles, 1951, 6 = Martin and Hutchins, 1980, 7 = Mullins et al., 1992, 8 = Munson, 1909, 9 = Munz and Keck, 1959, 10 = Ownbey and Morley, 1991, 11 = Reeves and Bain, 1947, 12 = Smith, 1978, 13 = Steyermark, 1978.

[y]*Vitis champinii* is a natural hybrid of *V. candicans* x *V. rupestris* (Galet, 1979).

[x]*Vitis doaniana* is a natural hybrid of *V. candicans* x *V. longii* (M.A. Walker, unpublished data).

study. Vines were head-trained and dormant pruned to 8 to 12 buds. Clusters present on the vines were removed at anthesis each year.

All vines were furrow irrigated each week during the 1991 growing season. Two irrigation treatments of either weekly furrow irrigations (I) or a nonirrigated (NI) drought stress treatment were imposed at the beginning of the 1992 growing season and continued during 1993. Soil water content in the field was monitored with a neutron probe (Troxler depth moisture gauge, model 3320) using 10 access tubes per treatment, and read at five successive 0.3 m increments beginning 0.3 m below the soil surface. An individual access tube site was located in both irrigation treatments near individual vines of *V. arizonica, V. champinii, V. riparia, V. rupestris* and *V. vinifera* 'Carignane'. Each site consisted of two access tubes, one within the row (0.5 m from the vine) and one between rows (0.5 m from the vine). Environmental conditions at this location were obtained from a weather station operated by the California Irrigation Management Information System ≈0.5 km from the vineyard.

Pruning weights were taken during the dormant period (from five replicate vines) in 1992 and 1993. All reported measurements of gas exchange, water potential and water potential components were collected from three replicate grapevines, two leaves per vine, during the 1992-growing season. At midday (one hour on either side of solar noon), fully exposed leaves were selected for gas exchange measurements between the 7th and 14th node counting from the base of the shoot. Net CO_2 assimilation rate (A) and stomatal conductance to water vapor (g_s) data were collected with a portable infrared gas analyzer, LCA-2, using the broad leaf cuvette (Analytical Development Company, Ltd., Hoddeson, England). Leaf intrinsic water use efficiency (WUE) was calculated dividing A by g_s.

Predawn leaf water potential (Ψ_{PD}) and midday leaf (Ψ_l) and stem (Ψ_{stem}) water potentials were measured on the same day as photosynthesis measurements with a pressure chamber (PMS Instrument Company, Corvallis, Ore.), according to the procedures of McCutchan and Shackel (1992). Measurements were made on leaves similar to those used for gas exchange. Leaf samples for osmotic potential (Ψ_π) were taken at predawn and quick-frozen on dry ice followed by storage at –80 °C. For analysis of Ψ_π, the leaf samples were thawed at 37 °C and osmotic potentials read on a vapor pressure osmometer (Wescor 5500; Wescor, Inc. Logan Utah).

Water relations and gas exchange measurements were taken on several dates spanning the growing season, so data were analyzed as a split plot (through time with day of year being the split). All measurements for each of the 17 species were collected on five paired days of year (DOY): 118 and 119, 140 and 141, 182 and 183, 204 and 205, 232 and 233 as 2 d were necessary to measure all replicates since we imposed a 2-h limit for readings at midday to minimize diurnal effects. These paired dates were considered as a single day for analysis. Least squares means for data analyzed on a seasonal basis are combined values from the five measurement dates using three replications. Means for gas exchange and Ψ parameters collected on the last measurement date are data from three individual vine replicates (two measurements per vine). Data were analyzed via analysis of variance (ANOVA) and mean sepa-

rations were determined using Duncan's multiple range test (DMRT). Additionally, predawn Ψ_π of each species, within each irrigation treatment, was analyzed as function of Ψ_{PD} throughout the growing season and an ANCOVA was used to test for differences among the slopes.

Drought performance indicators used to rank the species were pruning weights of the nonirrigated vines (averaged across the two years) and their percent reduction compared to the irrigated treatment. Since day of year had a significant effect on all water relations and gas exchange parameters measured, only measurements taken on the last date were used to assess the relative drought tolerance of the species in the nonirrigated treatment with the exception of Ψ_π data. Gas exchange performance indicators were the nonirrigated vines' A, g_s and WUE. Vine water status parameters used were the Ψ difference in Ψ_l and Ψ_{stem} and the percent Ψ_{PD} – midday Ψ_{stem} gradient portion of the total Ψ_{PD} – midday Ψ_l gradient (Chone et al., 2001). The predicted osmotic potential of each species in the NI treatment, at a Ψ_{PD} of –0.205 MPa (using the results from the ANCOVA mentioned in the previous paragraph) was calculated and used as a relative indicator of the species' ability to accumulate solutes. The –0.205 MPa Ψ_{PD} value was chosen as it was the overall seasonal mean of all species in both irrigation treatments. The gas exchange and Ψ characteristics of the species in the NI treatment were also compared to those of the irrigated treatment. Each species was assigned a number (1 to 17) in each category. For example the species with the highest A was assigned number 1, while the species with the lowest, number 17. The species with the lowest reduction in A compared to its irrigated counterpart was assigned number 1, while the greatest reduction in A (NI vs. I) the highest number (17). Values in the rankings table were tested for skewness and kurtosis and the results indicated that the data were normally distributed. In addition, Bartlett's test of the species' rankings in each category indicated that their variances were homogeneous. Subsequently, a one-way, completely randomized ANOVA was conducted on the 13 drought performance values and species' means separated using DMRT.

Results

Precipitation from 1 Apr. until the last measurement date in 1992 totaled 3 mm, whereas the total for the same time period in 1993 was 10 mm. Soil water content was significantly lower in the nonirrigated plots than in the irrigated plots both years (data not given). Based upon neutron probe readings, the amount of water depleted in the soil profile of the NI treatment amounted to 0.74 and 0.94 m^3 of water in 1992 and 1993, respectively. Applied water and depletion of water in the soil profile of the irrigated treatment amounted to greater than 1.8 m^3 per vine both years.

All days in which midday Ψ and gas exchange were measured were cloud free. Ambient temperature during each two-hour measurement period ranged from 23 to 29 °C and vapor pressure deficit (VPD) ranged from 1.5 to 2.5 kPa on the first four dates. Solar radiation, ambient temperature and VPD on the last measurement date(s) (19 and 20 Aug.) averaged 826 $W \cdot m^{-2}$, 34.5 °C and 3.2 kPa, respectively, for the 2-h measurement period.

Irrigation treatment had a significant effect on most of the measured parameters when averaged across dates (Table 2). There was a significant irrigation treatment by species interaction on all measures of vine water status taken predawn, stomatal conductance, and pruning weights in 1993. As the season progressed, measurement date had a significant effect on most of the measured parameters throughout the season.

Averaged across all species and irrigation treatments, measurements of vine water status (Ψ_{PD} and midday Ψ_l and Ψ_{stem}) decreased as the season progressed, with the exception of the irrigated vines' Ψ_{PD} (Fig. 1). Net CO_2 assimilation rate decreased almost linearly from DOY 135 until the last measurement date for the nonirrigated species while that for the irrigated treatment tended to level off from DOY 141 to the last measurement date (Fig. 2). Similar results were found for g_s (data not given).

Under nonirrigated conditions, the species with the least negative Ψ_{PD} on the last measurement date were *V. berlandieri*, *V. doaniana*, *V. treleasei*, and *V. vinifera* and they were significantly higher than *V. arizonica*, *V. champinii* and *V. riparia* (Table 3). Predawn Ψ_π generally decreased through the first half of the growing season for the vines in the NI treatment but it tended to increase throughout the remainder of the season for many of the species in that treatment (see Padgett-Johnson et al., 2000, for an example). An ANCOVA of the relationship between predawn Ψ_π and Ψ_{PD} indicated that the slopes differed significantly among species within each irrigation treatment (data not given). The predicted predawn Ψ_π (based on the above referenced ANCOVA) at a Ψ_{PD} of –0.205 MPa was greatest for *V. treleasei* and lowest for *V. monticola* and *V. riparia*. The predicted values of predawn Ψ_π were similar to the seasonal least squares means of each species in both irrigation treatments (data not given).

Midday Ψ_{stem} of nonirrigated *V. californica* on the last measurement date was significantly different from 15 of the other species (Table 3). The lowest value for Ψ_{stem} on that date was –1.46 MPa for *V. monticola* and *V. riparia*. *Vitis* species with a midday Ψ_l more negative than –1.65 MPa (*V. cinerea*, *V. champinii*, *V. monticola* and *V. riparia*) were significantly different from *V. californica* with a midday Ψ_l of –1.33 MPa. *Vitis champinii* had the lowest midday Ψ_l (–1.75 MPa) on the last date.

The difference between midday Ψ_l and Ψ_{stem} on the last measurement date was significantly greater for *V. champinii* and *V. californica* than 11 other *Vitis* species, i.e., those with $\Psi_l - \Psi_{stem}$ values <0.24 MPa (Table 3). There were no significant differences in this parameter among species in the irrigated portion of the study. The $\Psi_{PD} - \Psi_{stem}$ portion of the $\Psi_{PD} - \Psi_l$ gradients of *V. arizonica*, *V. californica*, *V. champinii* and *V. doaniana* (values <70) under

Table 2. Analysis of variance of irrigation (I) treatment, species, irrigation (I) × species (S) interaction, day of year (DOY) and I × S × DOY interaction on different vine water status measurements, net CO_2 assimilation rate (A), stomatal conductance (g_s), transpiration (E), intrinsic water use efficiency (WUE), and pruning weight (PWt) of 17 *Vitis* species. All data were collected during the 1992 growing season except the pruning weights of 1993; predawn leaf water potential = Ψ_{PD}, predawn leaf osmotic potential = Ψ_π, midday leaf water potential = Ψ_l, and midday stem water potential = Ψ_{stem}.

Parameter measured	I	Species	I × S	DOY	DOY × I × S
Ψ_{PD}	***	***	**	***	***
Ψ_π	***	***	***	***	NS
Ψ_l	***	***	NS	***	NS
Ψ_{stem}	***	***	NS	***	**
g_s	***	***	***	***	NS
A	***	***	NS	***	*
E	***	***	NS	NS	NS
WUE	*	***	NS	***	NS
PWt 1992	***	***	NS	NA	NA
PWt 1993	***	***	***	NA	NA

NS,*,**,***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

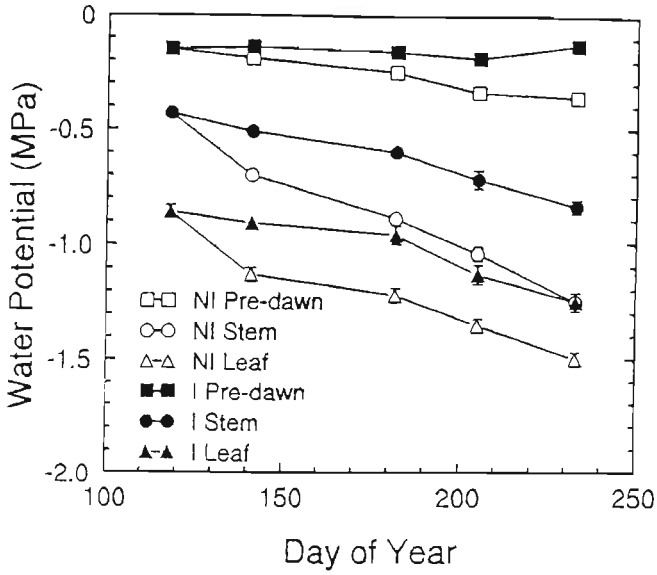

Fig. 1. Three measures of vine water status [Ψ_{PD} (predawn), midday Ψ_{stem} (stem), and midday Ψ_l (leaf)] for all species in the nonirrigated (NI) and irrigated (I) treatments on five different dates during the 1992 growing season. Each individual point is the mean of all 17 *Vitis* species used in the study. Bars, larger than the symbol, represent ± 1SE.

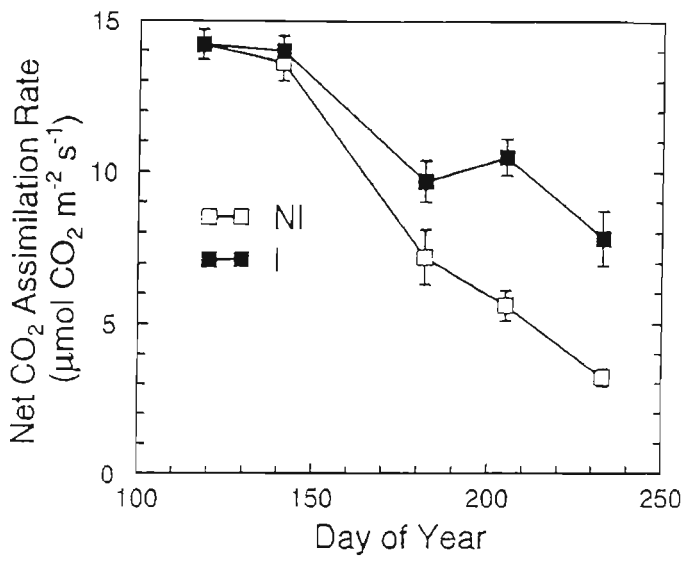

Fig. 2. Net CO_2 assimilation rate for all species in the nonirrigated and irrigated treatments on five different dates during the 1992 growing season. Other information as found in Fig. 1.

nonirrigated conditions were significantly different from 9 other species (values >83). There were also significant differences among species in the irrigated portion of the trial.

There were no significant differences in A on the last measurement date among species in the nonirrigated treatment; however, there were significant differences among the species in the irrigated treatment (Table 4). Stomatal conductance of nonirrigated *V. champinii* was significantly greater than 11 other *Vitis* species, i.e., those with H_2O values less than 170 mmol·m^{-2}·s^{-1}. *Vitis californica* had the highest g_s among species in the irrigated treatment. Lastly, there were significant differences in intrinsic WUE of species in the nonirrigated treatment with *V. rupestris* having the highest and *V. californica* and *V. candicans* having the lowest (Table 4).

There were significant differences in pruning weights between irrigation treatments species in 1992 and 1993 (Table 2) and among species in the nonirrigated treatment both years (Table 5). *Vitis champinii* had the highest mean pruning weight for both irrigation treatments, followed by *V. girdiana*, *V. doaniana* and *V. longii* (Table 5). *Vitis cinerea* and *V. berlandieri* had the lowest pruning weights regardless of treatment. The species with the greatest percent reduction in pruning weights, comparing irrigated to

Table 3. Predawn leaf (Ψ_{PD}), midday leaf (Ψ_l) and midday stem (Ψ_{stem}) water potentials of the nonirrigated (NI) species on the last measurement date. The difference between Ψ_l and Ψ_{stem} and the percent of the predawn to midday stem ($\Psi_{PD} - \Psi_{stem}$) gradient of the total predawn to midday leaf ($\Psi_{PD} - \Psi_l$) gradient on the last measurement date for both the irrigated (I) and nonirrigated vines and the predicted predawn Ψ_π at a Ψ_{PD} of –0.205 MPa are also given. Water potential values are expressed in MPa. Means followed by a different letter are significantly different at $P < 0.05$. Means were not significantly different in the irrigated (I), $\Psi_l - \Psi_{stem}$ column. The predicted predawn Ψ_π was not analyzed.

Vitis	Ψ_{PD}	Ψ_{stem}	Ψ_l	$\Psi_l - \Psi_{stem}$		$[(\Psi_{PD} - \Psi_{stem})/(\Psi_{PD} - \Psi_l)] \times 100$		Predicted predawn Ψ_π	
species		NI		NI	I	NI	I	NI	I
arizonica	–0.45 e	–1.14 b	–1.48 bcd	0.34 abc	0.40	66.3 ef	65.0 abcd	–1.33	–1.44
berlandieri	–0.31 ab	–1.36 b	–1.52 bcd	0.16 d	0.41	86.9 a	63.6 bcd	–1.27	–1.41
californica	–0.33 abc	–0.88 a	–1.25 ab	0.37 a	0.42	59.8 f	56.0 de	–1.45	–1.45
candicans	–0.33 abc	–1.19 b	–1.39 abc	0.20 ef	0.29	81.1 abc	73.6 a	–1.26	–1.16
champinii	–0.44 de	–1.34 b	–1.75 d	0.41 a	0.42	68.9 def	64.4 bcd	–1.33	–1.18
cinerea	–0.41 cde	–1.37 b	–1.68 cd	0.31 abcde	0.58	75.6 bcde	53.5 e	–1.37	–1.32
cordifolia	–0.34 abc	–1.12 b	–1.34 abc	0.22 cdef	0.43	78.0 abcd	59.5 cde	–1.39	–1.50
doaniana	–0.30 ab	–1.00 ab	–1.35 abc	0.35 ab	0.47	66.0 ef	53.5 e	–1.32	–1.32
girdiana	–0.41 cde	–1.22 b	–1.54 bcd	0.32 abcd	0.39	71.7 cde	60.1 cde	–1.20	–1.45
lincecumii	–0.36 bcd	–1.27 b	–1.48 bcd	0.21 def	0.36	80.5 abc	69.4 ab	–1.08	–0.98
longii	–0.36 bcd	–1.36 b	–1.60 bcd	0.24 bcdef	0.32	80.4 abc	71.5 ab	–1.14	–1.29
monticola	–0.40 cde	–1.46 b	–1.65 cd	0.19 ef	0.35	84.8 ab	69.5 ab	–1.55	–1.28
riparia	–0.46 e	–1.46 b	–1.70 cd	0.24 cdef	0.51	80.8 abc	57.9 cde	–1.55	–1.48
rupestris	–0.33 abc	–1.33 b	–1.51 bcd	0.18 f	0.47	84.7 ab	60.0 cde	–1.41	–1.37
solonis	–0.34 abc	–1.27 b	–1.47 cd	0.20 ef	0.37	82.4 abc	66.5 abc	–1.22	–1.51
treleasei	–0.27 a	–1.24 b	–1.46 cd	0.22 def	0.31	81.8 abc	73.6 a	–0.96	–0.99
vinifera	–0.30 ab	–1.10 b	–1.33 abc	0.23 cdef	0.37	78.1 abcd	65.5 abc	–1.43	–1.33

nonirrigated, were *V. riparia*, *V. monticola* and *V. lincecumii*, while *V. treleasei* was reduced the least.

The drought performance indicator means of *V. doaniana*, *V. longii*, *V. girdiana*, *V. arizonica* and *V. californica* were not significantly different from *V. champinii* (species with the lowest overall score) (Table 6). *Vitis berlandieri*, *V. lincecumii* and *V. cinerea* had lower scores than *V. riparia*, which was considered as the standard nondrought tolerant species. Based upon total points and their mean separations, species with a score of 100 points and below were considered highly drought tolerant while those with a score of 138 and greater, least drought tolerant. The remaining six species were classified as intermediate.

Discussion

Modern viticulture is dependent on the use of rootstocks resistant to Phylloxera (*Daktulosphaira vitifolia* FITCH) and other soilborne pests (Mullins et al., 1992). Most commercially available rootstocks today are either native North American *Vitis* species or the result of crosses between them. Due to the diversity of these species' native habitats (Table 1), differences in the ability to tolerate soil water deficits were expected. Multiple criteria (measurements of water status, gas exchange and growth characteristics) were used in this study to assess the drought tolerance of 16 North American *Vitis* species and *V. vinifera*. Since the vines were grown in the field

Table 4. Net CO_2 assimilation rate (A), stomatal conductance (g_s) and intrinsic water use efficiency (WUE, $A/g_s \times 10^3$) (NI treatment only) of 17 *Vitis* species on the last measurement date.[z] Other information as found in Table 3. There were no significant differences among means in the A, NI column.

Vitis	A		g_s		WUE
species	NI	I	NI	I	NI
arizonica	3.27	12.3 abc	172 abc	493 ab	19.8 bcd
belandieri	1.90	2.98 h	145 bc	268 b	13.6 cd
californica	2.98	11.9 abc	193 ab	550 a	12.2 d
candicans	2.68	13.4 ab	190 ab	473 abc	12.1 d
champinii	5.02	14.1 a	263 a	438 abcd	18.9 bcd
cinerea	1.28	4.57 fgh	65 c	348 bcd	25.4 abcd
cordifolia	4.53	7.63 def	140 bc	330 bcd	30.5 abcd
doaniana	2.70	3.6 gh	195 ab	310 cd	13.2 cd
girdiana	3.00	5.53 efgh	145 bc	360 bcd	19.8 bcd
lincecumii	1.90	7.27 defg	92 bc	448 abc	20.6 bcd
longii	4.62	6.93 defg	132 bc	318 bcd	33.1 ab
monticola	3.03	8.90 cde	182 ab	455 abc	17.7 bcd
riparia	2.97	10.1 bcd	138 bc	450 abc	22.2 bcd
rupestris	4.13	11.0 abcd	97 bc	420 abcd	42.4 a
solonis	2.70	7.83 def	105 bc	298 cd	25.4 abcd
treleasei	3.80	8.55 cdef	110 bc	387 abcd	33.4 ab
vinifera	4.17	8.77 cde	128 bc	398 abcd	31.6 abc

[z]A and g_s are expressed as $mmol \cdot m^{-2} \cdot s^{-1}$ CO_2 and $mmol \cdot m^{-2} \cdot s^{-1}$ H_2O, respectively.

Table 5. Pruning weights (Pwt) from the 1992 and 1993growing seasons for the NI treatment and mean Pwt for both years of the NI and I treatments for 17 *Vitis* species. Mean Pwt of the NI treatment are also expressed as a percent of the irrigated treatment (% of I). Other information as found in Table 3. There was no statistical analysis of the mean pruning weight values for the NI and I treatments.

	Pwt (kg/vine)				
Vitis	NI	NI	NI	I	NI
species	1992	1993	Mean	Mean	(% of I)
arizonica	1.59 bc	1.98 bc	1.78	4.34	41
berlandieri	0.56 c	0.69 c	0.63	1.55	41
californica	1.02 bc	1.09 c	1.06	3.24	33
candicans	1.11 bc	2.37 bc	1.74	4.51	39
champinii	4.95 a	6.08a	5.52	12.2	45
cinerea	0.36 c	0.78 c	0.57	1.50	38
cordifolia	0.71 bc	1.36 c	1.04	2.74	38
doaniana	2.51 b	2.57 bc	2.54	5.74	44
girdiana	2.1 bc	3.45 b	2.78	5.77	48
lincecumii	0.60 bc	0.73 c	0.66	2.38	28
longii	2.02 bc	1.88 bc	1.95	4.61	42
monticola	1.05 bc	1.33 c	1.19	4.42	27
riparia	0.65 bc	1.30 c	0.98	4.04	24
rupestris	1.43 bc	2.37 bc	1.90	4.42	43
solonis	1.72 bc	1.97 bc	1.84	3.78	49
treleasei	1.16 bc	1.72 bc	1.44	2.30	63
vinifera	0.77 bc	0.92 c	0.84	2.11	40

Table 6. Relative drought tolerance of 17 *Vitis* species based upon their total score. See Materials and Methods section for explanation of how each species was rated in each category. Mean score (not given) separation determined using Duncan's multiple range test. Different letters in the mean score column indicates species means are significantly different at $P < 0.05$.[z]

Vitis Species	NI A	NI/I A	NI g_s	NI/I g_s	NI A/g_s	NI Ψ_π	NI/I Ψ_π	NI Grad	NI/I Grad	NI $\Delta\Psi$	NI/I $\Delta\Psi$	NI PWt	NI/I PWt	Total	Mean score
champinii	1	9	1	2	12	8	2	4	3	1	1	1	4	50	a
doaniana	12	1	2	1	15	10	10	2	11	3	6	3	4	80	ab
longii	2	2	11	5	3	15	15	9	7	7	5	4	7	92	abc
girdiana	9	5	7	6	10	14	16	5	8	5	4	2	3	94	abc
arizonica	7	14	6	11	10	8	13	3	1	4	3	7	8	95	abc
californica	10	16	3	10	16	3	9	1	2	2	2	11	14	99	abc
vinifera	4	6	12	12	4	4	5	8	8	9	9	14	10	105	bcd
coriifolia	3	4	9	4	5	6	12	7	13	10	14	12	12	111	bcde
treleasei	6	7	13	14	2	17	11	13	5	10	7	9	1	115	bcde
monticola	8	11	5	8	13	1	1	16	10	15	11	10	16	125	bcde
rupestris	5	8	15	15	1	5	7	15	16	16	17	5	6	131	bcde
candicans	14	17	4	7	17	12	4	12	4	13	8	8	11	131	bcde
solonis	12	10	14	9	6	13	17	14	11	13	11	6	2	138	cde
riparia	11	12	10	13	8	1	6	11	15	7	15	13	17	139	cde
berlandieri	15	3	7	3	14	11	14	17	14	17	16	16	8	155	de
lincecumii	15	15	16	16	9	16	3	10	6	12	10	15	15	158	de
cinerea	17	13	17	17	5	7	8	16	16	6	13	17	12	165	e

[z]NI = not irrigated, I = irrigated, A = net CO_2 assimilation rate, g_s = stomatal conductance, A/g_s = intrinsic water use efficiency, Ψ_π = predicted predawn osmotic potential at a Ψ_{PD} of –0.205 MPa, Grad = $((\Psi_{PD} - \Psi_{stem})/(\Psi_{PD} - \Psi_l)) \times 100$, $\Delta\Psi = \Psi_{stem} - \Psi_l$, PWt = pruning weight.

without applied water, a gradual depletion of the soil water content occurred as the season progressed and thus changes in vine physiology and/or morphology in response to water stress would also have taken place gradually. It should be pointed out that, generalizations regarding results from this study are the result of an individual species' above and below ground response to water deficits. In a commercial vineyard situation, the grafted scion would have its own response to water deficits. It has been demonstrated, though, that the rootstock can affect the physiology of the scion under soil water deficit conditions (Padgett-Johnson et al., 2000).

A reduction in stomatal conductance to limit water vapor loss via transpiration is one drought avoidance mechanism (Kirkham, 1990; Passioura, 1994). Under nonirrigated conditions in this study, all species exhibited this behavior. However, the two species with the lowest g_s on the last date, *V. cinerea*, and *V. lincecumii*, also had the greatest reductions in g_s compared to their irrigated counterparts and ranked as least drought tolerant. A study on greenhouse-grown, one year-old 'Cabernet Sauvignon' grafted onto different rootstocks to investigate drought tolerance was conducted in France (Carbonneau, 1985). The ratio of leaf area to the reciprocal of stomatal conductance ($1/g_s$) was used as the basis for classification. Such a basis would presumably be a measure of growth and gas exchange. 'Rupestris du Lot' (*V. rupestris*) and 'Riparia Gloire' (*V. riparia*) were classified as susceptible to drought. The rootstock selections 7383 and 7405 (open pollinated *V. berlandieri*) were classified as resistant and less resistant to drought, respectively. When the pruning weight to seasonal mean $1/g_s$ ratios were calculated for species in the nonirrigated treatment of this study, *V. riparia*, *V. lincecumii*, *V. berlandieri and V. cinerea* ranked 14th, 15th, 16th, and 17th, respectively (out of the 17 species), while *V. rupestris* ranked 8th. The four lowest ranked species based on this criterion were also rated least drought tolerant in our study. *Vitis rupestris* would be classified as intermediate for drought tolerance using this criterion. Using the pruning weight to mean seasonal $1/g_s$ ratio, the top five species in this study were *V. champinii*, *V. doaniana*, *V. girdiana*, *V. longii* and *V. arizonica* (highest to lowest, respectively), all of which we ranked as most drought tolerant. Therefore, the means of classifying the drought tolerance of vines used by Carbonneau (1985) for the species in this study agreed favorably (the exception being *V. rupestris*) with our multiple criteria classification. However, our drought tolerance classification of one of the three species used in both studies (*V. berlandieri*) did differ from Carbonneau's ranking.

Another drought avoidance mechanism would be the development of a very deep, extensive root system (Jones, 1992). However, in our study a hardpan was present at a depth of 1.2 m, which restricted the exploration of roots to greater depths (Padgett-Johnson, 1999). Therefore, the ability of a species to avoid drought using this mechanism was not expressed in our study. Padgett-Johnson (1999) also found that the distribution of roots within the soil profile did not differ significantly among seven species (*V. arizonica*, *V. berlandieri*, *V. candicans*, *V. champinii*, *V. riparia*, *V. rupestris* and *V. vinifera*) that were examined in the nonirrigated portion of the vineyard. This would indicate these species had equal access to available water in the soil profile.

A plant's Ψ will decrease as soil water deficits develop and it has been reported that under water stress, drought-tolerant plants will maintain higher Ψs than drought-sensitive ones (Kirkham, 1990). However, in our study we used the differences in Ψ_{PD}, Ψ_l, and Ψ_{stem} to assess the water status of the vines for use in ranking a species' drought tolerance. This was due in part to the fact that the species having the lowest midday Ψ_l and one of the lowest values of Ψ_{PD} and Ψ_{stem} on the last measurement date was *V. champinii*. Its values were similar to *V. riparia*. However, *V. champinii* had the highest A, g_s and pruning weights, unlike *V. riparia*. It was recently reported that the difference between Ψ_{stem} and Ψ_l was linearly correlated with leaf transpiration (Chone et al., 2001). Such a relationship was also found in this study ($r^2 = 0.64$, data not given). Thus, *V. champinii* with low values of Ψ_{PD}, Ψ_l, and Ψ_{stem} had the highest $\Delta\Psi_{stem} - \Psi_l$ and that was reflective of its gas exchange measurements and its $\Delta\Psi_{stem} - \Psi_l$ was similar to the irrigated cohort's value. Thus, using only

absolute values of Ψ to rank a species may result in conclusions that are not consistent with actual performance.

Another factor influencing water uptake by plants is hydraulic conductance to water flow and differences among plant species have been demonstrated (Turner, 1986). Chone et al. (2001) proposed that the $\Psi_{PD} - \Psi_{stem}$ and $\Psi_{PD} - \Psi_l$ gradient proportions were reflective of the hydraulic conductance of the soil–stem pathway in grapevines. In our study, the proportion of the $\Psi_{PD} - \Psi_{stem}$ gradient to the total $\Psi_{PD} - \Psi_l$ gradient was lowest for *V. arizonica, V. californica* and *V. champinii* and their values were close to those of their irrigated cohorts. The assumption would be that hydraulic conductance of those nonirrigated species was high. The species with the lowest purported hydraulic conductance were all rated least drought tolerant. *Vitis rupestris*, has been reported to have narrow xylem vessels (Rives, 1925), which may possibly restrict the flow of water. However, one may have expected the irrigated *V. rupestris* also to have a low conductance, compared to the other species, but it didn't. It has been demonstrated that even moderate water stress can reduce vessel size and xylem hydraulic conductance of grape (Lovisolo and Schubert, 1998). The narrow vessels reported by Rives (1925) for *V. rupestris* may have been due to the fact the vines had been stressed when the measurements were taken.

Osmoregulation by plants is considered a drought tolerance mechanism (Kirkham, 1990; Passioura, 1994). Grapevines have been shown to osmoregulate ≈0.3 to 0.5 MPa in response to soil water deficits (Grimes and Williams, 1990; Schultz and Matthews, 1993; Rodrigues et al., 1993). Düring and Scienza (1980) examined drought tolerance in several *Vitis* species by excising leaves and then measuring Ψ_l for the next 30 min. It was assumed that leaves having the more negative Ψ_l were not osmoregulating while the opposite was true for leaves with less negative Ψ_l. It was concluded that *V. riparia* and *V. rupestris* were drought sensitive, as they had the most negative Ψ_l values, whereas, *V. monticola, V. berlandieri* and *V. cinerea* were drought tolerant because they had the least negative Ψ_l values. We classified three of the five species used in Düring and Scienza's study (*V. berlandieri*, *V. cinerea*, and *V. riparia*) in our least drought tolerant category while the remaining two, *V. monticola* and *V. rupestris*, were ranked intermediate. Therefore, our rankings differed from those species used in Düring and Scienza's study. While we did not explicitly measure osmoregulation (such as done in the studies on grapevines mentioned above) it would appear that the accumulation of solutes (or more negative values of Ψ_π measured in this study, Table 3) did not impart any significant ability of *V. riparia* or *V. monticola* to tolerate drought.

A third category of drought tolerant adaptations/mechanisms, are those associated with efficiency (Kirkham, 1990; Passioura, 1994). A greater WUE under drought conditions may result in continued productivity (Passioura, 1994). *Vitis rupestris* had the highest intrinsic WUE, whereas, *V. doaniana, V. californica* and *V. candicans* had the lowest (Table 4). If one were to calculate WUE as the ratio of biomass produced to the amount of water used in this study a different conclusion would be drawn. *Vitis champinii* and to a lesser extent *V. girdiania, V. doaniana* and *V. longii* (i.e., those species with the highest pruning weights under nonirrigated conditions, Table 5) would have had the greatest WUE. Soil water depletion at the five access tube sites in the nonirrigated portion of the vineyard were similar, indicating that the five vines at each location probably used the same amount of water as those with lower pruning weights. Therefore, intrinsic WUE (a single measurement of gas exchange on a particular day) did not provide an accurate assessment of the long-term production of biomass as a function of water used.

All *Vitis* species in this study exhibited some level of drought tolerance, not just avoidance as suggested by Smart and Coombe (1983). The interaction and coordination of these adaptations and mechanisms may provide a better means of describing a given species' ability to tolerate drought, if ultimately used as a commercial rootstock. Using multiple criteria to categorize drought tolerance in *Vitis* may be better than assessing the extent of drought tolerance in which only a single mechanism is measured (Carbonneau, 1985; Düring and Scienza, 1980).

The species ranked as most drought tolerant, were *V. arizonica, V. californica, V. champinii, V. doaniana, V. girdiana* and *V. longii*. Since the native habitats of *V. arizonica* and *V. californica* and *V. girdiana* are associated with canyons in the arid southwestern United States and stream banks in California, respectively (Table 1), the availability of mid- to late-season rainfall would probably be minimal. *Vitis champinii* and *V. longii* are found on dry, chalky, limestone soils or sandy soils and dry hillsides. The descriptions of the above two species' native habitats indicate that drought tolerance is a necessary attribute in these arid locations. *Vitis doaniana*, also ranked as highly drought tolerant, can be found in woods and stream bottoms, areas in which water deficits may be uncommon. Although this appears to contradict the idea of selection for drought tolerance, one parent of *V. doaniana* is *V. longii* (Table 1) and *V. doaniana* may have inherited some of *V. longii*'s drought tolerant characteristics.

The species determined to be the least drought tolerant in this study were *V. berlandieri, V. cinerea, V. lincecumii, V. riparia* and *V. solonis*. These species generally had low rates of A, g_s, and less favorable vine water statuses, low pruning weights under nonirrigated conditions and a greater reduction of those parameters when compared to the irrigated controls. *Vitis riparia* rootstock is usually not considered drought tolerant based upon vine water relations (Carbonneau, 1985; Düring and Scienza, 1980) and yield performance under dry-land conditions (Galet, 1979; Southey, 1992). In addition, its mesic habitat and range would also indicate that strong drought avoidance or tolerance mechanisms are not necessary. The native habitats of the other four *Vitis* species, also ranked as least drought tolerant are similar to that of *V. riparia* (Table 1).

All species ranked intermediate in terms of drought tolerance generally had mean performance scores that were not significantly different from five of the six species ranked as most drought tolerant. One of the intermediate drought tolerant species, *V. treleasei*, is a glabrous form of *V. arizonica*. It is unknown why there were differences among the two as their native habitats overlap.

Conclusions

The drought tolerance rankings of species in this study compared favorably with several other studies in which *Vitis* species were included. It has been concluded by Carbonneau (1985), Delas, (1992), Düring and Scienza (1980), Galet (1979) and Pongracz (1983) that 'Riparia Gloire' (*V. riparia*) is not drought tolerant, as was shown here. We also concluded that *V. berlandieri, V. cinerea, V. lincecumii*, and *V. solonis*, which responded similarly to *V. riparia* in many respects, are not drought tolerant. In this study *V. rupestris* was classified as intermediate to drought tolerant species, which differs from its rankings by Carbonneau (1985) and Southey (1992). 'Dog Ridge' and 'Ramsey' are two commercial rootstock cultivars derived from *V. champinii*; the species we concluded as having the highest drought tolerance in our study. Both of these rootstocks impart vigorous vegetative growth to their grafted scions (Pongracz, 1983) as would be expected from our results. However,

'Dog Ridge' and 'Ramsey' have been classified as being moderately susceptible and susceptible, respectively, to drought under South African conditions (Southey, 1992). Winkler et al. (1974) recommended 'Dog Ridge' for use on light textured soils (i.e., those with less water holding capacity). Fregoni (1977) has concluded that there is no definite relationship between excess vigor and drought tolerance of rootstocks. The differences in the conclusions noted above by Southey (1992) and Fregoni (1977) and our conclusions regarding *V. champinii* warrant further studies on the drought tolerance of this species when used as a grafted rootstock with an accompanying fruit producing scion. In such a case, actual fruit production in vineyards with less available water would be the major criterion with which to assess drought tolerance (Jones, 1992).

The classifications of drought tolerance for the 17 *Vitis* species used in this study may assist in breeding drought tolerant rootstocks. It is interesting to note that the commercial rootstocks typically classified as being highly drought tolerant (i.e., '110 Richter', '140 Ruggeri' and '1103 Paulsen') are *V. berlandieri* x *V. rupestris* hybrids. In this study, *V. berlandieri* was classified as least drought tolerant while *V. rupestris* was classified as intermediate. It would appear that these two species' hybrids either increase or maintain the scion's (commonly a *V. vinifera* cultivar) fruit production in a commercial situation, a factor not considered in this study. *Vitis champinii*, which we classified as the most drought tolerant, is a natural hybrid of *V. candicans* and *V. rupestris*, both of which were not considered to be highly drought tolerant in this study. In addition, the rootstocks derived from *V. champinii* are often discouraged for use in commercial vineyards due to their invigorating effect on the scion's vegetative growth, especially in situations where soil water is readily available, which may negatively impact fruit quality. Lastly, a wide range of characteristics, including pest resistance and ease of propagation, in addition to drought tolerance are considered when selecting species for use in breeding.

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Mineral Nutrition of grapevines and Fertilization Guidelines for California Vineyards

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Background

Commonly observed grapevine deficiencies in California include those associated with nitrogen, potassium, zinc and boron (Christensen et al., 1982). Less common deficiencies include those of iron, magnesium and manganese. Lastly, toxic effects of nitrogen, chloride and boron have been observed in California vineyards. One of the most important questions to answer in a vineyard fertilization management program is: How does one determine the need to fertilize? Many locations in the San Joaquin Valley and elsewhere in California have ground water pollution problems. The pollutants include, among others, nitrates. Therefore, a fertilization program should try to minimize the leaching of mineral nutrients below the root zone. Once the decision to fertilize has been made then one must determine how much and when to apply the fertilizer. Fertilizers can be costly and one can become more cost efficient if educated decisions regarding vineyard fertilizations are made.

Assessing vineyard/vine mineral nutrient status

There are various means to determine the need to fertilize grapevines. The observation of foliar and/or fruit mineral nutrient deficiencies on vines can be used. Unfortunately, these symptoms could indicate that the deficiency may already have caused a reduction in yield. Some grape producing countries use soil analysis to establish the need to fertilize a vineyard. However, it has been concluded that soil analysis for the determination of N, K (potassium), Mg (magnesium) and Zn (zinc) fertilization requirements in California is of no value (Christensen and Peacock, 2000). Those authors do conclude that soil and water analysis can be used to determine B (boron) toxicity levels.

Vine tissue analysis has long been used in California to assess the nutrient status of grapevines (Cook and Kishaba, 1956) and it is considered to be very reliable (Kliewer, 1991). The organ most often sampled on grapevines is the petiole; however, many growers may also sample the leaf blade. Generally, the petiole and blade will be analyzed separately and not as a single unit. In order to compare tissue analysis results from one year to the next it is advantageous to collect the samples at the same

phenological growth stage. The sampling of petioles will occur most commonly at bloom. A second sampling date chosen by some will be at veraison (berry softening). The petioles (or blades) used for the sample at bloom will be taken opposite a cluster along the shoot. The petioles sampled at verasion will be obtained from leaves that are considered mature (fully expanded) and probably on the exterior of the canopy. Research conducted in California has shown that the analysis of the fruit at harvest and canes at pruning could also be used to assess the nutrient status of grapevines (Kliewer, 1991). The most common form of nitrogen analyzed in petioles is both nitrate-N and total N while that for leaf blades is total N. The N analysis of fruit at harvest would include total N, the amino acid arginine or total amino acids. Lastly, the forms of N analyzed in canes would be total N and arginine.

Critical values of bloom-time petiole nitrate-N values have been established for Thompson Seedless grapevines in California (Christensen et al., 1978). It is assumed that a nitrate-N value less than 350 ppm (dry weight basis) is deficient, 350 to 500 ppm are questionable and 500 to 1200 ppm are adequate. Values over 2,000 are excessive. Adequate values of total N for petioles at bloom range from 0.5 to 3.0%, depending upon the country where those values were developed and cultivar (Kliewer, 1991). There is a linear correlation between bloom-time petiole nitrate-N and total N (Figure 1 and unpublished data of A.B. Iandolino and L.E. Williams). The percent total N of leaf blades will decrease as the season progresses and it is a function of degree-days (Williams, 1987), therefore, the time of leaf blade sampling will dictate the value obtained. Critical values of petiole analysis for K of Thompson Seedless in California are as follows: less than 1.0% is deficient, 1.0 to 1.5 % is questionable and over 1.5% is adequate. A bloom-time petiole K value of 0.8% or greater appeared to be adequate for Chardonnay and Cabernet Sauvignon, on different rootstocks, in a trial conducted by the author for the past three years (unpublished data). Values for other mineral nutrients have been determined for Thompson Seedless and can be found in Christensen, et al., (1982). These critical values also appear to be adequate for other cultivars and in different vineyard situations.

It has been observed that bloom-time petiole nitrate values will differ from year to year, cultivar to cultivar and whether the vines are on their own-roots or on rootstocks. Therefore, many feel that the critical values established for Thompson Seedless grapevines may not be appropriate in other vineyard situations. For example, the table grape cultivars Perlette and Flame Seedless will generally have lower values of petiole nitrate-N values at bloom than Thompson Seedless when grown at the same location and soil type (Table 1). The values in Table 1 also demonstrate yearly variation in petiole nitrate-N values. It should be pointed out that the cultivars used to obtain that data never showed any N deficiency symptoms. Irrigation type (drip vs. furrow irrigation) and whether the vines had been irrigated prior to the sample date also will influence petiole nitrate-N values when sampled at bloom. It was demonstrated that drip irrigated Thompson Seedless vines generally had lower petiole nitrate-N values (mean of four years was 345 ppm) than furrow irrigated vines (mean was 1176 ppm) and that non-irrigated vines also had lower petiole nitrate-N values than irrigated vines (L.E. Williams, unpublished data).

A study was conducted to determine if time of day or leaf location would influence petiole nitrate values of Thompson Seedless at bloom (Table 2). The highest nitrate-N values were for leaves collected at 4 pm and for leaves exposed to direct sunlight. At veraison, only leaf location had a significant effect on petiole nitrate-N (Table 3). Petioles from leaves in the shade had significantly greater nitrate-N than leaves in direct sunlight at veraison. Nitrate-N of Chardonnay petioles collected at bloom was not significantly affected by either time of day or leaf location (Table 4) while that of Cabernet Sauvignon was only affected by leaf location (Table 5).

Petioles were collected from Perlette and Flame Seedless grown in the Coachella Valley at bloom, veraison and harvest in 2002. Petioles were sampled on a diurnal basis for both cultivars at bloom. At bloom a composite of leaves exposed to direct sunlight and growing in the shade were used, they were not separated into sun and shade petioles. Petioles of both cultivars more than doubled their dry weight between bloom and veraison and gained another 17% between veraison and harvest (Table 6). Time of day significantly affected petiole nitrate-N of Perlette and nitrate-N and K of Flame Seedless at bloom (Table 7). Petiole nitrate-N was greatest at the 4 pm sampling time for both cultivars while K was greatest at midday for Flame Seedless.

During the Spring of 2002, clusters were counted on vines that were part of the fertilizer treatments imposed in the Thompson Seedless, Chardonnay and Cabernet Sauvignon vineyards prior to bloom in 2001. Cluster numbers of Thompson Seedless grapevines receiving either 50 or 100 lbs N per acre were significantly greater than vines receiving no applied N (Table 8). Petiole nitrate-N for the non-fertilized vines was less than 65 ppm while those of the fertilized vines was greater than 2400 ppm. The fertilizer treatments imposed in 2001 in the Cabernet vineyard had no effects on return fruitfulness in 2002 (Table 9). The un-irrigated vines in the Chardonnay vineyard had the lowest number of clusters, probably due to a lack of adequate water during the 2001 growing season.

Several generalizations can be drawn regarding what may influence the nutrient values of petioles. 1.) The type of leaf chosen to sample, whether it is in the sun, shade or opposite the cluster, will influence the values of nitrate-N and K. Sunlit leaves at bloom generally had higher values of petiole nitrate-N than either shaded leaves or leaves opposite the cluster. At veraison and prior to harvest, shaded leaves had greater values of petiole nitrate-N and K than sunlit leaves. 2.) Irrigation amount (when comparisons between the Irrigated and Non-irrigated treatments were made) had an effect on petiole nitrate-N and K late in the growing season. The irrigated treatment generally had lower values of nitrate-N and K when compared to the non-irrigated treatment. It is unknown at this time whether the water status of the vine is responsible for this effect. 3.) The three cultivars (Chardonnay, Cabernet Sauvignon and Thompson Seedless) used in this study (starting in 2001) generally responded to the treatments and sampling differences similarly. 4.) Values of bloom petiole nitrate-N below 100 ppm in 2001 were associated with fewer cluster numbers in 2002. The number of clusters on vines with petiole nitrate-N values above 100 ppm was not different from the fertilized vines.

A recent study was conducted in California by the author to determine if rootstock had an effect on the fertilizer use efficiency of Chardonnay and Cabernet Sauvignon scions. In that study, bloom-time petiole nitrate values were correlated with the N in the fruit at harvest, leaves at the end of the season (as they fell from the vine) and canes when the vines were pruned. The results indicated that the concentration of N generally increases in the fruit, leaves and canes as petiole nitrate-N increased from a low of 50 ppm to approximately 200 ppm. As the nitrate-N values at bloom in the petioles increased from 200 ppm to 10,000 ppm there was no further increase in the percent total N in the fruit, leaves or canes. These results indicate that a critical value of approximately 200-ppm (dry wt. basis) in the petioles at bloom may be sufficient under most vineyard conditions. The 200-ppm nitrate-N value, found in this study, may explain why the low values of nitrate-N in some cultivars and/or cultivar-rootstock combinations don't express deficiency symptoms at the "less than adequate" values originally established for Thompson Seedless. Therefore, establishing new critical values of nitrate-N for each cultivar and/or rootstock used may not be necessary. In support of these findings, a study by Spayd et al. (1993) found that yield of White Riesling increased almost five-fold when petiole nitrate-N values increased from 7 to approximately 200 ppm and then leveled off after that.

Determination of N fertilizer amounts

Once the decision has been made to fertilize the vineyard, the appropriate amount of fertilizer should be applied. Mineral nutrient budgets (i.e. the amount of nutrients the vine needs for proper growth and development) have been established in various studies around the world. It was determined that Thompson Seedless grapevines needed approximately 39 kg N ha^{-1} for the leaves, 11 kg N ha^{-1} for the stems (main axis of the shoot) and 34 kg N ha^{-1} for the fruit (Williams, 1987). The vineyard density was 1120 vines per hectare and the trellis system was a 0.45 m crossarm. It was also determined that the leaves contained greater than 22 kg N ha^{-1} after they fell from the vine and the canes at pruning contained approximately 17 kg N ha^{-1}. These values are comparable to other studies using Thompson Seedless. The total N (found in the fruit at harvest, leaves as they fell from the vine and prunings) in wine grape vineyards using a VSP trellis system varied from 24 to 65 kg N ha^{-1} over a three year period (L.E. Williams, unpublished data). The differences in N per hectare were primarily due to row spacing and final yield. The greatest N amounts were associated with closer row spacings and higher yields. The above results indicate that there is considerable N in both the leaves and canes of a vine and that when they are incorporated into the soil would contribute to the soil's organic matter and the availability of N.

The amount of K needed for growth of grapevines also has been determined. In the same vineyard used above to develop a N budget for Thompson Seedless grapevines, a K budget was developed (Williams et al., 1987). Leaves, stems and fruit needed approximately 13, 29 and 50 kg K ha^{-1}, respectively, during the growing season. The amount of K in the leaves and canes at the end of the season were equivalent to 9 and 12 kg K ha^{-1}. The amount of K found in the fruit at harvest, leaves as they fell from the vine and canes at pruning for two wine grape cultivars, on different rootstocks and at different

locations ranged from 25 to 67 kg K ha^{-1} over a three year period (L.E. Williams, unpublished data). Differences among K per hectare were due to same factors as discussed in the preceding paragraph for N in that study.

The above information in this section illustrates that there can be significant variation in the requirements of N and K per vineyard. This is due to differences in row spacings, trellis types, yield and overall growth of individual vines. Much of the N and K in the leaves and canes are returned to the soil for possible future use. Therefore, a better way in determining the fertilizer demands of a vineyard would be to calculate the amount of that nutrient removed in the fruit at harvest. Based upon several different studies it was determined that the average amount of N, P, K, Ca and Mg in one tonne of grapes at harvest was approximately 1.5, 0.3, 2.5, 0.5 and 0.1 kg, respectively (Mullins et al., 1992). In a recent study with Chardonnay and Cabernet Sauvignon on different rootstocks in California the amount of N in one tonne of grapes ranged from 0.98 to 1.58 kg while that for K ranged from 1.8 to 2.9 kg (L.E. Williams, unpublished data). Thus, if 20 tonnes of grapes were harvested per hectare, the average amount of N and K removed would be equivalent to 30 and 50 kg ha^{-1}, respectively. This would be the base amount of these two nutrients that one would want to replace with fertilizers.

The next requirement for determining the amount of fertilizer one needs is to estimate the efficiency with which the fertilizer is acquired by the vine. The author has conducted several N fertilizer use efficiency (FUE) trials in the San Joaquin Valley and in the coastal areas of California. These studies utilized fertilizers labeled with a non-radioactive isotope of N (^{15}N). As expected, FUE in a Thompson Seedless vineyard was more efficient under drip irrigation than furrow (surface) irrigation. The FUE (defined as the amount of ^{15}N found in the vine divided by the ^{15}N applied) was greater than 40% for the drip treatment compared to approximately 12% for the furrow irrigated treatment (Williams, 1991). The FUE for the drip treatment was similar regardless whether the vines were fertilized with a single application (28 kg N per ha) at berry set or whether the vines were given 5.6 kg N per ha every two weeks for a 10 week period. The FUE increased to greater than 50% when the treated vines were harvested the following year, indicating that the N fertilizer was present in the soil profile the second year after application. The above results could have been due to the fact that the vineyard had a clay pan at a depth of 1.5 m below the surface of the soil. Therefore, the N fertilizer was not leached below the root zone after the winter rainfall.

The second nitrogen FUE study was conducted to determine the effect of rootstock on N uptake by Chardonnay and Cabernet Sauvignon grapevines grown in the Napa and Salinas Valleys and at a vineyard in Paso Robles, along the central coast of California. The vines were drip irrigated at 100% of estimated vineyard ET (ET_c) and the labeled fertilizer was applied at berry set. Under the conditions of the study, rootstock had little effect on FUE at any of the four vineyard sites. As with my irrigation studies in these vineyards, the use of a VSP trellis system could have minimized any effect rootstock had on the vegetative growth of the vines. Therefore, the growth of all scions on the different rootstocks was similar as the vines were hedged to maintain shape. FUE varied considerably from one location to another. The greatest FUE (approximately 15%) was

obtained in the vineyard with the lowest bloom-time petiole nitrate-N values. The low FUE in this study, compared with that of Thompson Seedless in the San Joaquin Valley, may indicate the inherent fertility of the soils at these vineyard sites. Other studies have shown that soil type will affect the nitrogen FUE within a vineyard. It was found that the FUE of a N fertilizer was greater on a sandy soil (Conradie, 1986). The study by Conradie (1986), in addition to a study conducted by my graduate student at the University of California-Davis (Alberto Iandolino) in 1999 also proved that the timing of application affects FUE. Lastly, it should be pointed out that the FUE of vines irrigated at 50% of full ET was double that of vines irrigated at 100% of ET_c (L.E. Williams, unpublished data).

Using the information from the preceding paragraphs one would calculate the amount of N removed from the vineyard in the harvested grapes and then divide that number by the N FUE to obtain the amount of fertilizer to apply. Therefore, if one removed 30 kg of N per ha in the fruit and the FUE was 50% (or 0.5) then one would need to apply 60 kg N per ha. The same type of calculation would be used to determine fertilizer amounts for the other macronutrients such as potassium and magnesium. From a practical standpoint, the author is of the opinion that in a non-deficient vineyard (i.e. tissue analysis does not indicate a deficiency) the actual amount of N or K applied should only be the amount of that nutrient removed in the fruit without taking into consideration FUE. This is due to the uncertainty in obtaining reliable estimates of FUE for different mineral nutrients. As mentioned in my studies using ^{15}N, FUE can vary due to numerous factors including several different vineyard management techniques and soil type.

Kinds of fertilizers

The choice of N fertilizers for raisin vineyards in California can be based mostly upon cost (Christensen and Peacock, 2000). The same may apply for table grape and wine grape growers. The nitrate form of N allows the fertilizer to be available to the vines shortly after an application while the ammonium and urea forms require their transformation to nitrate in the soil profile. The liquid forms of N fertilizers are gaining in popularity due to their ease of handling and application via drip irrigation (fertigation). Many raisin and table grape growers will use farm manure as a source of N, with its application occurring during the dormant portion of the growing season. Lastly, the acidification potential of N fertilizers should be considered in a management program particularly in acid soils. This characteristic of N fertilizers has been outlined recently (Christensen and Peacock, 2000).

It has been concluded that one form of K fertilizer offers no advantage over the other forms (Christensen and Peacock, 2000). Thus cost may play a major role in determining which kind to use in California and whether is to be used in a fertigation program. For vineyards with Mg deficiencies the choice of a fertilizer would probably be magnesium sulfate. The two micronutrients mostly commonly needed in California vineyards are zinc and boron. Foliar and soil applications of the two fertilizers have been used in California (Christensen et al., 1982). Soil applications of Zn are more effective under

drip than furrow irrigation. Research has shown that neutral- or basic-Zn products are the most effective Zn fertilizers (Christensen and Peacock, 2000).

Timing of fertilization events

Nitrogen and potassium are required by the grapevine throughout its growth cycle. The major sink (the organ that requires the most of a particular mineral nutrient) for N is that of the leaves while the fruit is the major sink for K (Williams, 1987; Williams et al., 1987; Williams and Biscay, 1991). Approximately, two-thirds of the vine's annual requirement for N occurs between budbreak and several weeks after berry set. This is the period when the canopy is formed by the vine. The remaing third of the vine's annual requirement of N goes to the fruit after berry set. It should be pointed out that a portion of the N requirements of a grapevine could be derived from N reserves in the roots and other permanent structures of the vine. Anywhere from 15 to 25% of the N in the currents season's above ground growth may come from those reserves (Williams, 1991). The timing of the application of a N fertilizer should correspond to the demands of the vine. Using fertigation, one could apply the approximate amount of N needed by the vine on a weekly or bi-weekly schedule. I am of the opinion if one does not have drip irrigation, one-half the total N fertilizer, to be use for the season, could be applied four weeks after budbreak and the other half applied shortly after berry set. It is not recommended that an N fertilizer be applied at bloom since it may decrease the number of flowers that set. A few table grape growers want high values of petiole nitrate-N at bloom as they contend a high vine nitrogen status at that time assists in thinning the grape clusters (i.e. decreases berry set). The author does not recommend a N fertilizer application post-harvest, which is contrary to what others may recommend (Christensen and Peacock, 2000). This is due to the fact that only a small amount of N is actually taken up by the vine subsequent to harvest. Thus, the N that remains in the soil from such an application could be leached during the dormant portion of the growing season.

The uptake of K by the vine is a linear function of vine water use throughout the course of the growing season (L.E. Williams, unpublished data). This is due to the linear relationship between vine water use and the production of vine biomass during that time frame. It also indicates that the K within the vine is derived mostly from sources in the soil and very little remobilization of K from the permanent structures of the vine. This is unlike N where some of the current season's demand for N may be obtained from N reserves in the roots and trunk of the vine. These results would indicate that the timing of an application of a K fertilizer could occur at anytime throughout the growing season, especially if one used fertigation and applied a K fertilizer every year. However, it is recommended that vineyards deficient in K should receive a slug application of a K fertilizer during fall or winter such that precipitation can move the fertilizer into the root zone (Christensen and Peacock, 2000).

Both Zn and B deficiencies affect yields by reducing berry set and the formation of berries that fail to develop. A foliar application of a Zn fertilizer before or at anthesis (bloom) can be used. The application could coincide with a "stretch" or "bloom" application of GA_3 in seedless table grape vineyards where it may be used. A B fertilizer

can be applied via a soil broadcast, soil spray, or foliar application or in the drip system. The B fertilizer can be applied at any time.

The use of phosphorus (P), iron (Fe), manganese (Mn) and calcium (Ca) fertilizers and the appropriate time of their application have received little attention in California due to the low acreage where such deficiencies may occur. In many instances, only a small portion of the vineyard may express deficiency symptoms for such mineral nutrients as Fe and Mn. In those cases, a spot application of the fertilizer is sufficient. The expansion of new vineyards in the foothills of the Sierra Nevada Mountains and Pacific coast mountain ranges has occurred in areas with low soil pH. This has required the application of P fertilizers to those vineyards.

In addition of the application of the above-mentioned fertilizers, many table grape growers in California apply various foliar applications in order to enhance berry quality. Those foliar applications may contain urea, P, K, Ca, Fe, B, Mn and possibly organic material. These foliar fertilizers will be applied in conjunction with fungicides and/or GA_3 applications. There has been no research to date in California on the effectiveness of these products.

Effects of vineyard fertilization on vegetative and reproductive growth

It is desirable to apply fertilizers in order to correct mineral nutrient deficiencies in the vineyard. The application of a N fertilizer in a deficient situation will increase vine growth and productivity. For wine grape vineyards the addition of a N fertilizer may minimize "stuck" or "sluggish" fermentations at the winery. However, many studies in California have demonstrated that the application of a N fertilizer in a non-deficient situation will have no effect on growth or productivity. In addition, the application of too much N may stimulate vegetative growth resulting in the shading of buds, reducing fruitfulness and lowering yields. For wine grapes, juice and/or wine pH may be a function of the K concentration. The application of too much K fertilizer may therefore decrease wine quality. The above comments would indicate the importance of being able to assess vine nutrient status prior to the application of any vineyard fertilizer.

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Table 1. The effects of cultivar and year on petiole nitrate-N when sampled at bloom. The petioles were sampled from opposite a cluster when the individual cultivar was at approximately 70% bloom. The values are expressed on a dry weight basis. Data was not collected for Thompson Seedless in 1993.

	Year			
Cultivar	1990	1991	1992	1993
	(nitrate N; ppm)			
Flame Seedless	74	274	187	926
Perlette	66	215	49	703
Ruby Seedless	132	949	1088	1029
Thompson Seedless	316	1244	787	-----

Table 2. The effects of time of day and location of leaves on nitrate-N of Thompson Seedless petioles sampled at bloom in 2001. Vines had been fertilized with 100 lbs of N per acre (112 kg N/ha) prior to bloom. Nitrate-N is expressed in ppm (dry weight basis). There was no significant interaction between time of day and location. Leaf blades were exposed to direct sunlight (sun), shaded (shade) or located opposite a cluster at the time of sample.

	Location of Leaves			Ave. Effect of
Time of Day	Sun	Shade	Opposite Cluster	Time of Day
0800 h	3746	3358	3313	3506
1200 h	4008	3103	3392	3501
1600 h	4341	3571	3816	3910
Ave. Eff. Loc.	4065	3344	3507	
$LSD_{0.05}$	Time of Day = 243		Location = 234	

Table 3. The effects of time of day and petiole location of leaves on nitrate-N of Thompson Seedless petioles sampled at veraison in 2001. Vines had been fertilized with 100 lbs of N per acre (112 kg N/ha) prior to bloom. Nitrate-N is expressed in ppm (dry weight basis). There was no significant interaction between time of day and location. Leaf blades were exposed to direct sunlight (sun), shaded (shade) or located opposite a cluster at the time of sample.

	Location of Leaves		Ave. Effect of
Time of Day	Sun	Shade	Time of Day
0800 h	638	1568	1103
1200 h	980	1206	1093
1600 h	865	1444	1154
Ave. Eff. Loc.	827	1406	
$LSD_{0.05}$	Time of Day = ns	Location = 168	

Table 4. The effects of time of day and petiole location of leaves on nitrate-N of Chardonnay petioles sampled at bloom in 2001. Vines had been fertilized with 80 lbs of N per acre (90 kg N/ha) prior to bloom. Nitrate-N is expressed in ppm (dry weight basis). There was no significant interaction between time of day and location. Leaf blades were exposed to direct sunlight (sun), shaded (shade) or located opposite a cluster at the time of sample.

	Location of Leaves			
Time of Day	Sun	Shade	Opposite Cluster	Ave. Effect of Time of Day
0800 h	1847	2411	1935	2064
1200 h	2121	2395	1893	2136
1600 h	1970	2348	2135	2151
Ave. Eff. Loc.	1979	2384	1988	
$LSD_{0.05}$	Time of Day = ns		Location = ns	

Table 5. The effects of time of day and petiole location of leaves on nitrate-N of Cabernet Sauvignon petioles sampled at bloom in 2001. The vineyard was located near Oakville in Napa Valley. The vines had not been fertilized but they had been irrigated prior to bloom. Nitrate-N is expressed in ppm (dry weight basis). There was no significant interaction between time of day and location. Leaf blades were exposed to direct sunlight (sun), shaded (shade) or located opposite a cluster at the time of sample.

	Location of Leaves			
Time of Day	Sun	Shade	Opposite Cluster	Ave. Effect of Time of Day
0800 h	371	429	184	328
1200 h	358	392	194	315
1600 h	312	435	235	327
Ave. Eff. Loc.	347	419	204	
$LSD_{0.05}$	Time of Day = ns		Location = 173	

Table 6. Dry weight of petioles sampled at bloom, veraison and harvest of Perlette and Flame Seedless grapevines grown in the Coachella Valley. Samples were collected during the 2002-growing season. Samples collected at bloom were a composite (50/50) of leaves exposed to direct sunlight and leaves in the shade. Petioles at bloom also were collected at three times during the day (0800, 1200 and 1600 hours).

		------- Bloom (3/21) -------			Veraison (5/6)		Harvest (6/16)	
Cultivar	Replicate	0800 h	1200 h	1600 h	Sun	Shade	Sun	Shade
		---------- (g 75^{-1} petioles) ----------						
Perlette	I	9.0	8.1	7.7	16.5	18.0	19.5	19.1
	II	8.3	8.9	7.2	19.8	18.3	20.5	22.6
	III	8.0	7.7	7.7	18.6	16.8	23.2	22.3
	IV	7.7	7.7	6.9	19.5	17.0	24.1	20.6
Flame	I	8.4	7.5	7.1	15.6	16.4	18.4	17.6
	II	8.0	7.5	7.8	14.7	15.5	17.7	18.2
	III	8.0	7.5	7.2	15.0	14.7	17.7	17.0
	IV	8.0	7.7	7.8	15.5	15.0	17.6	17.3

Table 7. The effect of time of day on nitrate-N of Perlette and nitrate-N and K of Flame Seedless petioles sampled at bloom, March 21 2002, in the Coachella Valley. Values of nitrate-N are expressed in ppm (dry weight basis) and K in percent (dry weight basis). Means in a column followed by a different letter are significantly different at $P < 0.05$.

	Perlette	---------- Flame Seedless ----------	
Time of Day	Nitrate-N	Nitrate-N	K
0800 h	890 b	825 b	2.51 b
1200 h	985 ab	968 ab	2.74 a
1600 h	1083 a	1025 a	2.65 ab

Table 8. Bloom petiole nitrate-N and total N from 2001 and shoot and cluster number per four vines of Thompson Seedless in 2002. Treatments included vines that in 2001 received no applied water before bloom nor were fertilized, vines that had been irrigated prior to bloom but were not fertilized and vines that were irrigated prior to bloom and were fertilized with either 50 or 100 lbs of N per acre (56 or 112 kg N/ha, respectively) before bloom. Means within a column followed by a different letter are significantly different at $P < 0.05$.

Treatment in 2001	Bloom 2001 Nitrate-N	Bloom 2001 Total N	Shoot # 2002	Cluster # 2002
	(ppm dry wt.)	(% dry wt.)	(# 4^{-1} vines)	(# 4^{-1} vines)
No Irr./No N	64	0.72	365	159 b
Irrigated/No N	42	0.70	333	157 b
Irrigated/50 lbs	2450	1.33	359	200 a
Irrigated/100 lbs	2804	1.39	380	215 a

Table 9. Bloom petiole nitrate-N and total N from 2001 and cluster number per six vines of Chardonnay (grown in Carneros) and Cabernet Sauvignon (grown near Oakville in Napa Valley). Treatments included vines that were not irrigated prior to bloom, vines irrigated prior to bloom in 2001 and vines irrigated prior to bloom and fertilized with either no or 80 lbs of N per acre (90 kg N/ha), prior to bloom. Petioles for the 40 lbs N per acre treatment at Oakville had not been analyzed as of the date this report was written.

Treatment in 2001	Bloom 2001 Nitrate-N	Bloom 2001 Total N	Cluster # 2002
	(ppm dry wt.)	(% dry wt.)	(# 6^{-1} vines)
Chardonnay			
No Irr./No N	262	0.94	123
Irrigated/No N	152	1.02	171
Irrigated/80 lbs	1979	1.32	151
Cabernet Sauvignon			
No Irr./No N	145	0.73	144
Irrigated/No N	299	0.76	142
Irrigated/40 lbs	--	--	148
Irrigated/80 lbs	3215	1.30	144

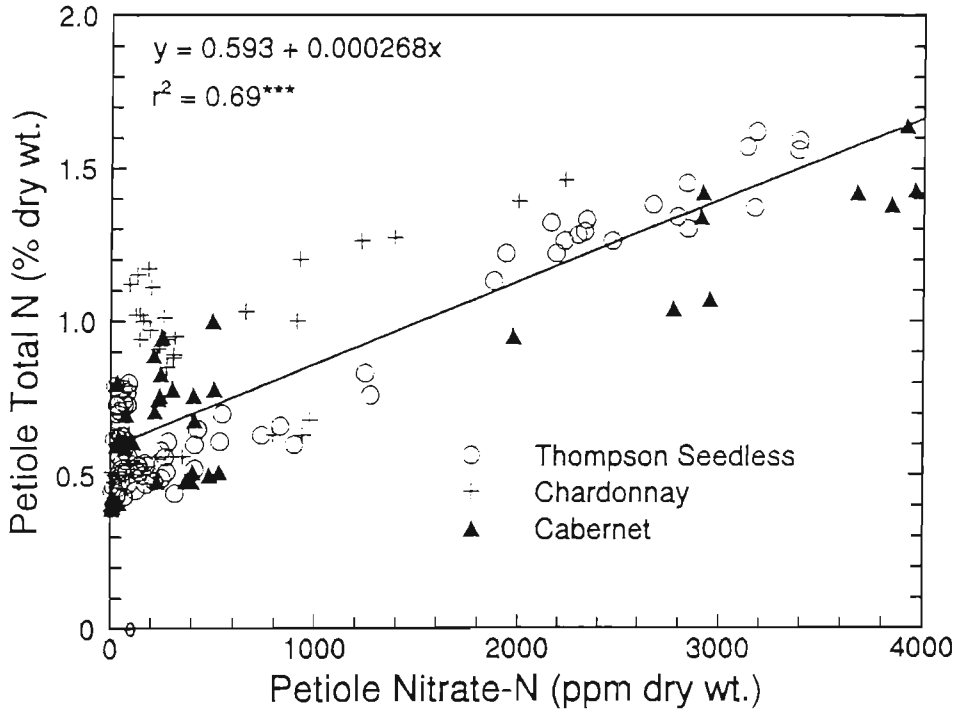

Figure 1. The relationship between petiole nitrate-N and petiole total N for three cultivars.

Interaction of Irrigation Amounts and Canopy Management Practices on Wine Grape Yield and Wine Quality in the San Joaquin Valley.

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Summary:

A study is being conducted at three different sites (Napa Valley, Livermore Valley and the San Joaquin Valley) to determine the interaction of irrigation amount and several canopy management practices on leaf, stem and cluster water relations, berry characteristics and productivity. The irrigation amounts are various fractions of estimated vineyard evapotranspiration (ET_c), the specific amounts were agreed upon by each grower/cooperator. The canopy management practices included the use of different trellis systems, vine and row spacings, row direction, cluster exposure and leaf removal. This report will include only data collected in Madera County.

The study site in Madera was conducted in a bilateral cordon trained Merlot vineyard. Water was applied at 0.4, 0.8 and 1.2 estimated vineyard water use. Canopy management practices included leaf removal in the fruiting zone either at berry set or veraison (leaves in the control treatment were not removed). Vine water status, as measured by midday leaf water potential, was significantly affected by irrigation amount but not canopy management practice. The amount of light measured in the fruiting zone was affected by both irrigation and canopy practices. Irrigation amount and leaf removal had a significant effect on berry weight, soluble solids, pH, titratable acidity and yield. Canopy management only affected soluble solids and yield. Both irrigation and canopy management had a significant effect on anthocyanin content in the skins. Wines were made on five of the nine treatments and are being evaluated.

Objectives:

Determine the interaction of irrigation amounts and several canopy management practices on grapevine water relations, fruit and wine composition and vine productivity of wine grapes grown in the North Coast, Central Coast and San Joaquin Valley of California.

Materials and Methods:

The vineyard site was located in Madera County. The cultivar used was Merlot on its own roots and the trellis was a cordon wire at a height of 42 inches and a foliage catch

wire 12 inches above that. Vine and row spacings were 7 and 12 feet, respectively. The vineyard rows were east/west and the vines were drip irrigated. The irrigation treatments were fractions (0.4, 0.8 and 1.2) of estimated full ET. The seasonal crop coefficients used were those calculated using the percent shaded area technique. The canopy management treatments included leaf removal in the fruiting zone either at berry set or veraison. The control was no leaf removal. Photon flux density (PFD) was measured just above the fruiting zone with a ceptometer.

Vine water status was determined by taking measurements of midday leaf water potential and cluster water potential using a pressure chamber on several dates during the growing season. In addition, diurnal measurements of leaf and cluster water potential were made several times during the season. Canopies were characterized by measuring shaded area beneath the vine at solar noon several times during the 2002-growing season. Pruning weights were measured during dormancy. Cluster (or berry) and canopy temperatures were measured with an infrared thermometer. Lastly, evaporative demand within the fruiting zone was measured with a relative humidity and temperature probe and read manually.

Berries were sampled at harvest and weighed. They were analyzed for soluble solids, titratable acidity, pH. Anthocyanins and phenols were measured using the procedures of Matthews and Anderson (1988). Berry characteristics were expressed on a skin surface area, per berry and per gram fresh weight basis. Small wine lots were made of five treatments (the 0.4 irrigation treatment with no defoliation, the 0.4 irrigation treatment defoliated at berry set and all defoliation treatments (control, defoliated at berry and defoliated at veraison) for the 0.8 irrigation treatment. Wine analysis and sensory evaluation were conducted on the wines.

The experimental design was a split plot factorial using completely randomized blocks. The main plot was irrigation amounts and they were split for leaf removal either at berry set or veraison or no leaf removal. The irrigation treatments were applied randomly across rows with a border row between treatments. Each individual plot consisted of 9 data vines (with one vine within the row serving as a border between treatments). The main plot was replicated five times across rows. Data were analyzed with SAS® Version 8 using ANOVA, ANCOVA and Duncan's multiple range test for comparisons of the means. Regression analyses were performed using CoHort Version 6 statistical software.

Results and Discussion:

The canopy management treatment imposed in the Merlot vineyard during the 2001-growing season was to throw canes on the north side of the row over the top of the vine. Since the shaded area (effective leaf area) of the canopy management treatments were less than the controls, applied water was greater than actually needed. Midday leaf water potential of vines with thrown canes was always less negative than the controls at a particular irrigation amount in 2001. In 2002, vines in the research plot were not irrigated until midday leaf water potential approached –1.0 MPa (-10 bars). By the time

berry set occurred (time to impose the first canopy management treatment) the shoots on these data vines were still upright and could not be thrown. This is illustrated in Table 1 where the shaded area (which is reflective of canopy size) of vines in the rest of the vineyard, which had been irrigated early on, was greater than the shaded area of the experimental plot. Therefore, in 2002 the canopy management practice was to remove leaves in the fruiting zone instead of throwing the canes. Leaf removal provided a better means of maintaining canopy size (Table 1, as measured by shaded area) while not affecting vine water status as a function of applied water amount (Table 2).

Leaf removal in the fruiting zone increased PFD in the fruiting zone for all irrigation treatments (Table 3). Measurements made on August 9 demonstrated that PFD in the fruiting zone of the 0.4 irrigation treatment, without leaf removal was similar to the 0.8 and 1.2 irrigation treatments with leaf removal. There was an increase in PFD between June 25 and August 9 for the three irrigation treatments without leaf removal. This was probably due to the fact that most shoots were still upright in June, while they had fallen by August 9. Photon flux density within the fruiting zone remained fairly constant between 1100 and 1400 hours (Table 4). The temperature of exposed fruit was always greater than clusters in the shade although irrigation amount did mitigate cluster temperature somewhat (Table 5). As was demonstrated in 2001, cluster water potential was more negative for vines receiving less water and when clusters were exposed to direct sunlight versus those in the shade (Table 6).

Vines at the Madera site were only irrigated once a week at a time when the cost of electricity was reduced. Therefore, the irrigation event took place on the weekend. Biweekly measurements of leaf water potential generally took place on Thursday or Friday. Midday leaf water potential for the three irrigation treatments generally declined throughout the season (Figure 1). The increased values of leaf water potential, on day of year 190, were due to the fact that the measurements were made on the Monday following an irrigation event. Leaf water potential of the 0.4 irrigation treatment still was significantly different from the other two on that date. The data in Figure 1 also shows that leaf water potential of vines irrigated early in the growing season were higher than those of vines in the experimental section of the vineyard that had not received water.

Irrigation treatments in the Merlot vineyard significantly affected berry weight, soluble solids, pH, titratable acidity and yield (Table 7). The canopy management treatments only affected soluble solids and yield. Leaf removal in the fruiting zone reduced yields an average of approximately 9% compared to the controls. Yield of the 0.4 and 0.8 irrigation treatments were 66 and 88% that of the 1.2 irrigation treatment. Based upon a vine and row spacing of 7 and 12 feet, respectively, (519 vines per acre) the mean yield of the experimental plot was 10.8 tons per acre, compared to 8 tons per acre in 2001. The highest and lowest yields of the treatments in 2002 were equivalent to 13.5 and 8.0 tons per acre, respectively.

Both irrigation amount and leaf removal had a significant effect on anthocyanins measured in the berries' skins (Table 8). This was regardless whether anthocyanins were expressed on a per skin area basis, per berry basis or per mg fresh berry weight basis.

There was a significant interaction of irrigation amount and canopy management on the phenolic content per berry (Table 9). Small lot wines were made from the fruit of all canopy management treatments irrigated at 0.8 of estimated ET_c and for the control and berry set defoliation treatments of the 0.4 irrigation treatment. The soluble solids at harvest of these five treatments averaged 25.3 °Brix (Table 10). Wines were bottled in the Spring of 2003 and analyzed for phenols, tannins and anthocyanins (Table 11). In general, values of the above three mentioned components were greater for the 0.4 irrigation treatment compared to those of the 0.8 irrigation treatment. Leaf removal, whether at berry set or veraison increased the values of phenols, tannins and anthocyanins when compared to the non-defoliated treatment.

There was a significant effect of irrigation treatment and canopy management treatment on pruning weights (Table 12). There were no significant interactions. Irrigating at 0.4 of estimated ET_c significantly reduced vegetative growth compared to the other two irrigation treatments. Leaf defoliation at berry set significantly reduced pruning weights compared to no defoliation or defoliation at veraison.

Conclusions

Once this study is completed (it will be conducted for another two years) we should have a better understanding of the effects of canopy management practices on cluster water status and whether this might contribute to the perceived effects of light on fruit quality in the field. Data collected in the Merlot vineyard in Madera County indicates that leaf removal, with greater cluster exposure to sunlight, proved beneficial. This was evident for both anthocyanin and phenolic analyses of the fruit and the wine and tannin analysis of the wine.

The data also indicate that a higher priority should be given to irrigation management for vineyards in both hot and cool climates of California. Proper irrigation scheduling with the appropriate water amounts may result in a canopy where little or no canopy management practices are necessary.

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Table 1. The percent shaded area per vine for the various irrigation and canopy management treatments during the 2002-growing season for the Merlot vineyard in Madera County. The values in the Simpson Vineyard column were measurements made on vines irrigated prior to the vines in the experimental portion of the vineyard. Shaded area was determined using a grid placed on the ground beneath the vine's canopy and a photograph was taken with a digital camera. The images were then digitized with a software package. Vine and row spacings in the vineyard were 7 x 12 feet (2.13 x 3.66 m = 7.8 m^2 per vine), respectively.

	% shaded area					
Calendar Date	Simpson Vineyard	1.2 Control	0.8 Control	0.8 Defoliated[1]	0.4 Control	0.4 Defoliated[1]
May 3	11.8	10.9				
May 9		11.8				
May 17		19.2				
May 24	25.7	21.9				
June 6	47.8	38.0				
June 21	38.0	41.3	37.2		30.0	
June 25			39.4	35.5	33.6	30.1
August 22		42.8[2]	40.0	39.2	33.1	35.8
				(38.5)[3]		(36.0)[3]

[1] The values in these columns are for vines in the 0.8 and 0.4 irrigation treatments defoliated at berry set.

[2] The percent shaded area for the 1.2 irrigation treatment, defoliated at berry set, was 40.2 on August 22.

[3] These values are for the 0.8 and 0.4 irrigation treatments defoliated at veraison and measured on August 22.

Table 2. Midday leaf water potential (1 MPa = 10 bars) of Merlot grapevines as a function of date, irrigation treatment and canopy management. Irrigation treatments were applied water amounts at 0.4, 0.8 and 1.2 of estimated ET_c. Canopy management treatments consisted of leaf removal in the fruiting zone either at berry set (set) or veraison (ver).

Date	Canopy Man.	Irrigation Treatment 0.4	Irrigation Treatment 0.8	Irrigation Treatment 1.2	Ave. Effect Can. Man.
		MPa			
July 5	Control	-1.19	-1.03	-0.83	-1.02
	Defoliated: set	-1.18	-1.01	-0.84	-1.01
	Ave. Effect Irr	-1.18	-1.02	-0.83	
	$LSD_{0.05}$	Irr. = 0.02 CM = ns Interaction = ns			
July 8	Control	-1.03	-0.79	-0.72	-0.84
	Defoliated: set	-1.00	-0.83	-0.70	-0.84
	Ave. Effect Irr	-1.01	-0.81	-0.71	
	$LSD_{0.05}$	Irr. = 0.04 CM = ns Interaction = ns			
July 25	Control	-1.38	-1.16	-0.89	-1.14
	Defoliated: set	-1.34	-1.16	-0.83	-1.11
	Ave. Effect Irr	-1.36	-1.16	-0.86	
	$LSD_{0.05}$	Irr. = 0.04 CM = ns Interaction = ns			
August 9	Control	-1.41	-1.23	-0.98	-1.20
	Defoliated: set	-1.28	-1.16	-0.89	-1.11
	Defoliated: ver	-1.26	-1.16	-0.91	-1.11
	Ave. Effect Irr	-1.32	-1.17	-0.92	
	$LSD_{0.05}$	Irr. = 0.03 CM = 0.03 Interaction = ns			
August 22	Control	-1.34	-1.14	-0.84	-1.11
	Defoliated: set	-1.38	-1.09	-0.83	-1.10
	Defoliated: ver	-1.35	-1.12	-0.82	-1.10
	Ave. Effect Irr	-1.36	-1.12	-0.83	
	$LSD_{0.05}$	Irr. = 0.02 CM = ns Interaction = ns			

Table 3. The effects of date, irrigation treatment and canopy management on photon flux density (PFD) in the fruiting zone of Merlot grapevines grown in Madera County in 2002. Each value is the mean of 30 individual measurements. Ambient PFD was 1864 and 1768 μmol m^{-2} s^{-1} on June 25 and August 9, respectively. The control vines were not defoliated. Vines were defoliated at berry set (set) or veraison (ver).

		Irrigation Treatment			Ave. Effect
Date	Can. Man	0.4	0.8	1.2	Can. Man.
		Photon Flux Density (μmol m^{-2} s^{-1})			
June 25	Control	151	76	59	96
	Defoliated:set	437	500	317	418
	Ave. Effect Irr.	294	280	196	
	$LSD_{0.05}$ Irr. =[1]	CM =[1]	Interaction = 80		
August 9	Control	375	192	99	222
	Defoliated: set	509	460	348	439
	Defoliated: ver	477	445	464	462
	Ave. Effect Irr.	454	366	304	
	$LSD_{0.05}$ Irr. =[1]	CM =[1]	Interaction = 96		

[1]LSDs not listed due to significant interaction.

Table 4. The effect of time of day and irrigation treatment on photon flux density (PFD) measured in the fruiting zone of Merlot grapevines grown in Madera County on July 8 2002. All irrigation treatments had been defoliated in the fruiting zone at berry set. No statistical analysis was conducted on the data.

	Irrigation Treatment		
Time of Day (h)	0.4	0.8	1.2
	PFD (μmol m^{-2} s^{-1})		
1100	429	547	578
1200	505	545	520
1300	601	511	453
1400	456	374	403

Table 5. The effects of irrigation treatment and exposure (sunlit vs. shaded) on cluster temperature measured on Merlot grown in Madera County. Measurements were taken on July 8 2002. Irrigation treatments were 0.4, 0.8 and 1.2 of estimated vineyard ET_c. Temperature was measured with a hand-held infrared thermometer. Ambient temperature at the time of measurement was 34.5 °C (94.1 °F) (30, 37 and 40 °C = 86, 98.6 and 104 °F, respectively). Each value is the mean of 14 individual replicates.

Time of Day (h)	Exposure	Irrigation Treatment 0.4	Irrigation Treatment 0.8	Irrigation Treatment 1.2	Ave Effect Exposure
		(°C)			
1500	Sunlit	39.7	38.8	38.1	38.8
	Shaded	32.8	31.3	31.1	31.7
Ave. Effect Irrigation		36.3	35.1	34.6	
		$LSD_{0.05}$ Irr. = 0.71	Exposure = 0.58	Interaction = ns[1]	

[1] not significant

Table 6. The effect of irrigation amount and exposure (sunlit vs. shaded) on cluster water potential of Merlot grapevines grown in the San Joaquin Valley measured on July 5 2002. Each value is the mean of 5 individual cluster replicates.

Irrigation Treatment	Sunlit Cluster	Shaded Cluster	Ave. Effect Irrigation
	(MPa)		
1.2	-0.96	-0.79	-0.88
0.8	-1.06	-0.90	-0.98
0.4	-1.30	-1.19	-1.25
Ave. Effect Exposure	-1.11	-0.96	
$LSD_{0.05}$	Irrigation = [1]	Exposure = [1]	Interaction = 0.033

[1] Not applicable as there was a significant interaction between irrigation treatment and exposure level.

Table 7. Characteristics of berries sampled August 21, 2002, in a Merlot vineyard in Madera County. Vines were irrigated at three fractions; 0.4, 0.8 and 1.2 of estimated ET_c. Canopy management practices included leaf removal in the fruiting zone either at berry set or veraison. The control consisted of no leaf removal. Yield data collected on September 10th is also included. ns = not significant.

Canopy Management	Irrigation Amount 0.4	0.8	1.2	Ave. Effect Can. Man.
	Berry weight (g 150^{-1} berries)			
Control	182	224	229	212
Berry Set	177	217	227	207
Veraison	181	221	236	213
Ave. Effect Irr.	180	221	231	
	$LSD_{0.05}$ Irr. = 7.7	CM = ns	Interaction = ns	
	Soluble Solids (°Brix)			
Control	22.7	21.8	20.6	21.7
Berry Set	22.5	21.4	20.1	21.3
Veraison	22.9	21.7	20.9	21.8
Ave. Effect Irr.	22.7	21.7	20.5	
	$LSD_{0.05}$ Irr. = 0.38	CM = 0.38	Interaction = ns	
	pH			
Control	3.69	3.66	3.62	3.66
Berry Set	3.72	3.70	3.63	3.68
Veraison	3.74	3.62	3.64	3.67
Ave Effect Irr.	3.72	3.66	3.63	
	$LSD_{0.05}$ Irr. = 0.04	CM = ns	Interaction = ns	
	Titratable acidity (g L^{-1})			
Control	4.97	6.02	6.35	5.78
Berry Set	4.60	5.50	6.48	5.39
Veraison	4.69	5.74	6.19	5.54
Ave. Effect Irr.	4.75	5.75	6.21	
	$LSD_{0.05}$ Irr. = 0.36	CM = ns	Interaction = ns	
	Yield (kg 4^{-1} vines)			
Control	65.0	81.7	94.6	80.5
Berry Set	55.9	76.3	84.7	72.3
Veraison	58.6	77.4	88.1	74.7
Ave. Effect Irr.	58.9	78.5	89.1	
	$LSD_{0.05}$ Irr. = 4.8	CM = 4.8	Interaction = ns	

Table 8. The effects of irrigation amounts and canopy management on anthocyanin content measured on berries of Merlot grapevines grown in the San Joaquin Valley. Data were generated from berries sampled at harvest in 2002.

Canopy Management	Irrigation Treatment 0.4	0.8	1.2	Ave. Effect Canopy Man.
		(mg cm^{-2} skin)		
Control	0.622	0.497	0.490	0.536
Berry Set	0.614	0.568	0.532	0.568
Veraison	0.634	0.626	0.530	0.596
Ave. Effect Irrigation	0.623	0.564	0.517	
	$LSD_{0.05}$ Irr = 0.021	CM = 0.020	Interaction = ns	
		(mg $berry^{-1}$)		
Control	3.01	2.87	2.83	2.90
Berry Set	3.07	3.21	3.16	3.15
Veraison	3.08	3.52	3.25	3.28
Ave. Effect Irrigation	3.06	3.20	3.08	
	$LSD_{0.05}$ Irr = ns	CM = 0.19	Interaction = ns	
		(mg g^{-1} fresh berry wt)		
Control	2.48	1.92	1.85	2.08
Berry Set	2.60	2.22	2.09	2.30
Veraison	2.55	2.39	2.07	2.34
Ave. Effect Irrigation	2.44	2.18	2.00	
	$LSD_{0.05}$ Irr = [1]	CM = [1]	Interaction = 0.25	

[1] Not listed due to significant interaction.

Table 9. The effects of irrigation amounts and canopy management on phenolic content measured on berries of Merlot grapevines grown in the San Joaquin Valley. Data were generated from berries sampled at harvest in 2002.

Canopy Management	Irrigation Treatment 0.4	0.8	1.2	Ave. Effect Canopy Man.
		(mg cm^{-2} skin)		
Control	1.42	1.47	1.38	1.42
Berry Set	1.48	1.50	1.55	1.51
Veraison	1.33	1.51	1.45	1.43
Ave. Effect Irrigation	1.41	1.49	1.46	
	$LSD_{0.05}$ Irr = ns	CM = ns	Interaction = ns	
		(mg $berry^{-1}$)		
Control	6.87	8.29	7.95	7.70
Berry Set	7.41	8.63	9.22	8.42
Veraison	6.48	8.50	8.90	7.96
Ave. Effect Irrigation	6.92	8.47	8.69	
	$LSD_{0.05}$ Irr = na	CM = ns	Interaction = 1.51	
		(mg g^{-1} fresh wt.)		
Control	5.65	5.52	5.12	5.43
Berry Set	5.79	5.60	5.75	5.71
Veraison	5.25	5.71	5.32	5.43
Ave. Effect Irrigation	5.56	5.61	5.40	
	$LSD_{0.05}$ Irr = ns	CM = ns	Interaction = ns	

na = statistical analysis was not conducted on this data set.

Table 10. The effects of irrigation amount and canopy management (CM = defoliation at berry set (BS), veraison (V) or no defoliation (C)) on must composition of Merlot. The irrigation treatments (Irr) were 0.4 and 0.8 times estimated full ET_c. The fruit was harvested on September 10, 2002.

Treatment Irr/CM	Soluble Solids (°Brix)	Titratable Acidity ($g\ L^{-1}$)	pH
0.4/C	25.6	4.6	3.77
0.4/BS	25.8	4.1	3.75
0.8/C	25.2	4.1	3.68
0.8/BS	24.6	4.3	3.76
0.8/V	25.1	4.9	3.68

Table 11. The effects of irrigation amount and canopy management on the composition of Merlot wine. Other information is as found in Table 11. Below, anthocyanins are abbreviated Anthos. Wines were analyzed at Enologix®.

Treatment Irr/CM	Total Phenols	Tannins	Monomers	Free Anthos.	Total Anthos.	Complex Anthos.
	($mg\ L^{-1}$)					
0.4/C	1464	645	523	269	379	85
0.4/BS	1636	803	535	271	394	102
0.8/C	1425	585	566	249	346	70
0.8/BS	1620	739	612	244	353	80
0.8/V	1616	823	497	270	386	97

Table 12. The effects of irrigation amount (fraction of estimated ET_c) and canopy management (leaf defoliation in the fruiting zone) on pruning weights of Merlot grapevines from the 2002-growing season. 1 kilogram (kg) = 2.2 pounds.

Canopy Management	Irrigation Treatment 0.4	0.8	1.2	Ave. Effect Can. Man.
	($kg\ vine^{-1}$)			
Control	0.79	1.33	1.35	1.16
Berry Set	0.68	1.06	1.15	0.96
Veraison	0.77	1.21	1.33	1.10
Ave. Effect. Irr.	0.75	1.20	1.28	
	$LSD_{0.05}$ Irr = 0.10	CM = 0.11	Interaction = ns	

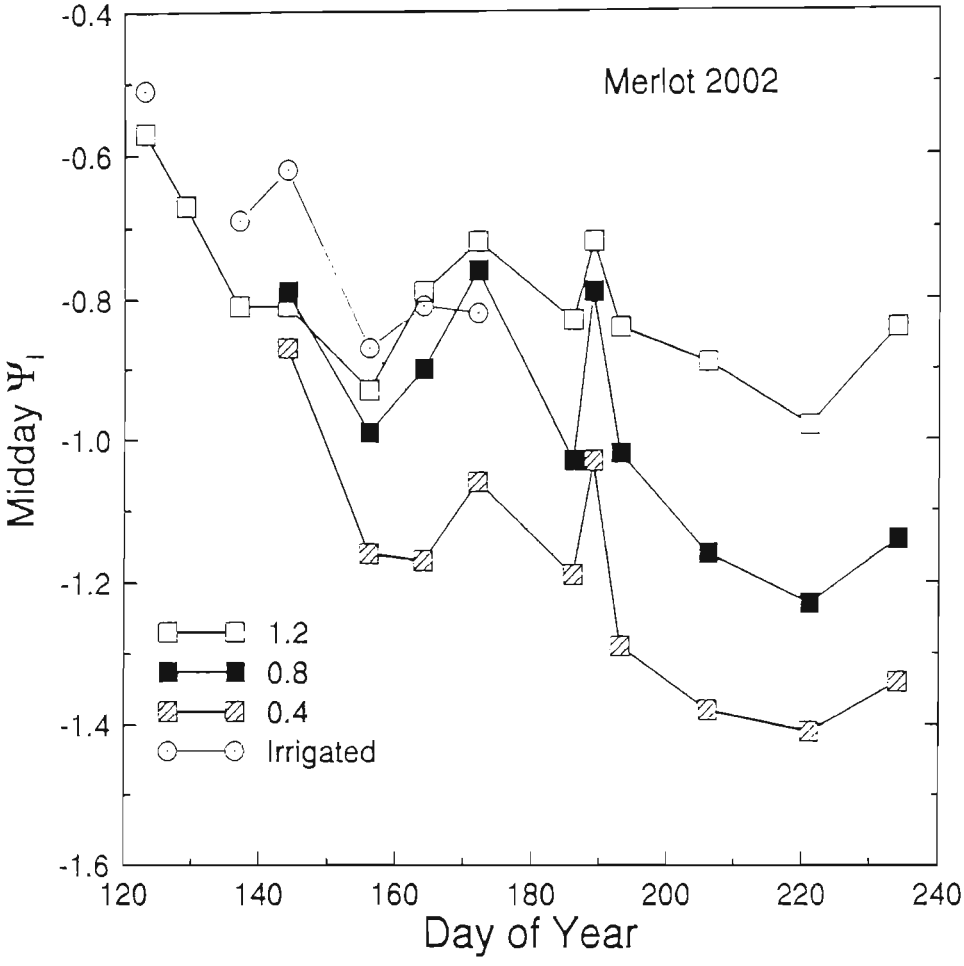

Figure 1. The seasonal course of midday leaf water potential of Merlot grapevines grown in Madera County. Irrigation treatments were applied water amounts at a fraction of estimated ET_c. "Irrigated" refers to leaf water potential measured on the grower/cooperator's vines that had been irrigated early in the season. Each value is the mean of at least 5 individual leaf measurements.

Project Title: Comparison of Irrigation Management Strategies to Optimize Wine Grape Productivity and Fruit Composition

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Summary:

A study was conducted in a Cabernet Sauvignon vineyard at J. Lohr Winery, in the Paso Robles area. Treatments included four irrigation strategies: sustained deficit irrigation (SuDI - where vines are irrigated at some fraction of vineyard water use throughout the season), partial rootzone drying (PRD – where vines are deficit irrigated on one side of the vine for two weeks and then switched to the other side for two weeks), regulated deficit irrigation (RDI – where vines are deficit irrigated as some time during the growing season) and depletion of soil moisture (water is depleted in the soil profile until a critical value of vine water status is reached and an irrigation event then takes place). Applied water amounts at various fractions (0.375, 0.56, 0.75 and 1.12) of estimated ET_c were included in each of the irrigation strategies, with the exception of the soil water depletion treatment.

Vine water status was monitored throughout the growing season. The results indicated that the leaf water potential of vines irrigated a specific fraction of estimated ET_c were similar regardless of irrigation management technique. For example, if the vines were irrigated at 0.375 times ET_c, midday leaf water potential was similar regardless if sustained deficit irrigation (SuDI) or partial rootzone drying (PRD) was being used. Stomatal conductance also was similar at a specific irrigation amount between the two irrigation techniques. Based upon the original PRD work conducted in Australia this should not have occurred. The lack of significant differences in berry size, soluble solids and yield between vines irrigated with PRD and SuDI at the three irrigation amounts would also indicate that PRD had no distinct advantage over deficit irrigating vines at some fraction of estimated ET_c seasonally or at a specific phenological stage.

This study also included RDI as an irrigation management technique. The results indicate that deficit irrigation between berry set and veraison and then irrigating at greater applied water amounts thereafter, is a good as deficit irrigating throughout the growing season with regard to berry size. Deficit irrigation from veraison to harvest was only

minimally useful in reducing berry size under the conditions of this study. Berry size of vines irrigated only once every two weeks was similar to that of the 0.357 ET_c irrigation amount using SuDI, PRD and RDI from set to veraison. This may indicate that this less precise method would be useful in reducing berry size. Lastly, there were few effects of the treatments on yield the first year of the study.

Berry anthocyanin and phenol compounds have not been measured as of the date this report was written. It is unknown how the above-mentioned irrigation amounts and management techniques will influence those two important characteristics of the fruit. Wine was not made from fruit of any of the treatments in 2002. The cooperator has indicated that small wine lots will be made from the fruit in 2003.

Objective of Proposed Research:

A comparison was made among four different irrigation management strategies in a Cabernet Sauvignon vineyard located at Paso Robles, California. The irrigation management methods included: 1.) Sustained deficit irrigation (SuDI) at various fractions (0.375, 0.56, 0.75 and 1.12) of estimated ET_c, 2.) Partial rootzone drying (PRD) at the first three aforementioned fractions of ET_c, 3.) Regulated deficit irrigation between berry set and veraison or from veraison to harvest at the abovementioned fractions of ET_c (when deficit irrigation was not applied, vines were irrigated at 1.12 times estimated ET_c) and 4.) Monitoring vine water status (measurement of midday leaf water potential) and irrigating at a pre-determined leaf water potential value. Vine water status and vegetative and reproductive growth were monitored for each method and irrigation level. Wines of selected treatments were not made at harvest in 2002.

Experimental Procedures to Accomplish Objective:

The Cabernet Sauvignon vineyard used for this study was located near Paso Robles at the J. Lohr Winery. Vine and row spacings in the vineyard were 6 and 10 feet, respectively. The trellis was a VSP and row direction was north south. The rootstock used in this vineyard is 5C.

The irrigation management strategies used in the study were as follows:

1.) The first treatment will be sustained deficit irrigation (SuDI) at various fractions of estimated vineyard ET_c. Irrigation treatments did not commence in the vineyard until close to berry after the irrigation system had been modified for the imposition of the treatments. Once irrigations began, vines were irrigated at 0.375, 0.56, 0.75 and 1.12 times estimated ET_c. ET_c at 100% was determined by the following equation: $ET_c = K_c \times ET_o$, where K_c equals the crop coefficient for a VSP trellis with a 10 ft. row spacing and ET_o is potential ET. Potential ET was obtained from the PR1 weather station operated by the Paso Robles Vintners and Growers Association. The applied water amounts in each treatment (fraction of ET_c) remained the same up until harvest. Irrigation frequency was twice weekly.

Prior to that time vines had been irrigated at least once to twice per week by the grower-cooperator at 75% of ET_c. The above listed treatments were such due to the fact the remainder of the vineyard was irrigated by the grower cooperator at 75% of ET_c (using two emitters per vine). The 0.375 treatment was established by removing one emitter and the 0.56 treatment was established by having three emitters per two vines down the row. The 1.12 treatment was established by adding an additional emitter per vine.

2.) The second treatment was the irrigation of the vines using partial rootzone drying (PRD). Irrigation amounts were the same fractions of those used for the first three irrigation SuDI treatments (listed above). Two drip lines were placed on either side of the vines' trunk (east or west) prior to commencement of irrigation. One line had an emitter on the north side of the vines' trunks and the other line had an emitter on the opposite (south) side of the vines' trunks. This allowed us to alternate sides when irrigating the vines (i.e. wet and dry sides). The sides were alternated every two weeks during 2002.

3.) The third irrigation management treatment was the application of differing amounts of water at different phenological stages of vine growth. From the initiation of seasonal irrigation until bloom all vines in 2002 were irrigated at 0.75 of ET_c. Between berry set and veraison, three treatments were imposed with vines irrigated at 0.375, 0.5, and 0.75 times estimated ET_c. After veraison, these treatments were irrigated at 1.12 of ET_c until harvest. From the initiation of irrigations until veraison another set of vines were irrigated at 1.12 that of ET_c. Then between veraison and harvest another set of three irrigation amount treatments were imposed using amounts similar to those used between bloom and veraison.

4.) The fourth treatment was to schedule frequency of irrigation based upon the depletion of the water in the soil profile. Once water has been depleted such that midday leaf water potential was approximately –1.4 MPa, the vines were irrigated. The irrigation event was approximately 8 hours in length. Total applied water was approximately 24 gallons per event. This continued throughout the remainder of the 2002-growing season.

Midday leaf water potential was measured to determine the water status of all treatments. A minimum of 5 individual leaf replicates were measured per treatment each time they are taken. Water potential measurements were made several times during the growing season and on occasion on a diurnal basis for selected treatments.

Berries were sampled prior to harvest and weighed. They were analyzed for soluble solids, pH and titratable acidity. Berries of all treatments will be analyzed for anthocyanins and phenolics sometime in February or March 2003. Fruit was harvested when deemed appropriate by the cooperator. Vegetative growth will be estimated by measuring pruning weights during the dormant portion of the growing season.

The experimental design was a completely randomized block. Each experimental unit was replicated five times and consisted of ten vines down the row with yield data collected from the middle four vines. Data was analyzed via Analysis of Variance and Tukey's test for multiple comparisons of the means. Regression analysis will be used where appropriate.

An additional experimental plot was established during 2002 in the three rows just west of the above, described study site. Three irrigation treatments were imposed: 1.) Sustained deficit irrigation at 1.12 times estimated ET_c, 2.) Sustained deficit irrigation at 0.56 of ET_c and 3.) Partial rootzone drying at 0.56 of ET_c. This was done to fully test the concept of PRD without the conflicting analysis of the other irrigation management techniques used in the previously outlined study. Experimental design and analysis of the data were similar to that described above.

Summary of Major Research Accomplishments and Results:

The irrigation treatment amounts and strategies were imposed mid-June in 2002, two weeks subsequent to budbreak. Irrigation amounts at 100% of estimated ET_c (for a VSP trellis on 10 foot rows) was calculated weekly by the PI and given to the cooperator. Applied water amounts for several of the treatments were measured with an in-line water meter (attached to the drip tubing). In most instances, the applied water amounts, measured with the water meter, were similar to the amount of water a specific treatment should have received.

Leaf water potential was measured throughout the growing season for selected treatments and on several occasions, it was measured on vines in all treatments (a total of 14 treatments). The first measurement of the season occurred on June 5 at 1600 hours just prior to when the treatments were imposed. Temperature at the time of measurement was 42.2°C (108°F). Leaf water potential averaged –1.06 MPa. On July 9th, leaf water potential was measured on all (all applied water amounts at a fraction of ET_c) of the SuDI and PRD treatments. There were significant differences among the irrigation amounts but not between the SuDI and PRD techniques. August 21, 2002 was the last date in which leaf water potential was measured on all of the irrigation treatments (Table 1). The amount of applied water at the time the measurement was made, had the predominate effect on leaf water potential. As might be expected, the RDI treatment from set to veraison, being irrigated at 1.12 ET_c on August 21, differed from all of the other irrigation management strategies examined.

Irrigation amount again had the greatest effect on berry weight (Table 2). Vines irrigated with less water from set to veraison had smaller berries regardless of irrigation strategy. Berries of the RDI set to veraison strategy had sizes similar to the SuDI and PRD at similar irrigation amount despite the fact that they received applied water amounts at 1.12 ET_c from veraison to harvest. The imposition of water deficits from veraison to harvest (RDI, veraison to harvest) had less effect on reducing berry size at any of the irrigation amounts during that time frame.

There was a significant interaction between irrigation amount and strategy on soluble solids (Table 2) and pH (Table 3), but in most cases the differences were minimal. Neither irrigation strategy nor amount had a significant effect on titratable acidity. It did appear that the RDI set to veraison irrigation amount treatments were lower than those from the other irrigation strategies. Lastly, there was a significant interaction between irrigation strategy and amount on yield (Table 4), however, only one treatment differed significantly from two of the others. This may be expected as this was the first year of the study.

The additional study conducted west of the experimental site had results similar to those reported for the main study (Table 5). Vines irrigated at 1.12 ET_c had significantly larger berries that the two 0.56 ET_c treatments (using either SuDI or PRD). The treatments had no significant effects on the other measured parameters.

Outside Presentations of Research:

Since this research was only initiated during the 2002-growing season, no presentations have been given as of this date.

Research Success Statements:

This study was to have been initially conducted in a vineyard at Meridian Winery in Paso Robles. Unfortunately, the vineyard manager at Meridian changed his mind and was unwilling to cooperate. The study was switched to a Cabernet Sauvignon vineyard at J. Lohr Winery, also in the Paso Robles area. Personnel at this winery have been willing cooperators. Due to the change in location, it took longer to establish the irrigation treatments (modification and addition of drip lines and emitters) than originally planned. The imposition of the irrigation treatments did not occur until two weeks after berry set, later than we had anticipated.

Vine water status was monitored throughout the growing season by measuring leaf water potential at midday or several times on a diurnal basis. On a few occasions, stomatal conductance was measured with a porometer. The results indicated that the leaf water potential of vines irrigated a specific fraction of estimated ET_c were similar regardless of irrigation management technique. For example, if the vines were irrigated at 0.375 times ET_c, midday leaf water potential was similar regardless if SuDI or PRD was being used. Stomatal conductance also would be similar between the two irrigation techniques. Based upon the original PRD work conducted in Australia this should not have occurred. In addition, the lack of significant differences in berry size, soluble solids and yield between vines irrigated with PRD and SuDI at the three irrigation amounts would also indicate that in fact PRD had no distinct advantage of just deficit irrigating vines at some fraction of estimated ET_c.

This study also included RDI as an irrigation management technique. The results indicate that deficit irrigation between berry set and veraison and then irrigating at greater applied water amounts thereafter, is a good as deficit irrigating throughout the growing

season with regard to berry size. Deficit irrigation from veraison to harvest was only minimally useful in reducing berry size under the conditions of this study. Berry size of vines irrigated only once every two weeks was similar to that of the 0.357 ET_c irrigation amount using SuDI, PRD and RDI from set to veraison. This may indicate that this less precise method would be useful in reducing berry size. Lastly, there were few effects of the treatments on yield the first year of the study.

Berry anthocyanin and phenol compounds have not been measured as of the date this report was written. It is unknown how the above-mentioned irrigation amounts and management techniques will influence those two important characteristics of the fruit. Wine was not made from fruit of any of the treatments in 2002. The cooperator has indicated that small wine lots will be made from the fruit in 2003.

Funds Status:

Monies obtained for this study have been spent or encumbered as of this date (January 22, 2003).

Table 1. The effects of irrigation strategies and irrigation amounts on midday leaf water potential of Cabernet Sauvignon grapevines measured on August 21, 2002. The vines were grown in a vineyard near Paso Robles, California. The irrigation amounts were various fractions (0.375, 0.56, 0.75 and 1.12) of estimated full ET_c. The irrigation strategies were sustained deficit irrigation (SuDI), partial rootzone drying (PRD), and regulated deficit irrigation (RDI) from either berry set to veraison (set – ver.) or from veraison to harvest (ver. – har.) at the indicated irrigation amount fractions. Vines in the RDI treatments were irrigated at 1.12 times estimated ET_c when not deficit irrigated. The dry down treatment consisted of irrigating vines every two weeks for approximately 8 hours. Measurements were taken between 1400 and 1530 hours. There was a significant interaction between irrigation strategy and irrigation amount.

Irrigation Strategy	Irrigation Amount	Leaf Water Potential (MPa)
SuDI	0.375	-1.31 fg
	0.56	-1.23 e
	0.75	-1.12 d
	1.12	-0.95 a
PRD	0.375	-1.31 fg
	0.56	-1.20 e
	0.75	-1.13 d
RDI (set – ver.)	0.375	-1.04 c
	0.56	-1.02 bc
	0.75	-0.96 ab
RDI (ver. – har.)	0.375	-1.29 f
	0.56	-1.21 e
	0.75	-1.13 d
Dry Down	na	-1.36 g

Table 2. The effects of irrigation strategies and irrigation amount on berry weight and soluble solids of Cabernet Sauvignon berries sampled on September 17, 2002. The vines were grown in a vineyard near Paso Robles, California. There were significant interactions between irrigation strategy and irrigation amount for both berry weight and soluble solids. Other information is as found in Table 1.

Irrigation Strategy	Irrigation Amount	Berry Weight (g 150^{-1} berries)	Soluble Solids (°Brix)
SuDI	0.375	118 ef	24.3 a
	0.56	135 cde	24.0 ab
	0.75	156 ab	23.1 ab
	1.12	156 ab	23.5 ab
PRD	0.375	120 ef	23.8 ab
	0.56	132 def	23.8 ab
	0.75	150 abc	24.1 a
RDI (set – ver.)	0.375	123 def	23.2 ab
	0.56	137 cd	22.9 b
	0.75	157 a	23.3 ab
RDI (ver. – har.)	0.375	140 bcd	24.0 ab
	0.56	151 abc	24.1 ab
	0.75	155 ab	23.5 ab
Dry Down	na	116 f	23.4 ab

Table 3 The effects of irrigation strategies and irrigation amount on pH and titratable acidity of Cabernet Sauvignon berries sampled on September 17, 2002. The vines were grown in a vineyard near Paso Robles, California. There was a significant interaction between irrigation strategy and irrigation amount for pH. There were no significant effects of the treatments on titratable acidity. Other information is as found in Table 1.

Irrigation Strategy	Irrigation Amount	pH	Titratable Acidity ($g\ L^{-1}$)
SuDI	0.375	3.69 abc	5.45
	0.56	3.74 a	5.31
	0.75	3.67 abc	5.25
	1.12	3.69 abc	5.48
PRD	0.375	3.60 c	5.49
	0.56	3.63 bc	5.40
	0.75	3.69 abc	5.48
RDI (set – ver.)	0.375	3.60 c	4.73
	0.56	3.66 abc	4.86
	0.75	3.72 ab	4.85
RDI (ver. – har.)	0.375	3.69 abc	5.28
	0.56	3.63 bc	5.37
	0.75	3.66 abc	5.00
Dry Down	na	3.68 abc	5.22

Figure 4 The effects of irrigation strategies and irrigation amount on yield of Cabernet Sauvignon berries sampled on September 17, 2002. The vines were grown in a vineyard near Paso Robles, California. There was a significant interaction between irrigation strategy and irrigation amount for yield. Other information is as found in Table 1.

Irrigation Strategy	Irrigation Amount	Yield (kg 4^{-1} vines)
SuDI	0.375	38.4 ab
	0.56	35.3 ab
	0.75	44.9 a
	1.12	44.4 a
PRD	0.375	32.8 b
	0.56	35.2 ab
	0.75	37.5 ab
RDI (set – ver.)	0.375	37.5 ab
	0.56	41.3 ab
	0.75	38.9 ab
RDI (ver. – har.)	0.375	37.0 ab
	0.56	36.6 ab
	0.75	39.2 ab
Dry Down	na	35.1 ab

Table 5. The effects of sustained deficit irrigation at 1.12 of estimated ET_c and SuDI and PRD at 0.56 of ET_c on berry characteristics and yield of Cabernet Sauvignon measured in a vineyard near Paso Robles. The rows in which this study was conducted were just west of the rows used to conduct the study in the above-mentioned tables. The treatments had a significant effect on berry weight but none of the other measured parameters.

Treatment	Berry Wt. (g 150^{-1} berries)	°Brix	pH	TA (g L^{-1})	Yield (kg 4^{-1} vines)
SuDI 1.12	173 a	23.4	3.66	4.99	42.4
SuDI 0.56	143 b	23.2	3.67	4.88	36.9
PRD 0.56	143 b	23.5	3.63	4.94	39.2

ESTIMATION OF IRRIGATION REQUIREMENTS FOR TABLE GRAPE VINEYARDS IN THE SAN JOAQUIN VALLEY AND THE EFFECTS OF IRRIGATION AMOUNTS ON BERRY CHARACTERISTICS AND PRODUCTIVITY

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GRAPE PRODUCTION AREAS OF CALIFORNIA

The majority of raisins produced in California are grown within 125 km of the city of Fresno, located in the San Joaquin Valley. Table grapes are produced in the Coachella Valley, approximately 160 km east of Los Angeles and the southern San Joaquin Valley. Table grape production in the San Joaquin Valley extends from just north of Fresno to south of Bakersfield. The largest wine grape production area in California is the San Joaquin Valley (which is usually divided into the northern and southern portions). Other major wine grape production areas include Napa and Sonoma Valleys in Northern California, and the Central Coast areas including the Salinas Valley and areas in San Luis Obispo and Santa Barbara Counties further south. Smaller wine grape production areas are located in the foothills of the Sierra Nevada mountains and the Temecula Valley just north of the city of San Diego in southern California.

The Coachella Valley has a desert climate characterized by extremely hot summers (maximum temperatures of 50°C are not uncommon) and mild winters. Budbreak will occur in mid-January when vines are sprayed with hydrogen cyanamide, and harvest concluded by late May – early June. Fortunately, the extremely high summer temperatures occur in July and August. Rainfall is usually less than 50 mm per year. The soils are sandy with low water and nutrient holding capacities. Rooting depth in these soils is limited because they are highly stratified. The evaporative demand (Reference ET [ET_o]) in the Coachella Valley from mid-January to the end of harvest can range from 650 to 800 mm. Yearlong ET_o can be 2000 mm. The maximum ET_o value will approach 8.5 mm per day close to harvest.

The San Joaquin Valley is a semi-arid region with hot summers (maximum temperatures approximately 44°C) and cool winters. Grapevines and deciduous fruit trees will generally accumulate enough chilling units each winter so as not to affect budbreak. Budbreak of grapevines will occur early to mid-March and harvest (depending upon grape type) will occur from the end of July to September. Rainfall is a function of location within the valley, more to the north and less to the south. For example, rainfall in Stockton (at the northern end of the valley) may approach 400 mm per year. Rainfall in the central San Joaquin Valley (Fresno) averages 250 mm per year while that in Bakersfield (southern end of the valley) is approximately 180 mm. The major portion of the rainfall will occur during the winter months. The majority of grapevines are grown in the eastern portion of the San Joaquin Valley where the soils are mostly sandy loams, although there are small areas that can be very sandy. Soils in the western portion of the San Joaquin Valley are heavier, clay loam type soils. The rooting depth of the eastern San

Joaquin Valley can be limited by clay-pans. The soil water and nutrient holding capacities of these soils are moderate to good. There can water infiltration problems on some of the soils. Reference ET from the time of budbreak to the end of October will range from 1000 to 1250 mm in the San Joaquin Valley. Daily maximum ET_o may approach 7 mm.

The coastal, wine grape production areas are characterized by warm days and cool nights although high temperatures (40 to 47°C) may occur for a few days each growing season depending upon location. Some areas may have fog lasting late into the morning. Rainfall again is greater in the coastal valleys located further north and diminishes the further south one travels. For example, rainfall in the Napa and Sonoma Valleys will range from 500 to 1000 mm per year while the Salinas Valley it averages only 250 mm per year. Most of the soils in the coastal production areas are clay loam to clay type soils of good water and nutrient holding capacities. Reference ET between budbreak and harvest will range from 900 to 1000 mm.

IRRIGATION MANAGEMENT

Irrigation types and availability of water

Due to the high evaporative demand and the amount of rainfall and its timing (during the dormant portion of the growing season) irrigation of vineyards is required at most locations in the State of California. The majority of the raisin grape vineyards are flood irrigated but many of the newer plantings are utilizing drip irrigation. Water used for irrigation is primarily obtained from wells (ground water) but a small fraction of the raisin growers in specified irrigation districts will use water stored in reservoirs with runoff from the Sierra Nevada Mountains. Ground water may contain nitrates in sufficient amounts that meet vineyard nitrogen demands. There are also locations where the well water contains excess nitrates that can be detrimental to grapevines.

The majority of table grape vineyards will use drip irrigation. This provides access to the grapevines at any time in order to control fungal pathogens. In the Coachella Valley water is obtained from the All-American canal supplied with water from the Colorado River. Water quality is generally very good. Table grape vineyards in the San Joaquin Valley are similar to raisin vineyards in that most irrigation water is obtained from wells. Water quality problems are the same as mentioned previously for raisin vineyards.

Wine grape vineyards in the northern, coastal valleys of California are dependent upon both ground water and the collection of winter rainfall in small reservoirs for irrigation purposes. Along the central coast of California irrigation water is obtained from wells. There are a few locations where the water from individual wells is somewhat saline and therefore leaching is required in years where winter rainfall is insufficient.

Water use by non-water stressed grapevines

The main driving force of vineyard water use (or evapotranspiration; ET_c) is energy derived from the sun. This energy is required to covert water which is in a liquid state inside the leaf to water vapor, which is lost through the stomata (microscopic pores located on the lower side of the leaf's blade). This loss of water from the vine is called transpiration. As can be seen in Figure 1,

daily vine water use is more highly correlated with net radiation than with ambient temperature. Other environmental factors that will affect transpiration include wind and vapor pressure deficit (as the relative humidity decreases vapor pressure deficit increases). Vine water use decreases to almost zero at sunset as stomata are closed due to darkness. Lastly, the vine also is able to control its water use by regulating the opening and closing of the stomata.

Vine water use will vary throughout the growing season (Figure 2). Water use is low early in the season, from budbreak to one month later, as there is little leaf area during that time (Figure 3). Once there is appreciable leaf area and the evaporative demand increases, vine water use will increase almost linearly until final canopy size is developed. Water use will decrease late in the season due to leaf aging or other factors such as insect damage. When grapevines are girdled to increase berry size of some table grape cultivars, stomatal conductance (which is a measure of the pore size of the stomata) decreases. In the 1995 growing season, vine water use actually decreased during the period the girdle remained open (for approximately a four week period). Subsequent to this, vine water use will increase again until it levels off at full canopy, sometime in July.

How berries grow

Numerous factors should be considered when devising an irrigation strategy for the production of table grapes in the San Joaquin Valley. Most studies conducted on grapevines have indicated that water deficits affect vegetative growth to a greater degree than fruit growth. Thus it is important not to stress grapevines during the period of canopy development. An adequate canopy is a necessity to protect the berries from sunburn. Subsequent to budbreak, shoot growth increases rapidly with the canopy reaching its maximum size sometime towards the end of June/first of July in the Fresno area. Studies conducted at the Kearney Ag Center and elsewhere in the San Joaquin Valley have demonstrated that soil moisture may be able to provide most of the vine's water requirements from budbreak to the end of April, especially if there are periods of rainfall during this time. Exceptions to this would be vineyards situated on sandy soils and/or with shallow rooting depths or vineyards with a cover crop. Another generalization derived from irrigation studies on grapevines is that vegetative growth is much more affected by water deficits than is photosynthesis (the production of carbohydrates by leaves). Therefore, once the canopy has developed sufficient leaf area moderate water deficits can be imposed such that the leaves remain fully functional while the rate of shoot growth is much reduced.

The degree to which berry growth is affected by water deficits is dependent upon the time when the water stress is imposed. Berry growth is most susceptible to water stress during Stage I of berry growth (between bloom and 4 to 5 weeks later). It is during this time cell division is occurring in the berry and it is only during Stage I when cell division occurs. The ultimate size of a berry is determined in part by the number of cells, which is a function of cell division. Therefore, if cell division is reduced by water stress during this stage then final berry size is reduced. Extra water applied later on will not overcome a stress imposed during this stage. Cells will initiate growth or elongate during Stages I and III of berry growth. Stage III occurs subsequent to veraison (when berries begin to soften and colored varieties begin to turn color). Growth during Stage III is less susceptible to water deficits than during Stage I. From the above discussion it is apparent that about the only time one does not want to impose a water stress is the period from bloom to 4 weeks later. A mild stress at Stage I will result in

only a non-significant reduction in berry size. Lastly, it has been demonstrated that sugar accumulation in the fruit, which begins subsequent to veraison, is less susceptible to water deficits than is berry growth.

Vine water status in the current season can also affect potential crop the next growing season. It has been demonstrated that deficit irrigated grapevines are more fruitful than vines receiving too much applied water. A mild water stress imposed during fruit bud differentiation (which occurs from bloom to veraison in spur pruned varieties and from bloom to just prior to harvest in cane pruned varieties) increased bud fruitfulness of Thompson Seedless grapevines grown in the San Joaquin Valley and Perlette and Flame Seedless grapevines grown in the Coachella Valley.

Effects of irrigation amounts on berry characteristics and yield of table grapes

The above examples of vine water use were determined with the use of a weighing lysimeter (Figures 1 and 2). The vines in the lysimeter were never short of water as they were irrigated whenever they used 2 mm (8 liters) of water throughout the irrigation season. Therefore, they may have been irrigated from 5 to 6 times a day during mid-summer. As pointed out in the previous section, vine and berry growth is less susceptible to mild water stress at certain stages of growth when compared to others. I was thus, interested in determining the effects of irrigating vines either above or below that amount on vine productivity, berry characteristics and final yield. The below examples of the effects of applied water amounts were obtained by irrigating vines at various fractions of water used by vines in the lysimeter (full ET). When the vines in the lysimeter were irrigated daily throughout the season vines in the other treatments were also irrigated but at the fraction of full ET for that designated treatment. The irrigation season generally began the first week in May and was terminated the last week in October.

The soil water content in the irrigation treatments that were deficit irrigated (less than full ET) decreased throughout the growing season while the soil water content in treatments irrigated above full ET increased slightly as the season progressed (Figure 4). Pruning weights taken during the dormant portion of the growing season increased almost linearly from zero applied water up to 140% of full ET. Pruning weights averaged 1.36 kg per vine (1.5 tonnes per ha) fresh weight at the zero applied water treatment and 5.2 kg per vine (5.8 tonnes per ha) at 140% of full ET.

A study was conducted in 1994 to determine the effects of these irrigation amounts on berry size of vines that were trunk girdled only, sprayed with GA_3 at berry set only or both practices combined. All vines were sprayed with GA_3 at bloom to flower thin the clusters. Berry weight was maximized at irrigation amounts between 60 and 80% of full ET for vines that were either only girdled or sprayed with GA_3 at berry set. Berry size for vines that were both girdled and sprayed with GA_3 at set was maximized at water application amounts at 100% of full ET. These latter results are similar to those obtained in the 1996 growing season (Table 1). Berry weight leveled off at the 100% irrigation level, however, there were no significant differences in weight among the 80 to the 140% level treatments. An interesting result obtained in 1994 was that berry diameter was maximized at irrigation amounts at 40% of full ET for the girdled only treatment and at 60% of full ET for the GA_3 at set only treatment. When vines were both girdled and sprayed with GA_3 at set, diameter continued to increase, albeit only slightly, as applied water increased up to the 140% treatment. It would appear that berry diameter may be less affected by severe soil water deficits than is berry weight.

For several years irrigation studies were conducted in a Flame Seedless and Perlette vineyard in the Coachella Valley and two Thompson Seedless vineyards in the San Joaquin Valley. In those studies, irrigations treatments were not imposed until either berry set (when vines were girdled) or veraison (in the Coachella Valley) or at berry set only (in the San Joaquin Valley). Treatments included water application amounts between 50 and 150% of estimated full ET. At no time was there a significant effect of applied water amounts on berry weight in the Coachella Valley. Irrigation amounts at 50% of ET_c decreased berry weights at the Delano and Fowler sites (in the San Joaquin Valley). The results from both valleys indicate that water deficits at 75% of ET_c imposed after berry set do not significantly affect berry size.

Vine water status will affect the concentration of sugars and acids in the fruit. Crop load (yield) has also been demonstrated to affect the concentrations of sugar and acid in the berry. In a study conducted in the lysimeter vineyard at the Kearney Ag Center in 1995 we examined the interaction of irrigation amounts and crop load on berry characteristics of Thompson Seedless vines used to make table grapes (i.e. table grape production practices were used to increase berry size). At harvest soluble solids decreased and titratable acidity (TA) increased in the fruit as applied water amounts increased. There were slight differences in both sugar and acid at each irrigation level as a function of cluster number per vine. Generally, vines with less fruit had higher sugar and lower acid levels. There were no significant differences in yield as a function of irrigation treatments from 40 to 140% of full ET within a crop load treatment. Yields for the 15, 25, and 35 clusters per vine treatments averaged 10, 16 and 23 kg per vine, respectively. Thus, the applied water treatments had the major effect on berry soluble solids and TA in this study while crop load had less of an effect. Results from the irrigation studies conducted in the Coachella Valley on Flame Seedless and Perlette are similar to that just mentioned, ie. as applied water increased soluble solids decreased and titratable acidity increased.

Soil water deficits generally have been shown to improve color of red and black colored wine grape varieties. Both early and late season water deficits have proven beneficial. However, no differences in color of Flame Seedless berries were observed in the Coachella Valley when vines were irrigated at various fractions of full ET, including deficit irrigations. This may be due to the earlier harvest date of table grapes (i.e. at lower sugar levels) compared to wine grapes. In addition, the use of Ethrel and/or girdling at veraison to help color the fruit may mask any effect of deficit irrigating red or black table grapes.

Studies conducted at the Kearney Ag Center have demonstrated that yields of Thompson Seedless grapevines used for raisin production are maximized at irrigation amounts between 60 and 80% of full ET depending upon trellis type. This is due to the fact that the number of clusters per vine are greatest at the 60 and 80% applied water treatments. Over irrigating Thompson Seedless grapevines reduces yields due to fewer clusters per vine while under irrigating those vines reduces berry size. In 1996, yields of Thompson Seedless grapevines used to produce table grapes was maximized at an irrigation amount equal to 80% of full ET (Table 1). Yields of the irrigation treatments greater than this leveled off or decreased slightly. There were no significant differences in yield of Thompson Seedless vines irrigated at amounts from 50 to 150% of estimated full ET in two commercial vineyards located in the San Joaquin Valley (Figure 5). These results indicate that: 1.) irrigation amounts applied the previous year may affect fruit bud differentiation, which determines

cluster number in the current season and ultimately final yield (data of Kearney study), and 2.) deficit irrigation subsequent to berry set in the current season does not adversely affect final yield at harvest.

Scheduling irrigations using current season's weather data

Seasonal evaporative demand remains fairly constant from year to year in the San Joaquin Valley, therefore, irrigation schedules can be established using historical weather data. However, there can be periods during the growing season where evaporative demand departs significantly from historical values and the use of a standard irrigation schedule for current season irrigation amounts may result in the application of too much or too little water. This was demonstrated during the 1996 growing season where evaporative demand during the first week of June was 30% greater than historical demand. During the last week of June in 1996, evaporative demand was 10 to 50% less than historical values. Therefore, vines during this period could have either been under irrigated, the first week of June and over irrigated, the last week of June in 1996 using historical data.

The information needed to schedule irrigations throughout the current growing season is daily reference ET (ET_o) values and reliable crop coefficients. Reference ET is the water used per unit time by a short green crop completely shading the ground and ideally is of uniform height and never short of water. Reference ET is a measure of the evaporative demand of a particular region throughout the year. Current (or real-time) ET_o data in the State of California are available from the California Irrigation Management Information System (CIMIS). The crop coefficient (K_c) is the fraction of water used by a specific crop (in this case grapevines) compared to that of ET_o. The K_c depends upon the stage of vine development, degree of cover, height and canopy resistance (stomatal regulation by the vine). The non-water stressed seasonal K_c developed at the Kearney Ag Center with the use of the weighing lysimeter is found in Figure 6. These K_cs were determined by dividing the water use of vines growing in the lysimeter daily (Figure 2) by ET_o values obtained from a CIMIS weather station at the Kearney Ag Center. The crop coefficient increases as the amount of foliage on the vine increases and then levels off throughout the remainder of the season.

When grapevines are girdled water use will remain constant or actually decrease slightly. The seasonal K_cs reflecting this are shown in Figure 7. When scheduling irrigation for table grape vineyards I assume the K_c will remain constant as long as the girdle is open. Once it heals, the K_c will increase until full canopy is reached. The data in Figure 7 also illustrates that row spacing will affect water use of table grape vineyards using a traditional crossarm trellis. As row spacing decreases, water use per land area will increase.

The seasonal K_cs shown in Figures 6 and 7 are only appropriate for vineyards using a California standard crossarm trellis. I have developed a technique in which a K_c could be developed for any trellis configuration and canopy size. I found that the K_c is a linear function of the amount of shade cast on the ground at midday (Figure 8). Shaded area can be determined by measuring the width (or amount) of shade on the ground with a tape measure, using a grid placed on the ground and estimating shade within each square or by taking a digital photograph and with the use of computer software, digitizing the amount of shade.

The percent shaded area of three trellis systems were measured during the 2000-growing season (Figure 9). It can be seen that the overhead trellis used to produce dried on the vine raisins develops much more quickly than the canopy of the gable or standard trellises. However, by the end of the year, shaded area of the gable and overhead trellises are similar. The crop coefficient can be calculated by multiplying percent shaded area (a whole number) by 0.017 (the slope of the data in Figure 8). For example, a trellis with 40% shaded area (area of shade divided by total area per vine) would have a K_c of 0.68 (40 x 0.017 = 0.68). The seasonal K_cs for the three trellis systems of Figure 9 and the lysimeter (Figure 6) area shown in Figure 10. Degree days used in this figure start to accumulate March 15th, which is the approximate date of budbreak each year.

To schedule the current season's daily irrigation requirements (or vine ET) one can use the following equation:

$$ET_c = K_c \times ET_o$$

where ET_c is vine ET, K_c is the daily crop coefficient and ET_o, is the daily reference ET. Figure 7 contains the seasonal crop coefficients used to schedule irrigation amounts in trials conducted in commercial Thompson Seedless vineyards west of Fowler and east of Delano over a four year period. The K_c levels off at a value of 0.7 beginning with girdling and remains such for the next four weeks (until the girdle heals). The highest K_c used in 1996 was 0.85. It was felt that this value was sufficient to maintain the vine's canopy and not adversely affect berry size. This particular value (0.85) is only appropriate for the vineyards used in the Fowler and Delano irrigation experiment and may not be used in other cases. In my irrigation studies I have found that using last week's ET_o values and the current week's K_c is sufficient for scheduling weekly irrigation amounts.

Conclusions

The crop coefficients presented in the above example would be utilized to irrigate vines such that they were not stressed throughout the growing season. It should also be pointed out that they are for vineyards that do not use cover crops. Research conducted at the Kearney Ag Center has demonstrated that water use of vineyards using cover crops can be increased anywhere from 20 to 40% compared to clean cultivated vineyards. The absolute amount is dependent upon whether the cover crop is incorporated into the soil and at what time of the season this is done.

Clearly, one could deficit irrigate subsequent to berry set and not affect berry size or yields appreciably and that practice may ultimately increase yields in future years if bud fruitfulness is enhanced. Deficit irrigations subsequent to berry set will probably enhance the accumulation of sugar in the fruit and decrease TA more rapidly. While deficit irrigations have not improved the color of Flame Seedless in the Coachella Valley, such a practice may improve color of later maturing red or black table grapes in the San Joaquin Valley. Lastly, since many varieties are very susceptible to sunburn it should be reiterated here that a full canopy should be developed prior to imposing a moderate water stress.

If one wants to minimize pumping and/or water costs then deficit irrigation can be used with minimal effects on berry quality or yield. Deficit irrigation amounts should be calculated

first by determining full ET for your particular vineyard (which would be dependent upon stage of vine growth and trellis used). The equation given above: $ET_c = K_c \times ET_o$ would be used. This value would then be multiplied by some fraction, for example 0.8 (80%), to determine the actual amount of water to apply per vine.

Table 1. The effect of applied water amounts on relative berry size and yield of Thompson Seedless grapevines managed as table grapes. The applied water amount at 1.0 was determined with a weighing lysimeter. The vines within the lysimeter were irrigated whenever 2 mm of water was used. The other irrigation treatments were irrigated whenever the lysimeter was watered but at the designated fraction. Vine density within the vineyard was 1317 vines per ha. Maximum berry weight was 6 grams while maximum yield was 22 kg per vine.

Applied Water (fraction of full ET)	Berry Weight	Packable Yield
	----- (percent of greatest weight or yield) -----	
0.0	44	10
0.2	67	36
0.4	75	68
0.6	84	94
0.8	95	100
1.0	100	90
1.2	95	95
1.4	98	91

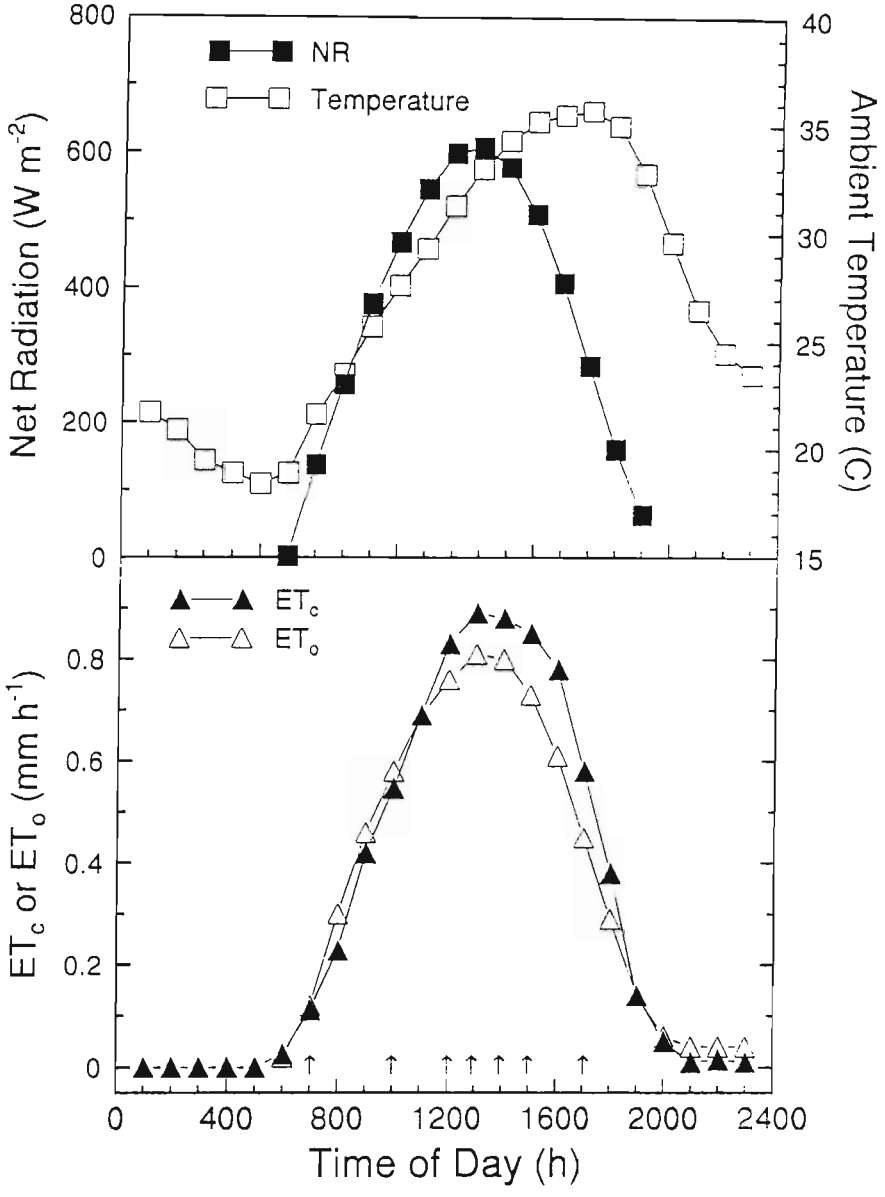

Figure 1. The daily time course of water use by Thompson Seedless grapevines grown in a weighing lysimter in the San Joaquin Valley of California and reference ET (ET_o) . The arrows at the bottom of the lower figure indicate when the vines were irrigated (with 8 liters of water per vine) during the day. Area per vine was 7.55 m^2.

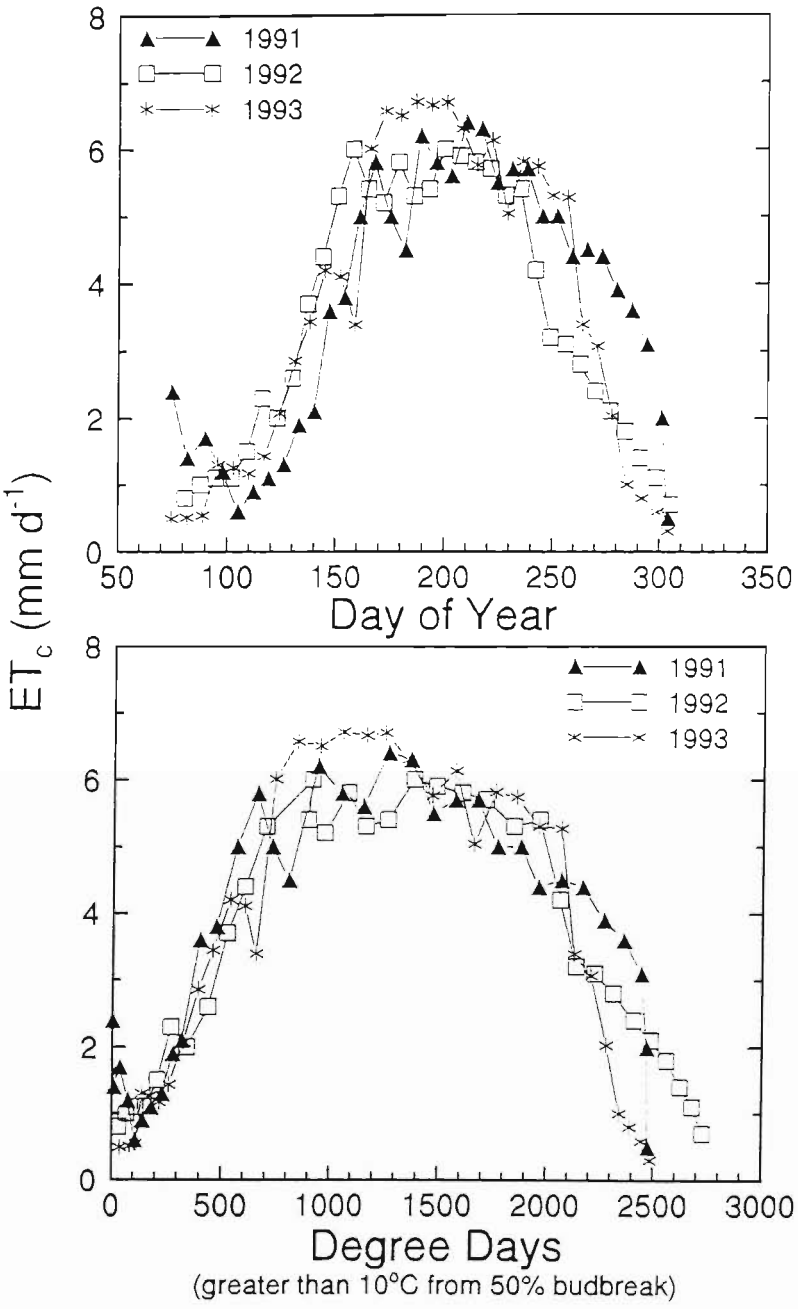

Figure 2. The seasonal progression of daily water use (ET_c) measuring during the 1991, 1992 and 1993 growing seasons with a weighing lysimter. The vines in the lysimeter used a 0.6 m crossarm as the trellis.

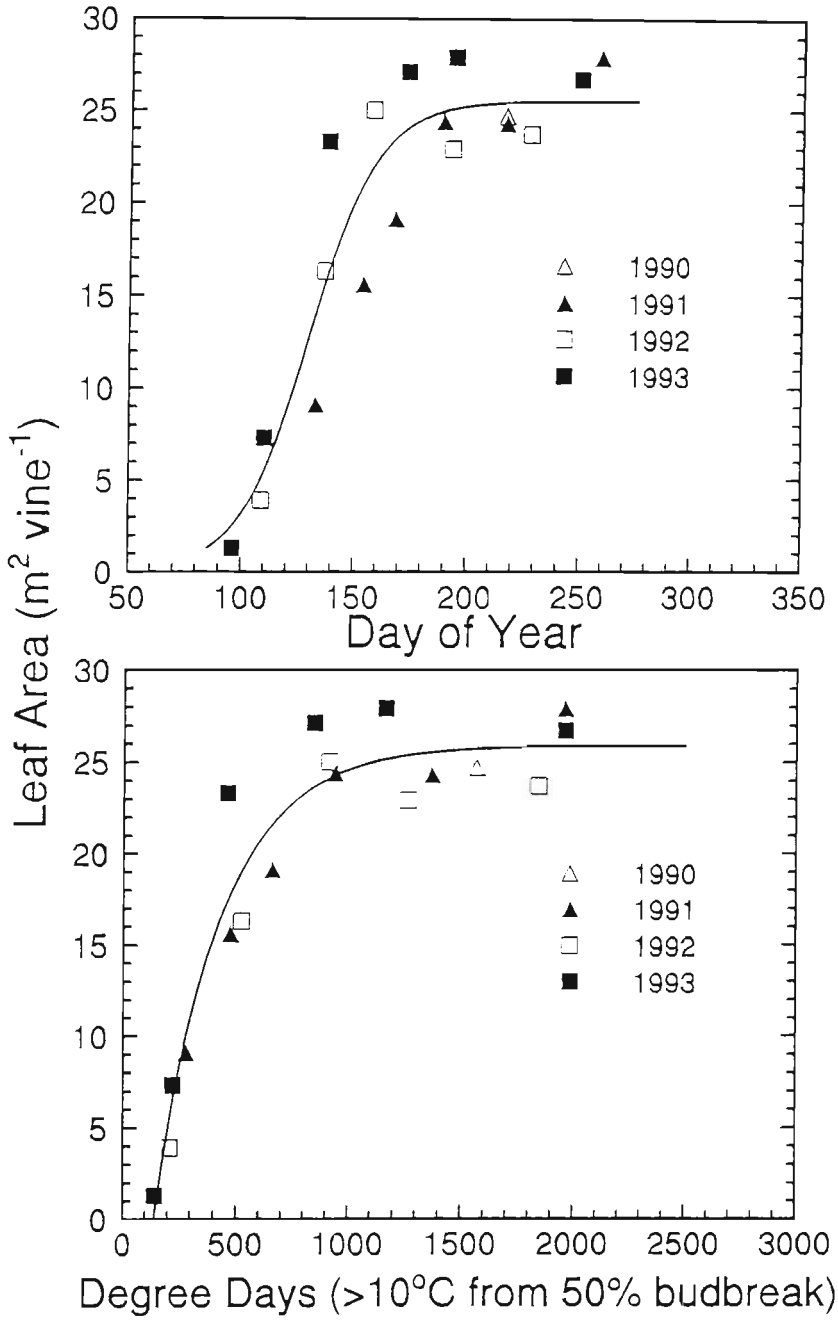

Figure 3. Leaf area development of Thompson Seedless grapevines as a function of day of year (DOY) and degree-days (DDs) measured from budbreak over a four year period.

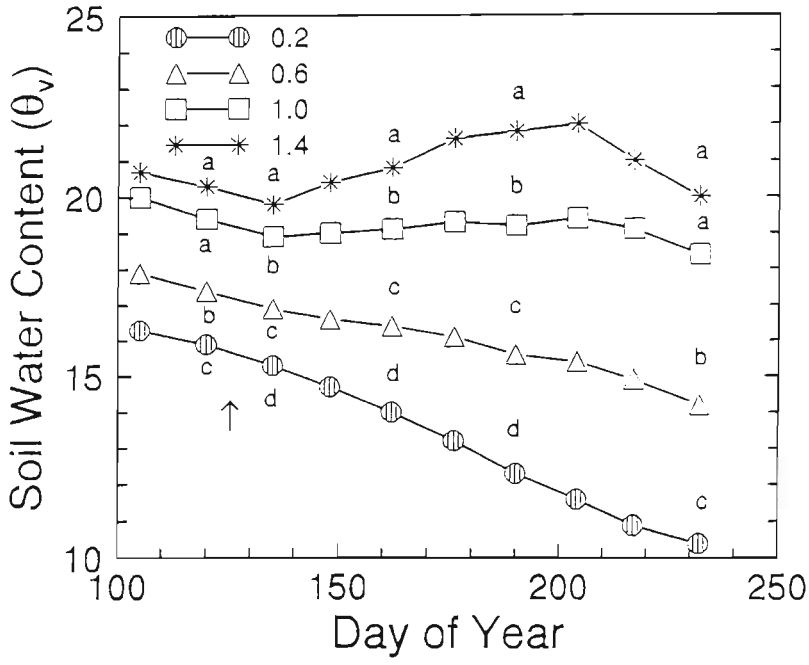

Figure 4. Soil water content for four irrigation treatments measured during the 1993-growing season. Each data point is the mean of three access tube sites. The arrow represent the date (May 3) irrigations began. Data points accompanied by a different letter on the same date indicates significant differences among irrigation treatments at $P < 0.05$.

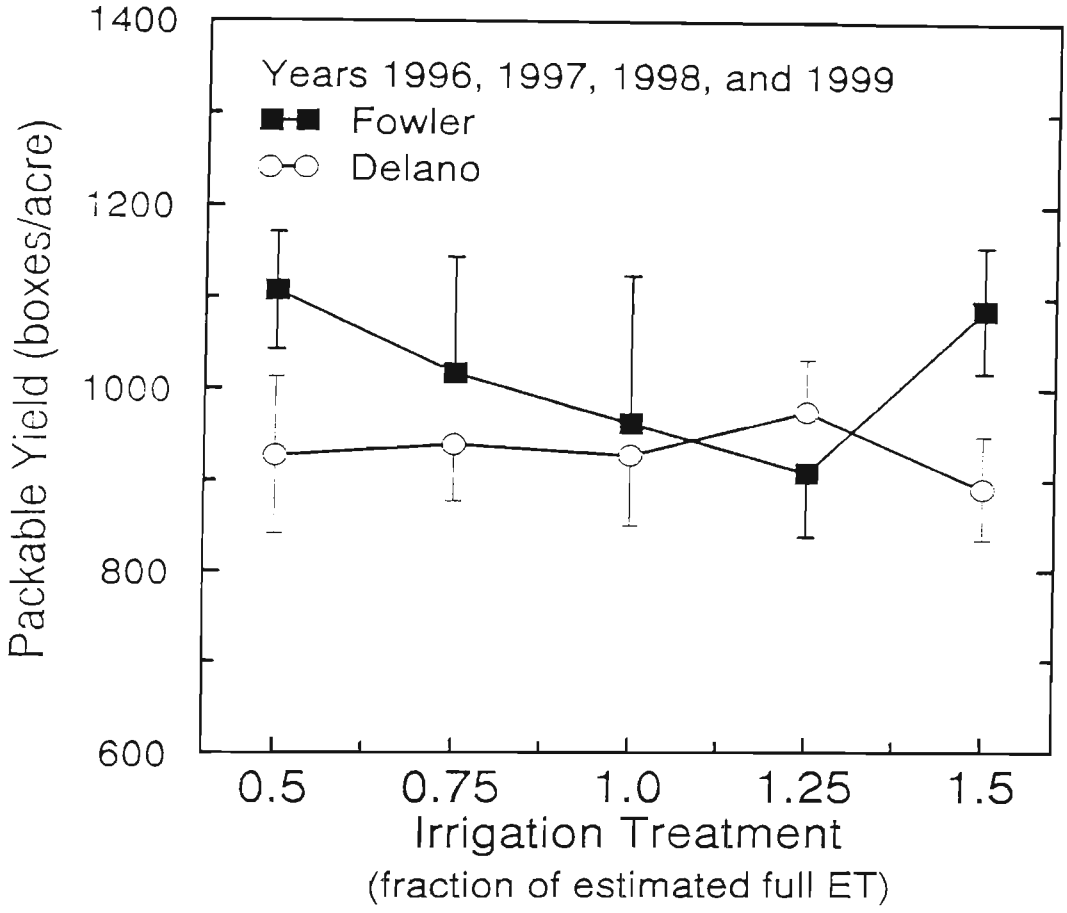

Figure 5. The effects of different applied water amounts on yield of Thompson Seedless grapevines used to produce table grapes in two vineyards (near the cities of Fowler and Delano) located in the San Joaquin Valley of California. Each data point represents the mean (± one standard error) over the four years of the study. One box is equivalent to approximately 9 kg of fruit and there are 2.47 acres per hectare.

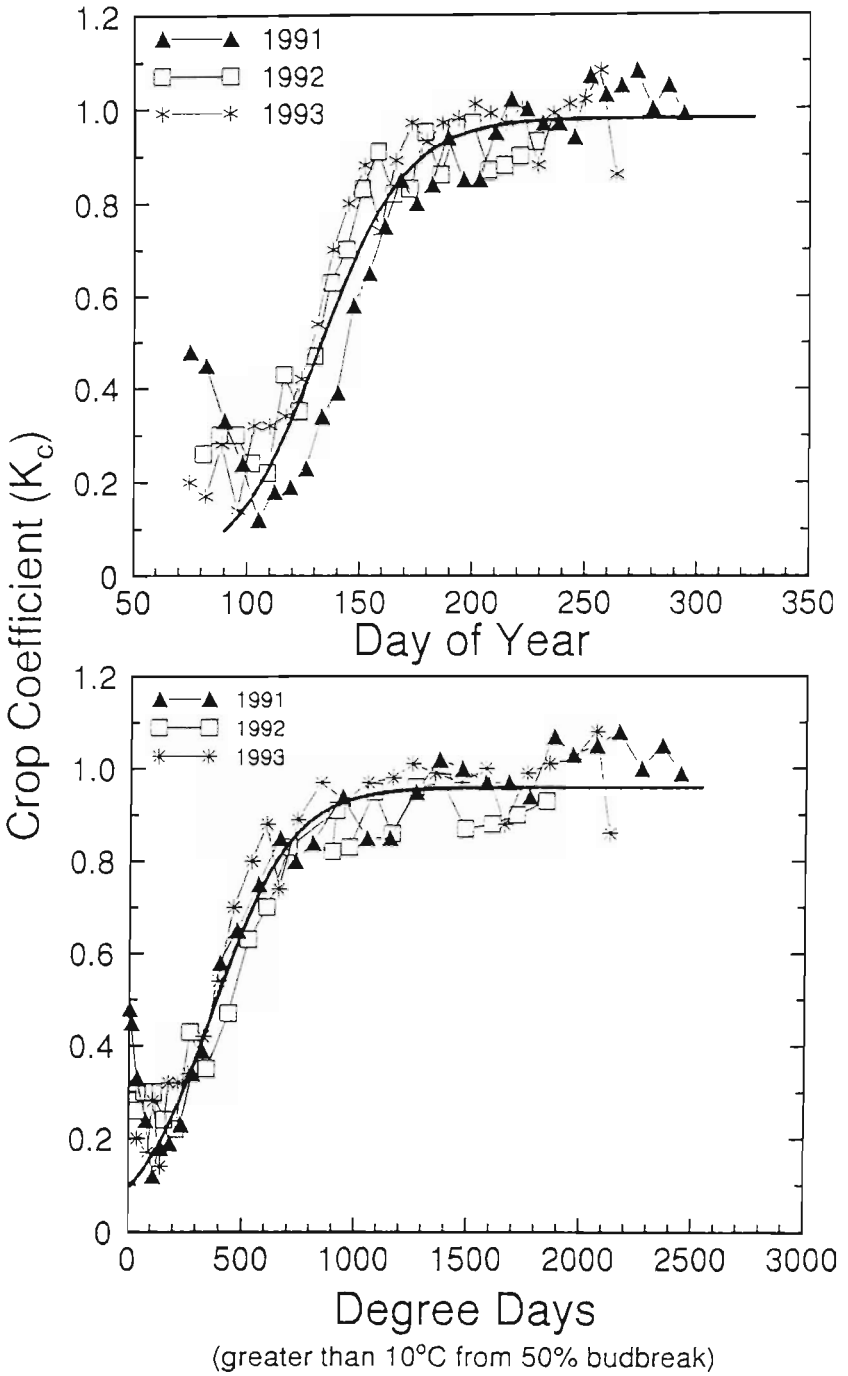

Figure 6. The seasonal progression of the crop coefficient for Thompson Seedless grapevines calculated for the 1991, 1992 and 1993-growing seasons and grown in a weighing lysimeter. The K_c as a function of day of year (DOY) and degree-days (DDs) were fit to the following equations: $y = 0.98/(1 + e^{(-(x - 132)/19)})$, $R^2 = 0.85$ and $y = 0.96/(1 + e^{(-(x - 373)/169)})$, $R^2 = 0.92$, respectively.

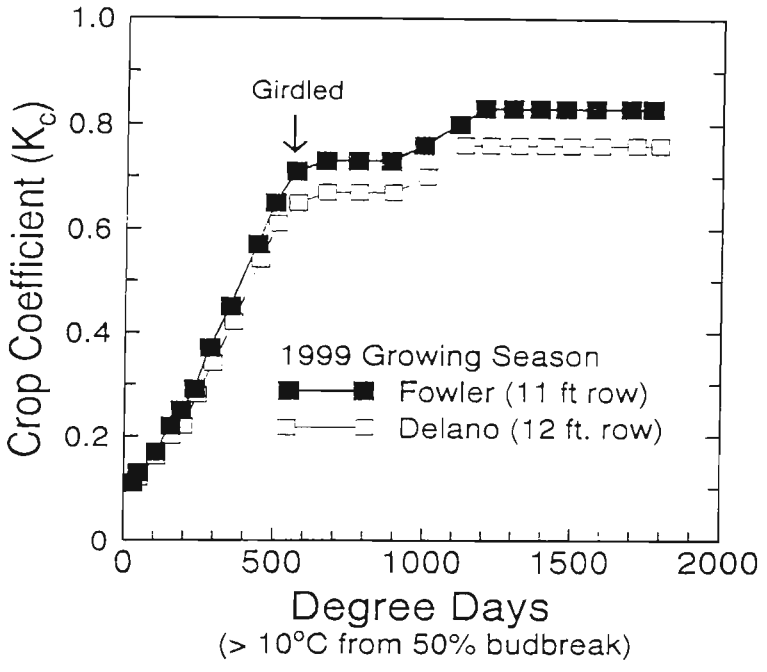

Figure 7. The seasonal crop coefficient used for two different Thompson Seedless table grape vineyards. It was assumed that the K_c levels off for a period of four weeks after the vines are trunk girdled. The seasonal crop coefficients differed within the two vineyards due to differences in row width. The row width at Fowler was 3.35 m and that of the Delano vineyard was 3.66 m.

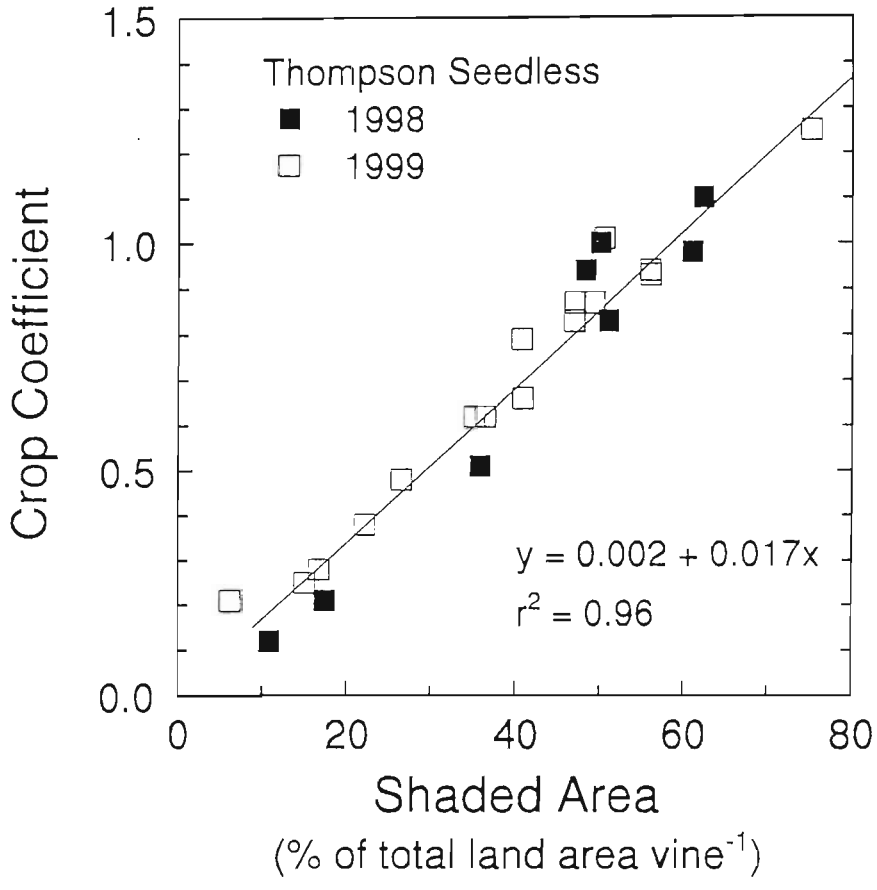

Figure 8. The relationship between the crop coefficient and the percent shaded area measured beneath Thompson Seedless grapevines grown in a weighing lysimeter at midday. Data were collected during the 1998 and 1999-growing seasons.

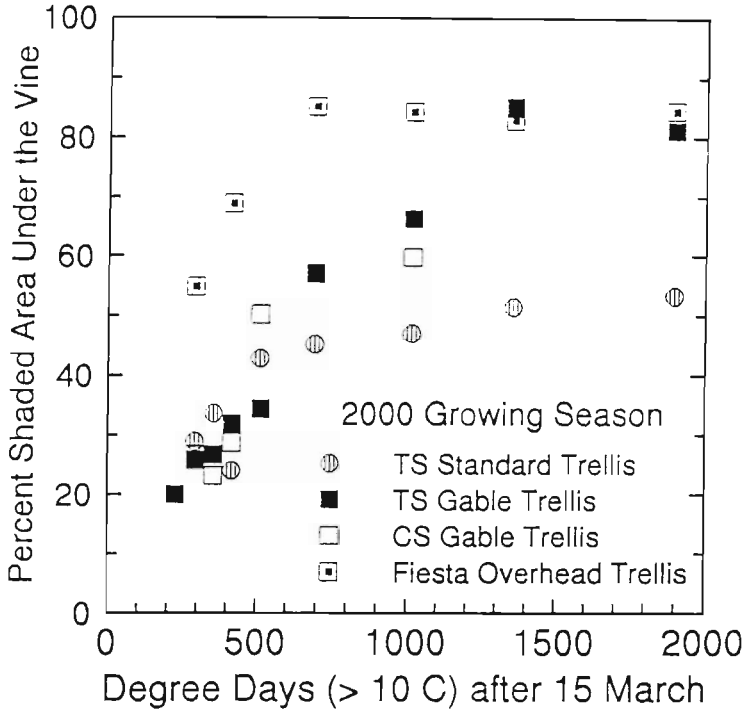

Figure 9. Ther percent shaded area measured beneath four different trellis systems at midday during the 2000-growing season. The standard trellis was a 1.2 m crossarm, slanted to the south. All row widths were 3.66 m. TS = Thompson Seedless, CS = Crimson Seedless and Fiesta is a raisin cultivar.

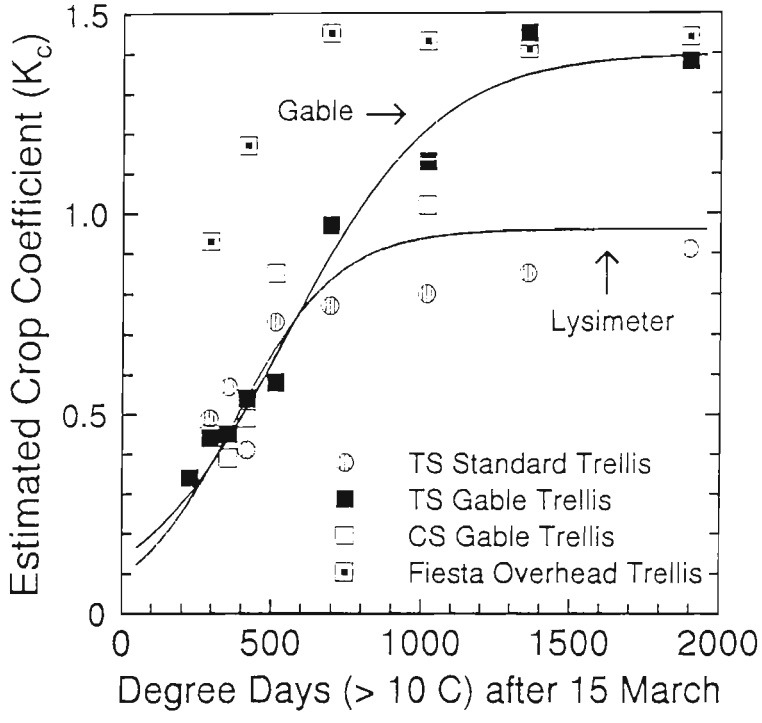

Figure 10. The estimated seasonal crop coefficients for the trellis systems given in Figure 9 at a row width of 3.66 m. The crop coefficient was calculated by multiplying the percent shaded area by the slope given in Figure 8. The seasonal K_c for the vines grown in the lysimeter (from Figure 6) is shown for comparison (the row width of the vines in the lysimeter was 3.45 m).

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ORIGINAL PAPER

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Water use of young Thompson Seedless grapevines in California

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Abstract Water use of Thompson Seedless grapevines during the first 3 years of vineyard establishment was measured with a large weighing lysimeter near Fresno, California. Two grapevines were planted in a 2×4×2 m deep lysimeter in 1987. The row and vine spacings in the 1.4-ha vineyard surrounding the lysimeter were approximately 3.51 and 2.15 m, respectively. Vines in the lysimeter were furrow-irrigated from planting until the first week of September in 1987. They were subsequently irrigated with subsurface drip-irrigation whenever they had used 2 mm of water, based upon the area of the lysimeter (equivalent to 8 liters per vine). The trellis system, installed the second year, consisted of a 2.13 m long stake, driven 0.45 m into the soil with a 0.6 m cross-arm placed at the top of the stake. Crop coefficients (K_c) were calculated using measured water losses from the lysimeter (ET_c) and reference crop evapotranspiration (ET_o) obtained from a CIMIS weather station located 2 km from the vineyard. Water use of the vines in 1987 from planting until September was approximately 300 mm, based on the area allotted per vine in the vineyard surrounding the lysimeter. Daily water use just subsequent to a furrow-irrigation event exceeded ET_o (>6.8 mm day^{-1}). Water use from budbreak until the end of October in 1988 and 1989 was 406 and 584 mm, respectively. The initiation of subsurface drip-irrigation on 23 May 1988 and 29 April 1989 doubled ET_c measured prior to those dates. Estimates of a 'basal' K_c increased from 0.1 to 0.4 in 1987. The seasonal K_c in 1988 increased throughout the season and reached its peak (0.73) in October. The highest K_c value in 1989 occurred in July. It is suggested that the seasonal and year-to-year variation in the K_c was a result of the growth habit of the vines due to training during vineyard establishment. The results provide estimates of ET_c and K_c for use in scheduling irrigations during vineyard establishment in the San Joaquin Valley of California and elsewhere with similar environmental conditions.

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Introduction

There have been numerous estimates of crop water use for mature grapevines. However, estimates of crop water use for grapevines during the first 3 years of vineyard establishment are limited (Myburgh et al. 1996; Peacock et al. 1977). Evapotranspiration techniques that have been used previously for grapevines required assessments of various soil and/or water parameters (Araujo et al. 1995a; Erie et al. 1982; Grimes and Williams 1990; Stevens and Harvey 1996; van Rooyen et al. 1980) that may limit their accuracy. Sap flow sensors have been used on young and mature vines in conjunction with models of soil water evaporation to estimate crop evapotranspiration (ET_c) (Lascano et al. 1992; Ginestar et al. 1998; Yunusa et al. 1997a, 1997b). The reliability of sap flow sensors, especially on large vines, has been questioned (Tarara and Ferguson 2001). Micrometeorological methods to estimate sensible and latent heat flux in vineyards also have been used (Oliver and Sene 1992; Spano et al. 2000; Yunusa et al. 2000). Such techniques require large areas of uniform fetch and extensive instrumentation (Grimmond et al. 1992). Unfortunately, individual vineyard blocks in many grape production areas are quite small, limiting the use of micrometeorological methods under those conditions.

Lysimeters are the standard for ET_c measurements (Prueger et al. 1997). Drainage lysimeters have been used to measure the water use of grapevines (Evans et al. 1993; Rollin et al. 1981; van Rooyen et al. 1980). Such lysimeters can provide accurate crop water-use values on a weekly basis (Buwalda and Lenz 1995) and daily estimates when used in conjunction with extensive measurements of the soil water content within the lysimeter (Evans et al. 1993). However, greater accuracy and sensitivity can be obtained with weighing lysimeters, which measure ET directly (Hatfield 1990). With the appropriate instrumentation, weighing lysimeters can accurately determine ET_c on an hourly or shorter time basis.

A large weighing lysimeter was constructed near Fresno, California, to measure the ET of Thompson Seedless grapevines (Phene et al. 1991). Water use during the first season was recorded by manually reading the scale on a near-daily basis. Continuous hourly measurements of vine ET were determined during the second and third years of the study. Vine ET was then used to develop crop coefficients for use in irrigation management of vines used for raisin and table grape production in the San Joaquin Valley of California. Results presented here describe the water use of grapevines during the first 3 years of vineyard establishment.

Materials and methods

A 2×4×2 m deep weighing lysimeter was installed at the University of California Kearney Agricultural Center located in the San Joaquin Valley of California (36°48′ N, 119°30′ W) in 1986. Two *Vitis vinifera* L. (cv. 'Thompson Seedless', clone 2A) grapevine cuttings were planted in the lysimeter on 9 April 1987. The two vines were 2.15 m apart and 0.925 m from either end of the 4 m long lysimeter. The vines were 1.0 m from the sides of the lysimeter. Cuttings were also planted in the vineyard surrounding the lysimeter with vine and row spacings of 2.15 and 3.51 m, respectively (7.55 m^2 per vine). Row direction was east–west. The vines planted on either side of the lysimeter down the row were 2.15 m from the respective east or west vine inside the lysimeter. The vineyard was approximately 1.4 ha (168×82 m) and was surrounded by a mixture of annual and perennial crops.

Vines within the lysimeter were furrow-irrigated from planting until the first week in September 1987, after which they were subsurface drip-irrigated. Two furrows were dug manually, one on either side of the cuttings, within the lysimeter. The edge of the furrows was located 0.15 m from the cuttings. Furrows were approximately 0.4 m wide at the top, 0.2 m wide at the bottom, 0.3 m in depth, and 3.8 m in length (almost the entire length of the lysimeter, 4.0 m). Vines in the surrounding vineyard were furrow-irrigated all season long. Vine water use was determined by reading the scale manually almost on a daily basis. Therefore, readings were taken just prior and subsequent to a furrow-irrigation to determine the amount of water to apply. The vines were allowed to grow without any support the first year. During the winter, each vine was pruned to one, two-bud, spur.

Drip-irrigation for the remainder of the vineyard, and the trellis system, were installed during vine dormancy of the first growing season (January 1988). The trellis of the vines within the lysimeter consisted of a 2.13 m long wooden stake driven 0.45 m into the soil at each vine. A 0.6 m cross-arm was placed atop the stake and wires attached at either end of the cross-arm to support the vine's fruiting canes. Wooden end posts, 16 cm in diameter, with cross-arms, were placed in the soil at both ends of the lysimeter for additional support. The trellis for the vines in the lysimeter was self-contained and not attached to the trellis system used down the remaining sections of the row to ensure that it was part of the lysimeter mass.

During the second growing season, a single shoot from each vine was trained up the stake in order to form the trunk. Any clusters that were present at this time were removed. Once the shoot's apex was 15 cm above the cross-arm, it was topped to stimulate lateral shoot growth and to form the head of the vine. Midway through the growing season all remaining lateral shoots that had formed along the future trunk were removed. During vine dormancy, the vines were pruned to two, 12-node, fruiting canes (these canes contained the forthcoming growing season's cluster primordia). The third growing season (1989) was the first cropping year. Standard horticultural practices to control disease and insect pests of grapevines were performed as necessary by field station personnel each year.

The soil container of the lysimeter was weighed with a balance beam and load cell configuration, with most of the weight being eliminated using counterweights. The soil, a Hanford fine sandy loam (coarse-loamy, mixed, nonacid, thermic Typic Xerorthent), was excavated from the lysimeter site in eight layers and stockpiled for use in refilling the tank. Soil bulk density was measured between 0.3 and 1.8 m depth in the soil profile during excavation. The lysimeter tank was filled manually in 0.15-m layers and compacted to approximately the original bulk density (1.57 Mg/m^3). Before filling, stainless steel fritted tubing placed at a 0.6 m spacing was installed in a 2.4 mm-thick layer of diatomaceous earth at the bottom of the lysimeter to act as a drain. The calibrated accuracy of the lysimeter was ±0.025 mm of water and the overall resolution of the system was 400 g or 0.05 mm of water. The hourly loss of mass by the lysimeter was assumed to be due to the water loss by transpiration, soil evaporation and drainage. A more detailed description of the lysimeter and its construction can be found in Phene et al. (1991).

Vines in the lysimeter after 5 September 1987 and the rest of the vineyard at the beginning the 1988 growing season were irrigated at a rate of 4 $l\,h^{-1}$ with in-line drip emitters, spaced every 0.30 m. The drip tubing within the lysimeter was buried approximately 0.4 m below the surface of the soil, 0.3 m from the vines. Half of the vines within the surrounding vineyard were irrigated with subsurface drip-irrigation and the other half with the drip tubing attached to a wire suspended in the row 0.4 m above the soil surface. Irrigation water for the lysimeter was supplied from two 300-l water tanks suspended on the weighbridge supporting the lysimeter (to insure that this water was a part of the lysimeter's mass). The lysimeter's mass was recorded hourly to determine ET_c of the two vines and the lysimeter soil surface, and the change in mass was compared with a 16-l threshold value of water loss, equivalent to 2 mm ET_c over the 8 m^2 lysimeter surface. When the threshold was exceeded, the lysimeter was irrigated. At midnight the water tanks were refilled; the inflow was measured with a flow meter and recorded electronically, and the new lysimeter mass was used as a baseline for the next day. No drainage was recorded during the 3-year study period. A datalogger (21X Micrologger, Campbell Scientific) was used to monitor and control the system and to communicate with a computer at the Water Management Research Laboratory (WMRL) in Fresno, California. Data were downloaded to the WMRL computer for processing daily at midnight. The number of irrigations per day, throughout the 1988 and 1989 growing seasons, ranged from 0 to 4.

Reference crop evapotranspiration (ET_o) data were obtained from a California irrigation management information system (CIMIS) weather station located 2 km from the vineyard site. Variables measured and calculations used to determine hourly and daily ET_o from CIMIS can be found in Snyder and Pruitt (1992). The summation of hourly ET_o values was used with the summed hourly values of measured vine evapotranspiration (ET_c) to calculate the daily crop coefficient. The crop coefficient (K_c) was calculated as the ratio of ET_c/ ET_o. The ET_c measured by the lysimeter was adjusted to an area equivalent loss of an individual vine in the lysimeter

4 m^2 of surface area) to that of an individual vine in the surrounding vineyard (7.55 m^2 of surface area) by multiplying by 0.53. It was assumed that soil water evaporation in the area outside the lysimeter, not measured, especially after the initiation of drip-irrigation in 1988 and 1989, was minimal in the absence of rainfall.

Soil water content (SWC) within the lysimeter was monitored using the neutron back-scattering technique with a neutron moisture probe (Model 503 DR Hydroprobe moisture gauge; Boart Longyear, Martinez, Calif.). Two access tubes were placed approximately 0.5 m from each vine within the row (approximately 1.0 m between the two tubes) and inserted to a depth of 1.8 m. Readings were taken at depths of 0.23, 0.45, 0.75, 1.05, 1.35, and 1.65 m from the soil surface. The neutron probe was calibrated according to Dickey and Schwankl (1980) and water content values expressed as percent by volume (θ_v). Field capacity of this soil type was approximately 22.0 θ_v while SWC at a soil moisture tension of −1.5 MPa was approximately 8.0 θ_v (Araujo et al. 1995a).

Leaf area of vines within the lysimeter was estimated using non-destructive methods. At various times during the growing season (see Results section for specific dates) the number of shoots and individual shoot lengths of each vine within the lysimeter were measured. At the same time a minimum of 20 individual shoots of varying lengths were collected from vines in the surrounding vineyard. The length of each shoot was measured and leaf area determined with an area meter (model LI-3100; Li-Cor, Lincoln, Neb.). The relationship between shoot length and leaf area was determined via regression analysis on each date that data were collected. In most cases a linear or quadratic equation was used to fit the data with R^2 values in excess of 0.9. Total leaf area of vines in the lysimeter was then calculated based upon the relationship between shoot length and leaf area and the number of shoots per vine. Once the measurement of shoots on the lysimeter-grown vines became too demanding in 1989, the leaf areas of vines ($n = 3$) in the vineyard surrounding the lysimeter were destructively determined and the values assumed to be representative of the lysimeter vines. There were no obvious visual differences in canopy size between the two vines growing in the lysimeter and vines growing elsewhere in the vineyard. Estimated leaf area of vines in the lysimeter compared favorably with leaf area measured on vines growing in the surrounding vineyard during 1989.

Degree-day data were obtained from the University of California Statewide Integrated Pest Management Project's website. Temperature data used in calculating degree-days were obtained from the CIMIS number 39 weather station at the Kearney Agricultural Center. Degree-days were calculated using the sine method with a lower threshold of 10°C.

Results

Amounts of rainfall occurring during the three growing seasons were 12 mm in 1987, 62 mm in 1988 and 46 mm in 1989 (Table 1). Almost half of the rainfall in 1989 occurred on 20 September. Reference crop evaporation (ET_o) from the planting date in 1987 to the beginning of drip irrigation was 887 mm, while that to 7 October was 1,052 mm. Reference crop ET for the 1988 and 1989 growing seasons, from budbreak until the last day in October, was 1,147 and 1,182 mm, respectively. Over the same time period, accumulated degree-days (DDs) were 2,664 in 1988 and 2,537 in 1989.

Furrow irrigations in 1987 took place on six dates, between the day after planting and the end of August (Table 2). The amount of water used from one furrow-irrigation event to another was generally less than that applied. Daily ET_c values were greatly affected by an irrigation event (Fig. 1). Although ET_c was not determined on every date subsequent to an irrigation event, the amount of water depleted from the lysimeter on those dates that were measured was considerable. For example, when water was applied on 28 May (DOY 148), ET_c for the next 3 days (28–31 May) was equivalent to 6.8 mm per day. However, by 2 June (DOY 153), ET_c had dropped to 3.8 mm per day. On 6 August, vines were irrigated at 1100 hours and the mass of the lysimeter recorded at 1200 hours. Between 1200 hours on 6 August and 1300 hours on 7 August the loss of water was equivalent to 6.9 mm. Water loss between 7 August and 10 August amounted to 3.7 mm per day. Thus, furrow-irrigation resulted in a wet soil surface that caused a large soil surface evaporation component following an irrigation event.

Due to technical difficulties, reliable measurements of vine water use once drip-irrigation commenced in 1987 occurred only on a few days. Each of the last two data points in Fig. 1 represent water use measured on two consecutive days.

High soil-water evaporation following a furrow-irrigation event greatly elevated K_c values. The K_c on days following an irrigation event occasionally exceeded unity, but then rapidly declined. With the development of leaf area as the season progressed, the crop coefficient on the days preceding irrigation gradually increased.

Table 1 Rainfall events recorded in 1987 between planting and 10 October and during the 1988 and 1989 growing seasons between budbreak and 31 October. Date of budbreak in 1988 was 11 March and in 1989 it was 20 March

Year	Calendar date	Day of year	Rainfall (mm)
1987	1 May	120	3.0
	15 May	135	3.9
1988	14 April	105	27.6
	19 April	110	26.5
	20 April	111	0.8
	21 April	112	1.7
	22 April	113	4.5
	23 April	114	1.1
1989	22 March	81	3.5
	29 March	88	8.9
	5 May	125	11.9
	12 May	132	1.8
	20 September	263	20.0

Table 2 Dates and amount of applied water for furrow-irrigation in 1987 and measured water use (ET_c) between dates of application. Values are based on an area of 7.55 m^2 per vine. Values in parentheses in the Date of irrigation column represent day of year (DOY)

Date of irrigation	Irrigation amounts (mm)	Inclusive dates of ET_c	ET_c (mm)
10 April (100)	37.1	10 April to 4 May	32.5
5 May (125)	58.1	5 May to 27 May	50.1
28 May (148)	63.2	28 May to 23 June	60.5
24 June (175)	61.2	24 June to 16 July	51.0
17 July (198)	52.6	17 July to 5 August	48.5
6 August (218)	58.8	6 August to 4 September	46.8

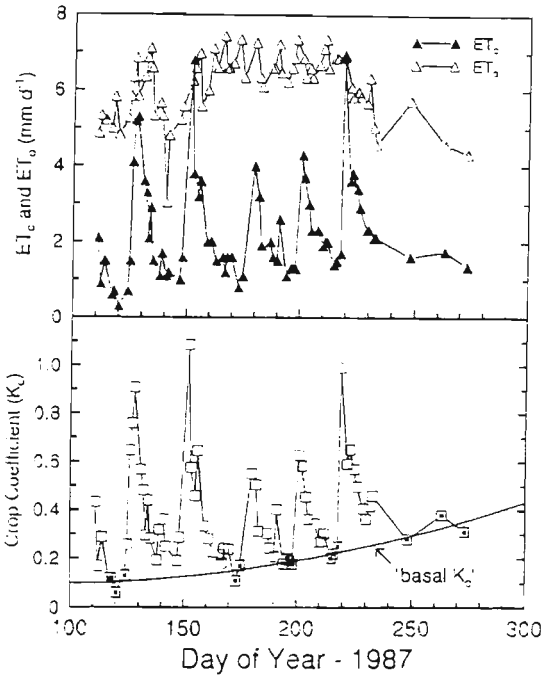

Fig. 1 Thompson Seedless measured water use (ET_c), reference crop ET (ET_o) and the calculated crop coefficient (K_c) during the first year of vine growth. The vines were planted on 9 April. Water use was measured with a weighing lysimeter and expressed on an area per vine basis of 7.55 m^2. The regression line using the lowest K_c values ($y = 0.155 - 0.001304x - 0.00000744x^2$) where x equals DOY, represents a 'basal' crop coefficient. The *filled data points* were used to determine the 'basal' K_c

indicating increasing vine transpiration. Estimated leaf area per vine on 10 July (DOY 161) and 22 September (DOY 265) were 0.75 and 1.4 m^2, respectively. A polynomial regression line was calculated through the lowest K_c points and expressed on a DOY basis. The resulting daily 'basal' K_c was multiplied by daily ET_o to estimate vine transpiration from planting through 4 September and 10 October (Table 3). The estimated vine transpiration of 140 mm was approximately 50% of the measured total vine water use between planting and the beginning of drip-irrigation, implying that soil evaporation was approximately 50% of the first-year water use with furrow-irrigation.

The second growing season during vineyard establishment is when the trunk and head of a grapevine are formed. Early on, only one shoot per vine is allowed to grow and it is trained to grow up the stake to form the trunk. It is not until lateral shoot growth takes place along the primary shoot (future trunk) that significant leaf area is formed. The shoot forming the trunk reached the cross-arm the last week in May and was topped 2 weeks later (leaf area was estimated to be approximately 1.5 m^2 per vine). At this time lateral shoots grew vigorously from the top eight nodes. Lateral shoots from below the top eight nodes had already been removed.

The high ET_c values early in the 1988 season (DOY 110–140) (Fig. 2) was due to evaporation from the wet soil surface following the large amount of rainfall that occurred during the second and third weeks of April (Table 1). During the period from 12 April (DOY 103) to 9 May (DOY 130) cumulative ET_c was 39.4 mm, which was equivalent to 63% of the rain that fell during April. A large increase in ET_c occurred when daily irrigations commenced on DOY 144 (Fig. 3). ET_c increased from 0.5 mm on DOY 143 to 1.62 mm on DOY 144, when 2.75 mm of water was applied and the K_c

Table 3 Amount of irrigation, measured wateruse (ET_c) and reference crop evapotranspiration(ET_o) and estimated vine transpiration from date of planting (9 April) until 4 September, 1987. Estimated vine transpiration was calculated using the 'basal' crop coefficients shown in Fig. 1. Daily values of ET_o and 'basal' crop coefficients were multiplied and then summed from planting until the specified date. Values are based upon the area per vine within the vineyard surrounding the lysimeter (7.55 m^2)

Dates	Amount of irrigation	Measured ET_c	ET_o	Estimated vine transpiration
		(mm)		
9 April to 4 September	331	289	887	140
9 April to 10 October	-	-	1,052	199

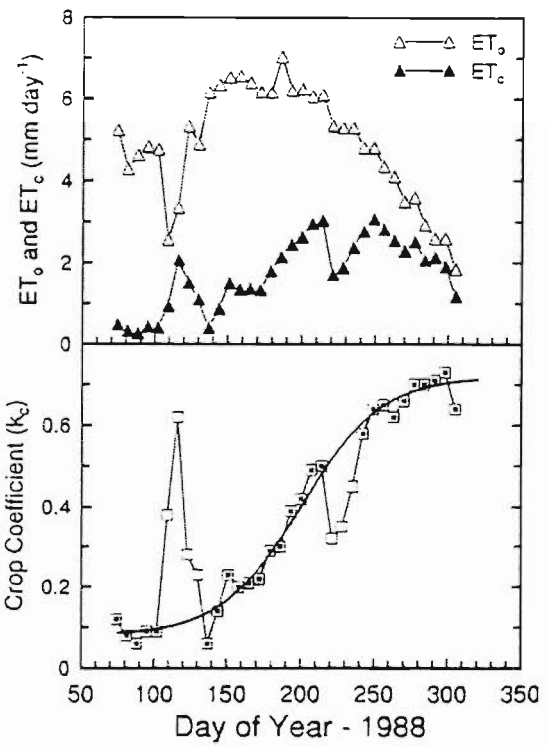

Fig. 2 Daily (weekly amounts/7) vine water use (ET_c), reference crop evapotranspiration (ET_o) as a weekly average, and the resulting K_c measured during the second year of vine establishment. Date of budbreak was 11 March. Vines were trained up the trellis stake in order to form the trunk and ultimately the head of the vine during the second year. The K_c curve was the following: $y = 0.08 + (0.64/(1 + e^{(-(x - 200).27)}))$, where x equals DOY. The *filled data points* were used to generate the equation

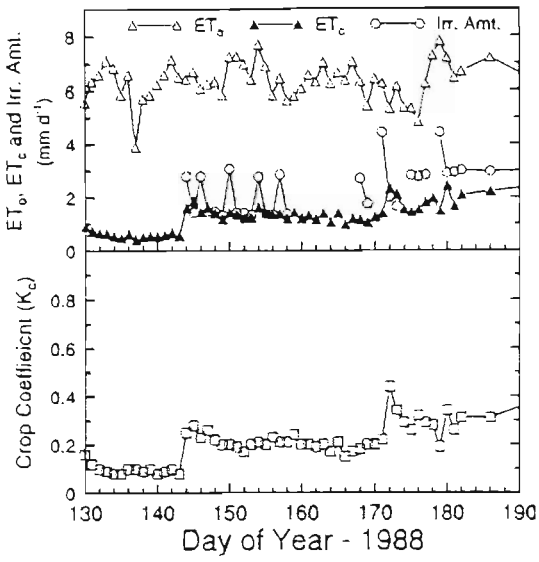

Fig. 3 Daily vine water use (ET_c), reference crop evapotranspiration (ET_o) and crop coefficient (K_c) measured from DOYs 130–190 of the 1988 growing season. Irrigation amounts (*Irr. Amt.*) are also given and are expressed on an area per vine basis of 7.55 m^2. Irrigation began on DOY 144. There were several days in which the vines were not irrigated

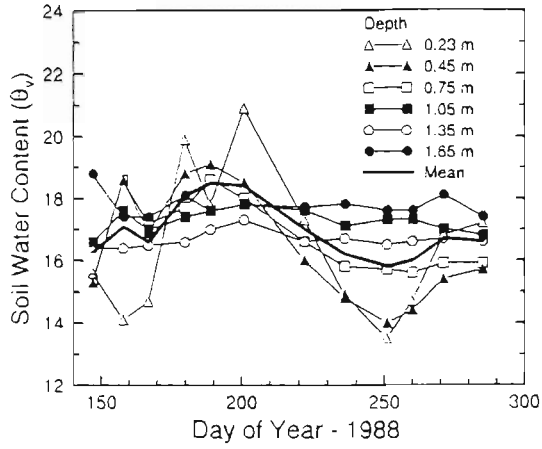

Fig. 4 Soil water content (*SWC*: expressed as percent by volume = θ_v) measured in the lysimeter throughout the 1988 growing season. Each data point is the mean of measurements taken in two access tubes. The mean is of all depths in both access tubes. Soil water content at field capacity was approximately 22.0 θ_v while that at a soil moisture tension of −1.5 MPa was approximately 8.0 θ_v

increased from 0.08 to 0.24 over the same time-frame. Water use remained fairly constant for the next 27 days despite varying amounts of applied water and no applied water during the period DOY 159–168. Applied water amounts of greater than 4 mm per day on DOYs 171 and 179, did increase ET_c and the K_c on DOYs 172 and 180, respectively. After the end of June (DOY 183), irrigations within the lysimeter replaced ET_c whenever 16 l of water was lost from the lysimeter. Water use increased from that point on until DOY 210 (Fig. 2). On that date, three or four lateral shoots were removed from the upper portion of the newly formed trunk on each vine within the lysimeter. The removal of these shoots comprised approximately 50% (4 m^2) of the total estimated leaf area (8 m^2) per vine at that time. Water use and the K_c increased rapidly thereafter due to vigorous growth of the remaining four lateral shoots (two of which were retained as next year's fruiting canes at pruning) growing from the head of each vine. The K_c remained quite high right up until the end of October (DOY 304). Unfortunately, no estimation of leaf area at the end of the season was made that year. It should be pointed out that lateral shoots arising out of the four lateral shoots left on the vine grew quite vigorously and some extended nearly midway between the rows.

The first measurement of soil water content (SWC) took place just prior to the first irrigation in 1988 (Fig. 4). On the second measurement date the use of subsurface drip-irrigation is reflected by the increase in SWC at the 0.45 and 0.75 m depths, but SWC at the 0.23 m depth declined. The decrease in SWC at the 0.45 and 0.75 m depths on the third date was due to a lack of irrigation between DOYs 159 and 168. The application of more than 4 mm per day on DOYs 171 and 179 resulted in an increase in SWC at the 0.23 m depth and the wetting of the soil surface. Soil water content at a depth of 1 m or more was relatively constant throughout the growing season.

The third growing season began with the vines having two fruiting canes left after pruning. Leaf area per vine estimated shortly after irrigations commenced was approximately 5 m^2 (Table 4). Maximum leaf area was approximately 13 m^2 per vine in September.

Drip-irrigation within the lysimeter commenced on 29 April (DOY 119) in 1989. ET_c increased from 1.31 mm per day in the week prior to the first irrigation to 3.38 mm per day in the first week of irrigation (Fig. 5). The crop coefficient increased from 0.29 to 0.64 during the same time-frame. The dip in ET_c and ET_o during the week of 9 May (DOY 129) was due to two rainfall events (Table 1). Irrigation was resumed for the next 3 weeks at amounts comparable to ET_c except for the week of 29 May (DOYs 149–155) when the vines received no applied water. Subsequent to that period ET_c and the K_c increased rapidly, both reaching a peak in the week of 12 July (DOYs

Table 4 Estimated leaf area per vine during the 1989 growing season. Date of budbreak was 20 March (DOY 79). Degree-day data were obtained from the UC Statewide Integrated Pest Management Project using temperature data from the CIMIS number 39 weather station (at the Kearney Agricultural Center). A lower threshold of 10°C was used

Calendar date	Day of year	Degree-days from 50% budbreak	Leaf area (m^2 vine^{-1})
25 April	115	296	4.5
23 May	143	554	5.9
7 June	158	706	7.4
11 July	192	1176	9.4
9 August	221	1627	11.9
13 September	256	2093	12.9

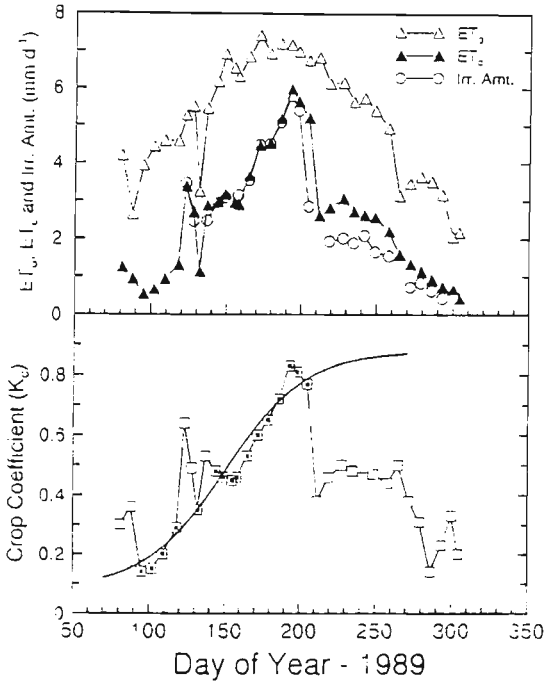

Fig. 5 Daily vine water use (ET_c), reference crop evapotranspiration (ET_o), irrigation amount (*Irr. Amt.*) and crop coefficient (K_c) measured during the 1989 growing season. Date of budbreak was 20 March. There are several intervals in which the vines received no applied water. The crop coefficient as a function of DOY was the following: $y = 0.08 - 0.8\,(1 - e^{[-(x - 150)/27]})$, where x equals DOY. Other information is as given in Fig. 2

194–200). From DOY 206 onwards, the lysimeter experienced both electrical and mechanical problems. During the week of 19 July (DOYs 199–206) vines were only irrigated with approximately 50% of the amount of water that they used. The following week they were not irrigated and ET_c decreased from 5.2 mm per day to 2.6 mm per day. At this time a marked decline in the K_c occurred. By DOY 220, however, ET_o values declined in roughly the same proportion as ET_c and the K_c was constant until DOY 270.

The SWC started high in the 1989 growing season (Fig. 6) and decreased at all depths even after irrigation started and a 9 May (DOY 129) rainfall event. The resumption of irrigation the following week increased SWC, with a drop during the week there were no irrigations (DOY 166), the exception being SWC at the 0.23 m depth, which increased. Soil water content decreased from DOY 189 until DOY 222 due to a combination of deficit irrigation and no irrigation for 1 week. Once irrigation resumed, at amounts less than ET_c, SWC leveled off and remained relatively constant until the last measurement date.

Discussion

Vine water use (ET_c) from planting in 1987 until the beginning of drip-irrigation on 5 September was equivalent to 289 mm, while ET_c from budbreak until the end

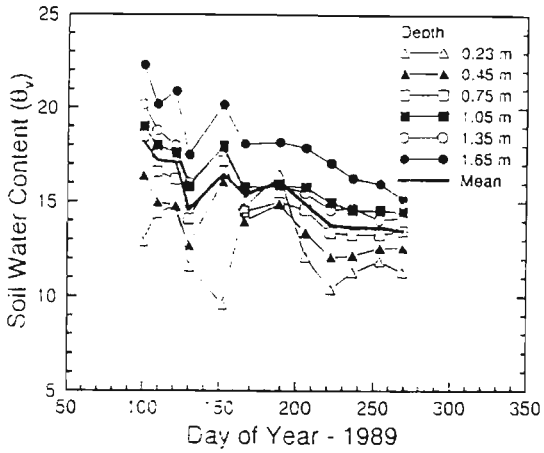

Fig. 6 Soil water content measured in the lysimeter throughout the 1989 growing season. Other information is as given in Fig. 4

of October in 1988 and 1989 was 406 and 584 mm, respectively. These values are similar to the highest ET_c values reported by Myburgh et al. (1996) but greater than those reported by Peacock et al. (1977) for water use during the first 3 years of vineyard development. The differences between our results and those of Peacock et al. (1977) may have been due to the fact that the vines in this study were flood-irrigated during the first year, and in years 2 and 3 drip-irrigation was supplied whenever 16 L of water was lost from the lysimeter. The vines in the Peacock et al. (1977) study were either drip- or sprinkler-irrigated (two different treatments) all 3 years and water application amounts were those required to maintain soil moisture tension at between −0.005 and −0.015 MPa.

Araujo et al. (1995b) reported that water use of 3-year old Thompson Seedless vines was 437 and 517 mm of water for drip- and furrow-irrigated vines between budbreak and harvest at a maximum leaf area per vine of 18.9 and 15.1 m^2, respectively. Our measured ET_c amount during year 3 for drip-irrigated vines between budbreak and harvest was approximately 500 mm, with a maximum leaf area of approximately 13 m^2 per vine. Therefore, ET_c of the drip-irrigated vines in the lysimeter was still greater than estimated by Araujo et al. (1995b) despite similar evaporative demand, the malfunction of the lysimeter from July to the end of the season (i.e. less water was applied than used) and less leaf area per vine. Our maximum daily water use (almost 6 mm per day) in year 3 was three times greater than that reported by Lascano et al. (1992) for 3-year old Chardonnay vines grown in Texas. The Chardonnay vines, however, only had a maximum leaf area of less than 5 m^2 per vine.

The major portion of ET_c during the first year was due to evaporation of water from the soil surface after a furrow-irrigation and the fact that the two vines' canopies were quite small even 6 months after planting (1.4 m^2 leaf area per vine). The amount of water used as ET_c after an irrigation event was comparable to ET_o for

1–3 days following the application of water. Araujo et al. (1995a) concluded that soil evaporation after a vineyard furrow-irrigation event could be 7–8 mm per day. Soil water evaporation estimated in this study on DOY 219 was 5.8 mm [ET_c on DOY 219 (7.0 mm) – ET_c on DOY 218 (1.2 mm) = 5.8 mm]. This value is somewhat less than the soil water evaporation estimated by Araujo et al. (1995a), perhaps due in part to the smaller furrow size used in this study compared with Araujo et al. The daily soil water evaporation values obtained in this study are similar to those determined on bare soils or soils with a sparse canopy by measuring soil moisture depletion with a neutron probe (Lascano and van Bavel 1986; Lascano et al. 1987) or using microlysimeters (Daamen et al. 1993). The patterns of evaporation were consistent with the two distinct phases of the drying process of the soil following an irrigation or significant rainfall event proposed by Hillel (1971) and Ritchie (1972).

The amounts of water lost via soil evaporation for furrow-irrigated vines in a mature vineyard (maximum leaf area of approximately 10 m^2 $vine^{-1}$) have been reported (Yunusa et al. 1997b). Total irrigation amounts during the first and second years of that study were 293 and 321 mm, respectively, while rainfall amounted to 167 mm in the first year and 172 mm in the second. Their estimate of soil water evaporation was equivalent to 274 and 329 mm each year, respectively. Their values of soil evaporation were similar to what we report here as ET_c with similar applied water amounts. Soil evaporation accounted for approximately 50% of estimated ET_c in their study, while we concluded that a minimum of 50% of the ET_c measured in this study during the first year was due to evaporation of water from the soil, with vines having a much smaller leaf area.

From the end of the 1987 growing season throughout the 1988 and 1989 growing seasons, the vines were subsurface drip-irrigated. There are several dates during these two seasons when one could obtain an approximate value of soil surface evaporation. In 1988, ET_c increased from 0.55 to 1.62 mm per day with the first irrigation (2.9 mm of water) of the season (Fig. 3, DOY 144) and the K_c increased from 0.08 to 0.22. The lack of an increase in either ET_c or K_c for the next 30 days and small leaf area per vine (~1.0 m^2) at that time would suggest that increased vine transpiration was not responsible for the initial increase in ET_c. Increasing irrigation amounts from 1.77 mm on DOY 169 to 4.45 mm on DOY 170 increased ET_c from 1.3 to 2.3 mm and the crop coefficient from 0.2 to 0.44. On DOY 170 the 1 mm increase in ET_c was probably due to surface evaporation as the soil surface may have become wetted (See Fig. 4, increased SWC at the 0.23 m depth). In both cases, the soil surface would have been exposed to environmental factors conducive to high evaporation rates (Matthias et al. 1986) due to the low amount of grapevine foliage at that time. The increase in ET_c on both dates of approximately 1 mm was 16% of ET_o. Phene et al. (1993) have shown that bare soil evaporation using subsurface drip-irrigation measured with a lysimeter in western Fresno County, similar to the one used here, was 6% of ET_o.

Another example where soil evaporation from applied water could have been estimated occurred in 1989 for the days prior to DOY 124, 156 and 206. The week that irrigations commenced (beginning with DOY 119) ET_c increased by 2 mm (38% of ET_o) over the previous week despite a minimal increase in evaporative demand and no wetting of the soil surface (Fig. 6). ET_c leveled off thereafter at approximately 3 mm per day. No irrigation for 6 days (between DOYs 150 and 155) reduced ET_c 0.4 mm (6% of ET_o) compared with ET_c the previous week. Reducing the irrigation amount from 5.4 mm per day (for DOYs 194–198) to 2.8 mm per day in the week of DOY 205 (days 199 to 205) reduced ET_c 0.7 mm per day (10% of ET_o). Our estimates of daily soil evaporation using subsurface drip-irrigation were similar to those reported in an Australian vineyard using surface drip-irrigation (Yunusa et al. 1997a). Their estimates of soil evaporation also decreased as the season progressed, as it would appear that ours did.

The primary purpose for the installation of the weighing lysimeter was to establish crop coefficients for grapevines grown in the San Joaquin Valley. Crop coefficients currently used for grapevines are primarily suited for mature vineyards (Doorenbos and Pruitt 1977; Snyder et al. 1987) where growth and canopy characteristics are fairly constant from one year to the next. Seasonal leaf area development and maximum leaf area per vine differs among years during vineyard establishment (Araujo and Williams 1988; Araujo et al. 1995b). Results from those studies, together with leaf area measured in this study, demonstrated that canopy development varies markedly from the first through the third year of vine establishment, affecting vine water use and crop coefficients.

The initial use of furrow-irrigation after planting made it difficult to establish seasonal K_c values for these first-year vines. A second-order polynomial regression using all the data points in Fig. 1 (data not shown) resulted in a K_c of 0.35 at planting and a K_c of 0.4 at the end of September. We feel that the regression run through the lowest calculated K_cs in Fig. 1 ('basal K_c'), however, would be appropriate for drip-irrigated vines. The fitted K_c curve for the second growing season (Fig. 2) reflected the lack of significant canopy early in the growing season when a single shoot was trained up the trellis stake to form the trunk and then growth (from lateral shoots) as the head was established. The continued shoot growth late in the season, with little leaf senescence, and the lack of a crop was probably responsible for the K_c not decreasing until well into November. Published crop coefficients for mature vines, those producing a crop, decrease once harvesting has taken place (Doorenbos and Pruitt 1977; Snyder et al. 1987). A curve similar to that derived in the second year was used to describe the seasonal progression of the K_c during year 3. It reflects the earlier development of the

vines' canopies in year 3, compared with year 2, and a higher maximum K_c. It is felt that the marked decline in the K_c during July in year 3 would not have occurred if the lysimeter had functioned properly. Therefore, the fitted curve (Fig. 5) reflects our assumption that vine water use would have resulted in a constant value of the K_c until well into October, similar to that in year 2.

Conclusions

Data collected in this study demonstrated that surface evaporation using furrow-irrigation was at least 50% of ET_c during the first year of vineyard establishment. Much of the rainfall early in the growing season, a time when the vine canopies were small during years 2 and 3, was also lost to evaporation under the conditions of the study. The 'basal K_c' the first year of the study ranged from 0.1 early on to 0.4 at the end of the season. The seasonal K_c during the second growing season increased up until late in the growing season, at which time it appeared to level off at a value of 0.7. The seasonal K_c in 1989 increased from 0.1 to greater than 0.8 (from budbreak until the lysimeter malfunction at mid-season). It is unknown whether the precipitous drop in vine water use mid-season that year and the lack of increased water use after irrigations resumed were due to severe vine stress or to the amount of water subsequently applied by the lysimeter.

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ORIGINAL PAPER

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Water use of mature Thompson Seedless grapevines in California

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Abstract Water use of Thompson Seedless grapevines was measured with a large weighing lysimeter from 4 to 7 years after planting (1990–1993). Above-ground drip-irrigation was used to water the vines. Vines growing within the lysimeter were pruned to four and six fruiting canes for the 1990 and 1991 growing seasons, respectively, and eight fruiting canes in the last 2 years. Maximum leaf area per vine at mid-season ranged from 23 to 27 m^2 across all years. Reference crop evapotranspiration (ET_o) averaged 1,173 mm between budbreak and the end of October each year, with a maximum daily amount of approximately 7 mm each year. Maximum daily vine water use (ET_c) was 6.1, 6.4, 6.0, and 6.7 mm (based upon a land area per vine of 7.55 m^2) for 1990, 1991, 1992, and 1993, respectively. Seasonal ET_c was 718 mm in 1990 and ranged from 811 to 865 mm for the remaining 3 years of the study. The differences in water use among years were probably due to the development of the vine's canopy (leaf area), since they were pruned to differing numbers of fruiting canes. These differences were more pronounced early in the season. Soil water content (SWC) within the lysimeter decreased early in the growing season, prior to the initiation of the first irrigation. Once irrigations commenced, SWC increased and then leveled off for the remainder of the season. The maximum crop coefficient (K_c) calculated during the first year (1990) was 0.87. The maximum K_c in 1991, 1992, and 1993 was 1.08, 0.98, and 1.08, respectively. The maximum K_c in 1991 and 1993 occurred during the month of September, while that in 1992 was recorded during the month of July. The seasonal K_c followed a pattern similar to that of grapevine leaf area development each year. The K_c was also a linear function of leaf area per vine using data from all four growing seasons. The decrease in K_c late in the 1991, 1992, and 1993 growing seasons, generally starting in September, varied considerably among the years. This may have been associated with the fact that leafhoppers (*Erythroneura elegantula* Osborn and *E. variabilis* Beamer) were not chemically controlled in the vineyard beginning in 1991.

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Introduction

Seasonal water use of mature grapevines has been measured in several studies using various methods (Evans et al. 1993; Grimes and Williams 1990; Peacock et al., 1987; Prior and Grieve 1987; van Rooyen et al. 1980; van Zyl and van Huyssteen 1980, 1988; Williams and Matthews 1990; Yunusa et al. 1997a, 1997b). Results from the aforementioned studies indicate that vineyard water use varies considerably. It is unknown, however, how much of the variability from vineyard to vineyard reported above is the result of differences in production practices or the method of determining vine water use.

A weighing lysimeter was installed near Fresno in the San Joaquin Valley of California to directly measure evapotranspiration (ET_c) of grapevines. Thompson Seedless grapevines were planted in the lysimeter in 1987 and results from the first 3 years of growth are presented in a previous paper (Williams et al. 2003). This paper will report on vine water use from year 4 to year 7 after planting (four cropping seasons). In addition, daily and diurnal vine water use will be presented. Lastly, seasonal crop coefficients (K_c) were developed in order to provide the information necessary to schedule irrigations in vineyards similar to the one used in the study.

Materials and methods

The weighing lysimeter at the University of California Kearney Agricultural Center, containing two *Vitis vinifera* L. (cv. Thompson Seedless) grapevines, as described in the preceding paper (Williams et al. 2003), was used in this study. The data presented herein were collected from 1990 to 1993. Technical aspects of measuring vine water use (ET_c) were similar to those previously given, as was the source of reference crop evapotranspiration (ET_o) data and calculation of degree-days (DDs).

Vines in the lysimeter were irrigated with 4 l h^{-1} in-line drip emitters, spaced every 0.30 m. The drip tubing was attached to a wire suspended 0.4 m above the soil surface. This differs from the two previous years (1988 and 1989), as subsurface drip-irrigation was used (Williams et al. 2003). The number of irrigations per day throughout the 1990 to 1993 growing seasons ranged from 0 to 7.

The summation of hourly ET_o values was used with the summed hourly values of measured vine evapotranspiration (ET_c) to calculate the daily crop coefficient. The crop coefficient (K_c) was the ratio of ET_c:ET_o. The ET_c measured by the lysimeter was adjusted to an area equivalent loss of an individual vine in the lysimeter (4 m^2 of surface area) to that of vines in the surrounding vineyard (7.55 m^2 of surface area), once irrigations had commenced, by multiplying by 0.53. It was assumed that soil water evaporation in the area outside the lysimeter was minimal. Estimates of soil water evaporation (using the neutron probe) midway between rows in 1992 ranged from 0.26 mm day^{-1} at the end of May to 0.09 mm day^{-1} in the second week of September.

Leaf area of vines within the lysimeter was estimated using non-destructive methods (Williams et al. 2003). Once the measurements of shoots on the lysimeter-grown vines became too difficult, the leaf area of vines in the vineyard surrounding the lysimeter were destructively determined and the values were assumed to be representative of the lysimeter vines. Pruning weights (a measure of vegetative growth) and yields measured on the two vines within the lysimeter during each year of the study were similar to vines growing in the surrounding vineyard.

Vines were pruned to four fruiting canes for the 1990 growing season, six canes for the 1991 growing season and eight canes for the 1992 and 1993 growing seasons. Standard horticultural practices to control disease and insect pests of grapevines were performed as needed by field station personnel each year. No pesticides were used to control western grape (*Erythroneura elegantula* Osborn) or variegated (*E. variabilis* Beamer) leafhoppers, however, during the 1991 through 1993 growing seasons.

Results

Rainfall amounts varied considerably among water years (from 1 November the previous year to 31 October in the present year) and the amount that fell during each growing season (from date of budbreak until the end of October) (Table 1). In most years, the majority of in-season rainfall occurred during March, the month in which budbreak normally takes place for Thompson Seedless grapevines at this location (Table 2).

The record amount of rainfall that fell during 1993 was reflected in the high soil water content measured within the lysimeter early in the season, compared with the other years (Fig. 1). The 1993 season was the first time that water drained from the lysimeter. Irrigations generally commenced prior to anthesis, the last week in April to the first week in May each year (Table 2). Prior to that date, soil water content decreased. Once irrigations were initiated, soil water content increased and then leveled off and remained relatively constant until the last measurement date of the season (Fig. 1). The seasonal pattern and absolute amounts of soil water content for vines in the vineyard surrounding the lysimeter receiving the same amounts of water were similar to those within the lysimeter (unpublished data). The decrease in soil water content in 1990 between days of year (DOYs) 125 and 160 was associated with a period

Table 1 Total rainfall from 1 November (the previous year) to budbreak (BB) and rainfall amounts and their date of occurrence between budbreak and 31 October during the 1990, 1991, 1992 and 1993 growing seasons at the Kearney Agricultural Center, California

Growing season	Calendar date	Day of year	Rainfall (mm)
1990	1 November (1989): BB		128
	4 April	93	2
	23 April	113	21
	23 May	143	7
	28 May[a]	148	27
	8 August	220	4
1991	1 November (1990): BB		162
	17 March	76	25
	18 March	77	31
	19 March	78	11
	20 March	79	9
	24 March	83	9
	25 March	84	6
	26 March	85	7
	27 March	86	2
	1 April	91	2
	26 October	299	16
1992	1 November (1991): BB		241
	14 March	74	5
	30 March	90	8
	12 April	103	3
	2 May	123	15
1993	1 November (1992): BB		350
	13 March	72	4
	17 March	76	5
	25 March	84	32
	26 March	87	9
	4 April	94	2
	17 April	107	2
	23 May	143	3
	5 June[a]	156	5

[a] The amounts for these two dates include rain that fell on the previous day

Table 2 Dates of budbreak, initiation of irrigation, harvest and the accumulation of degree-days from budbreak to 31 October measured each year of the study. Degree-days were obtained from the University of California Statewide Integrated Pest Management Project using a base temperature of 10°C

Year	Date of budbreak	Date of 1st irrigation	Date of harvest	Degree-day accumulation
1990	18 March	27 April (117)[a]	27 August (239)[a]	2,564
1991	15 March	8 May (128)	22 September (265)	2,475
1992	14 March	8 May (129)	4 September (248)	2,728
1993	10 March	3 May (123)	21 September (263)	2,486

[a] Day of year is in parenthesis

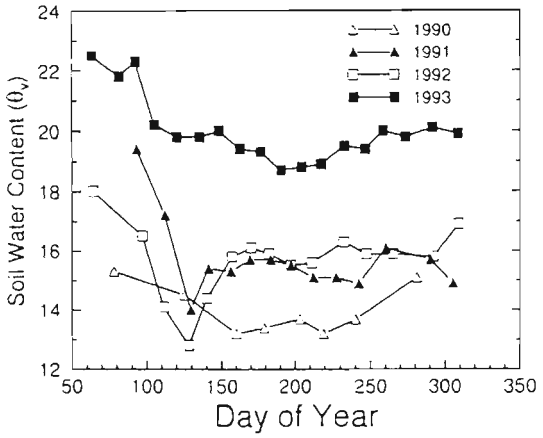

Fig. 1 Soil water content (expressed as percent by volume: θ_v) measured in the lysimeter during each growing season of the study. An individual data point is the average of two access tubes measured at six depths (from 0.23 to 1.65 m below the soil surface)

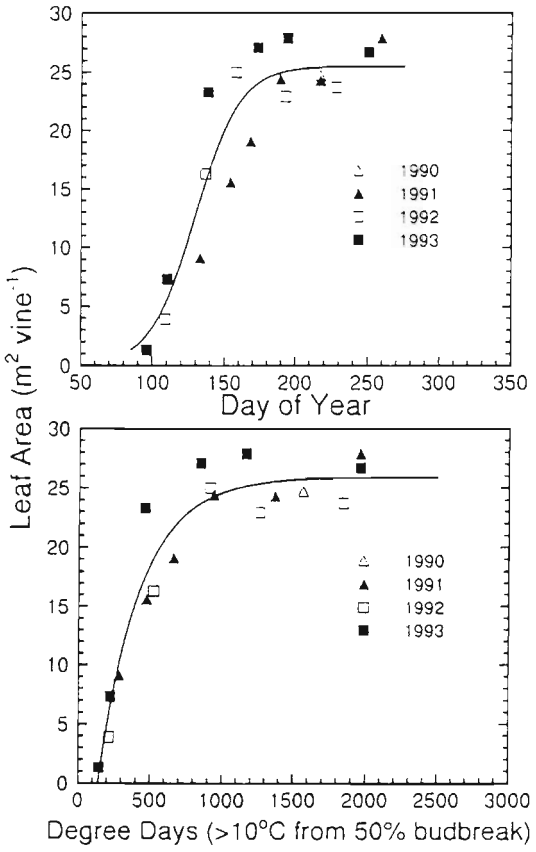

Fig. 2 Leaf area development of Thompson Seedless grapevines as a function of day of year (*DOY*) and degree-days (*DDs*) measured from budbreak over the course of the study. The dependent variable of the equations (x) represents DOY and DDs, respectively, for the top and bottom portions of the figure. The equations used to describe leaf area as a function of DOY and DDs were: $y = 25.5/(1 + e^{(-(x - 130)/15.5)})$, $R^2 = 0.86$ and $y = -16.1 + 42.0(1 - e^{(-(0.00347)x)})$, $R^2 = 0.92$, respectively

in which the vines within the lysimeter were not irrigated (between DOYs 147 and 153) and due to rainfall on DOYs 143 and 148.

Table 3 Reference crop evapotranspiration (ET_o) and water use (ET_c) measured each year of the study from budbreak until the end of October. Water use in liters per vine was that directly measured by the lysimeter, while water use in millimeters was direct lysimeter water use divided by area per vine in the vineyard. Reference crop ET data were obtained from the CIMIS (number 39) weather station at the Kearney Agricultural Center, California

Year	ET_o (mm)	ET_c (l vine^{-1})	ET_c (mm)
1990	1,209	5,418	718
1991	1,188	6,532	865
1992	1,170	6,123	811
1993	1,124	6,472	857

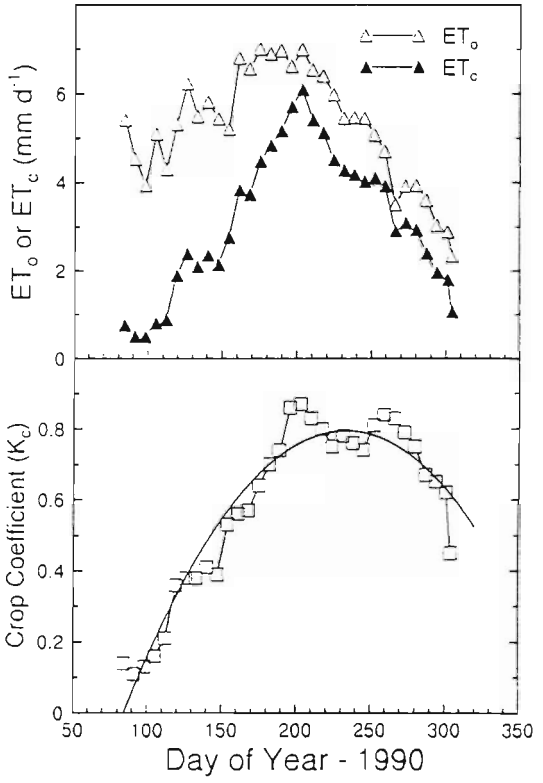

Fig. 3 The seasonal progression of daily water use (ET_c), measured with a weighing lysimeter in 1990, reference crop evapotranspiration (ET_o) and crop coefficients (K_c) as a function of Day of Year (*DOY*). Each *data point* is the average daily value for a 7-day period. The seasonal K_c values were fitted to the following equation: $y = -1.16 - 0.0168x - 0.000036x^2$, $R^2 = 0.92$

The maximum estimated leaf area per vine at full canopy ranged from 23 to 27 m^2 vine^{-1} across all seasons (Fig. 2). This was despite the fact that vines had been pruned to different numbers of fruiting canes in the first 3 years. Leaf area development (LAD) in 1991 appeared to lag behind LAD in 1992 and 1993 when plotted as a function of DOY, but there was no such lag when leaf area was plotted versus degree-days (DDs).

Reference crop ET (ET_o) from budbreak until the end of October each year ranged from 1,124 to 1,209 mm (Table 3). There was generally a large variability in ET_o early in the growing season, resulting from

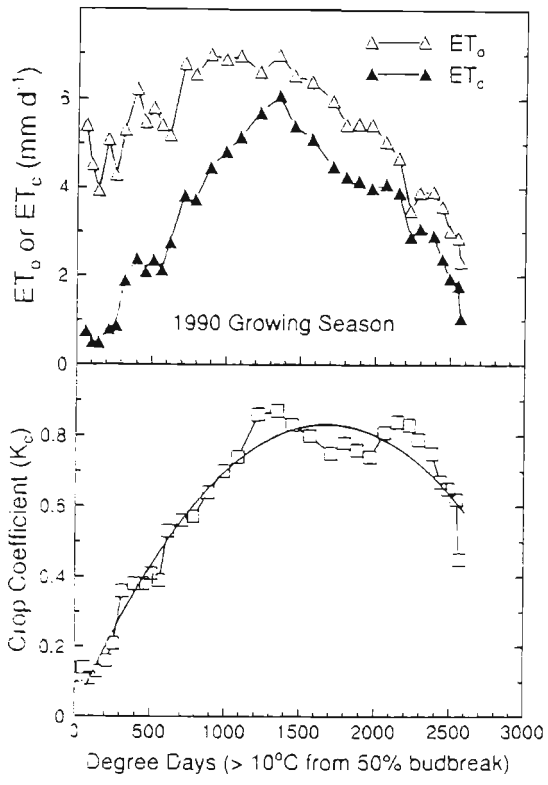

Fig. 4 The seasonal progression of daily ET_c, ET_o and K_c measured in 1990 as a function of degree-days from date of budbreak. Each *data point* is the average daily value for a 7-day period. The seasonal K_c values were fitted to the following equation: $y = 0.0129 - 0.000377x - 0.000000291x^2$, $R^2 = 0.95$

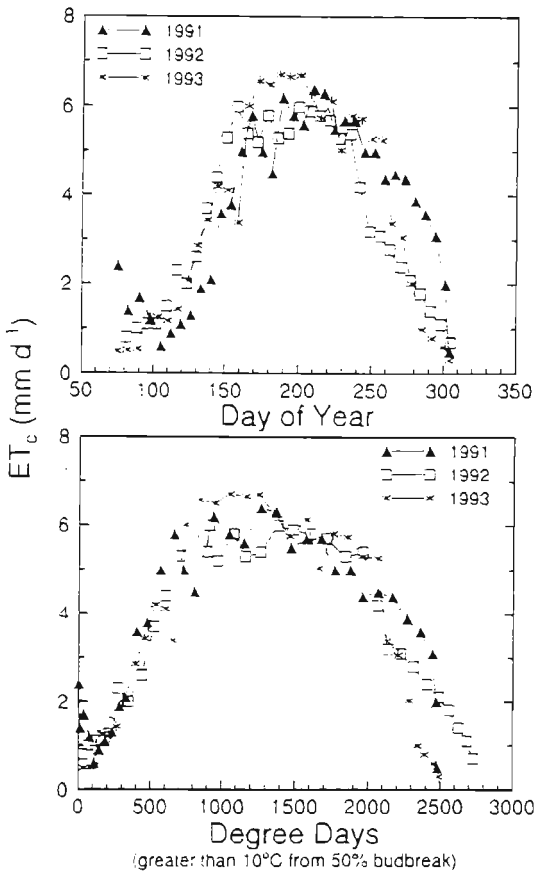

Fig. 5 The seasonal progression of daily water use (ET_c) measured during the 1991, 1992, and 1993 growing seasons with a weighing lysimeter. Seasonal ET_c as a function of day of year (*DOY*) and degree-days (*DDs*) were fitted to quadratic equations with: $ET_c = -11.05 + 0.1665*DOY - 0.000417*DOY^2$; $R^2 = 0.78$; $ET_c = 0.182 + 0.0088*DD - 0.000003302*DD^2$, $R^2 = 0.88$. Other information is as given in Fig. 3

cloud cover and/or rainfall events. Maximum daily ET_o, using a 7-day running average, was approximately 7 mm each year (illustrated in Fig. 3).

Grapevine water use increased from less than 0.5 mm per day on DOY 100 in 1990 to more than 2 mm per day by DOY 130 (Figs. 3 and 4). Step increases in ET_c on DOYs 113 and 150 were due to temporary increased soil evaporation associated with rainfall events (Table 1). The maximum ET_c of the season occurred in mid-July when leaf area was 24.4 m^2 vine^{-1} and evaporative demand was highest. At this time shoots of the vines were hedged (to facilitate the movement of equipment down the row) removing 4.1 m^2 of leaf area per vine. The decrease in ET_c after this date was due to a reduction in canopy and/or a reduction in ET_o (Fig. 3). The crop coefficient (K_c) for 1990 reached a maximum of 0.87, coinciding with maximum leaf area, and then oscillating between 0.74 and 0.84 until the end of September (DOY 275). The K_c declined to 0.45 by the end of October. The seasonal K_c values for 1990 expressed as a function of both DOY (Fig. 3) and DDs (Fig. 4) were fitted to quadratic equations with the fit being rather better when using DDs.

The seasonal course of ET_c from 1991 to 1993 was similar, with the greatest values of ET_c (almost 50 l day^{-1} or approximately 6.6 mm day^{-1}) occurring during the period between 23 June (DOY 174) and 20 July (DOY 201) in 1993 (Fig. 5). Maximum hourly water use at midday during that time period ranged from 0.82 to 0.95 mm h^{-1} (6.2 to 7.1 l h^{-1}). The daily course of ET_c measured with the lysimeter closely followed that of ET_o and net radiation (Fig. 6). There appeared to be less variability in the seasonal progression of ET_c among years when it was expressed as a function of DDs from budbreak rather than using DOY in this study. ET_c decreased more rapidly in 1992 and 1993 than in 1991 when expressed as a function of DOY but less so when expressed as a function of DDs. The decrease in ET_c did not appear to be related to date of harvest (Table 2), as harvest did not occur in 1992 until 2 weeks after the large decline in ET_c that year.

Seasonal water use in 1990 was 718 mm (5,400 l vine^{-1}) from budbreak until the end of October (Table 3). This was approximately 60% of ET_o during that time frame. Vine water use between budbreak to end of October for the next 3 years were similar and averaged 844 mm per year (6,375 l vine^{-1}), that value being approximately 73% of average ET_o.

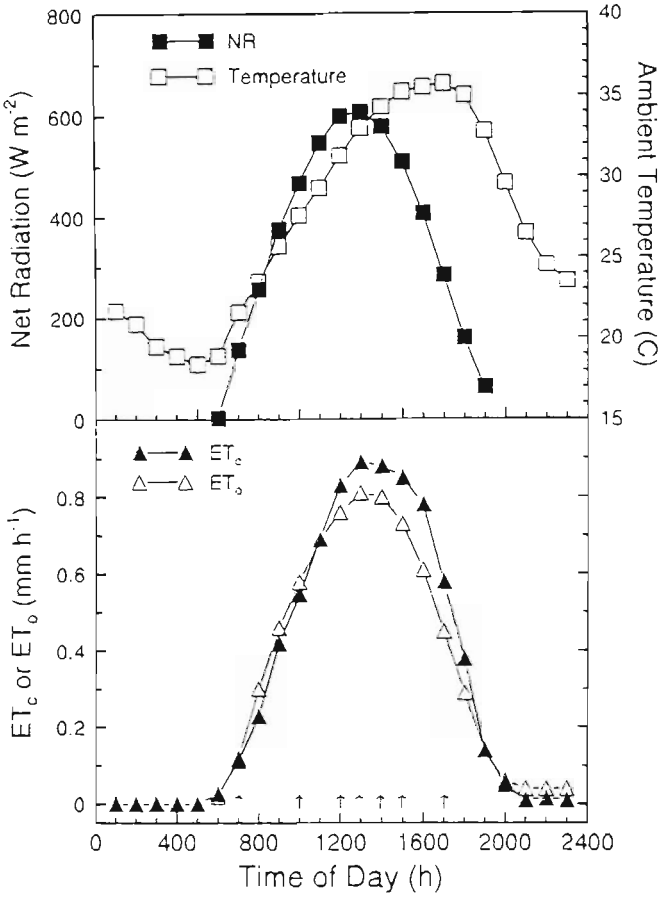

Fig. 6 The daily time course of Thompson Seedless water use on 7 July 1993 measured with a weighing lysimeter. Values of hourly net radiation (NR), ambient temperature (T) and reference crop evapotranspiration (ET_o) were obtained from the CIMIS weather station at the Kearney Agricultural Center. Net radiation values less than zero were not included. Values of water use (ET_c) were expressed on an area basis of 7.55 m^2. *Arrows at the bottom* indicate an irrigation event

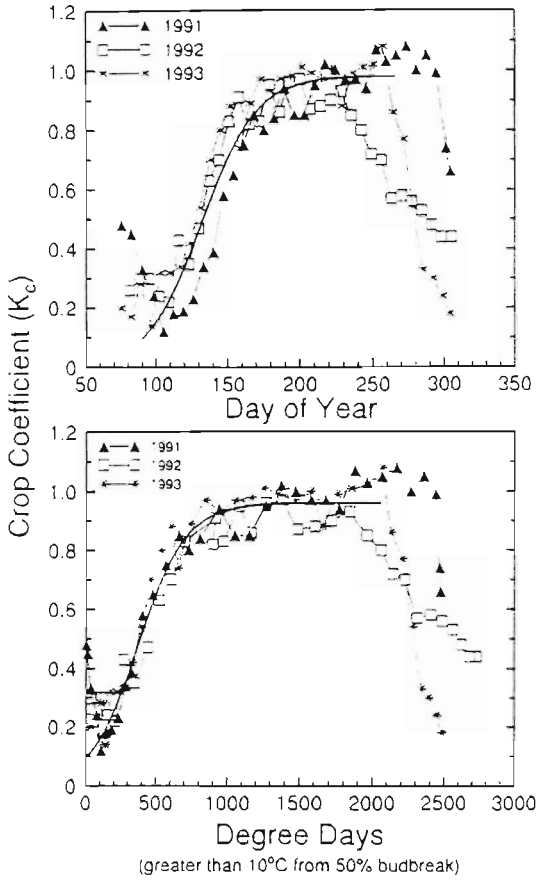

Fig. 7 The seasonal progression of the crop coefficient for Thompson Seedless grapevines calculated for the 1991, 1992, and 1993 growing seasons. The K_c as a function of day of year (DOY) and degree-days (DDs) were fit to the following equations: $y = 0.98\,(1 - e^{(-(x - 132)/19)})$, $R^2 = 0.85$ and $y = 0.96\,(1 + e^{(-(x - 2575)/169)})$, $R^2 = 0.92$, respectively. The *first three data points* of each year and those data points where the K_c started to decline precipitously later in the growing season were not used to generate the equation for both DOY and DDs (total $n = 69$: $n = 26$, 20, and 23 in 1991, 1992, and 1993, respectively). Other information is as given in Fig. 3

Once early-season rainfall had subsided, the seasonal K_c increased almost linearly when plotted either as a function of DOY or DDs (Fig. 7). The maximum K_c was 1.08 in 1991 and 1993 late in the growing season and 0.98 in July (DOY 200) of 1992. A decline in the K_c from a value of 1.0 did not occur until the third week of October in 1991. In 1992 there was a more gradual decline in the K_c, starting at the end of August (DOY 235). There was a steep drop in the K_c during the week of 16 September (DOY 258) in 1993, after reaching its highest value of the season.

The K_c values shown within Fig. 7 were fitted to a sigmoid-type equation with three parameters when expressed as a function of DOY and DDs. High K_c values due to rainfall early in each growing season and the K_c values late in the season, once they started to decline, were not used to generate these equations. The prediction of the seasonal K_c using quadratic equations for both DOY and DDs resulted in R^2 values less than for the sigmoid-type equations ($K_c = -1.184 + 0.01879*DOY - 0.00004623*DOY^2$, R^2 =

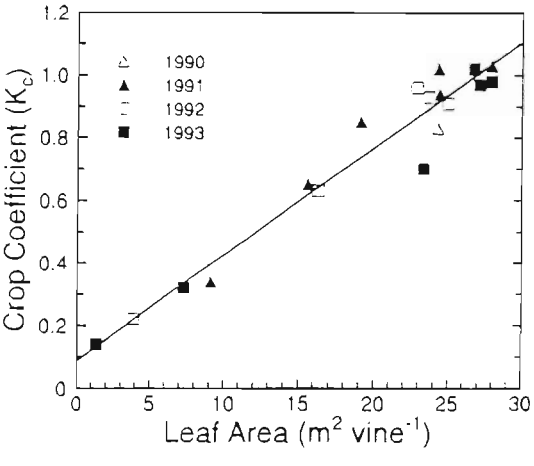

Fig. 8 The relationship between crop coefficient (K_c) and leaf area of Thompson Seedless grapevines calculated over the course of four growing seasons. Leaf area was estimated several times during each growing season. The crop coefficients used in this figure were those calculated for the week that leaf area was determined. Data were fit to the following equation: $y = 0.088 + 0.034x$, $R^2 = 0.94$

0.66: $K_c = 0.1594 - 0.001148*DD - 0.0000003939*DD^2$, $R^2 = 0.78$, respectively). A cubic equation did not improve the R^2 values for the K_c as a function of DOY or DDs. Lastly, the K_c was a linear function of leaf area per vine using data from all 4 years (Fig. 8).

Discussion

The ET_c values measured in this lysimeter study are greater than those reported in several other studies conducted in mature vineyards using different cultivars (Erie et al. 1982; Evans et al. 1993; Oliver and Sene 1992; Saayman and Lambrechts 1995; van Rooyen et al. 1980; van Zyl and van Huyssteen 1980), Thompson Seedless in California (Peacock et al. 1987) and Sultana (syn. Thompson Seedless) in Australia (Yunusa et al. 1997a, 1997b). Our water-use values, however, are similar to those of Grimes and Williams (1990) using Thompson Seedless grown in California and Prior and Grieve (1987) using Sultana grown in Australia. The differences in water use between our study and some of the others cited above are probably due to differences in production practices such a pruning level, trellis size, canopy management practices involving leaf removal, irrigation type and frequency, and prevailing climatic conditions. On the other hand, some of the studies used techniques that are based upon assumptions that may detract from their accuracy, whereas in this study the lysimeter directly measured ET_c. In addition, the high frequency with which the vines in the lysimeter were irrigated (water applied whenever 16 l had been used) resulted in vines that would not have been stressed at any time throughout the growing season. This was confirmed by measurements of midday leaf water potential (Williams et al. 1994).

Maximum daily ET_c in this study was approximately 6.6 mm (50 l per vine) and this occurred when ET_o was 7 mm day^{-1}. Leaf area per vine at this time was in excess of 27 m^2. There are only a few studies where daily grapevine ET_c has been measured or estimated. Stevens and Harvey (1996) reported a maximum daily ET_c of 13.6 mm (119 l $vine^{-1}$) at an ET_o of 11.6 mm for Colombard grapevines grown in Australia and irrigated with full cover microjets. Those vines had a maximum leaf area of 24 m^2 $vine^{-1}$. Daily ET_c of drip-irrigated Sultana grown in Australia approached a maximum of only 3 mm, or approximately 25 l per vine (Yunusa et al. 1997a). Using data presented in the Yunusa et al. (1997a) paper, we calculated that the Sultana vines had a maximum leaf area of 26.8 m^2. Lastly, Heilman et al. (1996) reported a maximum daily ET_c of 5.1 mm (26 l $vine^{-1}$) for Chardonnay grapevines (7.1 m^2 leaf area) grown in Texas and that vine transpiration accounted for 82% of ET_c. Even if the data in the above studies were normalized to a per leaf area basis, there would still be large differences among maximum rates of daily vine water use.

The weighing lysimeter measured ET_c on an hourly basis and there are just a few studies in which comparisons can be made. The use of sap-flow sensors has recently been used to measure transpiration of grapevines and daily and hourly transpiration values have been published (Eastham and Gray 1998; Heilman et al. 1994, 1996; Lascano et al. 1992). Maximum flux density of latent heat in a Chardonnay vineyard in Texas on a diurnal basis was approximately 300 W m^{-2} while that of the canopy (using a sap-flow sensor) was 100 W m^{-2} (Heilman et al. 1994). The maximum flux density on a diurnal basis reported here (Fig. 6) was approximately 600 W m^{-2}. It is doubtful that our value of vineyard latent heat was predominated by soil evaporation, as found in the study by Heilman et al. (1994) since, at the time our measurements were made, the canopy shaded all of the wetted area of the soil beneath the drip line. In a subsequent study, Heilman et al. (1996) determined that more than 80% of the total daily latent heat flux of a vineyard with an open hedgerow canopy (which increased solar radiation interception when compared with Heilman et al. 1994) was due to vine transpiration. This value is similar to estimates by Ayars et al. (2003) with peach trees.

Maximum hourly transpiration of Maroo Seedless grapevines having 13.4 m^2 of leaf area in Australia was greater than 0.4 l h^{-1} (Eastham and Gray 1998). While the leaf area of the Thompson Seedless grapevines used in this study were double that of the Maroo Seedless, maximum hourly ET_c in Fig. 6 was 16 times greater. It was also six times greater when the two are expressed as a function of water use per square meter of leaf area per hour (0.03 l m^{-2} h^{-1} for Maroo Seedless and 0.19 l m^{-2} h^{-1} for Thompson Seedless). Even if soil evaporation accounted for 20% of ET_c in this study our hourly values would still be considerably greater than that for Maroo Seedless. Recently it has been demonstrated that sap-flow sensors may underestimate transpiration on vines with large trunks (Tarara and Ferguson 2001), which may have been the case in the Maroo Seedless study.

The K_c relates ET of a crop under optimum soil water conditions to that of ET_o (Doorenbos and Pruitt 1977). It has been demonstrated that grapevine ET_c/ET_o (Stevens and Harvey 1996) or ET_c/Class A pan evaporation (van Zyl and van Huyssteen 1980) decreases linearly once soil water content decreases below field capacity. The purpose of irrigating the vines within the lysimeter whenever they had used 16 l of water was to insure that water was not limiting vine transpiration. It is interesting that mean soil water content within the lysimeter varied among the 4 years, the driest in 1990 and wettest in 1993, but that maximum water use and K_c were similar at comparable canopy size. The high frequency irrigation used here, even in 1990, would have maintained at least a portion of the soil profile close to field capacity. Phene et al. (1989) have clearly demonstrated this principle with field crops using similar weighing lysimeters.

The seasonal progression of ET_c and K_c reported here reflects the increase in canopy size early in the season up to a maximum, at which time the hedging of shoots maintained the vines' leaf area fairly constant from that

point on. The maximum leaf area estimated for the vines in the lysimeter were similar to those determined in previous studies for this cultivar (Williams 1987a, 1996; Williams and Matthews 1990). We also found that the K_c was a linear function of the leaf area from shortly after budbreak until August. Ayars et al. (2003) found that the K_c was a linear function of the amount of light intercepted by peach (*Prunus persica* L.) trees. It could be assumed that as leaf area increases so would the amount of solar radiation intercepted by our grapevines and the amount of ET_c. The maximum shaded area beneath the vine's canopy at midday in this study was estimated to be approximately 60% of the total land area per vine at which time a K_c of 1.0 was measured. This K_c is similar to that reported by Ayars et al. (2003) when solar radiation interception of the peach trees was 60%.

The seasonal progression of the K_c reported here is similar to that used by others for grapevines grown either in California or elsewhere (Doorenbos and Pruitt 1977; Grimes and Williams 1990; Snyder et al. 1987). This pattern differs from those developed for grapevines grown in the state of Washington (Evans et al. 1993) where the K_c increases more slowly early on, reaches a maximum for a short period and decreases dramatically well before harvest. The maximum K_c values we calculated here were very close to or in excess of 1.0. The maximum K_c reported by Stevens and Harvey (1996) was close to 1.2. Doorenbos and Pruitt (1977) suggested a maximum K_c of 0.75 for vines similar to those used in this study while Grimes and Williams (1990) and Snyder et al. (1987) reported 0.8 as their maximum K_c. The maximum K_c for the lysimeter grown vines was more than double that (0.41) used in a study by Peacock et al. (1987) for Thompson Seedless grapevines grown in the San Joaquin Valley. Peacock et al. (1987) though, calculated the K_c to be a fraction (0.75) of the percent shaded area measured beneath the vine at midday. The maximum shaded area in that study was 55% ($0.55 \times 0.75 = 0.41$). The crop coefficient is dependent upon numerous factors, one of these being variations in soil evaporation depending upon irrigation type and frequency (Jagtap and Jones 1989). The differences in the above maximum K_c value at midseason reported in this study and those also used for Thompson Seedless in the San Joaquin Valley (Grimes and Williams 1990; Peacock et al. 1987) may be due to differences in irrigation frequency and/or scheduling and possibly the method with which ET_c was determined.

The quadratic equation used to calculate seasonal K_c values by Grimes and Williams (1990) would overestimate vine ET in this study early in the growing season for all years studied (1990–1993) and underestimate vine ET late in the growing season. While a quadratic function would fit our seasonal K_c values adequately, it is felt that sigmoid type equations, similar to those used to describe the development of leaf area would be more appropriate to describe our seasonal K_c values either as a function of DOY or DDs. In fact, the linear fit method to calculate the K_c used by Allen et al. (1998) and Snyder et al. (1987) could also be adapted to our seasonal K_c, at least up until late in the growing season. While there was a decrease in the K_c values toward the end of each growing season here, it varied considerably from year to year. As mentioned previously, leafhoppers (*Erythroneura elegantula* Osborn and *E. variabilis* Beamer) were not chemically controlled, beginning with the 1991 growing season, due to a study being conducted in the vineyard surrounding the lysimeter. Just prior to and subsequent to harvest, the third brood generally reaches its peak population numbers. Feeding on grapevine leaves by leafhoppers can decrease stomatal conductance (L.E. Williams, unpublished data) and, at high enough populations, vines can be defoliated. It appeared that, as the years progressed, the populations within the vineyard increased considerably so that by 1993 a precipitous drop in the K_c was due to defoliation. In subsequent years, when leafhoppers were controlled, the K_c remained constant from mid-season up until the end of October (unpublished data).

The use of DDs to plot the seasonal K_c may be better than using DOY. It was shown in this study and elsewhere that leaf area development (Williams 1987a) and phenology (Williams 1987b) of Thompson Seedless grapevines are highly correlated with DDs. The use of DDs would also eliminate early-season variability in vine growth due to weather conditions. Crop coefficients developed at the Kearney Agricultural Center with the weighing lysimeter have been used successfully in the Coachella Valley of southern California to schedule irrigations where budbreak occurs 2 months prior to that in the Fresno area (L.E. Williams, unpublished data). This was accomplished by calculating the K_c as a function of DDs from budbreak for three different cultivars.

Conclusions

The daily water use of high frequency, above-ground, drip-irrigated Thompson Seedless grapevines grown in the San Joaquin Valley of California peaked at values greater than 50 l $vine^{-1}$ (6.6 mm), while seasonal water use was greater than 800 mm the last 3 years of the study. The seasonal water use was 60% of ET_o in 1990 and was 73% of ET_o for the remainder of the study. The maximum K_c calculated in this study was greater than 1. This occurred when leaf area per vine was generally greater than 25 m^2. The K_c was also a linear function of leaf area per vine. The use of degree-days (DDs) was somewhat more useful in predicting the K_c than day of year (DOY).

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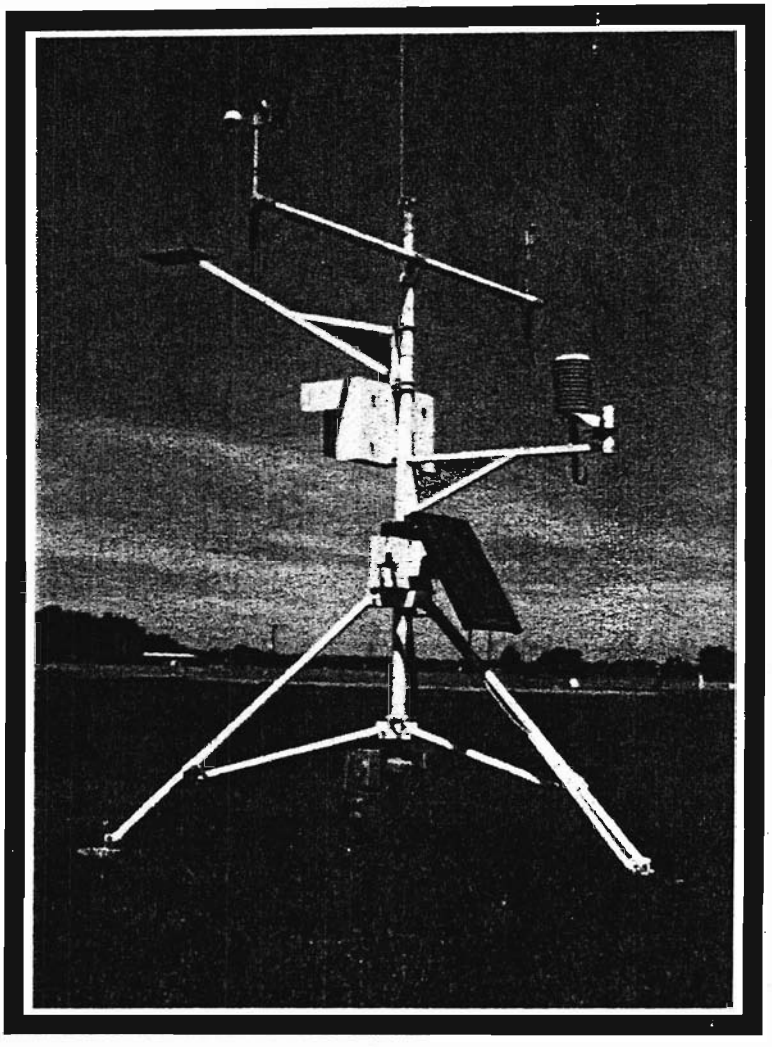
FIFTEEN YEARS OF GROWTH AND A PROMISING FUTURE



December 1997

CIMIS

The California Irrigation Management Information System

State of California
The Resources Agency
Department of Water Resources

FIFTEEN YEARS OF GROWTH AND A PROMISING FUTURE

The California Irrigation Management Information System

Pete Wilson
Governor
State of California

Douglas P. Wheeler
Secretary for Resources
The Resources Agency

David N. Kennedy
Director
Department of Water Resources

FOREWORD

From farmers to golf course irrigators, thousands of water users have found the California Irrigation Management Information System to be an important source of irrigation information. Through the accurate and timely weather data provided by its 94 weather stations, CIMIS estimates plant water usage in many parts of California and makes that information accessible to all.

California's irrigated agriculture and its residential, industrial, and business landscapes depend on water. Because plant growth and yield are directly related to the amount of irrigation water available to satisfy plant evapotranspiration, CIMIS data enables all types of irrigators to make efficient irrigation decisions.

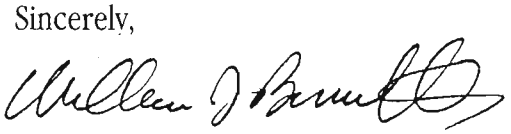
This report summarizes the development and achievements of CIMIS from its inception in 1982 to the present. It describes the status and trend in the growth of the program in terms of stations, number of users, types of users, extent of use, benefits, and future advances.

I would like to thank water agencies, farmers, farm advisors, irrigation specialists, golf course and park managers, and other CIMIS users who, by using and disseminating CIMIS data, have enhanced the program's success. Their efforts significantly help to further advance efficient water use in California.

Information on how local agencies and others can use CIMIS is contained in two publications, *CIMIS Agricultural Resource Book* and *CIMIS Urban Resource Book*. To obtain these or any other materials mentioned in this publication, contact Department of Water Resources' Bulletins and Reports, 1416 Ninth Street, Sacramento, California 95814, or telephone (916) 653-1097.

For further information on the CIMIS Program, contact Baryohay Davidoff, Chief, Agricultural Water Conservation Section, at telephone (916) 327-1788; e-mail baryohay@water.ca.gov, or contact the CIMIS personnel listed on page.

Sincerely,



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Division of Planning and Local Assistance

The Resources Agency

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INTRODUCTION

This report summarizes the development of CIMIS from 1982. It describes the remarkable progress CIMIS has made in terms of stations, number of users, and the many benefits accrued from its use.

Crops and landscaping use over 90 percent of California's developed water supplies for the production of food and fiber and urban beautification. Accurate information on the amount of water lost from the soil surface (evaporation) and the amount of water used by plants (transpiration) is necessary for efficient irrigation. The combined value of these losses for irrigated grass is called reference evapotranspiration (ETo). By evaluating weather information at a site, the CIMIS computer estimates reliable reference evapotranspiration data. This data can then be used by farm and landscape irrigators for efficient irrigation, and by agencies for development of water management plans.

Since 1954, DWR has used evaporation pans to collect ETo data. In 1982, through a joint research and development effort of UC Davis and DWR, the computerized weather station system was established as an additional method to collect the data. In 1985, the administration and implementation of the program and its further development was turned over to DWR. CIMIS stations collect hourly weather data such as solar radiation, wind speed and direction, relative humidity, air and soil temperature, and rainfall. All of this data is transmitted to a central computer in Sacramento where it is checked for accuracy. Based on the weather data, the CIMIS computer estimates reference evapotranspiration at each station site and stores it to provide on-demand localized information.

CIMIS is the major source of ETo and other weather data for many agricultural and landscape water users, farm advisors, and other irrigation specialists. Given the interrelated nature of the supply and demand sides of water management, CIMIS forms the backbone of many management programs on the demand side. It complements supply side programs such as snow surveys, reservoir capacity estimates, and rainfall measurements.

CIMIS is a network of 94 automated and computerized weather stations located at key agricultural and urban areas of the State. The stations collect climatological data and transmit it to a main computer located at 1416 Ninth Street in Sacramento. After quality control of the data, irrigated grass water requirements or a reference evapotranspiration is calculated for each station. The data then is available to the agricultural and urban water users for irrigation of agronomic crops, landscapes, golf courses, and parks.

THE BENEFITS

In 1995, the University of California, Berkeley, Cooperative Extension conducted a survey on the benefits accrued from using CIMIS. The survey results showed yield increases and applied water reductions from using CIMIS. For the 134,000 acres of irrigated agricultural land that the survey represented, an average annual yield increase of 8 percent was attributed to CIMIS. The survey results also found an average applied water reduction of 13 percent. For the 55 growers interviewed, reduction in applied water and the increase in yield amounted to an estimated annual benefit of $14.7 million.

Table 1 shows the amount of money some of the 55 growers saved as a result of using CIMIS. Only a few crops were selected from each of the fruit and nut, vegetable, and field crop categories. The 8,778 acres of landscape in the survey had an annual applied water reduction of 5,793 acre-feet, or water cost savings of $2.3 million.

Nonirrigation-related Benefits

While ***Table 1*** gives benefits from reduction in water use and increases in yield, there are also benefits that are not directly related to irrigation.

CIMIS is used extensively by pest control advisors (PCAs) for integrated pest management. The University of California's statewide Integrated Pest Management (IPM) program obtains data from CIMIS daily. IPM uses CIMIS data to calculate "degree days," which is used extensively by farm advisors and PCAs to advise farmers on pest control. Some growers also use CIMIS data when making pest management decisions. "Degree days" is also used extensively by the produce and canning industries in the prediction of germination, maturity, and harvest dates of many fresh market produce. Pest management benefits include reduced pesticide application, improved crop quality, and reduced risk of crop damage. A clear indication of the benefit of us-

Purpose

CIMIS development began in 1982 as a joint research and development project between the University of California Cooperative Extension, and the Department of Water Resources' Water Conservation Office. The goal was to:

- *Design a system which would use computerized weather data to estimate crop water use.*
- *Disseminate up-to-date quality information to the public.*
- *Provide irrigation scheduling programs to water users.*
- *Provide new methods for educating agricultural and landscape irrigators.*

Background

The University of California completed the research and development phase of CIMIS in 1985 and accomplished the following:

- *Established a network of 43 computerized weather stations.*
- *Developed a data dissemination system accessible by phone and computer.*
- *Determined some crop coefficients.*

Upon completion of this phase, the program was implemented by DWR.

Crop	Water † $	Yield ‡ $	Total $	Benefit/ Acre $
	Fruit and Nut Sample			
Almonds	246,000	2,426,500	2,672,500	165
Apples	900	13,900	14,800	148
Avocados	-141,350*	738,000	596,500	308
Nectarines	225	3,475	3,700	148
Pistachios	370,150	6,755,000	7,125,000	255
Plums	556	12,445	13,000	163
	Vegetable Sample			
Artichokes	2,500	326,200	328,700	66
Broccoli	2,750	106,100	108,850	297
Cauliflower	5,750	334,100	339,850	352
Celery	3,350	345,750	349,100	717
Lettuce	26,000	1,361,000	1,387,000	375
	Field Crop Sample			
Alfalfa	47,790	325,700	373,500	40
Cotton	345,300	810,500	1,155,800	46

†Money saved due to reduced water bill resulting from using CIMIS.
‡Increased income from increased yield resulting from using CIMIS.
*Negative number indicates increased water use with CIMIS

Table 1. Water, Yield, and Total Benefits to Growers from CIMIS

ing CIMIS data in various demand management options is the example offered by Irvine Ranch Water District. The District's allocation of water is based on CIMIS ETo. Its tiered pricing structure is considered more equitable by IRWD's customers when changes in water use due to weather conditions are taken into account.

Other benefits of CIMIS stem from use of CIMIS for air quality management, wildlife management, and fire protection. These benefits are more difficult to quantify.

PROGRESS

Since 1985, the number of stations, registered users, and calls to the CIMIS central computer have more than doubled. This progress is due in part to upgrades in equipment, the addition of new dissemination points, and the outreach activities conducted by the Department of Water Resources.

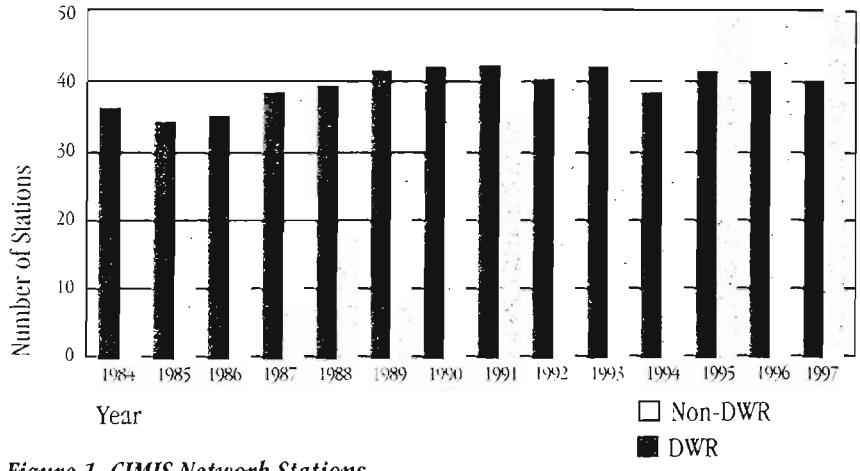

Figure 1. CIMIS Network Stations

CIMIS is the largest standardized automated agricultural weather station network in the nation. The number of weather stations in the CIMIS network has grown from 42 in 1985 to 94 at present. DWR owns 40 stations and the remaining 54 stations are owned and maintained by local agencies. DWR calibrates all stations annually.

Figure 1 shows the increase in the number of both DWR and non-DWR owned CIMIS stations. Additionally, to meet the demands of evolving technologies, the weather station equipment has been and will continue to be upgraded. (***Figure 2*** shows a typical CIMIS station.)

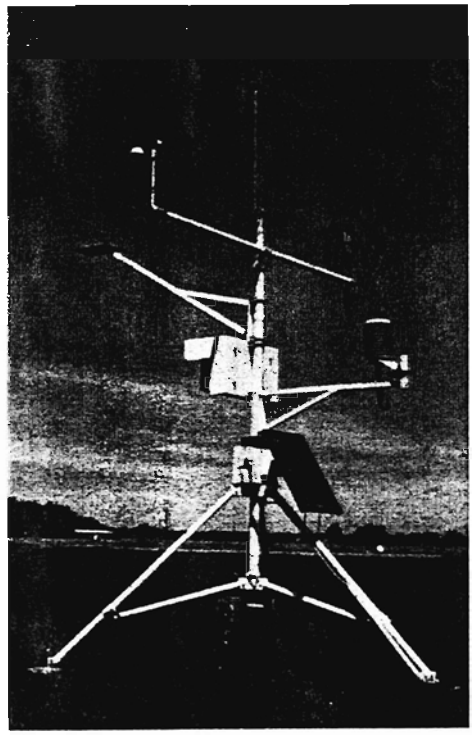

Figure 2. Typical CIMIS Station

STATION LOCATIONS

The locations of current weather stations are shown in Figure 3. In addition to these stations, CIMIS data is also available from 40 historical stations that are not shown in Figure 3. Historical stations are stations that were relocated as a result of a change in land use that did not meet the station site criteria.

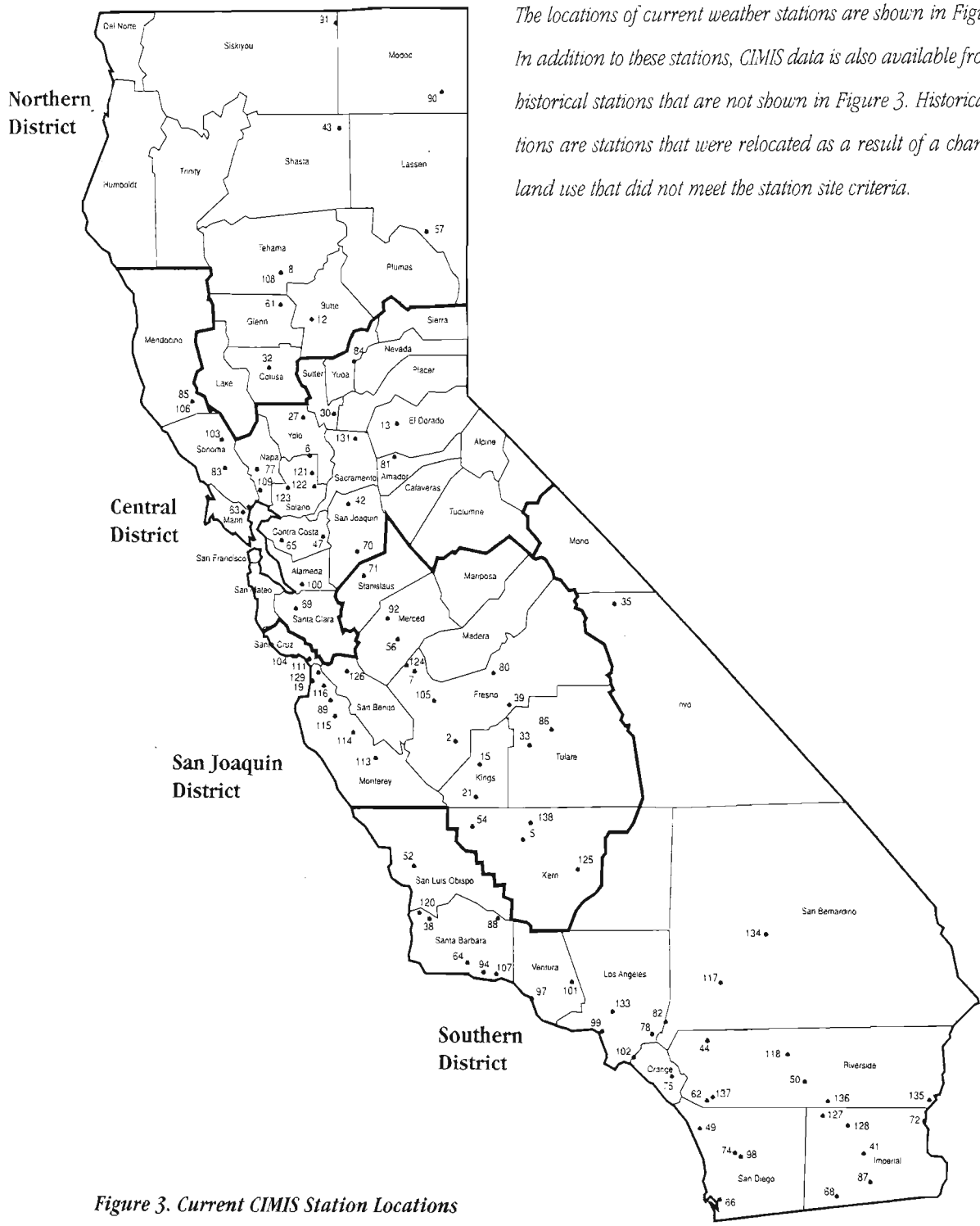

Figure 3. Current CIMIS Station Locations

USER INFORMATION

Registered Users

The fact that thousands of people are registered users of the CIMIS system is evidence of its benefits. As indicated by Figure 4, the number of users has grown from 250 in 1986 to 2,500 in 1996; this is on average a 25 percent increase per year. It is likely that the actual number of direct users is much higher, as some people rely on other's IDs and passwords to access the CIMIS computer. Since the system is unable to discern when several people use one ID, the number of direct users is probably underestimated.

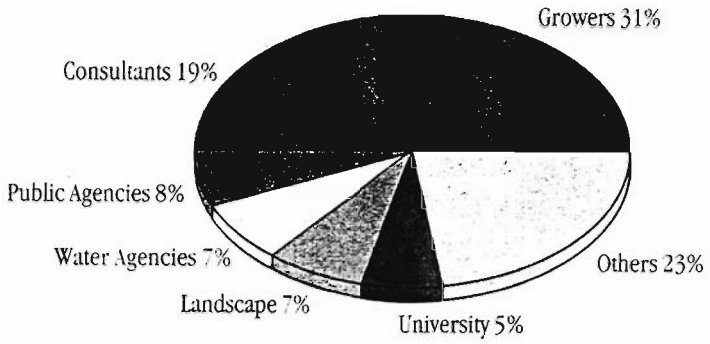

Figure 5. Registered Users Categories

User Categories

Figure 5 presents the CIMIS registered users categories. Although there are several categories of registered users, approximately 50 percent of the users consist of only two user categories--growers and consultants. The growers category includes a wide range of operations, from large agricultural operations to specialty farmers who grow small, intensive truck crops. The consultants category includes both irrigation consultants and nonwater consultants. The nonwater consultants include individuals who do not deal directly with irrigation scheduling. Pesticide applicators, farm product suppliers, farm commodity buyers, engi-

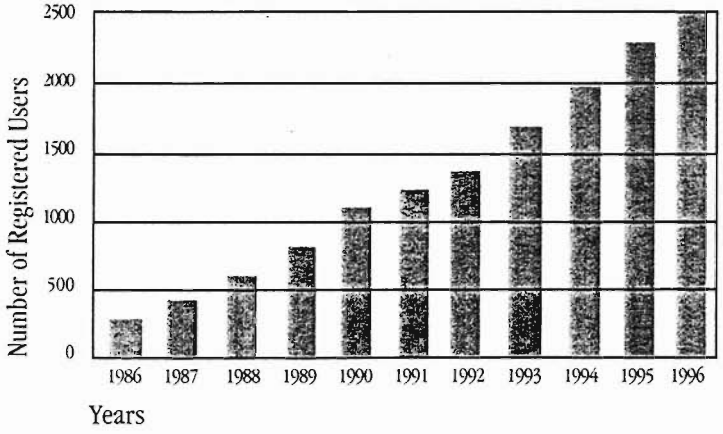

Figure 4. Number of Registered Users

Note: Research and development began in 1982; implementation did not begin until 1985.

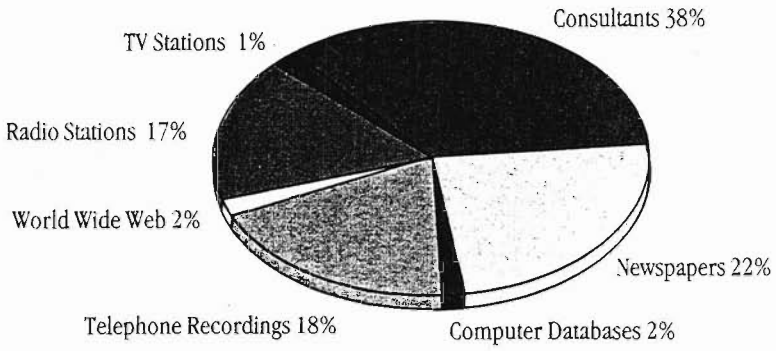

Figure 6. Composition of CIMIS Dissemination Points

neers, weather forecasters, and environmental design firms fall under nonwater consultants. Public agencies, cemeteries, home owners, park and golf course managers, city landscape managers, water agencies, and universities make up most of the remaining 50 percent of users. There is some CIMIS use by nonagricultural groups including the Air Resources Board, wastewater engineers, landscape architects, reservoir designers, lawyers, and private investigators.

Information Dissemination Media

Dissemination of CIMIS data has expanded beyond direct access to the CIMIS computer by individuals. Various groups and organizations now disseminate the information they obtain from the CIMIS computer.

Figure 6 lists seven of these categories. The exact number of people who receive information from some of these sources is impossible to calculate due to their modes of dissemination. Consultants are those who have volunteered to have their names listed on the CIMIS computer. This list does not include all users in the consultants category.

Information Retrieval

Figure 7 shows a progressive increase in the total number of calls to the CIMIS computer from 1985 to 1996. The figure also shows an increase in the number of calls during periods when most crops are not being irrigated. This is most likely because of nonirrigation-related use, or general water management planning in the off season. The number of direct calls to the central computer has averaged about 22,000 each year over the last 3 years. This number represents only direct calls by registered users. It does not include potential dissemination of CIMIS information by these users to others.

The exact number of people who either receive or use information from some of these sources is not known. For example, it is difficult to determine the exact number of people who use CIMIS information received through other computer databases, newspapers, public and private agency newsletters, and radio stations.

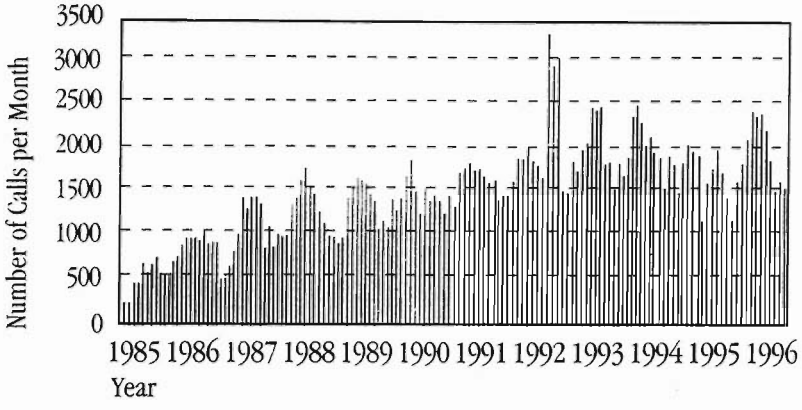

Figure 7. CIMIS Computer Calls

In 1994, 18 consultants were surveyed to find out the extent to which they used CIMIS in their services. Results of the survey showed that 10 used CIMIS data to provide services to 411 urban/agricultural regular customers. The acreage irrigated ranged from small landscapes of less than 1 acre to 40,000-acre farms. A survey of 17 agency telephone recording systems was conducted in 1993 and 1995. The results indicated that the estimated number of calls per month to 4 of the telephone recordings ranged from 20 to 240. There was a high number of calls (18,000 a month) to the National Weather Service (NWS). In addition to CIMIS data, NWS recordings include other data, such as weather forecasts.

Five of the agencies had records of the actual number of calls to their systems. Based on these numbers, the average number of calls to the 5 telephone recording systems was 680 calls per month, or 8,160 a year. The potential number of calls to all 17 telephone recordings is 27,000 calls per year.

OUTREACH ACTIVITIES

During the past ten years, DWR, in cooperation with other agencies, has developed information materials on CIMIS and DWR, in cooperation with farm advisors, State Universities, the University of California, and other public and private agencies. DWR also has ongoing irrigation workshops and experiments to determine crop coefficients. A package, CIMIS Alert, has been developed to assist agencies in setting up telephone recording systems. Additionally, *CIMIS Agricultural Resource Book* and *CIMIS Urban Resource Book* have been developed. These books provide comprehensive information for the whole CIMIS program and have examples of how public and private agencies are using CIMIS. They will reduce the research time for other agencies who may want to prepare a water management plan or irrigation scheduling program.

DWR recognizes the important role private consultants, farm advisors, and other irrigation specialists play in bridging the gap between data provided by CIMIS and irrigation scheduling. DWR has encouraged them to play an active role in assisting irrigators. DWR has provided a free listing of consultants and commercial irrigation scheduling software on the CIMIS computer, and also provides financial support to the University of California, California State University, and other public entities for workshops and research on development of crop coefficients, water management, and irrigation scheduling. The increase in the number of irrigation scheduling software programs that use CIMIS data and CIMIS-related workshops and classes is evidence that these specialists are playing an active role in promoting the use of CIMIS data.

What CIMIS can do for you...

Provides weather data to estimate crop water use

Disseminates up-to-date quality information

Determines crop coefficients

FUTURE OF CIMIS

To continue the success of the program, new developments and improvements must be undertaken to meet new challenges and technological advances. CIMIS will continue to help users deal with irrigation management problems by providing accurate and timely information needed for efficient water management. As part of updating CIMIS technology, a new computer came on line in August 1995. To take advantage of the recent public exposure to the internet, DWR has made access to the new computer available viaTelnet (aviion.water.ca.gov), in addition to accessibility by modem. A CIMIS home page has been developed and provides an additional avenue for CIMIS information and data dissemination. The world wide web address for the home page is http://wwwdpla.water.ca.gov/cgi-bin/cimis/cimis/hq/main.pl. The items in the sidebar below describe the major areas for CIMIS development as identified by CIMIS staff.

Development

- *Increasing public awareness of CIMIS data as a prime water demand-side management tool, and promoting its use in water management decisions.*
- *Increasing visibility of CIMIS and CIMIS data in news and information media such as television, newspapers, newsletters, radio, and the world wide web will help increase public awareness. This will be accomplished by developing a daily, weekly, and monthly ETo index that is easily understood by the public.*
- *Emphasizing the importance of CIMIS data in residential, industrial, and golf course irrigation.*
- *Adapting the latest information and computer technology to continue providing user friendly access and data retrievals. This will include use of point-and-click computer technology to retrieve information with minimal or no text writing.*
- *Expanding local dissemination of CIMIS data. Local dissemination of data may involve specific agricultural commodity groups dealing with tomatoes, almonds, avocadoes, cotton, vegetables, pears, peaches, grapes, and landscape and golf course entities.*
- *Developing a state-of-the-art methodology for short-term ETo forecasting for irrigation scheduling purposes.*

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ANEXO3

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